University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Offshore Technology Marine and Subsea Technology	Spring semester, 2013 Restricted access
Writer: Maria Urycheva	……МУ…… (Writer's signature)

Faculty supervisor: Professor Ove Tobias Gudmestad

External supervisors: Professor Anatoly Borisovich Zolotukhin (Gubkin University)
Kai B. Olsen (Ramboll)

Title of thesis:

New jack-up concept for Arctic conditions

Credits (ECTS): 30

Key words: Offshore, Arctic, Drilling rig, Jack-up, Drilling season, Design ice load	Pages: …68…… + enclosure: …13…… Stavanger, 14.06/2013 Date/year

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Abstract

Arctic exploration is one of the main trends in today's oil and gas industry. In shallow waters jack-up mobile drilling units are often used for drilling outside the ice season. The operating period of the jack-ups is strictly limited by the ice conditions. The jack-up should be transported to the site after the ice cover has cleared sufficiently and should be moved away before the sea freezes up.

A new concept of jack-up suggested by Ove T. Gudmestad (University of Stavanger) is considered in this thesis. The concept comprises a hull with icebreaking capabilities and four columnar legs placed on outrigger arms and equipped with protective collars so the jack-up can withstand ice loads in the early ice period. Drilling through one of the jack-up legs is suggested to protect the drill string from the ice impact. The leg should have a telescopic design so that the derrick could be skidded over it before drilling.

The purpose of the thesis is to evaluate the feasibility of a concept suggested for extended drilling season in Arctic waters. The important design issues i.e. protective collar geometry, required air gap, telescopic leg design, collar fixation system etc. are discussed. Wave and ice loads on the jack-up legs are calculated and the possible extension of the drilling season is estimated. The benefits of the new concept and its potential applications are discussed.

Поиск и разведка углеводородов на арктическом шельфе в настоящее время является одним из главных направлений развития нефтегазовой отрасли. Самоподъемные буровые установки (СПБУ) часто применяются для бурения на малых глубинах в летний период. Буровой сезон для СПБУ строго ограничен началом образования ледяного покрова. СПБУ может быть доставлена на место бурения только после того, как водная поверхность в достаточной мере очистится ото льда, и должна покинуть буровую площадку до того, как образуется лед.

В данной работе рассмотрена новая концепция СПБУ, предложенная профессором Уве Т. Гудместадом (Университет Ставангера). Новый дизайн включает ледостойкий корпус и четыре цилиндрические опоры, размещенные на выносных основаниях. Опоры оснащены конусообразными защитными конструкциями, снижающими ледовые нагрузки. Предложенный метод бурения через одну из опор СПБУ позволяет защитить буровую колонну от воздействия льда. Опора, используемая для бурения, должна иметь регулируемую длину.

Основной задачей данной работы является оценка технической применимости новой концепции для бурения в Арктике. Рассмотрены следующие аспекты проектирования: размеры и форма защитных конусов, требуемая высота подъема корпуса над уровнем моря, раздвижная конструкция опор, система фиксации конусов на опорах и др. Рассчитаны волновые и ледовые нагрузки на опоры СПБУ при бурении, проведена оценка продолжительности бурового сезона. Рассмотрены потенциальные области применения и преимущества новой концепции.

Acknowledgments

I would like to express my deep appreciation to my faculty supervisor, Professor Ove Tobias Gudmestad, who provided me the opportunity to investigate and to develop such an interesting topic. I am thankful very much for all his time, support and a great possibility for me to learn during this Master Thesis writing and the whole study period.

I sincerely appreciate the support and wise advices of my supervisor from Gubkin University, Professor Anatoly Borisovich Zolotukhin. I am very grateful to him for the unique opportunity to gain an experience of international education.

I am especially thankful to my external supervisor Kai B.Olsen and senior chief consultant John Wægter for their valuable comments and advices during the meeting in Esbjerg which contributed a lot to this study.

I wish also to thank my student colleagues and friends Boris Morozov for a useful discussion concerning the drilling process and Vadim Kutushev for his advices concerning the calculation of hydrodynamic loads.

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Nomenclature

Symbols

Latin characters

a	water particle acceleration	H_R	load to push the ice blocks up the slope trough the ice rubble
a_0	hull elevation above the mean water level	H_s	significant wave height
C_D	drag coefficient	H_T	load to turn the ice block at the top of the slope
C_M	inertia coefficient	h	distance from the high water level to the top of the cone
c	cohesion of ice rubble	h_i	ice thickness
D	cylinder diameter	h_r	rubble height
D_{cone}	cone diameter	$h_{ride\text{-}up}$	ice ride-up thickness
D_{leg}	leg diameter	h_t	circular tide
d	water depth with tide	KC	Keulegan Carpenter number
d_w	water depth	k	wave number
dq	quantity of heat conducted upward through the ice per unit area	k_i	mean thermal conductivity of ice
dt	time unit	l	cone height
E	elastic modulus	l_c	total length of the circumferential crack
E_1	complete elliptical integral of the first kind	l_f	latent heat of fusion of ice
E_2	complete elliptical integral of the second kind	R_p	return period
e	keel porosity	r_1	inner top radius of the cone
F_b	Archimedes force	r_1'	outer top radius of the cone
F_D	drag force on a slender cylinder per unit length	r_2	inner bottom radius of the cone
F_g	gravity force	r_2'	outer bottom radius of the cone
F_H	horizontal component of drift ice load	T	peak wave period
F_i	inertia force on a slender cylinder per unit length	T_a	mean ambient air temperature
F_{ice}	characteristic value of the ice action	T_m	melting point temperature of ice
F_V	vertical component of drift ice load	u	water particle velocity
F_w	wave load on a slender cylinder per unit length	u_a	amplitude of water particle velocity
g	gravity acceleration	V_1	volume of the cone
H	linear wave height	V_2	buoyancy element volume
H_B	breaking load	W	leg diameter with rack teeth
H_L	load required to lift the ice rubble on top of the advancing ice sheet prior to breaking it	w	structure width
H_P	load component required to push the sheet ice through the ice rubble	w_T	top diameter of the cone
		Y	Tresca yielding criterion

Greek characters

α	inclination angle of the structure surface from the horizontal	ρ_i	ice density
Δ	cone wall thickness	ρ_s	stainless steel density
ϕ	velocity potential function	ρ_w	water density
η	wave surface function	σ_f	flexural strength
λ	wave length	ω	wave angular frequency
μ	coefficient of kinetic friction between the ice and structure surface	ξ	relationship between the vertical and horizontal component
μ_i	ice-to-ice friction coefficient	θ	angle the rubble makes with the horizontal
υ	Poisson ratio	φ	friction angle of the ice rubble
ρ_a	air density		

Abbreviations

ABS	American Bureau of Shipping
BOP	Blow-out Preventer
BTOE	Billion Tons of Oil Equivalent
CE	Wave Crest Elevation above still water level
DNV	Det Norske Veritas
DP	Dynamic Positioning
ELIE	Extreme-level Ice Event
FDD	Freezing Degree-days
GRE	Glass-fiber Reinforced Epoxy
GSP	Grup Servicii Petroliere
HAT	Highest Astronomical Tide
HPJDR	High Pressure Jack-up Drilling Riser
HVAC	Heating, Ventilation and Air Conditioning
IACS	International Association of Classification Societies
ISO	International Organization for Standardization
MODU	Mobile Offshore Drilling Unit
MWL	Mean Water Level
MYADS	Mobile Year-round Drilling System
P&A	Plug and Abandonment
PC	Polar Class
PCD	Pre-positioned Capping Device
PIP	Preliminary Information Package
RMRS	Russian Maritime Registry of Shipping
SE	Surface Elevation above mean water level
SPS	Sandwich Plate System
SWL	Still Water Level
ULS	Ultimate Limit State
WIV	Windfarm Installation Vessel

1. Introduction

1.1 Background

Hydrocarbon exploration and development in Arctic is one of the main trends in today's oil and gas industry. According to recent estimations, by 2035 the demand for oil and gas will grow globally by 18% and 44%, respectively [11, p.7]. Huge resources, expected to be present in the Arctic area, force the industry to explore the deposits of the Arctic seas, though such exploration is very challenging.

The level of Arctic exploration, however, is relatively low at present. For example, in the Russian sector with estimated resources of 100 BTOE [11, p.13] one exploratory well is drilled approximately per 9,000 km^2 in the Pechora Sea and per 80,000 km^2 in the Kara Sea [11, p.31].

The main reasons for such low exploration activity are high risks and big expenditures for drilling in the Arctic. New technologies are needed to reduce drilling costs and to increase the efficiency of the drilling process.

1.2 Problem statement

Jack-up units and floating mobile offshore drilling units (MODU's) are normally used for drilling in Arctic areas. Conventional jack-ups can be utilized only in open waters. The installation of a jack-up can take place after the ice cover has cleared sufficiently for the jack-up to be maneuvered to site. At the end of drilling season the jack-up should be moved away before the sea freezes up and the jack-up could get stuck in the ice cover [12].

Even during the open water season ice floes can present a significant hazard for jack-up legs vulnerable to impact loads. Due to that, floating MODU's are often used even for shallow waters (less than 50 m) in case the drift ice is present on the site. But floating MODU's can have significant downtime due to the limited offset in shallow waters and typically require the control well equipment to be placed in a seabed cellar [13].

A jack-up which could withstand some level of ice loads and thus have an extended operational period is expected to be a more effective option for drilling in shallow Arctic waters.

1.3 Purpose and the scope of work

This research is focused on a new possible concept of jack-up for Arctic conditions which is able to start drilling earlier than conventional jack-ups and leave the drilling site after the ice has already started to form.

Development of any new concepts is a long-term process involving a number of specialists in design and construction. The scope of this work as a Master Thesis is limited to some specific issues of the new jack-up design which are, from the author's point of view, relevant for operations in Arctic.

The purpose of the present work is to investigate the feasibility of the suggested concept; to describe and analyze the main features of the rig design such as the shape of the legs and the hull, protective collar geometry, drilling through the telescopic jack-up leg etc.; to estimate the applicability of the new jack-up for Arctic conditions and the possibility to extend the operational season. Level of ice loads which the considered jack-up can withstand during operations is, by the author's opinion, a critical parameter for the drilling season extension. Thus, the jack-up ice load capability has been investigated in more detailed. Particular attention is paid to the design features contributing to the jack-up ice resistance (ice protective collar geometry and fixation system, drill string protection) and to the calculation of the acceptable ice loads during operations for the specific drilling location (the Pechora Sea waters). As a result, the potential drilling season extension has been estimated and some specific fields of the new jack-up application have been discussed.

The research covers:

- Brief analysis of the drilling rig market today
- Study of jack-ups utilized for drilling in Arctic nowadays
- Investigation of modern jack-up concepts suggested for this area
- The detailed description of a new solution proposed including:
    - hull and leg geometry
    - protective collar design and fixation system
    - telescopic leg design
    - drilling through the jack-up leg
    - winterization issues
- Investigation of theoretical basis for calculation of environmental loads on offshore structures
- Analysis of the optimal protective collar geometry
- Estimation of the air gap required
- Calculation of the environmental loads on the jack-up legs during operations
- Analysis of ice growth speed and possibility to extend the drilling season
- Discussion of possible areas of application for the suggested concept.

1.4 Thesis organization

Chapter 2 (State of the art for Arctic shallow water drilling) contains a brief analysis of the drilling rig market; describes the main features of a conventional self-elevating drilling platform; gives an overview of the jack-up drilling rigs utilized in Arctic and a new jack-up concepts suggested for this area; considers a possible combination of the jack-up and a ship design with reference to self-elevating installation vessels.

Chapter 3 (Description of the new concept) addresses the main aspects of the new concept, i.e. shape of the jack-up hull and legs, ice protective collars, jacking system, telescopic leg design and winterization. A detailed description of the concept with relevant sketches is given.

Chapter 4 (Theoretical basis for environmental load calculation) provides the theoretical basis for the calculation of environmental loads on the offshore structures. A relevant wave theory is chosen for a particular Arctic area (the Pechora Sea region). Two approaches to ice action calculations, i.e. elastic beam bending method and plastic method, are described.

Chapter 5 (Analysis of the protective collar geometry) contains the discussion of the geometrical parameters of the protective collars. The choice of the cone height and upward/downward sloping is explained, and an optimal sloping angle is determined based on a sensitivity analysis for the environmental loads. A possible geometry of buoyancy elements is suggested.

Chapter 6 (Calculation of environmental loads on jack-up legs) includes the estimation of the required air gap for given wave conditions, calculation of the design wave load on the jack-up legs and the estimation of the acceptable ice thickness for drilling operations.

Chapter 7 (Benefits of the new jack-up design) addresses the potential benefits of the new concept. The chapter contains an estimation how the drilling season can be extended due to ice capabilities of the new jack-up for the conditions of the Pechora Sea. It also comprises the discussion of some specific requirements and legislations for drilling in Arctic areas where the suggested jack-up can potentially be utilized.

2. State of the art for Arctic shallow water drilling

2.1 Offshore drilling rig market today

Today the market of offshore drilling rigs is huge. Of the 145 countries with a coastline, 51 had at least one drilling rig operating during 2010-2012 [7]. The offshore rig activity in 2012 has even exceeded the peak level of 2008 (Figure 1 [8]).

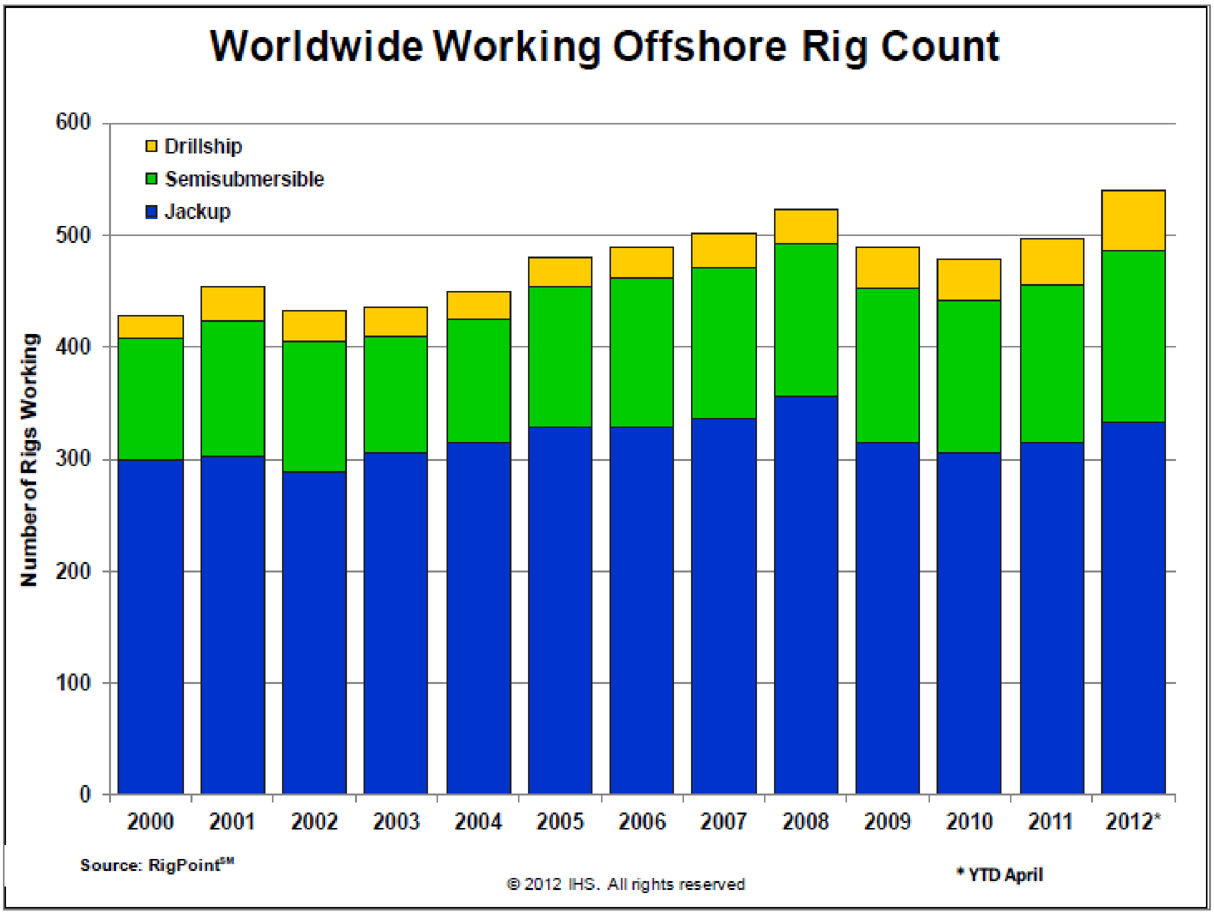


Figure 1 Jack-up supply and demand [8]

In 2010, drilling services generated approximately $45 billion in worldwide revenue and the new-build market supplied $18 billion in jack-ups, semisubmersibles and drill ships. The secondhand market realized approximately $7 billion in market exchanges and about $2 billion was spent on rig upgrades [7]. Over 60 rigs are planned to be delivered in 2013, 42 of them – jack-up drilling modules [8]. Some experts forecast that drilling rig market will suffer from oversupply. For example, according to IHS analysis the gap between jack-up rig demand and supply in North West

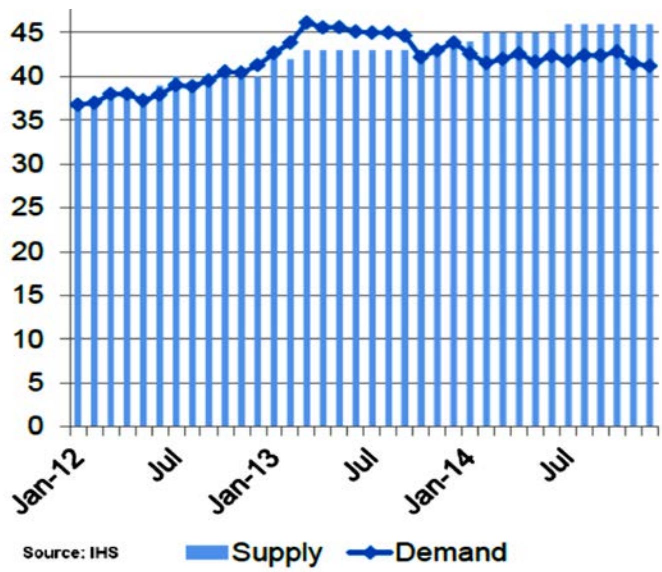


Figure 2 Offshore rig activity [8]

Europe will decrease in 2013 and the market will be oversupplied to the beginning of 2014 (Figure 2 [8]).
The cost of offshore jack-up rig varies with jack-up class and water depth capability. The average price in 2012 was about 170-180 million USD (Figure 3 [7]).

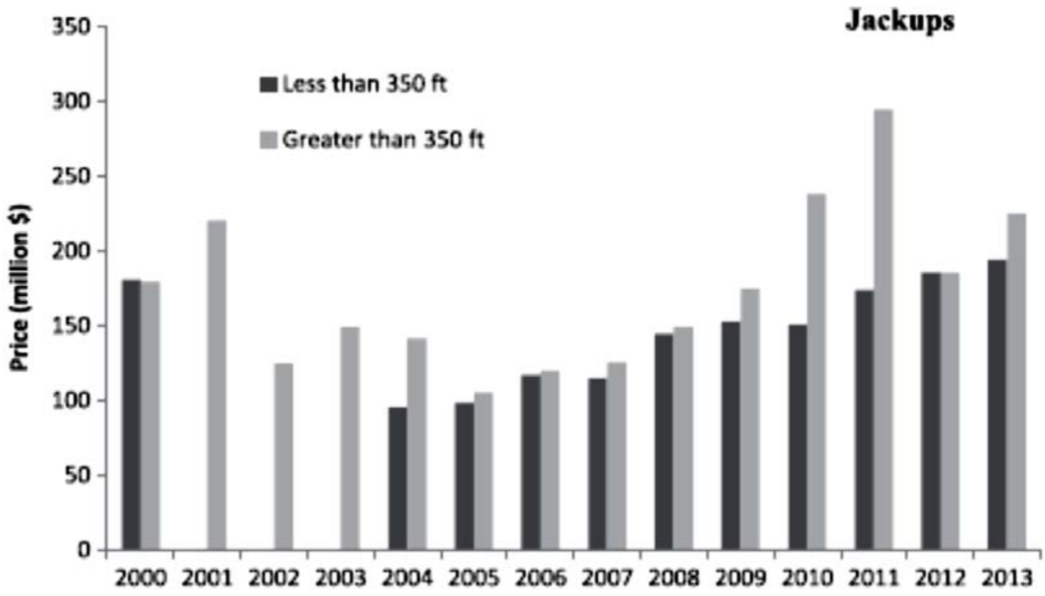


Figure 3 Average cost of jack-up deliveries [7]

When it comes to Arctic region, prices become much higher. Claudia Mahn, Energy Analyst North American, Northwest Europe and the Arctic (IHC), defines the following cost inflating factors [14]:

- Harsh operational environment
- Limited ice-class rig availability
- Cost of winterization/Arctic equipment
- Costly regulatory requirements
- Domestic rig-building capacity.

Jack-up day rates for Arctic region jack-ups increased and are nowadays close to 600,000 USD/day for some areas (Figure 4 [14]). This apparently leads to huge increase of well construction costs in Arctic and Sub-Arctic - from 50 million USD in Norwegian Barents Sea to 250 million USD for East Greenland (Figure 5 [14]).

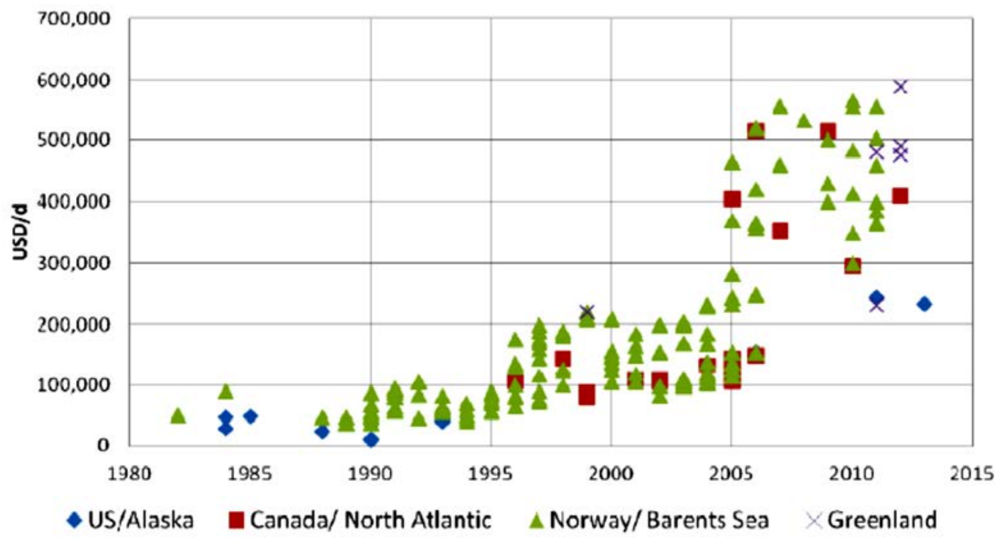


Figure 4 Arctic Offshore Rig Day Rates in Comparison 1984-2013 [14]

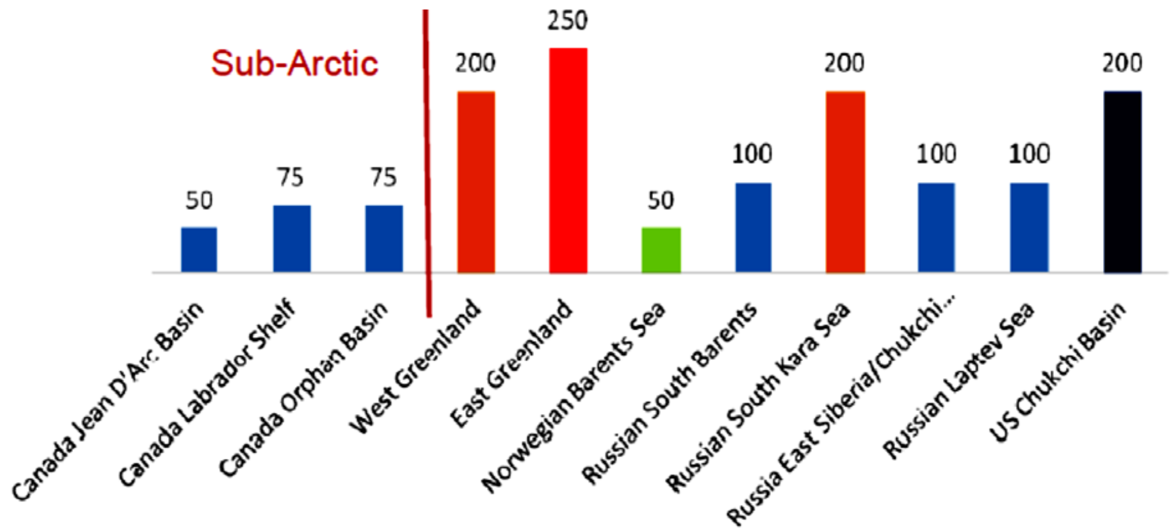


Figure 5 Representative exploration well costs for Arctic Offshore Basins (USD mil.) [14]

2.2 Traditional jack-up drilling unit

Since the first jack-up was built in 1954, jack-ups have become the most popular type of the drilling units for offshore exploration and development purposes [15]. On October, 2012 the world fleet of jack-up drilling rigs contained 493 installations in operation worldwide [16].

"**A self-elevating unit** or **jack-up** is a mobile unit having a hull with sufficient buoyancy to transport the unit to the desired location, and that is bottom founded in its operation mode. The unit reaches its operation mode by lowering the legs to the seabed and then jacking the hull to the required elevation" [17].

Jack-ups are widely used for exploration purposes basically because they have several advantages over floaters, i.e.:

- Jack-ups do not have heave motion and have very limited horizontal motion (maximum 1 m). It allows keeping the blow-out preventers (BOP) at the deck level. Well control,

especially in deep drilling at high pressure, is easier and more reliable with BOPs on the jack-up deck rather than on the seabed.
- The operating costs of a jack-up in drilling are lower than the costs of a semisubmersible (fewer personnel and simpler equipment) [18, p. 16].

Jack-up construction and operation costs are specified mostly by its class and operating water depth. The design of jack-up may vary according to the region and is characterized by:

1. Type of legs

Modern jack-up platforms usually have three or four legs but practically may have up to 6 legs. The legs are normally vertical, but also can be slightly tilted legs for better stability in the elevated condition. The legs are usually either designed as tubular with a circular or square cross section, or as trussed structures with triangular or square cross sections [18, p. 10].
Open-truss or lattice legs are made of tubular steel sections that are crisscrossed making them strong and light. Columnar legs represent huge steel tubes. Columnar legs are less stable and cannot adapt to stresses in the water as well as open-truss legs [15] but they can withstand higher impact loads and are easier to fabricate.

2. Foundation mode

Foundation mode jack-up units can be distinguished as independent leg jack-ups and mat-supported jack-ups.
Independent leg jack-ups are equipped with individual footings, called spud cans, spud tanks or doughnuts. Modern independent leg jack-ups have three lattice legs. Mat-supported jack-ups rest on a single footing (bottom mat or mud-mat or mat) connecting all the legs together. This mat is comparable in size or larger than the platform. Mat-supported jack-ups are only used in soft soils [18, p.7].

3. The operating water depth

The required leg length depends primarily on the water depth, which therefore determines jack-up's suitability for a given location [19]. The water depths for jack-up operations have grown rapidly in the past three decades, rising from about 20 m in the Gulf of Mexico in 1960 to 100-120 m in the North Sea in 1990. The maximum operating water depth of jack-ups depends on the environmental conditions and the penetration of the legs into the seabed [18, p.10-13]. The modern jack-ups can operate in a water depth up to 500 feet (~152 m) [16].

The tendency of further jack-up development is to design jack-ups for bigger water depths and extremely harsh environmental conditions, particularly for the Sub-Arctic and Arctic areas.

2.3 New concepts suggested for drilling in shallow Arctic waters

The exploration activity in the Arctic is growing fast. In March, 2013 Gazprom Neft contracted the GSP Jupiter, a jack-up drilling rig, owned by GSP Offshore (Romania). The operations are planned to start in the beginning of June and will be carried out in Dolginskoye oil field, located in the Pechora Sea, in the south eastern part of the Barents Sea, on the Russian continental shelf [20].

The GSP Jupiter is an offshore drilling unit built in 1987 and converted to cantilever jack-up in 2007 (see Figure 6 [1]). It has 4 triangular 400 feet long open-truss legs and can operate in water depths up to 300 feet (91 m). Basic dimensions of hull are 52.4 × 40.8 × 6.4 m. The rig satisfies ABS requirements and is able to operate in hard weather conditions (see Table 1 based on materials [3]):

Figure 6 GSP Jupiter [1]

Table 1 Operational and storm conditions for GSP Jupiter [3]

Operating conditions		
Wave height	37/9.1	feet / meter
Wave period	12	second
Wind speed	50 / 25.7	knots / m/s
Surface current speed	2/1	knots/ m/s
Storm conditions		
Wave height	39 / 11.9	feet / meter
Wave period	10	second
Wind speed	86 / 44.2	knots / m/s
Surface current speed	2/1	knots/ m/s

Obviously, such type of jack-up can operate only in open water. Conventional jack-ups can perform drilling in the shallow Arctic waters for about 45-90 days during the summer season. Sometimes this period is shortened even more by special state regulations, e.g. drilling shall only take place outside the fish reproducing period [21].

So there are several attempts made nowadays to extend the operational season of jack-ups thus reducing day rates and increasing the effectiveness of the drilling process.

One of the concepts proposed for Arctic conditions is the jack-up **“Arkticheskaya”** constructed in “Zvezdochka” shipyard for Gazprom (Figure 7 [9]). The jack-up hull comprises the rectangular pontoon and three trapezoidal outriggers. Drilling and production equipment and power unit are located in the pontoon. Ballast tanks, elevating mechanism, anchor winches and capstans are placed in the outriggers [22].

The jacking system is presented by three legs of truss-girder construction, each of them is equipped with rack-and-pinion hoisting devices with electromechanical drive [23]. The jack-up deck contains drilling unit, living quarter for 90 person, a helideck and 2 cranes with 40 ton capacity each. The jack-up is transported by towing (not self-propelled) [22].

New materials have been applied for this jack-up construction. Cherepovets factory “Severstal” (Russia) produced high-strength cold resistant steel specially intended for the rig support structure, the jacking system and the hull [24].

The main parameters for this jack-up are presented in Table 2 [22]. As can be seen from the table, the jack-up can withstand ice cake/brash ice loads.

Table 2 Main characteristics of “Arkticheskaya” jack-up platform [22]

Operational criteria		
Depth of drilling	6500	m
Number of wells	12	-
Crew	90	people
Exploitation conditions (extreme)		
Water depth	7-100	m
Wave height (1%)	15	m
Current velocity	0.5	m/s
Outside temperature during operations	From -30 to +30	°C
Ice conditions	Brash ice	

Figure 7 Arkticheskaya jack-up [9]

Another concept for Arctic shallow water drilling is an ice-worthy jack-up **"Gemini"** developed by Keppel Offshore & Marine and ConocoPhillips (see Figure 8 [10]). During the open sea season the potential rig will work as a conventional jack-up. When the ice forms the jack-up legs will be held in place by spud cans to prevent the lateral movement of the platform. The hull is specially designed to withstand ice loads and will be lowered into the water when the ice starts to form. The rig will be equipped with dual cantilevers to perform drilling operations during the limited operational season.

According to the patent [25], the concept will comprise:

- The hull with relatively flat shape of the upper part and an inclined shape of the lower part. Ice-bending shape extends from the deck level to the bottom of the hull, it is intended to direct ice around the hull and not under the hull;
- At least three truss form legs
- A jack-up device to both lift the leg from the sea bottom and push them down to the seafloor for installation. Also it is to push the hull up so that ice-breaking surface will interact with ice floes and fully out of the water in open water period
- Ice shields to protect the truss form legs from ice floe impact.

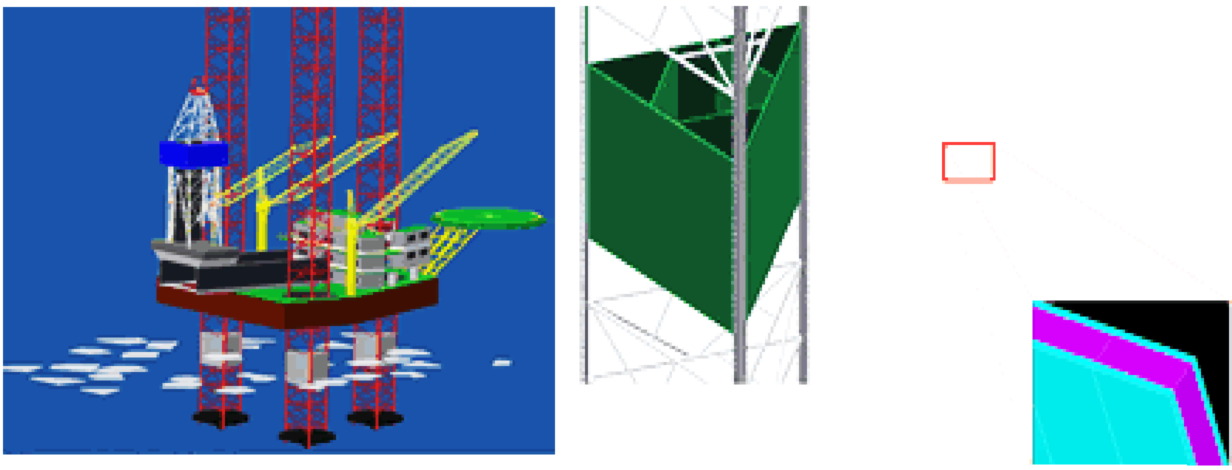
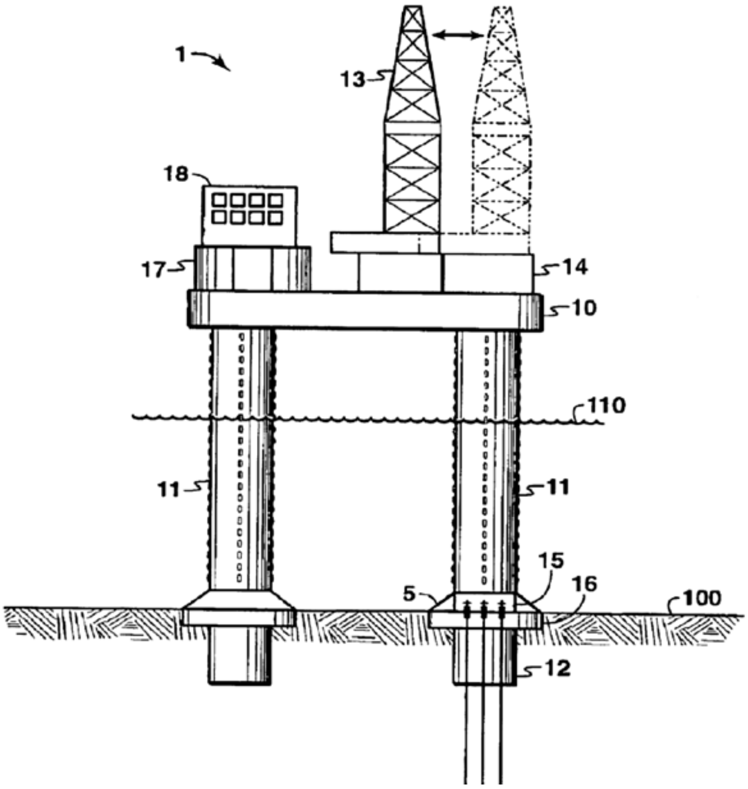


Figure 8 "Gemini" concept and an example of ice shields constructed from a composite material [10]

The ice shields are implemented to prevent the accumulation of ice rubbles within and between the jack-up legs [10]. The example of ice shield made from composite materials is presented on Figure 8. Due to extended area of interaction the ice load on such protective shields will increase in comparison with the open-truss structure. As an alternative, cone-shaped protectors are considered in the concept. These protective cones can be lowered from the hull when necessary. To prevent the ice build-up around the legs, the cones may be jacked up and down along the legs.
The jack-up is designed to be towed even in the harshest ice conditions including impacts from multi-year ice floes and ridges [26].

In 2007, C.R.Brinkmann and G.F.Davenport (ExxonMobile Upstream Research Company) patented a **mobile, year-round drilling system (MYADS)** [5] for drilling offshore wells and performing other activities in the Arctic and Sub-arctic environments. The jack-up contains a hull, two tubular legs with foundation and a drilling rig. The legs consist of an outer plate and an inner plate. The annulus between them is supposed to be filled with a bonding agent (see Figure 9 [5]).



1-MYADS
5-ice protective cone
10 –hull
11-legs
12-foundation system
13-drilling rig
14-skid beam
15-wellhead silo system
16-scour skirt
17-protective jack house
18-helideck
100-seabed
110-water level

Figure 9 Side view of MYADS [5]

“The jack-up is supposed to resists sub-arctic ice forces using "portalling action," in which the primary resistance to ice loading is mobilized through bending of the legs. The portalling action is the reaction of a portal frame to a load or force and is particularly relevant to the resistance of a bending force. In the present invention, the portal frame includes the legs of the MYADS and the platform connected to the legs. An increased leg diameter (outer plate diameter up to 20 m and greater) is preferable to increase the bending load resistance, which resists the ice forces” [5]. Drilling may be performed through one of the legs or through the ice-resistant caisson.

So, the resistivity of jack-up to some ice loads can be achieved by application of:

- cold-resistant materials
- tubular shape of the legs
- protective ice shields and cones
- reinforced multilayer structure of legs
- modified hull shape to withstand loads during transportation.

2.4 Self-elevating installation vessels

The idea considered in the thesis comprises a combination of the conventional jack-up and the icebreaking ship. Combination of jack-up unit and a ship is widely used for offshore wind turbine installation. Installation vessels are designed as ship-shaped self-elevating units, usually self-propelled.

One of the recent examples is a **Windfarm Installation Vessel (WIV)** designed and constructed for Swire Blue Ocean (Denmark) in 2012 (Figure 10 [6]). The vessel is equipped with 6 truss-type legs and a high-speed rack-and-pinion jacking system, and it is able to jack to a safe height of 22 m above the sea surface in 75 m water depth, where it can survive even the most severe storm conditions [6].

Some vessels have tubular legs, e.g. **“Sea Installer”** built for A2Sea (Denmark) in 2012 (Figure 11). This vessel can operate in three “modes”, is self-propelled and fitted with accommodation for two full installation crews:
• Floating crane vessel with restricted crane loads;
• Semi jacked-up vessel with reduced load on the legs for harbour use and on sites with difficult soil conditions;
• Fully jacked-up vessel [4].

The vessel has 4 columnar legs (83 m long) and a double hydraulic jacking system. The operating water depth is from 6.5 to 45 m with maximal significant wave height of 2 m for jacking operations.

Figure 10 Windfarm Installation Vessel (WIV) [6]

Figure 11 SEA INSTALLER [4]

Inwind Installer NG-10000-X3 (Figure 12 [27]) which is a 3-legged self-propelled DPII jack-up vessel represents a development from a more traditional offshore jack-ups with braced legs and a triangular jack-up hull. The hull shape has been further optimized to improve transit capabilities and forward speed. The vessel can perform installation operations in harsh environment and water depths from 20 up to 65 m.

Figure 12 Inwind Installer NG-10000-X3 [27]

The vessel may operate both as a self-contained installation and transportation unit that picks up the equipment from shore and transports it to the wind farm on own keel, or as a permanent installation platform which stays at the wind farm and receives the equipment for installation by feeder vessels [27].

Such vessels are used in relatively mild weather conditions. Jacking operation are restricted by a given maximum wave height, typically in the range of H_S=1.5-2 m [27].

3. Description of the new concept

3.1 Description of the idea

The new concept considered in the thesis represents a self-propelled jack-up which can start operations earlier and go away from the site later than conventional jack-ups can do. In order to be able to stay in place until the ice starts to form, the jack-up must withstand some ice loads; in particular during the drilling decommission phase and the tow away phase [12].

Hull

The jack-up deck house should resemble the geometry of an icebreaker. The front of the deck should have a bow with ice-breaking capabilities (see Figure 13 B). Walls of the hull should be inclined to reduce ice loads during interaction with drift ice and ridges. Ice will likely fail in a flexural failure mode that creates significantly lower ice actions in comparison with crushing failure mode (typical for vertical structures).

The hull should have four outrigger arms, two along each side of the jack-up hull (see Figure 13). Legs and necessary jacking equipment should be placed on the outriggers.

Legs

The jack-up should have four legs with mud mats and protective collars mounted on the outrigger arms. Tubular leg design should be used instead of open-truss design. Such structure will allow jack-up legs to withstand some ice loads in the beginning of and in the end of the drilling season. A traditional space-frame jacket leg structure would not resist ice and would quickly be filled with ice rubble.

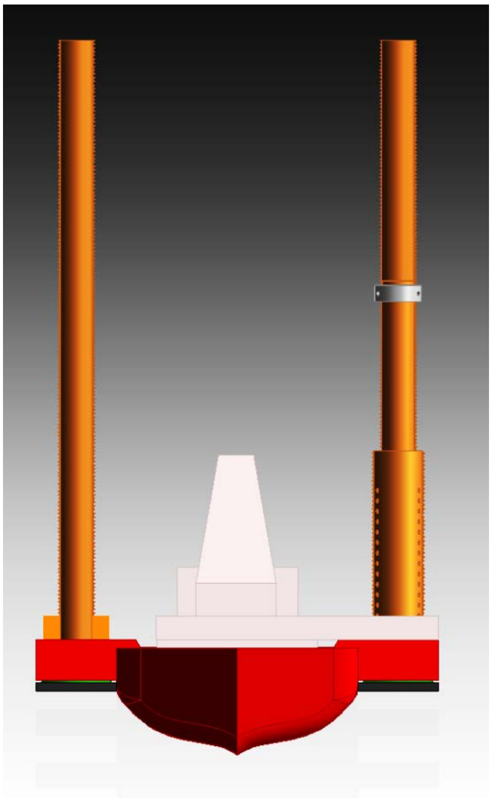
At least one of the legs should have a telescopic design, i.e. the length of this leg can be adjusted. The design of the telescopic leg will be considered further in detailed. It should be noticed that a jack-up with four legs can be stable at location should there be a problem with the bottom support condition for the leg carrying the drilling riser.

Drilling unit

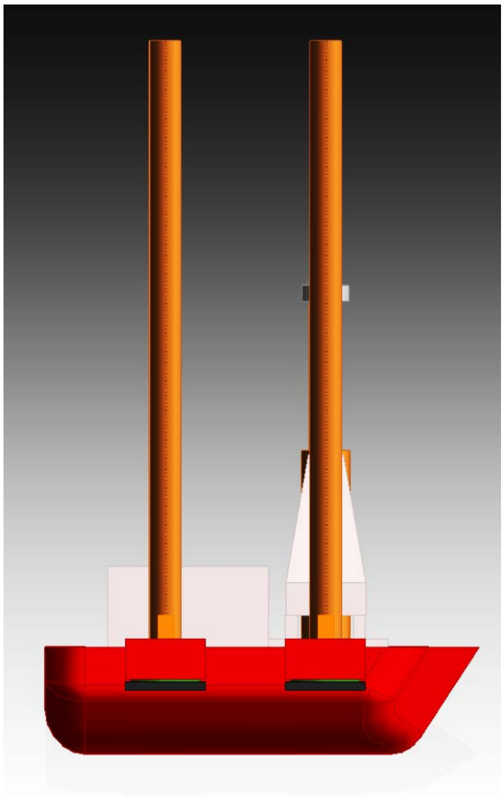
The derrick should be located close to the middle of the vessel during transportation (see Figure 13 C). After installation on the site the height of the telescopic leg should be adjusted if necessary (see Figure 14). The derrick should be placed over the leg with telescopic design by means of skid beams (see Figure 15). Drilling is supposed to be performed through the leg. Thus protection of the drill string from ice impact can be achieved that allows drilling even after the early ice has been formed. When operations are completed, the derrick should be skidded off back to initial position, the hull shall be lowered to the water and the legs shall be raised up for transportation to safe harbour.

Collars

To protect the jack-up legs from drift ice protective collars can be used. They should be placed in the outriggers during transportation and lowered along the legs to the water level when there is a threat of ice impact. The cones can be lowered by means of the separate system including wires/chains with blocks and locking mechanism to fix the cone on the leg.



A



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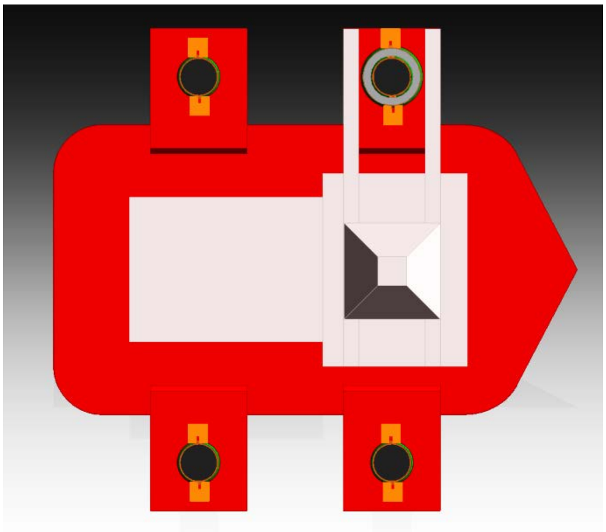


C

Color	Unit
	Hull with icebreaking capabilities
	Tubular legs
	Jacking equipment
	Drilling unit
	Protective collars
	Mud mats

Figure 13 New jack-up design (transportation mode) (A – front view, B – side view, C – top view)

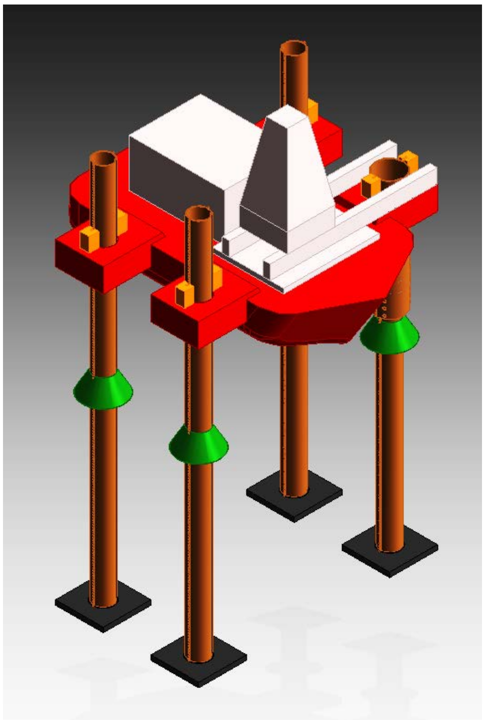


Figure 14 Telescopic leg adjustment

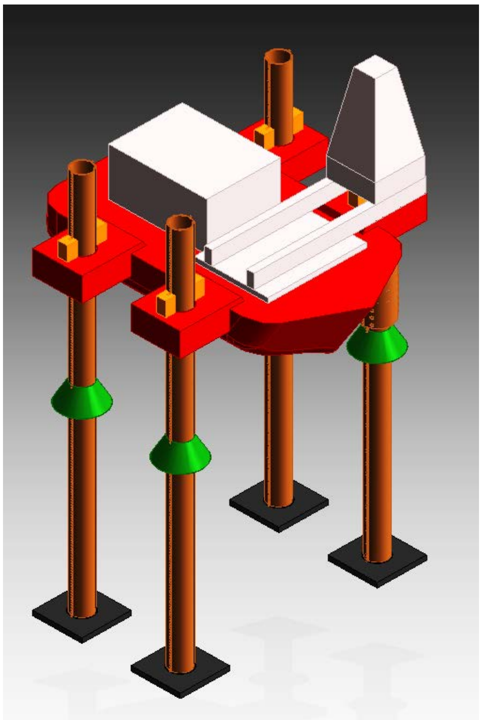


Figure 15 Derrick location during drilling

3.2 Discussion of the main concept features

In this chapter some important features of the new jack-up concept will be discussed more detailed and mostly in a qualitative way.

Hull

The jack-up is supposed to move through the thin ice in the end of the drilling season, so the hull with icebreaking capabilities is required. The sketches above (Figures 13-16) represent just the general idea of the hull shape. Proper design of the bow shape, midbody and stern shape is to be performed for the particular conditions and needs.

Bow. The bow shapes for icebreakers is determined by the stem, flare, buttock and water-line angles (see Figure 16 [28]). These angles influence the icebreaking, submergence and clearing efficiency [29]. The proper design of the bow is crucial because this part encounters the biggest ice loads.

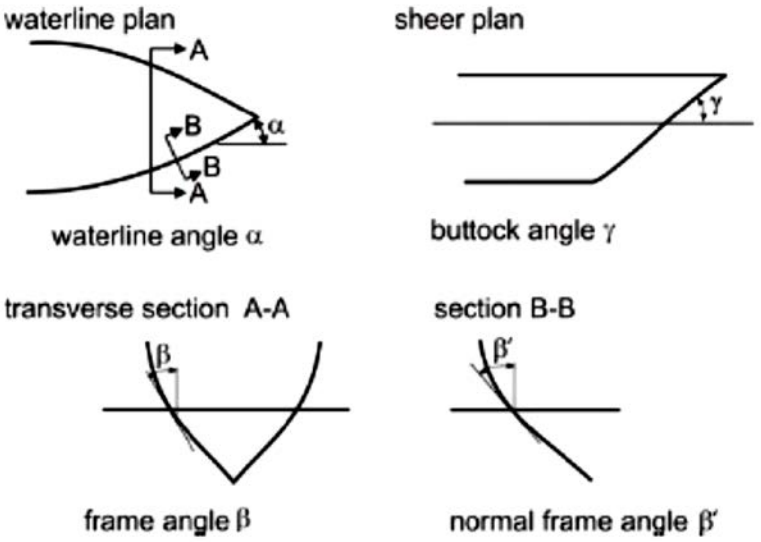


Figure 16 Main features of bow forms (after Dick and Laframboise 1989) [28]

There are various types of icebreaking bows, i.e. straight stem with parallel buttocks, concave stem, Melville bow, spoon bow with reamers, flat bow, Thyssen-Waas bow etc. In general they can be divided into conventional, or traditional and unconventional, or non-traditional (see Figure 17 [29]).

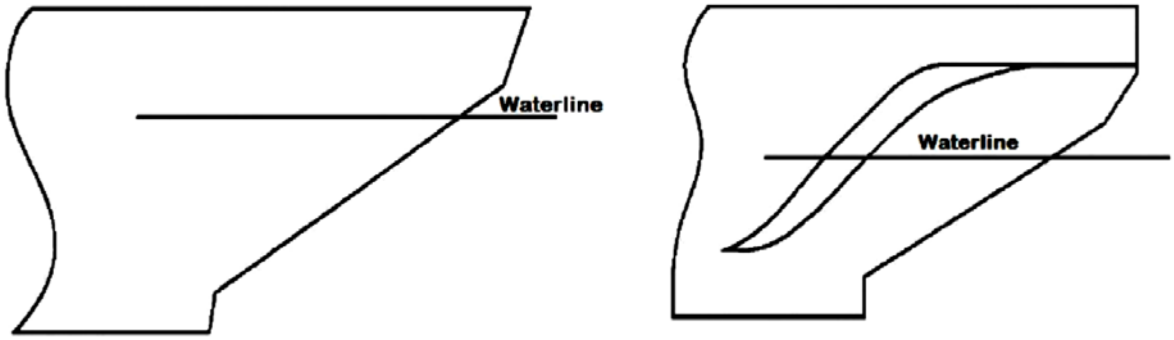


Figure 17 Conventional (left) and unconventional (right) bow shape [29]

A traditional bow provides icebreaking capability while the hull shape remains smooth. It results in better motion characteristics in open waters. Non-traditional bows require the change of the smooth shape of the hull. It would appear from past experience that the best traditional shapes have performed almost as well in level ice as the best non-traditional shapes [29]. Since the jack-up considered in this work is supposed to withstand only relatively low ice loads from early thin ice and will mainly operate in open waters, the conventional bow design can be recommended.

Midbody. The selection of the midbody shape must consider the effect on resistance, maneuverability, construction cost, and the required deadweight. The midbody shape is characterized by flare angle (over the full depth or locally), parallel midbody, and longitudinal taper [29]. To withstand ice loads, the shape of the hull shall be rounded. Then the ice forces will act on the hull sides under some angle lifting the vessel up and reducing ice loads on the hull.

Stern. The stern of the hull may be rounded as in Figure 13. This will allow deflection of the ice in the aft region of the vessel. Stern shape should be designed based on controllability, backing and protection of propellers and rudder [30]. Protection of the rudders and a propulsion system from ice impact can be reached by implementing different options, i.e. an ice horn, ice deflecting fins, ice skirt etc.

Outrigger arms. The main purpose of the outrigger arms is to provide a storage place for the legs, protective collars and jacking equipment saving the effective deck space. Such a solution has a significant drawback: environmental loads will create bigger moment on the structure in comparison with conventional jack-ups, where legs are placed inside the hull. On Figure 18, the moment created by vertical component of ice action has a longer arm and will cause stress concentration in the narrow part where the outriggers are connected to the hull.
Location of the legs with mud mats and cones inside the hull can be considered but such design will require much wider jack-up deck. Openings inside the hull, needed to lower the legs and protective cones down to the sea floor, will affect the icebreaking capabilities of the hull. So placing the legs and protective cones on the outriggers has at the moment been preferred for this concept.

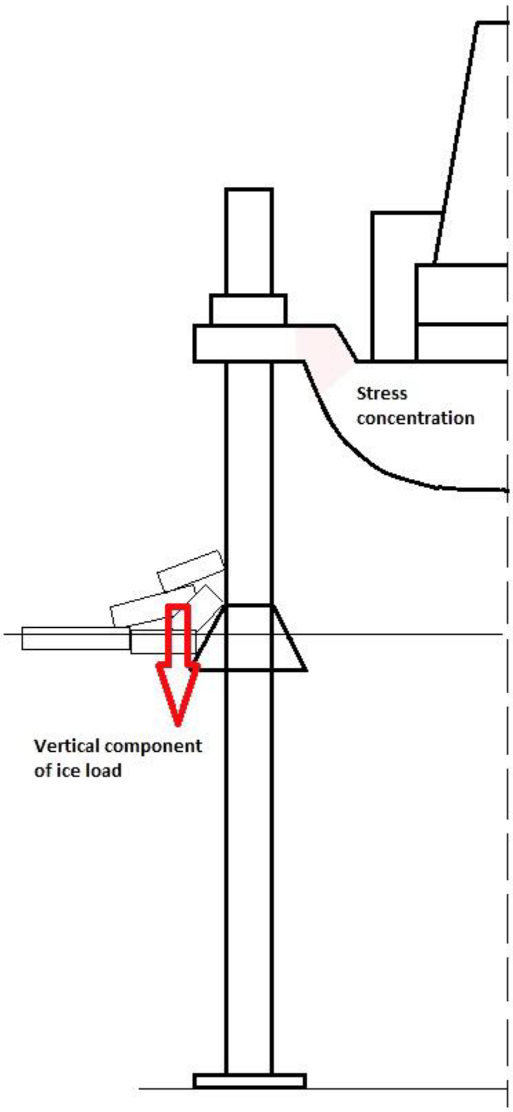


Figure 18 Moment from the ice load

Propulsion. It should be noticed that use of azipod propulsion system will make the vessel very maneuverable. The azipod resembles an outboard motor with very good maneuverability. Furthermore, use of side thrusters will enable sidewise movements even in ice conditions.

Materials. Arctic vessel may experience concentrated ice loads and low air temperatures (down to - 60°C).

Tensile and fatigue strength, corrosion resistance, fracture toughness and other parameters of the materials exposed to such low temperatures will differ significantly from those for the normal conditions.

“In 1996, the International Association of Classification Societies (IACS) issued new unified requirements, UR S6 (rev. 3), pertaining to the use of steel grades for various hull members. Included were requirements for structures exposed to low air temperatures. By these rules, the selection of steel grades is to be made on the basis of the design temperature, material thickness and the structural category” [31].

Except conventional steel plates with stiffeners, other modern solutions can be considered for the hull construction, e.g. «sandwich plate system» (SPS). The structure is made of two thin steel plates bonded to a polyurethane elastomer [31]. In comparison with stiffened plates, SPS has simpler structure, better fatigue and corrosion performance, greater strength and impact resistance, and allows reducing the weight of the hull [32].

These are only some features the hull should have to get icebreaking capabilities. In general, the vessel intended to operate in ice-infested areas shall satisfy special requirements, for example, IACS «Requirements concerning polar class” [28]. This document contains regulations concerning the structural design, construction materials, machinery system etc. for vessels operating in ice conditions. A vessel navigating in first-year ice during summer/autumn belongs to polar class PC6 or PC7 depending on ice thickness.

A relatively complex hull shape in comparison with conventional jack-up deck leads to some additional considerations which will be discussed below.

Air gap. One of the issues created by the suggested design is the required air gap of the jack-up deck. Hull elevation should be determined properly in order to exclude the possibility of the deck being hit by waves. Wave in deck may lead to the loss of stability and capsize. Examples of such accidents can be jack-ups hit in deck by hurricane waves in the Gulf of Mexico [12]. One of the jack-ups, Nabors Dolphin 105 (mat supported four-legged rig), was found after Hurricane Lili with mats floating upside down on the ocean surface and the hull sunk some distance from the location. The wave had possibly impacted the hull because of the low air gap or higher and shorter waves than expected [29].

The jack-up design considered in the thesis will require bigger depth of the deck than conventional drilling rigs have. It means the deck must be jacked up considerably (and possibly more than existing jack-ups) to avoid waves hitting the bottom of the deck during large waves [12]. General recommendation from DNV-RP-C104 [19] is that the air gap is not to be less than 10 per cent of the combined astronomical tide, storm surge and wave crest elevation above the mean water level. The air gap should be estimated for the particular Arctic area. Not only sea conditions but soil properties and possible leg penetration are to be investigated.

Roll motion. Another consideration of the suggested hull shape is increased roll motion. It should be noticed that the deck with inclined sides could roll considerably during transfer in waves so the outrigger arms must be designed for “wave in deck” conditions caused by roll [12]. While rolling, the moment from the buoyancy force (restoring moment) is less for ship-shaped hull than for a hull with vertical walls due to smaller uprighting arm BB’ (see Figure 19).

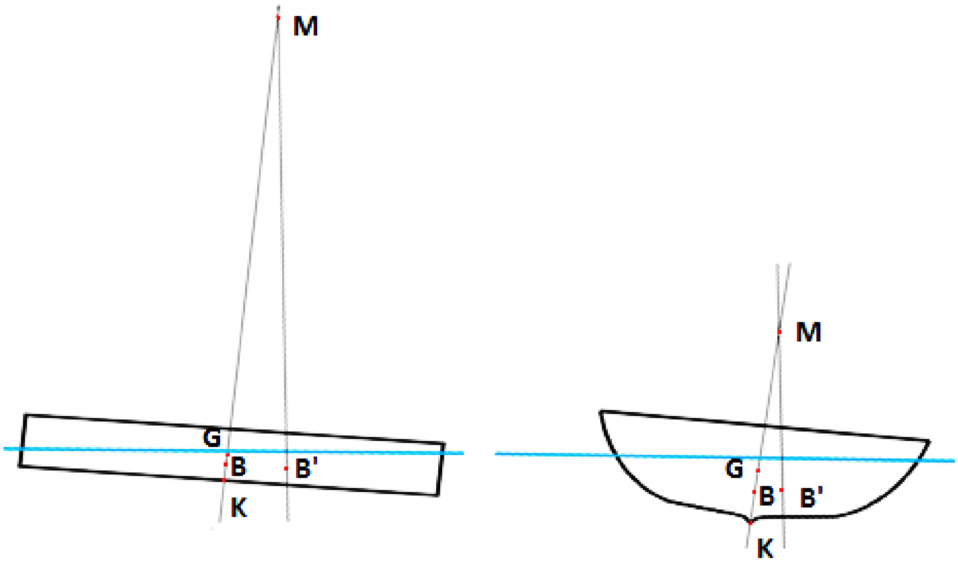


Figure 19 Metacenter for the rectangular and ship-shaped hull (M- metacenter, G – center of gravity, B – initial center of buoyancy, B' – center of buoyancy in roll, K – keel)

That leads to lower metacenter of hull with inclined walls. A lower metacenter results in worse roll hull stability and bigger roll period. So the outrigger arms interaction with waves shall be considered in the design. It is also advantages to limit the side inclination angle to some few degrees only.

Legs

The number of legs. Jack-ups are required to have at least three legs to achieve good stability, and most often they have three or four legs. A comparison of these two options is given in Table 3 based on materials by Bennet & Associates, L.L.C. [33, p.6].

Table 3 Comparison of three- and four-legged jack-ups

3-legged jack-up		4-legged jack-up	
+	-	+	-
Eliminated the need to build extra legs	Requires preload tankage → less usable space within the hull	Little or no preload tanks on board → more usable space within the hull	Need to build extra leg
Can carry more deck load in the afloat mode	Has no leg redundancy	Stiffer in the elevated mode	Reduced possible deck load in the afloat transit mode due to additional leg weight
Reduced number of elevating units (pinions, cylinders, etc.)→Less power/ maintenance requirements and less weight		Has leg redundancy	Wave, wind and current loads on additional leg

Typically three legs are used for independent leg jack-up. It allows reducing the weight of the structure and saves costs. The biggest disadvantage of this design is that the jack-up has no leg redundancy. If drilling is to be performed through one of the legs, the jack-up will lose stability and capsize in case of foundation problems near or under the mudmat or in case of blowout. So drilling has to be performed through the moon pool, i.e. the drill string will have no protection from early drift ice. Drilling operations shall be stopped when the ice starts to form.

Another disadvantage of three-legged design is the preload tankage requirements. The preload procedure allows the legs of jack-ups to penetrate into the soil to a depth sufficient to support the entire weight of the hull after it has been preloaded [34]. Sea water is pumped into preload tanks to increase the weight of the hull and is pumped out after the jack-up deck in until the jack-up has reached the preload weight. So preload water tanks are needed, that will reduce the effective space within the hull.

Four-legged jack-up has been preferred because it has leg redundancy as a significant advantage. If drilling is performed through one of the legs it is still possible to maintain jack-up stable on three legs in case of any accident or damage of the fourth leg. It allows protection of the drill string from ice actions. Drilling operations can be performed for the longer time even after some ice has been formed on the drilling site. The leg, which is supposed to be drilled through, should have a telescopic structure, so its length can be adjusted for each particular location in order to allow the drill rig to skid over the leg.

Four-legged jack-up can use the weight of two legs as a preload weight for other two legs, so preloading tanks are not needed. However, four-legged design leads to additional weight and cost of the jack-up.

Leg structure. Generally two options are available for jack-up leg structures – cylindrical and trussed (open-lattice) legs. Brief comparison of them is presented below (see Table 4).

Table 4 Comparison of cylindrical and trussed leg structures

Cylindrical legs		**Trussed legs**	
+	-	+	-
Smaller and have less deck area	Require more steel to be produced	Optimal steel utilization	Complicated to construct
Less complicated to construct	Big drag load	Lighter and stiffer	Less impact resistance
		Reduced drag load	

For open water conditions the trussed legs are preferable due to better response to environmental loads (waves, wind, tide). The newer units with operating water depth of 300 feet (~91.4 m) and greater all have trussed legs [33, p.6]. Open-lattice legs experience less drag loads that is important, as the considered jack-up will operate the most of time in the open waters.

When it comes to the Arctic area, leg resistance to ice impact becomes the main criterion. The open-lattice leg design is not suitable to resist the local ice forces, as individual members of the lattice structure are vulnerable to ice loads and would be bent or crushed by the local ice forces [5]. Cylindrical legs have higher strength and more likely will suit for ice conditions. However, current designs are not suitable to resist the high local ice loads as the legs are primarily designed to resist much smaller wave loading [5]. So the legs may need to be reinforced, for example, by application of special cold-resistive materials, as it was done for the Arkticheskaya rig, or by implementation of multilayer structure.

Independently on the leg design, the resistivity of the structure to the local ice impacts should be checked. Of particular concern is a situation when multiyear and particular strong ice floes are present [12]. Leg interaction with ice during transportation must be avoided for both concepts considered. For that purpose the legs together with mud mats are to be placed on outriggers sufficiently above the sea level, so ice floes would not impact the mud mats or legs themselves.

Jacking system. A hydraulic fixed rack and pinion jacking system can be recommended. The dual jacking system for the telescopic leg will be described further.

Protective collars

Significant ice loads will require strengthening the legs and will affect jack-up stability, even during the early ice period. But only a small part of leg length will be exposed to ice loads (the area of leg interaction with ice). So the ice actions should be reduced by application of protective collars.

Collar geometry. Several geometries have been suggested for protective structures such as vertical ice shields (e.g. “Gemini” concept) or ice protective cones (e.g. MYADS). Conical collars have been chosen for the new jack-up concepts. Inclined walls will experience significantly less ice load in comparison with the vertical shields because the ice will break most likely in a bending failure mode on sloping walls. Three key geometrical parameters, i.e. collar width, upward/downward slope and sloping angle, will be estimated later in this work. The amount of ice rubble can vary depending on slope angle and the width of the cone [35], that will influence the resulting ice loads.

Possible system for cone installation. One possible system for protective cone installation is suggested below.
During transportation the cones are stored inside the outriggers. During installation, the cones are lowered down to the sea floor on mud mats and are kept there until there is a threat of ice impact for the jack-up legs. Three or four chains from the platform are connected to the cone padeyes through an automatic pin system allowing remote disconnection of chains.
When necessary, the cones are lifted along the legs to the water level by means of chain system. A locking mechanism inside the cone allows fixing the cone on the leg. This mechanism can be operated electrically. An automatic control system with batteries is not recommended due to its low reliability at Arctic temperatures. A hydraulic control system may be ineffective due to hydraulic oil thickening at low temperatures. Another important disadvantage of the hydraulic control is that in case the hydraulic line is damaged by ice, it will lead to environmental pollution. So, electric control system is recommended.
The electric line runs from the platform inside the leg to the sea bottom and then through the opening in the leg to the locking mechanism inside the cone. Placed inside the cone, the hydraulic line is protected from the ice impact or damage by ice rubble accumulation. Since there is still a possibility for the electric line to be damaged by ice floes getting under the cone, double electric line can be recommended to increase the control system reliability.
When the cone is lifted to the required height, the locking mechanism inside the cone is activated around the leg. Then the chains can be disconnected from the cone by means of

automatic pin system (activated by the same electric line as used for cone locking mechanism) and lifted back to the platform. It will allow protection of chains from the possible damage by rubbles accumulating on top of the cone. Another option can be that the chains are left in place allowing adjustment of the cone position on the leg (e.g. in case of water level surge or personnel mistake). The cone is fixed on the leg at the required level by the locking mechanism.
When the jack-up should leave the site, the cone locking mechanism around the leg is unlocked, and the cones are lowered down to the sea floor by gravity force. In order to avoid the risk of mud mat damage by falling cones, the cones can have buoyancy elements to achieve almost neutral weight in sea water.
In case of big rubble accumulation, the cone can get stuck on the leg even when the locking mechanism is unlocked. Then it is recommended that the hull be lowered to the water level pushing the cone down through the ice rubble accumulation. When the cones are lowered down to the legs' mud mats, the legs can be lifted up together with cones for further jack-up transportation.

Materials. Cold-resistive materials should be selected for the protective cones based on the expected ice loads, e.g. stainless steels used for icebreaker ice belts. Composite structure can be considered. The material strength and friction coefficient are particularly important.

Behavior in waves. The cone shape has increased "drag" coefficient and lead to bigger vibrations. So the response of protective collars to wave loads and its influence on jack-up stability needs to be evaluated. It is suggested that the cones be lowered when the ice starts to form to avoid large loads due to waves.

Additional features. There are some additional features which can be implemented in the cone design. The heating of the legs at the ice interaction level can be applied to avoid the adfreezing of the ice rubbles on the legs and cones.
A gas agitation system to agitate the water around the legs and to reduce ice formation near the legs can be considered. Such solution has been patented for the ice worthy jack-up unit developed by ConocoPhillips to reduce issues with ice near the protective vertical shields on the jack-up legs [36].

Telescopic leg design

At least one of the jack-up legs should have telescopic design. Several jack-ups and jack-up barges have telescopic legs as a feature to reduce the leg height above the deck level, e.g. [37] and [38]. One possible solution for the telescopic leg design is presented below.

A simplified drawing of the telescopic leg in elevated mode is shown in Figure 20. The leg consists of two sections – outer shorter section and inner longer section. Both sections have rack teeth.

The outer section has a number of holes (e.g. with 1 m interval) placed in three vertical rows. A pinion system for the outer section is placed outside on the outrigger arm.

The inner section has three circular holes and a locking mechanism attached to its upper end. The locking mechanism represents a collar with the holes coinciding with the holes of the inner section. Cylindrical pins are running through the holes and can be pushed outwards hydraulically, constraining the relative motion of the inner and outer leg sections. A hydraulic line runs from the platform outrigger to the locking mechanism through the annulus between leg sections. The jacking system for the inner section is installed in the annulus between the inner and outer section in the lower part on a special support base. The mud mat is attached to the lower end of inner section, and the ice protective cone is placed on the mud mat. The mud mat has the circular opening for drilling.

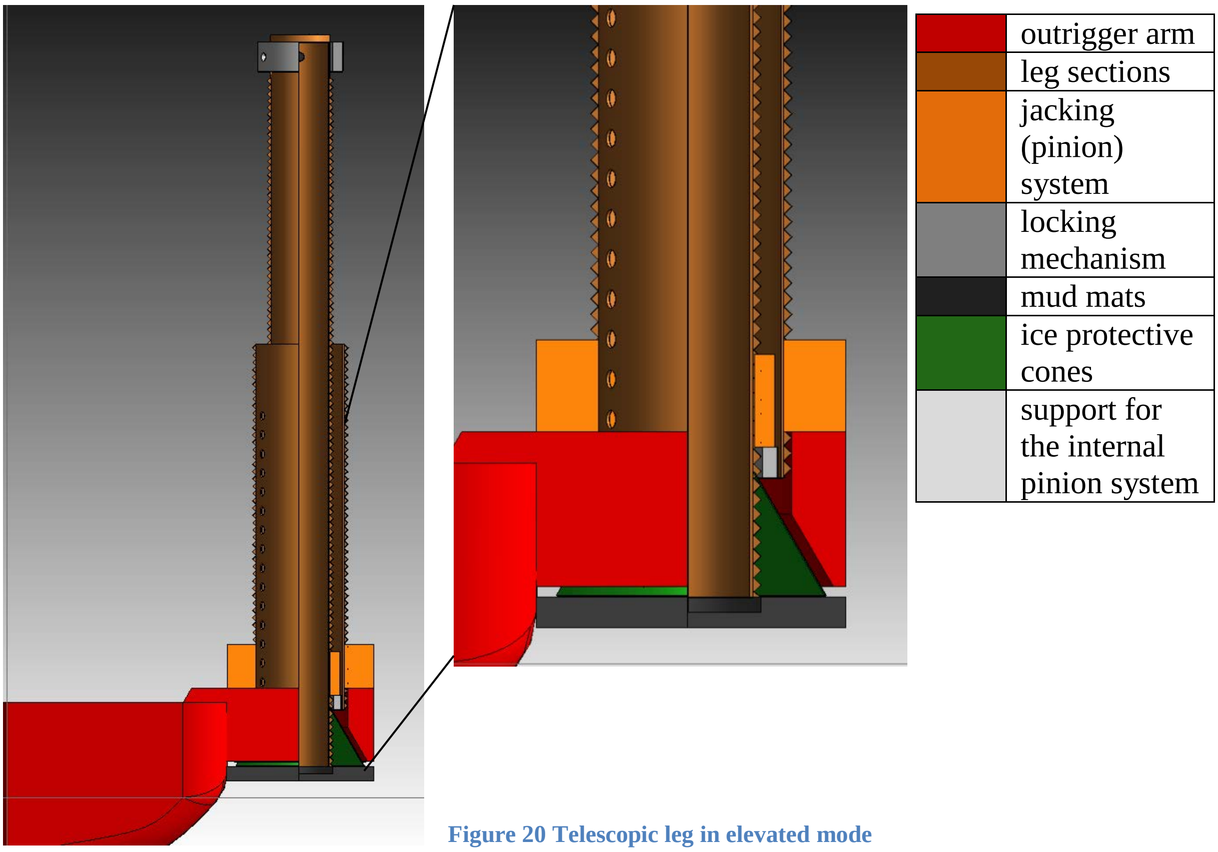


Figure 20 Telescopic leg in elevated mode

During installation, first the inner section is lowered down (together with the mud mat and the protective cone on top of it) moving within the outer section by means of the internal pinion system (see Figure 21 A). The inner section is lowered to such a depth, that the total length of the outer section and the extended inner section is equal to the distance from the outrigger (when hull is in elevated mode) to the sea bottom.

After the inner section is jacked down to the required depth, the pins of the locking mechanism are extended to the corresponding holes of the outer section, thus fixing the location of the inner section relatively to the outer section.

The next step is to lower down the outer section so that the mud mat reaches the bottom together with the three other legs. After preloading, the hull can be jacked up to reach the required air gap. Then the upper end of the outer section is within the outrigger and it is possible to skid the drilling derrick above the leg (see Figure 21 B)

When the ice starts to form, the protective cone is lifted from the mud mat by means of the chain system described above (Figure 21 C).

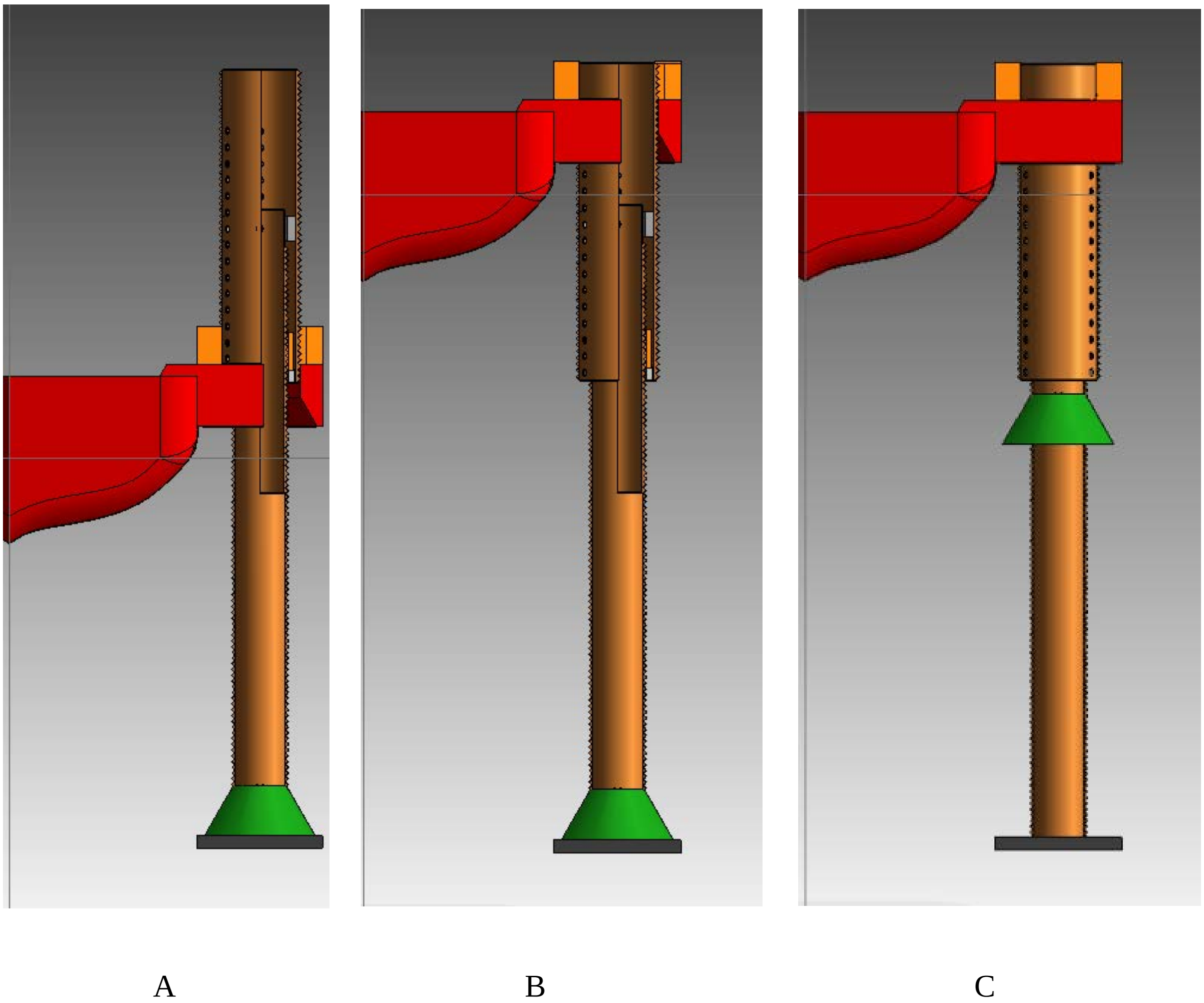


Figure 21 Telescopic leg installation

Since the pinion system inside the outer leg section should stay above the water level, this limits the allowable length of the outer section to 25-30 m approximately. Then the leg length can be changed only in range of 20-25 m and this reduces the range of operational water depths for the jack-up. This limitation can be overcome by changing the inner section of the leg for different water depth ranges.

After the drilling has been completed and the jack-up is ready to leave the site, the protective cones are lowered down to the mud mats. The hull is jacked down until it reaches the lower end of the outer telescopic leg section. Then, while the hull is jacking down further to the water along other three legs, the inner section of the telescopic leg should start lifting up by means of internal jacking system located in the annulus between outer and inner leg section. When the hull has reached the water, all four legs are raised out of the water for further transportation.

During transportation the leg with such structure is shorter than other legs but heavier. Possible asymmetry of the jack-up design can affect the vessel stability and should be compensated by ballasting the outriggers.

Drilling method

The drilling unit comprising the derrick with the integrated deck is placed on the skid beams. During the transportation it is located close to the mid ship. When the installation on the drilling location has been completed and the hull has been elevated, the drilling envelope is mounted on the outrigger in such a way that the derrick is placed above the telescopic leg.

Drilling through the leg has been widely used for jackets in Cook Inlet [39]. It ensures the protection of the drill string and risers from the drift ice impact. The inner diameter of the leg should be sufficient to perform the drilling operations through it.

Basically, drilling from the jack-up is performed with the wellhead equipment and blow-out preventer (BOP) on the deck and mudline suspension system at the sea bottom. The purpose of the mudline hangers is to suspend the casing strings at the mud line while the casings are extended up to the rig (see Figure 22).

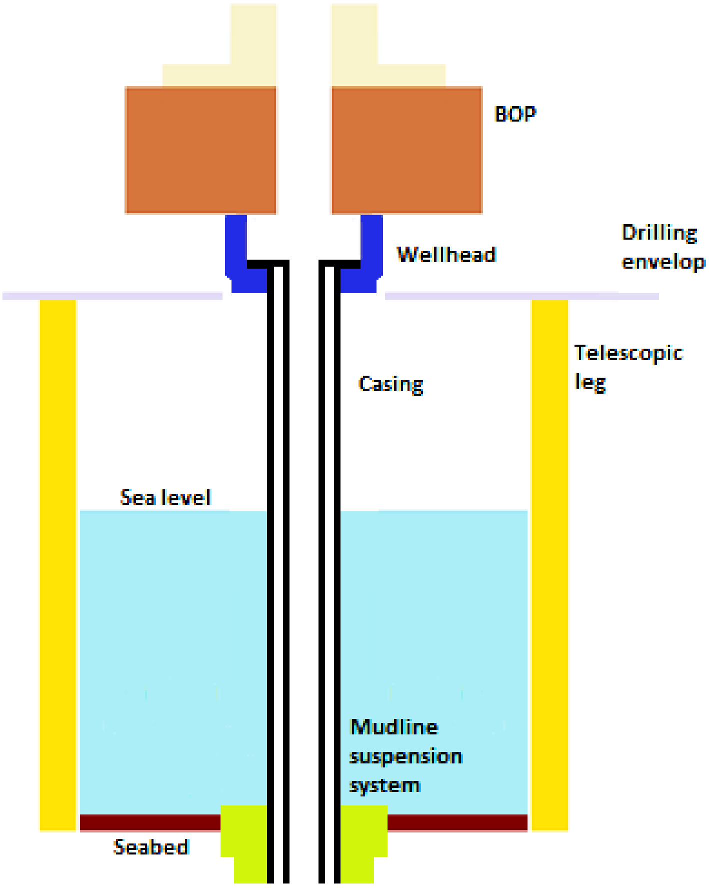


Figure 22 Drilling with surface wellhead

In order to drill a well from the jack-up, a High Pressure Jack-up Drilling Riser (HPJDR) system can be implemented. Such systems are installed on modern powerful jack-up rigs e.g. Maersk Resolute. The HPJDR system comprises a subsea wellhead with a hydraulic connector and a drilling riser that joins the wellhead connector to the surface BOP on the jack-up (see Figure 24) [40]. The BOP is located inside the drilling unit below the derrick and can be placed over the high pressure riser by a special carrier system. The mud return system can be also placed inside the drilling unit eliminating the need of its connection and disconnection while the drilling unit is skidded on the outrigger.

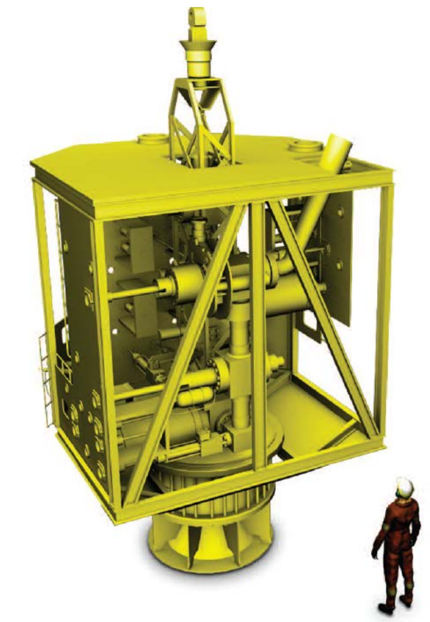


Figure 23 Pre-positioned Capping Device [2]

There are some modern technologies to be implemented for the Arctic area to reduce risks while drilling. One of them is a Pre-positioned Capping Device (PCD) developed by the Oil Spill Prevention and Response Advisory Group for water depths from 100 m to 3048 m and high pressure reservoirs (see Figure 23). This device has been included in the well control assembly for the exploration well to be drilled in 2014 in the Chukchi Sea by ConocoPhillips [41]. The PCD is installed on the subsea wellhead and is operated remotely. It allows closing the well by two single blind/shear rams. The size of the device is 4.6m x 3.97m x 7.14m. In order to implement this piece of equipment on the new jack-up rig, the geometrical dimension of the PCD should be properly adjusted to meet the working conditions inside the leg of the new jack-up.

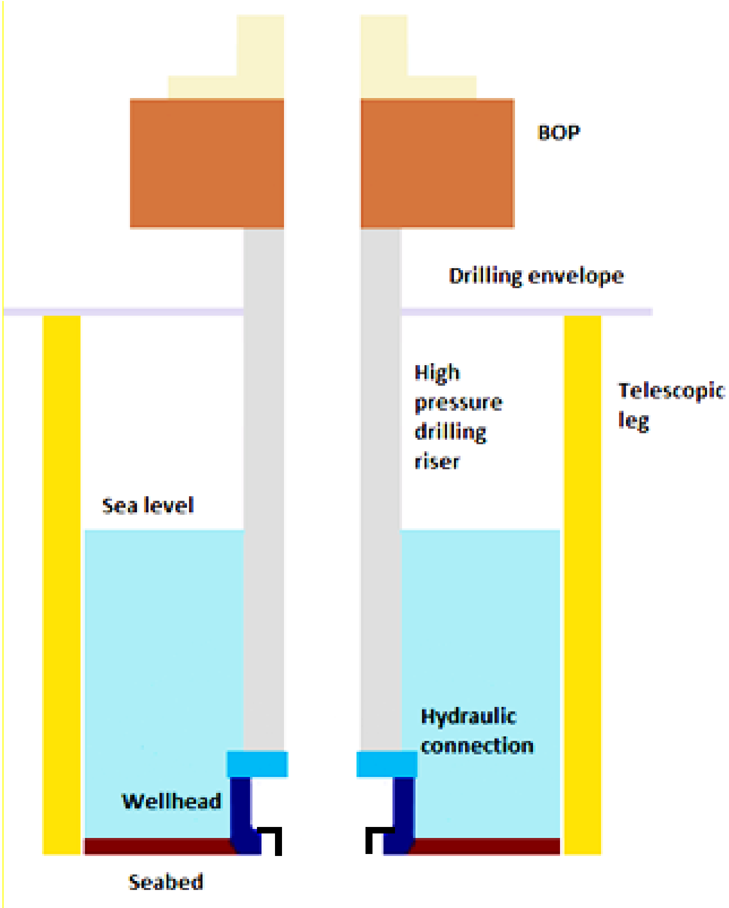


Figure 24 Typical configuration of jack-up drilling system

After drilling and/or well testing have been completed, the well should be abandoned. Plug and abandonment operations (P&A) will depend on the results of testing and on the specific regulations for the particular Arctic area.

If the well is planned to be reentered later, it should be plugged with cement to ensure the well integrity. Then, in case a surface wellhead system has been chosen, the casing extension from the mudline hangers to the deck is removed to the last casing size that is desired to cap. Then a cap should be placed in order to seal this casing string and all subsequent strings. Any remaining casing extensions are then removed, and the well location can be marked with a buoy or other locating device [42].

In case a HPJDR system was preferred, after plugging the well the drilling riser is disconnected from the wellhead and removed. The wellhead can be cut and recovered, or left in place to be recovered later by a multi-service vessel.

After the well is abandoned and the drilling equipment recovered, the drilling envelope should be skidded from the outrigger back to the initial position and the vessel can prepare to leave the location.

Winterization

The drilling rig operating in the Arctic conditions will encounter various environmental challenges, i.e. low temperatures, ice, icing, darkness etc. That means the concept considered should be properly winterized. Icing and low temperatures are two particular concerns of the rig winterization.

Low temperature affects:

- Personnel - cold or loss of body heat can lead to frostbite and hypothermia, both of them can lead to fatality [43]. So it is necessary to reduce the period of work on the open deck;
- Materials – all structural steels will experience reduced fracture toughness due to ductile-to-brittle transition [44]. Several techniques of increasing steel strength are available nowadays, e.g. Nickel alloying, reducing carbon content, advanced thermo-mechanical treatment etc.;
- Process equipment, machinery and safety systems – possibility of hydraulic fluid thickening, fire water freezing etc.

Icing may be caused by atmospheric precipitation (rain, fog, snow etc.) or by freezing sea spray. The most serious icing occurs due to spray from heavy seas in the extreme latitudes [43]. Considerable ice accretion affects:

- Vessel stability – not really relevant for big vessels;
- Access and operability of technical and safety equipment;
- Personnel – slips and trips due to ice on deck, ice falling from tall structures.

For winterization of the considered jack-ups special attention should be given to the following units.

Drilling unit. The derrick and the drill floor space are manned continuously during operation and occupied by the drilling equipment. The winterization design should be enforced in the areas for human working and drilling operations [45]. According to ISO 19906 requirements, drilling facilities should be fully enclosed except for the derrick or mast which may only need to be enclosed around the drill floor, at the racking board, and at the crown level. Bulk mud and cement tanks as well as pipe lay down areas may also be located external to the modules [46, p.92].

Fully enclosed design of areas containing hydrocarbons leads to significant increase of explosion risks. During a study performed by Scandpower AS [47] several important conclusions have been made:

- Enclosed process modules can be safe if the fire and explosion safety can be accurately calculated and safety drivers identified and optimized
- It is safer to divide process areas into several smaller modules than combining them into a large single one (will reduce fire frequency and blast loads, and also reduce potential loss of life by separating personnel from accidents)
- Fire and explosion design loads are strongly dependent on HVAC philosophy selected
- Ignition source isolation efficiency should be optimized.

Offshore platforms have adopted wind walls to protect the equipment from ice accretion, world widely [45]. Wind wall protection of the derrick with openings for ventilation can be suggested for the new concept.

Such solution has been suggested by Samsung experts during the study of winterization techniques for semi-submersible rig for Gasflot. The wind walls surround the derrick and the drill floor (see Figure 25). Only moon pool and several ventilation openings are not protected. Vee-doors were designed to close or open as per operation situation [45]. The work was performed according to the rules of the Russian maritime registry of shipping (RMRS).

During the winterization design location and quantities of heaters and blowers should be determined depending on local temperature and air change rate to satisfy hazardous requirements [48].

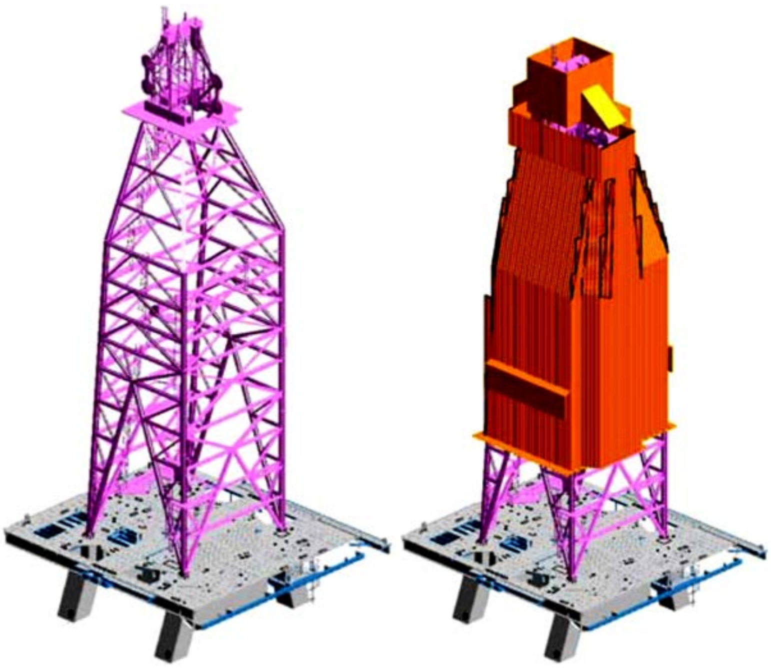


Figure 25 Derrick and Drill Floor without Wind Wall and with Wind Wall [45]

Drill floor and moon pool can be equipped with heating units as it was done for Aker H-6e Drilling Semi-Submersible [49]. Drilling cabin should be heated to provide the comfort of the operator and visibility (no ice on windows obscuring the view). Attention should be paid also to drilling and hydraulic fluids handling.

Accommodation and escape routes. Manned areas which do not contain hydrocarbons can be designed as fully enclosed units. Comfortable conditions for workers are achieved by heating and insulation. The heating is typically to provide and maintain an inside temperature of +20°C at the lowest outside temperature the offshore structure is designed for [43]. To reduce heat loss and avoid condensation the insulation of modules should be considered.

HVAC systems are of great importance. The ventilation must be designed properly to prevent blocking by atmospheric icing [43]. To avoid the accumulation of ice on windows (especially in control rooms and cabins) heaters or hot air blowers are to be installed.

Piping and process equipment. Materials for piping and pressure vessels shall be chosen based on the appropriate minimum design temperature. Low temperature carbon steels, austenitic steels and glass fiber reinforced epoxy (GRE) can be used.

Possible solutions for flow assurance maintenance suggested in ISO 19906 include elimination of pockets or dead ended pipes, self-draining design, heating, insulation, addition of chemicals etc.

According to ISO19906, piping for offshore platforms often involves numerous deck penetrations, which can present unique accessibility challenges. The design of heat tracing systems shall account for the installation, operations, and maintenance challenges in these areas, especially the areas below decks. When a piping system passes into indoor areas, the extent of heat tracing should be evaluated to ensure that there will be no icing in the system [46, p. 89].

Valves and pumps are particularly vulnerable to cold temperatures and ice accretion. They should be operable at the minimum designed temperature. If air operated and controlled equipment is used on deck, the air should be dry. If hydraulic equipment is used, the oil should be heated or of a low temperature quality. Electric junction boxes or controls should be resistant to water ingression and protected from ice build-up. Electric motors should be heated [43].

Safety equipment. Operability and access to lifeboats is one particular consideration of winterizing process. Evacuation equipment must function in any environmental conditions the jack-up is exposed to. Lifeboats and launching equipment shall be protected from icing. The most effective way of preventing sea-spray is by physical barriers (placing lifeboats into closed compartments). Heating the compartment will only be effective in combination with a closed compartment solution [50].

Evacuation and escape routes may be obstructed by ice accumulation on external doors. A double door (airlock) with space heaters or heat tracing around the external door frame [43] can be a solution.

Firefighting equipment may use water, foam or dry powder. Since dry powder may be ineffective at low temperatures [43], water or foam systems are preferable. Lloyd`s Register (UK) recommends to locate the equipment within heated passageways or in heated areas if possible. The water and foam systems may be drained; alternatively the water may be maintained with a constant flow through. Hydrants should be protected from ice buildup at the connection [43].

4. Theoretical basis for environmental load calculation

Environmental loads on the jack-up during operations are to be analyzed. A methodology for wave and ice load calculation is considered in this chapter. The calculations will be based primarily on DNV-RP-C205 “Environmental conditions and environmental loads” and ISO 19906 “Petroleum and natural gas industries – Arctic offshore structures”. References to some other sources will be given in the text.

4.1 Wave loads

Regular wave theories. In the operational mode, a quasi-static response of the structure is assumed. According to [51, p. 24], it is sufficient to use deterministic regular wave theory for such conditions. “Three wave parameters determine which wave theory to apply in a specific problem. These are the wave height *H*, the wave period *T* and the water depth *d*” [51, p. 24]. The appropriate wave theory can be chosen based on Figure 26 [51, p. 25].

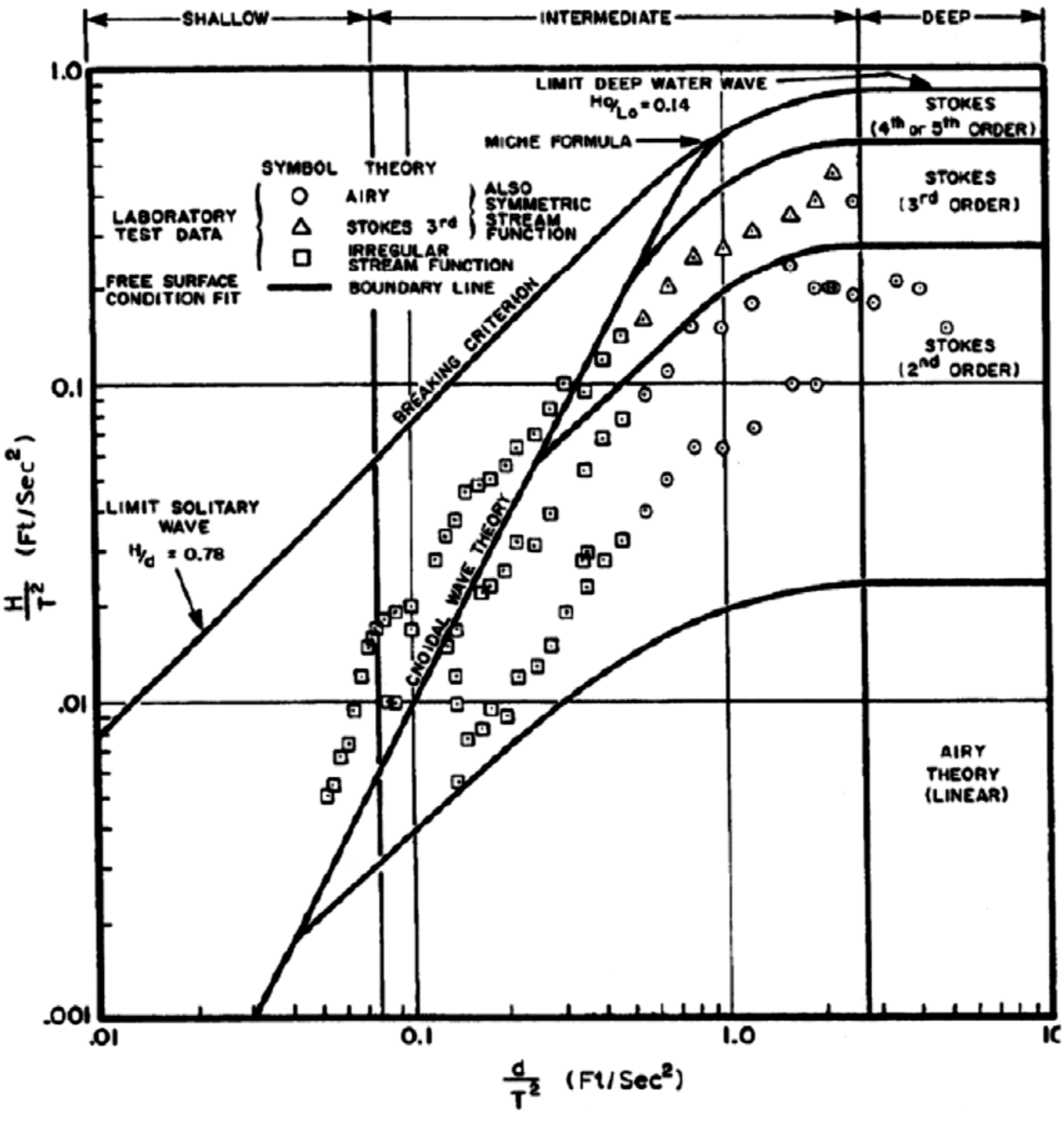


Figure 26 Ranges of validity for various wave theories. The horizontal axis is a measure of shallowness while the vertical axis is a measure of steepness (Chakrabarti, 1987) [51, p. 25]

Wave parameters. The Pechora Sea region has been chosen as a reference area for further calculations. Parameters characterizing the waves on a potential drilling site in the Pechora Sea are presented in Table 5 (based on [52, p.p.114-115]).

Table 5 Parameters of design waves in the Pechora Sea

Parameter	Symbol	Value	Dimension
Return period R_p=100 years			
Water depth	d_w	50	*m*
Significant wave height	H_s	7.5	*m*
Peak wave period	T	11.5	*s*
Wave length corresponding to *T*	λ	190	*m*
Return period R_p=50 years			
Circular tide	h_t	±1.25	*m*
Unperiodic storm surge	-	±3.35	*m*

Maximum wave height H is assumed as 1.9 times the significant wave height H_s [51, p. 41]. Parameters, required to choose the wave theory on Figure 26, are shown in Table 6 below.

Table 6 Parameters to validate wave theory

$\frac{d}{T^2}$	1.27	$\frac{Ft}{Sec^2}$
$\frac{H}{T^2}$	0.35	$\frac{Ft}{Sec^2}$

According to Figure 26, Stokes 3rd order theory should be implemented to describe the waves. As can be noticed on Figure 26, the theory is applicable for the intermediate and deep waters only, and the required series order increases with the wave steepness. The considered area of the Pechora Sea corresponds to the intermediate waters (the ratio of a wave length λ to the water depth *d* belongs to the interval $2 < \frac{\lambda}{d} < 20$).

Stokes wave expansion is an expansion of the surface elevation in powers of the linear wave height H [51, p. 26]. Airy (linear) theory represents the first-order Stokes theory and describes symmetric waves:

$$\eta(x, y, t) = \frac{H}{2} Cos\theta,$$

where $\theta = k(xCos\beta + ysin\beta) - \omega t$.

For the second-order Stokes waves, crests become steeper (multiplied by $1 + \frac{\pi H}{2\lambda}$) and troughs become wider (multiplication factor $1 - \frac{\pi H}{2\lambda}$).

The third-order Stokes theory considers the dependence of a phase velocity on the wave height. The velocity potential function ϕ is given as:

$$\phi = \phi^{(1)} + \phi^{(2)} + \phi^{(3)} = A \cdot Cosh\big(k(z + d)\big) \cdot Sin(kx - \omega t) + B \cdot Cosh\big(2k(z + d)\big) \cdot Sin\big(2(kx - \omega t)\big) + C \cdot Cosh(3k(z + d)) \cdot Sin(3(kx - \omega t)),$$

where all necessary parameters and calculated values can be found in Table 7:

Table 7 Parameters for 3rd order velocity potential function calculation

Symbol/formula	Value	Dimension
H	14.25	*m*
g	9.81	m/s^2
$\omega = 2\pi/T$	0.55	*rad/s*
$k = 2\pi/\lambda$	0.03	*rad/m*
$d = d_w + h_t$	51.25	*m*
$A = \frac{gH}{2\omega} \cdot \frac{1}{Cosh\,(kd)}$	45.51	m^2/s
$B = \frac{3H^2kg}{2^5 \cdot \omega \cdot Coth(kd)}(Coth^2(kd) - 1)^2$	0.22	m^2/s
$C = \frac{1}{2^9}(Coth^2(kd) - 1)(Coth^2(kd) + 3)(9Coth^2(kd) - 13) \cdot \frac{H^3k^2g}{\omega \cdot Cosh(3kd)}$	-0.002	m^2/s

Since the protective cones are small in comparison with the wavelength and fixed in place we can drop the variation of the x-coordinate and the expression for water particle velocity *u* is:

$$u = \frac{\partial\phi}{\partial x} = k \cdot A \cdot Cosh\big(k(z+d)\big) \cdot Cos(\omega t) + 2 \cdot k \cdot B \cdot Cosh\big(2k(z+d)\big) \cdot Cos(\omega t) + 3 \cdot k \cdot C \cdot Cosh\big(3k(z+d)\big) \cdot Cos(\omega t).$$

Then water particle acceleration *a* is:

$$a = \frac{du}{dt} = -k \cdot A \cdot \omega \cdot Cosh\big(k(z+d)\big) \cdot Sin(\omega t) - 2 \cdot k \cdot B \cdot \omega \cdot Cosh\big(2k(z+d)\big) \cdot Sin(\omega t) - 3 \cdot k \cdot C \cdot \omega \cdot Cosh\big(3k(z+d)\big) \cdot Sin(\omega t).$$

Wave loads. For slender structural members having cross-sectional dimensions sufficiently small to allow the gradients of fluid particle velocities and accelerations in the direction normal to the member to be neglected, wave loads may be calculated using Morison's load formula [51, p.52]. According to Morison equation, wave loads on a slender cylinder per unit length can be estimated as a sum of an inertia force and a drag force:

$$F_w(t) = F_i(t) + F_D(t) = \frac{\pi}{4}\rho C_M D^2 \cdot \dot{u} + \frac{1}{2}\rho C_D D \cdot u \cdot |u|,$$

where ρ is a water density [kg/m^3], D – cylinder diameter [m], C_D and C_M are drag and mass coefficients, respectively.

4.2 Ice loads

The jack-up considered in the thesis is intended to withstand only small ice loads from the first-year drift ice. Multiyear ice and ridges will cause much bigger ice loads and can create huge rubble accumulation around and in-between the legs so the jack-up can get stuck. Such situation must be avoided.

For calculation of drift ice loads on the cones the limit stress mechanism will be considered. The characteristic of limit-stress conditions is that the ice feature has sufficient driving force to fail the ice and completely envelop the structure and generate ice actions across its total width [46, p. 28].

Structures with inclined walls generally experience less ice loads than vertical structures with the same dimensions because the slope changes the failure mode from crushing to flexure. One potential challenge of sloping structures is the rubble accumulation around the sloping area. Ice rubbles can accumulate above and under the ice sheet complicating the interaction process and increasing the ice actions. Since the considered jack-up is not intended to stay in ice for a long time, the situation with huge rubble accumulation is not considered, and only flexure mode of ice failure is assumed.

Two methods of ice load calculation are proposed in ISO 19906 – a method based on elastic beam bending and a plastic method for cones.

4.2.1. Method based on elastic beam bending

According to this model, the horizontal (F_H) and vertical (F_V) components of drift ice loads on a sloping structure are connected through the parameter ξ, depending on the sloping angle and friction coefficient between the ice and structure surface [46, p.164]:

$$F_V = \frac{F_H}{\xi}, \quad \xi = \frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha}.$$

where:

ξ is the relationship between the vertical and horizontal component,

α is the inclination angle of the structure surface from the horizontal,

μ is the coefficient of kinetic friction between the ice and structure surface.

The horizontal load from drift ice on sloping structure can be obtained from the expression [46, p. 167]:

$$F_H = \frac{H_B + H_P + H_R + H_L + H_T}{1 - \frac{H_B}{\sigma_f l_c h_i}},$$

where:

H_B is the breaking load,

H_P is the load component required to push the sheet ice through the ice rubble,

H_R is the load to push the ice blocks up the slope trough the ice rubble,

H_L is the load required to lift the ice rubble on top of the advancing ice sheet prior to breaking it,

H_T is the load to turn the ice block at the top of the slope,

l_c is defined further below,

h_i is the ice thickness,

σ_f is the flexural strength.

The breaking load H_B can be calculated as:

$$H_B = 0.68 \times \xi\sigma_f \left(\frac{\rho_w g h_i{}^5}{E}\right)^{0.25} \left(w + \frac{\pi^2 L_C}{4}\right),$$

$$L_C = \left(\frac{Eh^3}{12\rho_w g(1-\upsilon^2)}\right)^{\frac{1}{4}},$$

where:

ρ_w is the sea water density,

g is the gravity acceleration,

E is the elastic modulus,

w is the structure width,

υ is the Poisson ratio.

The load component required to push the sheet ice through the ice rubble H_P can be calculated as:

$$H_P = \mathrm{w}h_r^2\mu_i\rho_i g(1-e)\left(1-\frac{\tan\theta}{\tan\alpha}\right)^2 \frac{1}{2\tan\theta},$$

where

h_r is the rubble height,

μ_i is the ice-to-ice friction coefficient,

ρ_i is the ice density,

e is the keel porosity ,

θ is the angle the rubble makes with the horizontal.

The load to push the ice blocks up the slope trough the ice rubble H_R can be calculated as:

$$H_R = \mathrm{wP}\frac{1}{\mathrm{Cos}\,\alpha - \mu\,\mathrm{Sin}\,\alpha},$$

$$\mathrm{P} = 0.5\mu_i(\mu_i+\mu)\rho_i g(1-e)h_r^2\,\mathrm{Sin}\,\alpha\left(\frac{1}{\tan\theta}-\frac{1}{\tan\alpha}\right)\left(1-\frac{\tan\theta}{\tan\alpha}\right) + 0.5(\mu_i+\mu)\rho_i g(1-e)h_r^2\frac{\mathrm{Cos}\,\alpha}{\tan\alpha}\left(1-\frac{\tan\theta}{\tan\alpha}\right) + h_r h_i \rho_i g\frac{\mathrm{Sin}\,\alpha + \mu\,\mathrm{Cos}\,\alpha}{\mathrm{Sin}\,\alpha}.$$

The load required for lifting the ice rubble on top of the advancing ice sheet prior to break it H_L can be calculated as:

$$H_L = 0.5\mathrm{w}h_r^2\rho_i g(1-e)\xi\left(\frac{1}{\tan\theta}-\frac{1}{\tan\alpha}\right)\left(1-\frac{\tan\theta}{\tan\alpha}\right) + 0.5\mathrm{w}h_r^2\rho_i g(1-e)\xi\tan\varphi\left(1-\frac{\tan\theta}{\tan\alpha}\right)^2 + \xi c w h_r\left(1-\frac{\tan\theta}{\tan\alpha}\right),$$

where:

c is the cohesion of ice rubble,

φ is the friction angle of the ice rubble.

The load to turn the ice block at the top of the slope H_T can be calculated as:

$$H_T = 1.5 \mathrm{w} h_i^{\,2} \rho_i g \frac{\operatorname{Cos}\alpha}{\operatorname{Sin}\alpha - \mu \operatorname{Cos}\alpha},$$

l_c is the total length of the circumferential crack, estimated as

$$l_c = \mathrm{w} + \frac{\pi^2}{4} L_c.$$

Input parameters for the drift ice in the Pechora Sea region are presented in Table 8 below.

Table 8 Input parameters for the drift ice load calculation

Parameter	Value	Dimension
w	8	m
μ	0.15	-
σ_f	0.4	MPa
ρ_w	1025	kg/m^3
g	9.81	m/s^2
E	5	GPa
υ	0.33	-
h_r	7	m
μ_i	0.03	-
ρ_i	910	kg/m^3
e	0.3	-
θ	α -10	degrees,°
φ	20	degrees, °
c	6	kPa

Since the acceptable ice thickness is expected to be relatively small (0.3-0.5 m), the cone width is for simplicity assumed to be constant at the ice interaction level and equal to 8 m (at the middle of the cone). Friction coefficient μ between the ice and the structure varies depending on the drift ice velocity from 0.05 to 0.3 and more. A value μ =0.15 is assumed as reasonable for drift velocities on the Dolginskoye field in the Pechora Sea [53].

Flexural strength of sea ice σ_f typically changes in the range 0.3-0.5 MPa typically [46, p. 195]. Another estimation suggested by ISO 19906 could be used that the flexural strength is approximately 1/9 of compressive ice strength.

Rubble height is an important parameter for the calculation of ice loads on sloping structures. Rubble height varies from several meters to 20 meters and more, 7 meter height has been assumed here since the ice thickness will be relatively small. The angle that the rubble makes with the horizontal axis is a difficult parameter to estimate. In principal, it should be obtained from the field data. Due to lack of information, this angle has been assumed to be 10^{o} less than the sloping angle, as recommended in ISO 19906 [46, p. 168].

The angle of internal friction should also be defined by experiment and varies from 11° to 67° in different studies. Cohesion of the ice rubble varies from 0 to 25 kPa.

4.2.2. Plastic method for cones

The method is based on a limit analysis solution for level ice actions on upward and downward breaking cones. The following functions are defined for the solution [46, p. 166]:

$$f = Sin(\alpha) + \mu \cdot E_1 \cdot Cos(\alpha),$$

$$g_r = \frac{Sin(\alpha) + \frac{\alpha}{Cos(\alpha)}}{\frac{\pi}{2} Sin^2\alpha + 2\mu\alpha \cdot Cos(\alpha)},$$

$$h_V = \frac{f \cdot Cos(\alpha) - \mu \cdot E_2}{\frac{\pi}{4} sin^2\alpha + \mu \cdot \alpha \cdot Cos(\alpha)},$$

$$W = \rho_i g \cdot h_{ride-up} \frac{w^2 - w_T^2}{4 \cdot Cos(\alpha)},$$

where:

α	is the slope of the structure measured from the horizontal (in radians),
w_T	is the top diameter of the cone,
h_r	is the ice ride-up thickness (assumed $h_r=2h_i$),
$E_1 = \int_0^{\pi/2} (1 - Sin^2\alpha \cdot Sin^2\eta)^{-0.5} d\eta$	is the complete elliptical integral of the first kind,
$E_2 = \int_0^{\pi/2} (1 - Sin^2\alpha \cdot Sin^2\eta)^{0.5} d\eta$	is the complete elliptical integral of the second kind.

The horizontal and vertical ride-up actions are given below, respectively:

$$H_R = W \frac{\tan(\alpha) + \mu E_2 - \mu f g_r Cos(\alpha)}{1 - \mu g_r}, \quad V_R = W \cdot Cos(\alpha) \cdot \left(\frac{\pi}{2} Cos(\alpha) - \mu\alpha - f h_V\right) + H_R h_V.$$

The horizontal and vertical breaking actions are obtained from the expressions:

$$H_B = \frac{\sigma_f {h_i}^2}{3} \cdot \frac{\tan(\alpha)}{(1 - \mu \cdot g_r)} \left(\frac{1 + Y \cdot x \cdot ln(x)}{x - 1} + G \cdot (x - 1)(x + 2)\right), \qquad V_B = H_B \cdot h_V,$$

where Y=2.711 - Tresca yielding, $G = (\rho_i g w^2)/(4\sigma_f h_i)$, $x=1+(3G+Y/2)^{-0.5}$.

Total action components in the horizontal and vertical directions are:

$$F_H = H_B + H_R, \qquad F_V = V_B + V_R$$

5. Analysis of the protective collar geometry

5.1 Parameters of collar geometry

Upward or downward slope of the cones, cone height and sloping angle are three parameters determining the collar geometry. They significantly influence the wave and ice loads experienced by the structure.

Upward/downward slope. For the same sloping angle and the size of the structure, upward sloping cones experience higher ice loads than downward sloping cones. Upward sloping cones provide additional weight on the seabed due to the rubble accumulation on the cones.
For the downward sloping cones, the vertical component of the ice load is directed upwards thus reducing effective shear resistance at the structure-seabed interface and influencing the stability of the structure. Due to stability issues, upward cone geometry has therefore been chosen for the present calculations. Should the downward slope be preferred, the ice loads will be less and the jack-up will be able to stay in place even longer.

Cone height. The height of the protective cones should be determined carefully. Insufficient height of the collars may result in damage of the jack-up legs due to ice impact. Too large cone height will lead to increased wave loads and additional weight of the structure. Cone geometry should also consider the variation of water level because the adjustment of the cone position on the leg after they have been installed once is a complicated and time-consuming operation. Based on the water level variation with tide ±1.25 m and maximum ice thickness expected during operations, i.e. 0.3-0.5 m, a cone height of 4 m has been suggested.

Sloping angle. The sloping angle is an important parameter for the protective cone geometry. The steeper is the angle, the more ice is crushed and the higher is the horizontal component of ice actions. Less sloping angle will potentially increase the rubble accumulation on the cone surface. Another disadvantage of wider cones is a bigger required size of the outriggers where the cones should be stored during transportation. A bigger cone diameter will also increase the wave loads on the structure in the operational mode.

Analysis of environmental load sensitivity to the cone angle will be performed further to determine the optimal collar geometry.

5.2 Sensitivity analysis

The influence of the sloping angle on the wave and ice loads has been investigated using Excel and MATLAB software. The assumed collar geometry is presented in Figure 27. Necessary dimensions are given in Table 9. Range of sloping angles from 20° to 80° is considered.

Table 9 Main geometrical parameters of cones

Leg diameter	D_{leg}	4	m
Cone wall thickness	Δ	0.05	m
Cone height	l	4	m
Distance from the high water level to the top of the cone	h	0.75	m

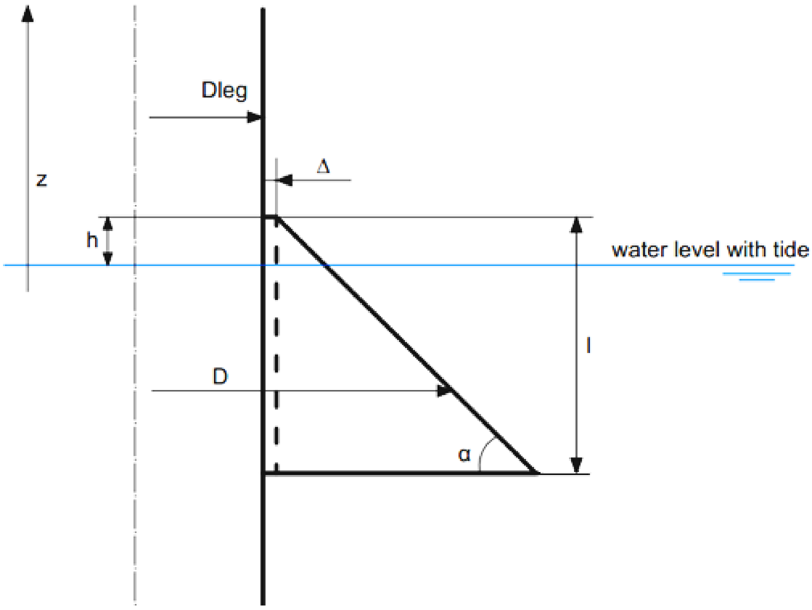


Figure 27 Protective cone geometry

5.2.1 Wave loads

According to Morison equation, inertia force contains the member D^2 which depends on the sloping angle. Also drag and mass coefficients depend on Keulegan Carpenter number $KC = \frac{u_a \cdot T}{D}$ (see Figure 28) increasing with the increase of sloping angle.

First, amplitude of water particle velocity varying with z is found:

$$u_a = u(t=0) = k \cdot A \cdot Cosh\big(k(z+d)\big) + 2 \cdot k \cdot B \cdot Cosh\big(2k(z+d)\big) + 3 \cdot k \cdot C \cdot Cosh\big(3k(z+d)\big)$$

Diameter of the cone depends on the sloping angle as:

$$D_{cone} = D_{leg} + 2\Delta + 2(-z + 0.75)/\tan(\alpha)$$

Variation of Keulegan Carpenter number with depth for 20° and 80° is presented in Table 10.

Table 10 Keulegan Carpenter number for different angles

z, m	u, m/s	α=20°		α=80°	
		D, m	KC	D, m	KC
0,75	4,54	4,10	12,73	4,10	12,73
0	4,43	8,22	6,19	4,37	11,67
-0,5	4,36	10,97	4,57	4,54	11,03
-0,75	4,32	12,35	4,03	4,63	10,74
-1	4,29	13,72	3,59	4,72	10,45
-1,25	4,25	15,10	3,24	4,81	10,18
-1,5	4,22	16,47	2,95	4,90	9,91
-1,75	4,19	17,84	2,70	4,99	9,66
-2	4,15	19,22	2,49	5,07	9,41
-2,25	4,12	20,59	2,30	5,16	9,18
-2,5	4,09	21,97	2,14	5,25	8,95
-2,75	4,06	23,34	2,00	5,34	8,73
-3	4,02	24,72	1,87	5,43	8,52
-3,25	3,99	26,09	1,76	5,52	8,32

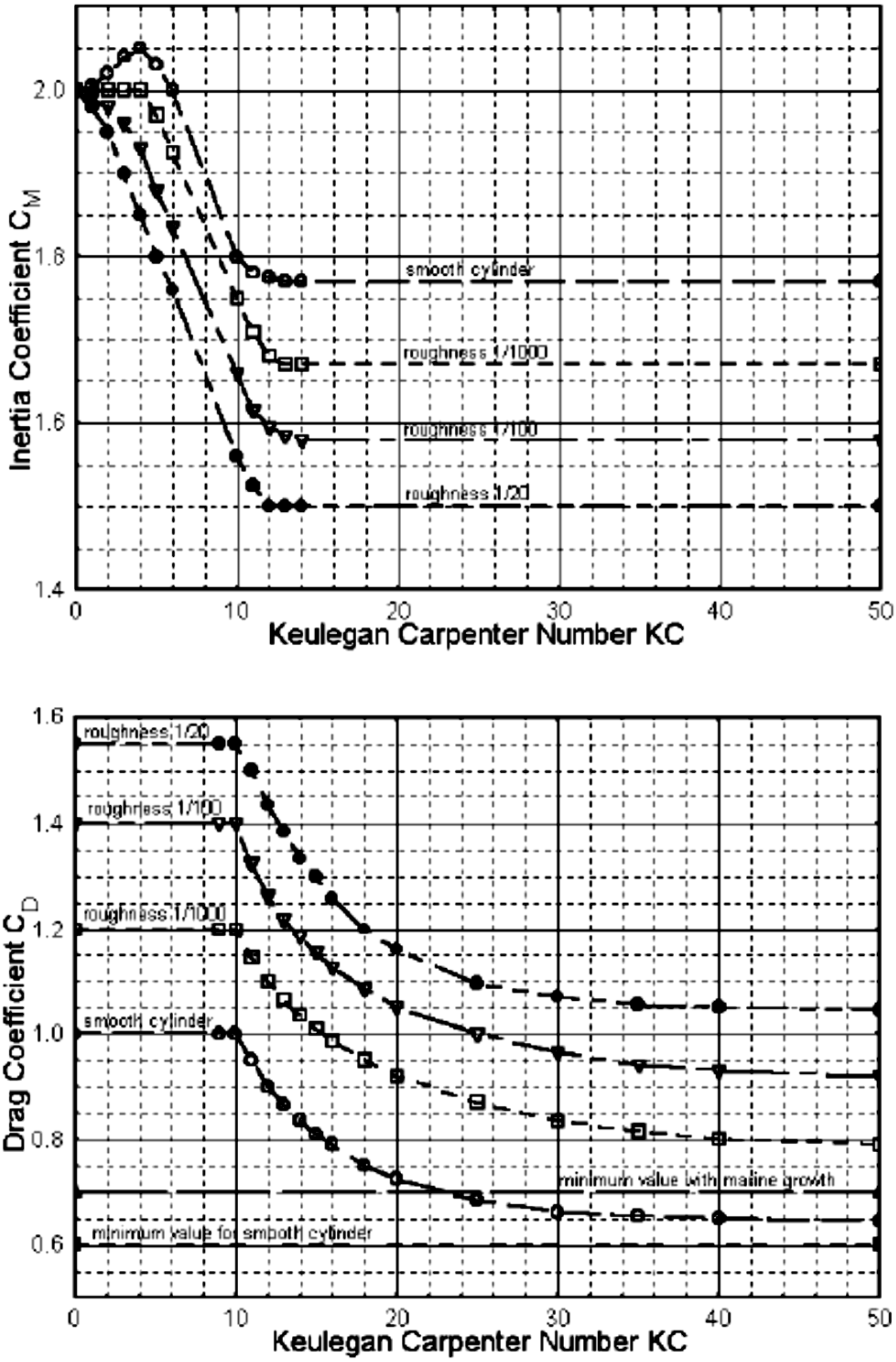


Figure 28 Suggested drag and inertia coefficient values from DNV [54, p. 12-19]

Since *tan(α)* is a continuously increasing function, the cone diameter will continuously decrease with the increase of sloping angle *α*. It means that the Keulegan Carpenter number KC, being inversely proportional to cone diameter, continuously increases with increasing angle *α* and varies from 1.76 to 12.73 (see Table 10). For this range of KC, drag coefficient for cones can be assumed constant and equal 1.2 (cone roughness is assumed 1/1000). This means the drag force depends linearly on the cone diameter. Total drag force on the cone then can be found as:

$$F_D = \frac{1}{2}\rho C_D \cdot D_{cone} \cdot u \cdot |u| = 0.6\rho \cdot \int_{-3.25}^{0.75} (D_{leg} + 2\Delta + 2(-z + 0.75)/\tan(\alpha)) \left(k \cdot A \cdot Cosh\left(k(z+d)\right) + 2 \cdot k \cdot B \cdot Cosh\left(2k(z+d)\right) + 3 \cdot k \cdot C \cdot Cosh\left(3k(z+d)\right)\right)^2 dz \cdot Cos(\omega t) \cdot |Cos(\omega t)|$$

The program scripts of the calculations in this chapter are presented in Appendix A. The total drag force on the cone varying with time is shown on Figure 29.

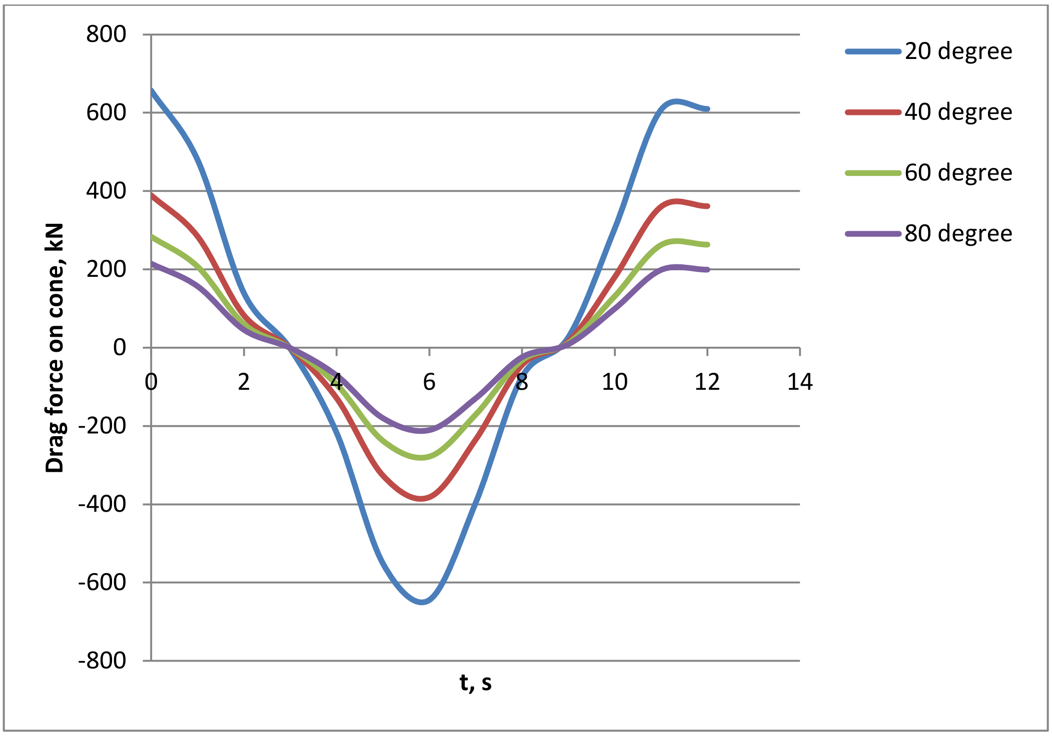


Figure 29 Drag force on protective cone

The inertia coefficient C_M varies significantly in the considered range of KC and can be approximated by a linear relation based on Figure 28:

$$C_M = 2.16 - 0.04 \cdot KC.$$

So, the inertia force for different angles can be calculated as:

$$F_i = \frac{\pi}{4} \cdot \rho \cdot \int_{-3.25}^{0.75} (2.16 - 0.04 \frac{u_a(z) \cdot T}{D(z,\alpha)}) \cdot D_{cone}(z,\alpha)^2 \cdot \dot{u}(z)$$

The inertia force varies significantly with the variation of the sloping angle (see Figure 30).

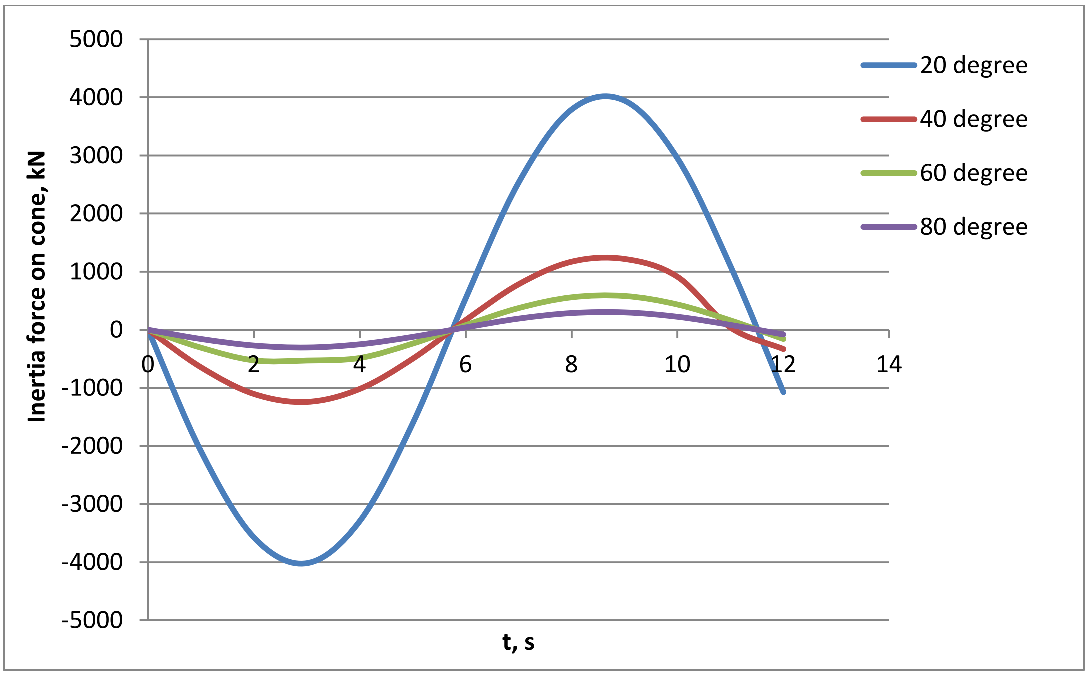


Figure 30 Inertia force on cone for different sloping angles

As can be noticed from the plots, the mass force dominates for less sloping angles of the cones. The variation of total wave force amplitude on the cone with the sloping angle is presented on Figure 31. The total wave force decreases with the increase of sloping angle because the cone diameter decreases.

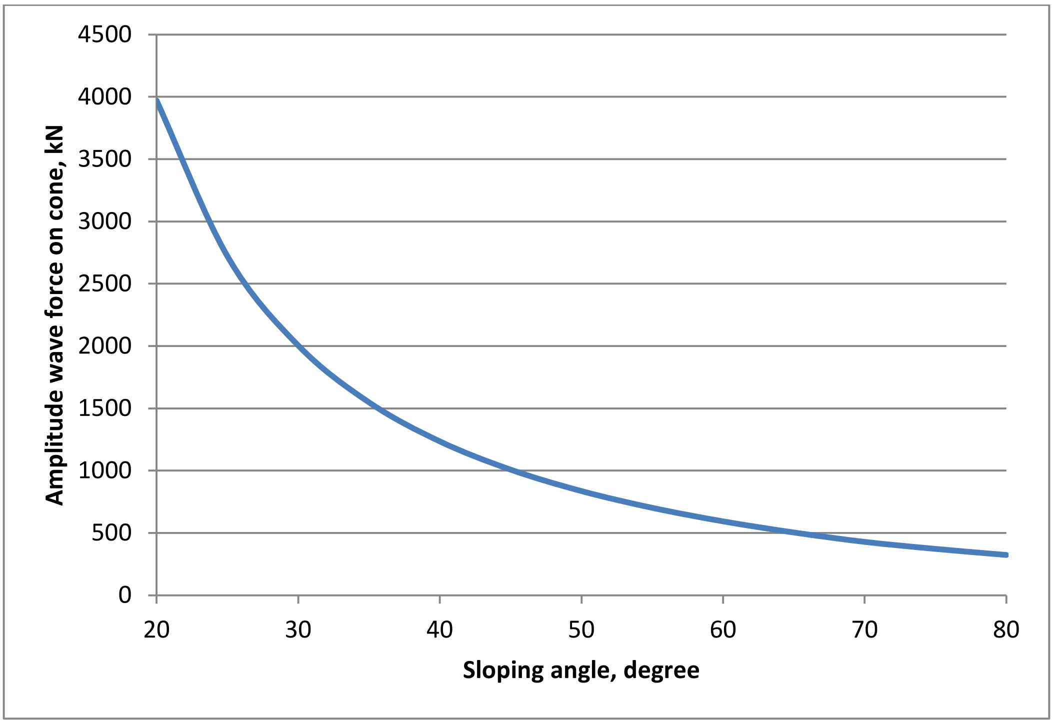


Figure 31 Amplitude wave force for different sloping angles

5.2.2 Ice loads

Elastic beam bending method. As it was shown before (see 4.2.1), the total ice load depends on the structure's width and the sloping angle. Due to relatively small expected ice thickness in the beginning of the ice season, the structure width at the ice interaction level can be assumed constant and equal the cone width in the middle part. Then the expression for the structure width is:

$$D_{cone} = D_{leg} + 2\Delta + 2 \cdot 2/\tan(\alpha)$$

Program scripts for calculations of ice load on cones are presented in Appendix A. As shown on Figure 32, total ice load does not vary significantly in the range of the sloping angles between 40° and 60°.

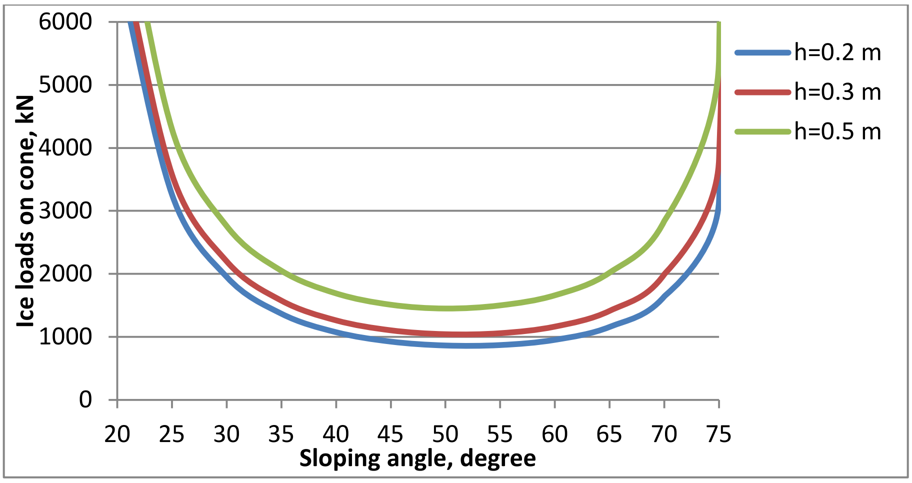


Figure 32 Ice load on cones for different ice thickness and sloping angles (elastic beam bending method)

Plastic method. The theory of the method is presented in paragraph 4.2.2, and the program script can be found in Appendix A. Ice load variation with the sloping angle for different ice thickness is shown on Figure 33. This method provides less ice loads than elastic beam bending method. The most important unknown parameter, which can cause inaccuracy of the results, is the ride-up ice thickness (assumed as twice the ice sheet thickness). The ice load is minimal in the sloping angle interval from 30° to 60° degrees approximately.

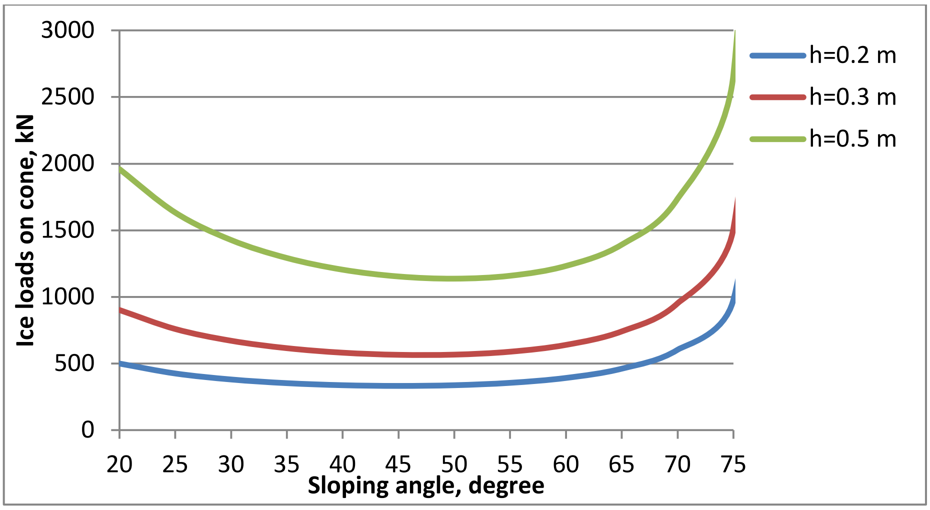


Figure 33 Ice load on cones for different ice thickness and sloping angle (plastic method)

5.2.3 Results

Wave and ice loads on the protective cones have been analyzed.

The wave loads decrease when the sloping angle increases. The smaller the sloping angle, the bigger is the cone width and higher wave loads are experienced by the structure.

Ice loads for very small sloping angles (less than 20° - 30°) are relatively big for the same reason – the increased cone diameter leads to bigger area of ice-structure interaction. For steep angles (about 70° - 80°) ice load increases dramatically because the ice failure mode changes from flexure to crushing. Results obtained by elastic beam bending method show stronger dependence on the sloping angle than those calculated by the plastic method. However, for both methods the ice loads are minimal in the sloping angle interval from 40° to 60°.

Since the cones are stored in the outriggers during transportation, the cone geometry will influence the geometry of the hull. From the construction point of view, smaller cone diameter is preferred.

Based on this analysis, a sloping angle of 60° is chosen as an optimal for the protective cones. So the cone's outer diameter will vary from 4.1 m at the top to 8.7 m at the bottom of the cone.

5.3 Buoyancy elements

As the protective cones are lowered down to the mud mats by gravity force, it is advisable to implement some buoyancy elements in the cone design. This will protect the mud mats and the cones themselves from the possible damage while the cones are moving by gravity to the sea floor.

For the chosen cone geometry, the buoyancy element volume will be calculated below. In the calculations, gravity force is assumed to be 5% higher than buoyancy force to provide slow lowering of cones in the sea water. Input data is given in Table 11, and the buoyancy element geometry is shown on Figure 34. The required buoyancy element volume V_2 is calculated below.

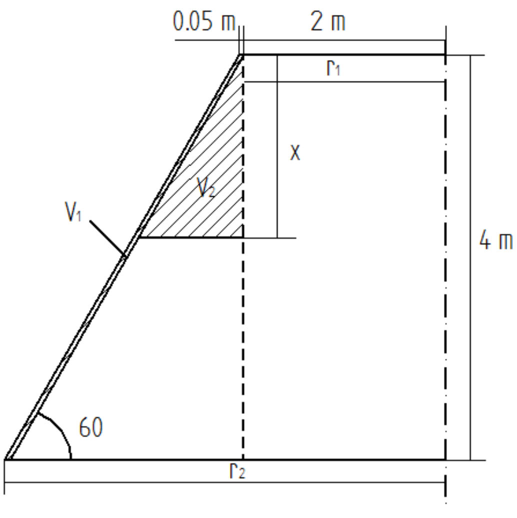


Figure 34 Buoyancy element geometry

Table 11 Input data for buoyancy element

Parameter	Symbol	Value	Unit
Stainless steel density	ρ_s	8000	kg/m^3
Air density	ρ_a	1.3	kg/m^3
Water density	ρ_w	1030	kg/m^3
Outer top radius	r_1'	2.05	m
Inner top radius	r_1	2	m
Outer bottom radius	r_2'	4.35	m
Inner bottom radius	r_2	4.3	m
Cone height	l	4	m

$$V_1 = \frac{1}{3}\pi l\left(\left({r'_1}^2 + {r'_2}^2 + r'_1 r'_2\right) - \left(r_1^2 + r_2^2 + r^1 r^2\right)\right) = 3.99\ m^3$$

$$V_2 = \frac{1}{3}\pi h\left(r_1^2 + (r_1 + 2x/\tan(60°))^2 + r_1 \cdot (r_1 + 2x/\tan(60°))\right) - \pi \cdot r_1^2 \cdot x$$

$$F_g \approx g \cdot (\rho_s V_1 + \rho_a V_2)$$

$$F_b = \rho_w g(V_1 + V_2)$$

$$F_g = 1.05 \cdot F_b$$

After substituting volumes V_1 and V_2, the parameter x =1.64 m and required buoyancy element volume V_2 = 25.7 m^3 have been obtained.

In principal, vulnerable parts of the locking mechanism (e.g. electrical actuators) can be placed inside the buoyancy tank to protect them from the sea water.

The calculations may contain some inaccuracy due to assumed material properties and the weight of the cone locking mechanism which has been neglected here. So, the buoyancy element volume may potentially need to be increased. Also other possible geometries of the buoyancy element can be considered. The main idea of this feature is to achieve almost neutral cone weight in the sea water to make lowering of the cones slow and safe.

6. Calculation of environmental loads on jack-up legs

One of the goals of the present work is to evaluate the drilling season duration for the suggested jack-up. An operational season in the Arctic will be limited by the ice loads that the jack-up's legs can withstand in the fall. When the ice grows and the ice loads approach the design load value, all operations must be stopped and the jack-up shall move away.

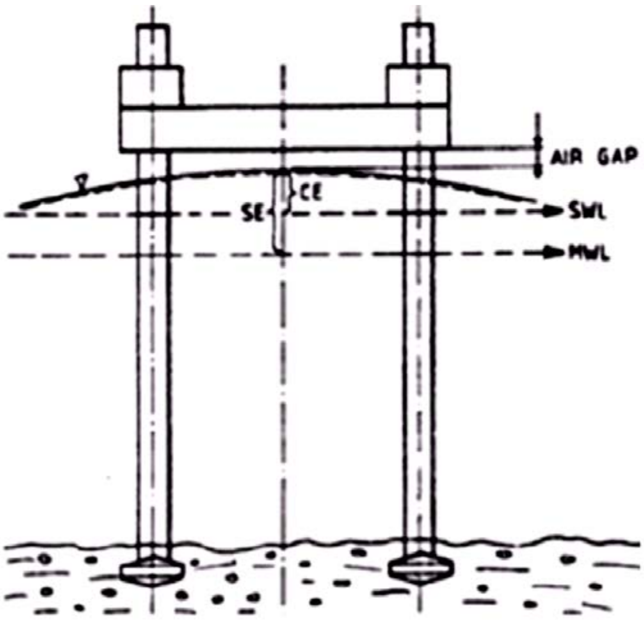
To estimate the acceptable ice thickness, some limitations for ice loads on the jack-up's protective cones should be set. It is suggested that the design ice load should not exceed the design wave load on the structure.

In this chapter, the following sequence of calculations is presented:

- calculation of the required air gap
- an estimation of the design wave load on the jack-up leg with cones for the selected area,
- calculation of the corresponding ice thickness giving the same load,
- evaluation of the ice growth velocity for different weather scenarios and the estimation of possible drilling season extension.

6.1 Required air gap

As it was mentioned in 3.2, the hull of the jack-up due to its rounded shape should be lifted higher in comparison with conventional jack-ups. The air gap is defined as the clear distance between the hull structure and the maximum wave crest elevation (see Figure 35 [19, p.67]).



MWL = mean water level.
SWL = still water level.
CE = wave crest elevation above SWL.
SE = surface elevation above MWL.

Figure 35 Definition of air gap [19, p. 67]

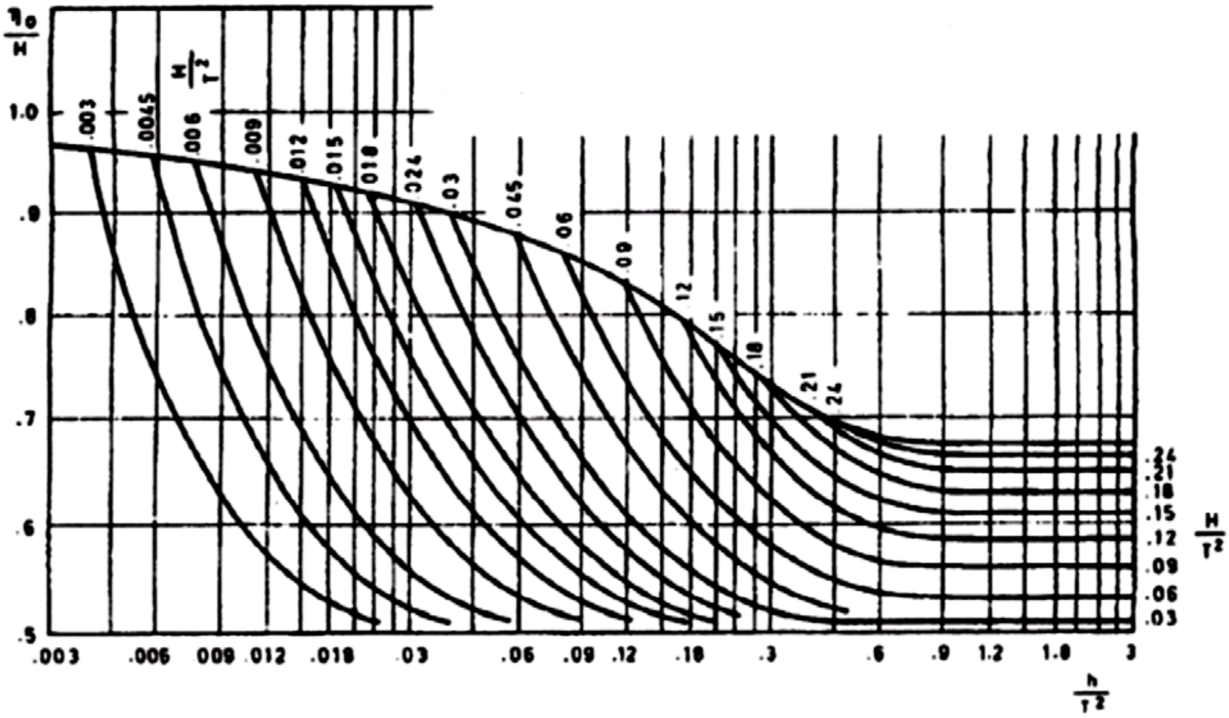
Still water level can be found as a highest astronomical tide (HAT) including storm surge:

$SWL = d_v + h_t + strom\ surge = 50 + 1.25 + 3.35 = 54.6$ m

From the 3rd order Stokes theory the crest elevation at the chosen reference area can be found as:

$$\eta = \frac{H}{2}Cos(\theta) + \frac{1}{4}Coth(kd) \cdot (3Coth^2(kd) - 1) \cdot \frac{H^2}{4}k \cdot Cos(\theta) - \frac{3}{8}(Coth^4(kd) - 3 \cdot Coth^2(kd) + 3) \cdot \frac{H^3}{8} \cdot k^2 \cdot Cos(2\theta) + \frac{3}{64}(8Coth^6(kd) + (Coth^2(kd) - 1)^2) \cdot \frac{H^3}{8}k^2 \cdot Cos(3\theta) = 9.91 \text{ m}$$

Also, crest elevation above the still water level may be calculated according to Figure 36 [19, p.68].



η_o = crest elevation above still water (metres).
H = wave height (metres).
T = wave period (seconds).
H = still water depth (metres).

Figure 36 Crest elevation [19, p. 68]

For $\frac{d}{T^2} = 0.38\ \text{m/s}^2$ and $\frac{H}{T^2} = 0.11\ \text{m/s}^2$ the crest elevation above the still water level is 9.12 m.

The air gap is not to be less than 10% of the combined astronomical tide, storm surge and wave crest elevation, but is not required to be greater than 1.2 m [19, p. 67].

$airgap = 0.1 \cdot (1.25 + 3.35 + 9.91) = 1{,}45$ m.

So the hull elevation above the mean water level is:

$a_0 = 1.25 + 3.35 + 9.91 + 1.45 = 15.96$ m.

The air gap may need to be increased because of the possibility of freak wave occurrences. These are unexpectedly large and/or steep waves, and neither their probability of occurrence nor their physics is well understood [51, p. 37].

Another consideration for the air gap calculations is the apparent global warming effect in Arctic. Average temperatures in the Arctic region are rising twice as fast as they are elsewhere in the world [55]. Increasing temperature leads to the extension of ice-free Arctic areas resulting in wind waves and storm increase. For example, the increase of extreme wave maximum for the Stockman field will be approximately 1.3 m by 2015 in comparison with the average values for the period from 1958 to 2002 [56]. So, higher waves can be potentially expected in the Arctic waters in future.

6.2 Design wave load

Design wave load is determined as a wave load on the jack-up legs and protective cones. Normally the protective cones are lowered only when the ice is forming. But since the operation of lowering cones down to the water level is quite complicated and time-consuming, there is still a possibility that high waves will occur when the cones have been already installed on the legs. The situation, when waves act on the jack-up legs and protective cones, is considered as the most unfavorable with respect to wave loads, so the design wave load will be calculated for such conditions.

Drag coefficient for the tubular jack-up legs depends on the size of rack teeth. For the flow normal to the rack, drag coefficient C_D can be found as [51, p.60-61]:

$$C_D = C_{D1}\frac{W}{D}\text{, where } C_{D1} = \begin{cases} 1.8 & : W/D < 1.2 \\ 1.4 + W/3D & : 1.2 < W/D < 1.8 \\ 2 & : 1.8 < W/D \end{cases}$$

Geometrical parameters D and W (see Figure 37) represent the leg diameter and the leg diameter with rack teeth, respectively.

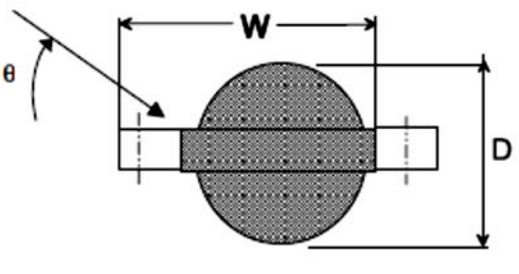


Figure 37 Split tube chord [51, p. 61]

Assuming the rack teeth height 0.2 m and $W/D = 4.2/4 = 1.05 < 1.2$, drag coefficient for the jack-up legs is:

$C_D = 1.8 \cdot 1.05 = 1.89$.

The added mass coefficient C_M =*1* may be applied for all heading, related to the equivalent volume $\pi D^2/4$ per unit length [51, p.61]. Wave crest height is $\frac{H}{2} \cdot \left(1 + \frac{\pi H}{2\lambda}\right)$.

So, drag force on the jack-up legs and protective cones can be calculated as:

$$F_D = \frac{1}{2} \cdot 1.89 \cdot \rho \cdot D_{leg} \int_{-51.25}^{-3.25} u(z) \cdot |u(z)| \, dz + \frac{1}{2} \cdot 1.2 \cdot \rho \int_{-3.25}^{0.75} (D_{leg} + 2\Delta + 2(-z + 0.75)/\tan(60°)) \cdot u(z) \cdot |u(z)| \, dz + \frac{1}{2} \cdot 1.89 \cdot \rho \cdot D_{leg} \int_{0.75}^{wave\ crest} u(z) \cdot |u(z)| \, dz$$

Inertia force can be calculated as:

$$F_M = 1 \cdot \rho \cdot \pi \cdot \frac{D_{leg}{}^2}{4} \int_{-51.25}^{-3.25} a(z) \, dz + \frac{\pi}{4} \cdot \rho \cdot \int_{-3.25}^{0.75} (2.16 - 0.04 \frac{u_a(z) \cdot T}{D(z)}) \cdot (D_{leg} + 2\Delta + 2(-z + 0.75)/\tan(60°))^2 \cdot a(z) \, dz + 1 \cdot \rho \cdot \pi \cdot \frac{D_{leg}{}^2}{4} \int_{0.75}^{wave\ crest} a(z) \, dz$$

Total design wave force on the legs and protective cones is:

$$F_w = F_D + F_M$$

The program script of the calculations can be found in Appendix B. Total design wave force is shown on Figure 38. Maximum design wave force obtained is 2.4 MN.

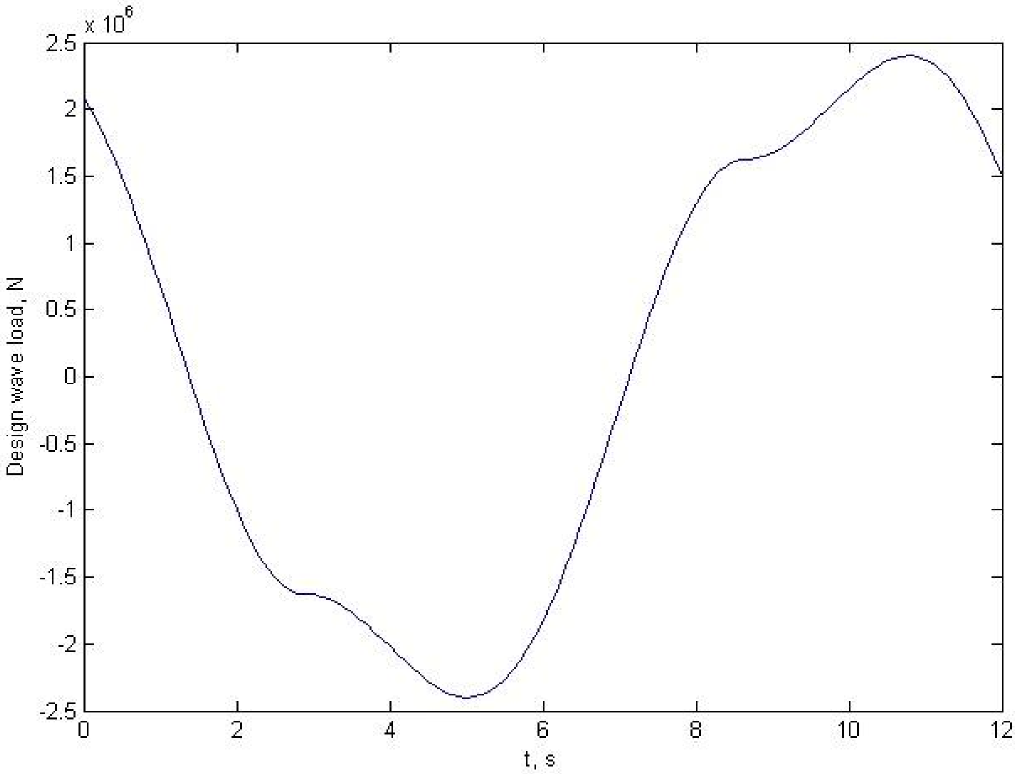


Figure 38 Design wave force on the leg and protective cone

6.3 Calculation of acceptable ice thickness

According to ISO 19906, the structure shall be designed for the ultimate limit states (ULS) for strength and stiffness [46, p. 21]. For ULS, the characteristic value for actions arising from the extreme-level ice event (ELIE) shall be determined based on an annual probability of exceedance not greater than 10^{-2} [46, p.22]. It is required that factored action effects shall not exceed factored resistances [46, p.19]. Action factor for the environmental actions can be determined from Table 12 [46, p.25].

Table 12 Exposure levels L1 and L2: ULS and ALS action factors and action combinations [46, p.25]

Action combination	Limit state action factors						
	Permanent action (*G*)		Variable action (*Q*)		Environmental action (*E*)		Accidental action (*A*)
	Dead (*G1*)	Deformation (*G2*)	Long duration (Q_1)	Short duration (Q_2)	EL	AL	
ULTIMATE LIMIT STATES							
1 Gravity and Deformation – long and short duration	1,30[a] or 0,90[b]	1,00	1,50[a]	1,50[a]	0,70[c]	-	-
2 Extreme environmental	1,10 or 0,90[b]	1,00	1,10 or 0,80[b]	-	1,35 (L1)[c,d] 1,10 (L2)[c,d,e]	-	-
3 Damaged condition[f]	1,10 or 0,90[b]	1,00	1,10 or 0,80[b]	-	1,00	-	-
ABNORMAL (ACCIDENTAL) LIMIT STATES							
4 Abnormal environmental	1,00	1,00	1,00	-	-	1,00[c]	-
5 Accidental	1,00	1,00	1,00	-	-	-	1,00

The drilling rig for Arctic conditions, as a manned evacuated structure with high consequences of the potential hazard, as categorized as the exposure level L1 structure (based on [46, p. 20] . According to Table 12, the action factor 1.35 has been chosen for the environmental actions.

The design ice action is suggested to be equal to design wave loads 2.297 MN. Then the characteristic value of the ice action can be found as:

$$F_{ice} = \frac{F_W}{1.35} = \frac{2.4}{1.35} = 1.78\ MN.$$

So, the acceptable ice thickness can be found as an ice thickness providing the ice load on the cones equal to 1.78 MN.

Sensitivity of the ice loads to the sloping angle variation has been investigated in Paragraph 5.2.2. In this chapter, variation of the ice loads with the ice growth is estimated to find the acceptable ice thickness. All program scripts applied can be found in Appendix B.

Elastic beam bending method. As can be noticed from Figure 39, ice loads strongly depend on the ice thickness. For the 1.78 MN the corresponding ice thickness is 0.54 m.

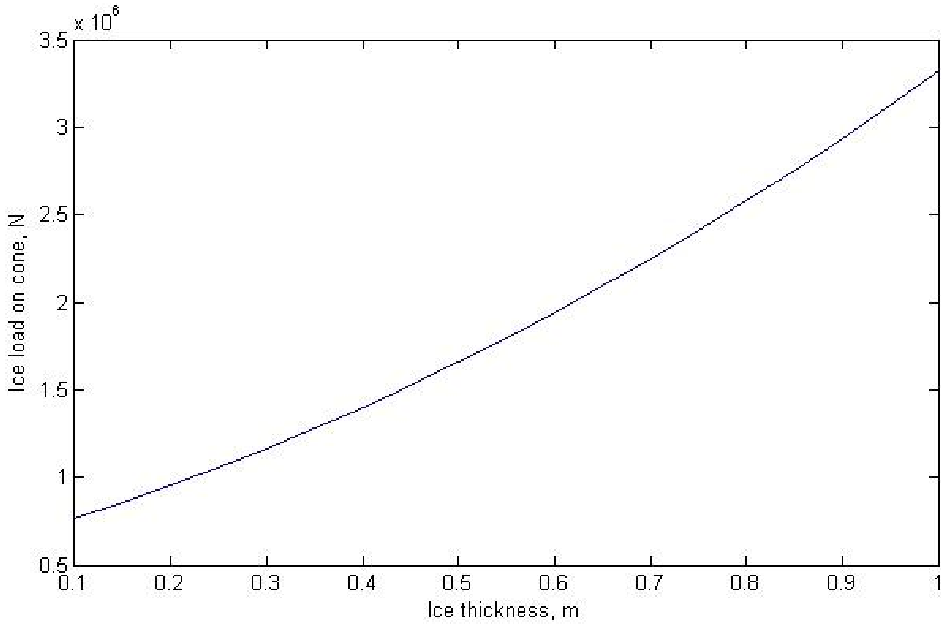


Figure 39 Ice load on the cone (elastic beam bending method)

Plastic method. As it is shown on Figure 40, this method provides significantly lower ice load in comparison with elastic beam bending method and this results in bigger acceptable ice thickness. For the load 1.78 MN the corresponding ice thickness is 0.76 m.

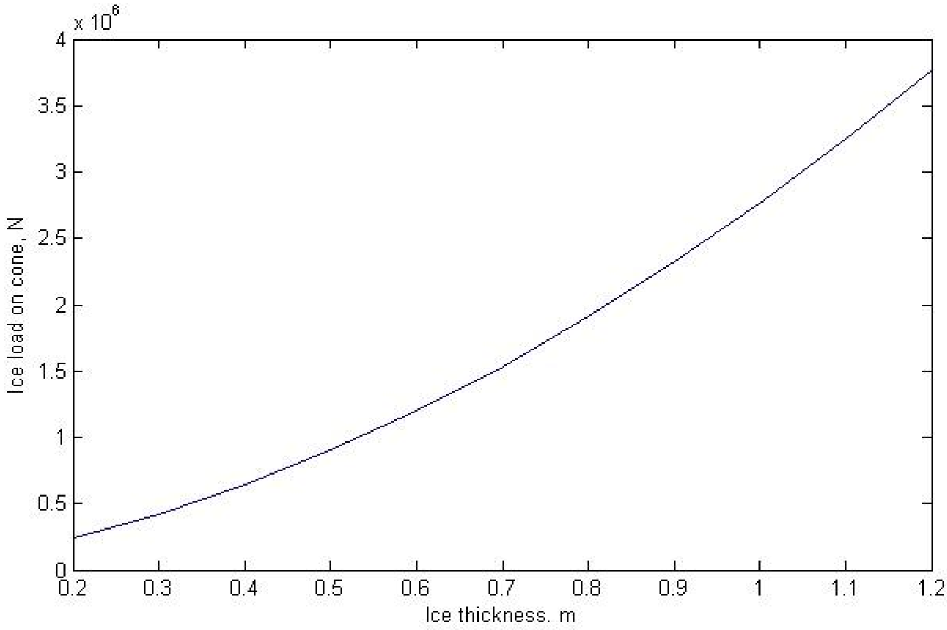


Figure 40 Ice load on the cone (plastic method)

Calculations by both methods contain some uncertainties, primarily connected to the ice properties and the ice rubble accumulation geometry. The lower value of the acceptable ice thickness 0.52 m, obtained by beam bending method, will be used further to estimate the drilling season extension.

7. Benefits of the new jack-up design

7.1 Drilling season extension

The acceptable ice thickness calculated above is 0.54 m. It should be noted that such estimation, even after implementation of the action factor, contains many assumptions and uncertainties and should be checked for the particular Arctic area based on the accurate data.

As it was mentioned in the concept description, the suggested jack-up is not intended to withstand high ice loads. The jack-up having the drill string protected inside the leg is able to withstand some ice loads during operations. However, if a significant rubble accumulation occurs the jack-up may get stuck in the ice. Also ridges may affect the jack-up legs which are not designed for heavy ice loads.

Such risks must be avoided, so the jack-up crew shall prepare to leave the drilling site before the ice accumulates significantly around the jack-up legs. Based on all said above, the acceptable ice thickness during the drilling is suggested to be limited by 0.3 m. This thickness is assumed as a target ice thickness when the jack-up must start to prepare for leaving the site. A demobilization period is assumed to take approximately one week.

To estimate the possible extension of the drilling season, the ice growth velocity should be determined. Since the heat transport through the already formed ice thickness limits the ice growth, the ice growth rate will obviously be reduced with the increase of the ice thickness. The quantity of heat conducted upward through the ice per unit area in time *dt* is given by [53, p. 17]:

$$dq = -k_i \frac{T_a - T_m}{h_i} dt = l_f \rho_i dh_i$$

where:

k_i	is the mean thermal conductivity of ice,
T_a	is the mean ambient air temperature,
T_m	is the melting point temperature of ice,
h_i	is the ice thickness,
l_f	is the latent heat of fusion of ice,
ρ_i	is the density of solid ice.

Integrating the equation and assuming the initial ice thickness equal to zero, for the values:

$$k_i = 2.21\ \mathrm{W/m \cdot {}^\circ C},\ \ l_f = 333.4\ \mathrm{kJ/kg},\ \ \rho_i = 910\ \mathrm{kg/m^3}$$

the following relation can be obtained:

$$h_i^2 = 0.0013\, FDD.$$

In a simple way, *FDD* (degree-days of freezing) can be taken as a sum over days with freezing multiplied with the average temperature for each day [53, p. 17].

A number of empirical relations have been obtained to estimate the ice growth. For example, the empirical formula proposed by Zubov (1943) (h_i is in cm):

$$h_i^2 + 50h_i = 8\,FDD$$

or by Lebedev (1938) [53, p. 19]:

$$h_i = 1.33|FDD|^{0.58}\ .$$

FDD parameters for the target (0.3 m) and acceptable (0.54 m) ice thickness formation are shown in Table 13:

Table 13 Freezing degree days

FDD [°C·days]	Heat equation	Zubov formula	Lebedev formula
for h_i =0.3 m	69	300	215
for h_i =0.54 m	192	702	594

FDD provided by the heat equation is much less than those obtained from Zubov and Lebedev formulas. There are at least two reasons for this discrepancy: the snow cover on top is neglected and the heat input from the ocean is neglected [53, p. 17]. The formula obtained by Lebedev and based on measurements from 24 station years in different areas of the Russian Arctic is expected to provide more accurate estimations for the Pechora Sea region. It will be applied further to calculate the ice growth period.

The Pechora Sea conditions are presented in Table 14 (based on [46], p. 380-381):

Table 14 The Pechora Sea conditions

	Parameter	Average annual value	Range of annual values
Air temperature	Maximum (°C)	8.8	8 to 10
	Minimum (°C)	-19	-18 to -20
	Freezing degree days	2500	2300 to 2800
Ice occurrence	First ice	25 October	20 October to 5 Nov
	Last ice	5 July	25 June to 15 July

Since the ice growth depends on the air temperature, it is difficult to estimate the extension of the drilling season without an accurate weather forecast. The measurements from the Pechora Sea coastal meteorological stations in 2012 are used to give a general understanding of how the drilling season could be extended. Data from three meteorological stations Mys Konstantinovsky, Khodovarikha and Varandey (see Figure 41 [57]) and the corresponding ice growth are presented in Table 15 (based on the data from Arctic and Antarctic Research Institute [58]).

Figure 41 Meteorological station locations (A - Mys Konstantinovsky, B - Khodovarikha, C - Varandey) [57]

Table 15 Ice growth calculation (yellow mark – the duration of target thickness (0.3 m) formation, red mark – the duration of design ice thickness (0.5 m) formation)

Date	Time interval, days	Air temperature measurements								
		Khodovarikha			Mys Konstantinovsky			Varandey		
		Air temperature, °C	FDD, °C day	Ice growth, m	Air temperature, °C	FDD, °C day	Ice growth, m	Air temperature, °C	FDD, °C day	Ice growth, m
31.10.	2	-2,4	1,2	0,01	-0,5	-	-	0,3	-	-
1.11.	1	-3,4	2,8	0,02	-3,1	1,3	0,02	-4,7	2,9	0,02
5.11.	4	-8,2	28,4	0,09	-11,8	41,3	0,12	-8,5	29,7	0,10
7.11.	2	-3,9	32,6	0,10	-4,6	46,9	0,12	-6,2	38,5	0,11
8.11.	1	0,4	32,6	0,10	0,2	46,9	0,12	0,2	38,5	0,11
12.11.	4	-3,7	40,2	0,11	-4,6	58,1	0,14	-6	55,3	0,14
14.11.	2	-3,6	43,8	0,12	-4,3	63,1	0,15	-11,3	74,3	0,16
15.11.	1	-5,1	47,1	0,12	-3,6	64,9	0,15	-4	76,5	0,16
19.11.	4	0,1	47,1	0,12	-0,8	64,9	0,15	-1,8	76,5	0,16
21.11.	2	-1,8	47,1	0,12	-2,2	65,7	0,15	-2,1	77,1	0,17
22.11.	1	-5,8	51,1	0,13	-6,4	70,3	0,16	-5,7	81	0,17
26.11.	4	-11,6	90,3	0,18	-22	151,1	0,24	-18	145,8	0,24
28.11.	2	-24	134,7	0,23	-23,6	194,7	0,28	-21,2	184,6	0,27
29.11.	1	-	134,7	0,23	-21,4	214,3	0,30	-26,2	209	0,29
3.12.	4	-11,2	172,3	0,26	-10,2	247,9	0,33	-7,6	232,2	0,31
5.12.	2	-10,2	189,1	0,28	-12,9	270,1	0,34	-14,4	257,4	0,33
6.12.	1	-8,2	195,5	0,28	-10,4	278,7	0,35	-10,7	266,3	0,34
10.12.	4	-10,8	231,5	0,31	-15,9	335,1	0,39	-14,9	318,7	0,38
12.12.	2	-23,3	274,5	0,35	-21,7	374,9	0,41	-27,8	370,7	0,41
13.12.	1	-19,2	291,9	0,36	-19,4	392,5	0,42	-19,4	388,3	0,42
17.12.	4	-12,6	335,1	0,39	-16,4	450,9	0,46	-16	445,1	0,46
19.12.	2	-11,8	355,1	0,40	-	450,9	0,46	-17,3	476,1	0,48
20.12.	1	-12	365,3	0,41	-16,6	465,7	0,47	-14,3	488,6	0,48
24.12.	4	-3,2	370,9	0,41	-5,4	480,1	0,48	-6	505,4	0,49
26.12.	2	-19,2	405,7	0,43	-18,5	513,5	0,50	-17,1	536	0,51
27.12.	1	-24,8	428,7	0,45	-23,9	535,6	0,51	-18	552,2	0,52
29.12.	3	-17,9	477	0,48	-14,9	574,9	0,53	-17,3	598,7	0,54
10.1.	12	-28,4	796,2	0,64	-26,4	870,1	0,67	-23,2	855,5	0,67

The duration of target ice thickness (0.3 m) formation is marked yellow in Table 15, and the period for design ice thickness (0.54 m) formation is marked red. For the last year weather conditions, the jack-up could continue drilling for 4-5 weeks after the ice had started to form and would have 4 weeks more to leave the site safely until the critical ice thickness was formed.

The estimations presented in this chapter are quite approximate due to many assumptions and uncertainties. Besides the important ice parameters varying for different locations, the weather forecast is crucial for the estimation of the operational season duration.

The possible extension of the drilling season should be estimated properly for each year for every particular location. The actual situation on the site will define the drilling period. The possibility of drilling in the ice-infested water should be estimated by the jack-up crew basing on the reliable weather forecast.

It should be also mentioned that due to the icebreaking capabilities of the jack-up hull the jack-up can be on location earlier in summer that will allow extending the operational season even more. Placement on location cannot start, however, before the water is cleared from ice floes that could damage the integrity of the legs.

7.2 Potential areas of application

Due to the extended drilling season and the technical documentation provided, we will claim that the new jack-up can be a reliable and economically effective solution for Arctic drilling. Application of such exploration rig allows drilling and testing the well in one operational season.

Nowadays the drilling season is strictly limited by the ice presence at the drilling location. In the end of 2012 Imperial Oil (ExxonMobile) presented a Preliminary Information Package (PIP) describing a potential exploration program in the Beaufort Sea. A potential multi-season drilling program is shown on Figure 42.

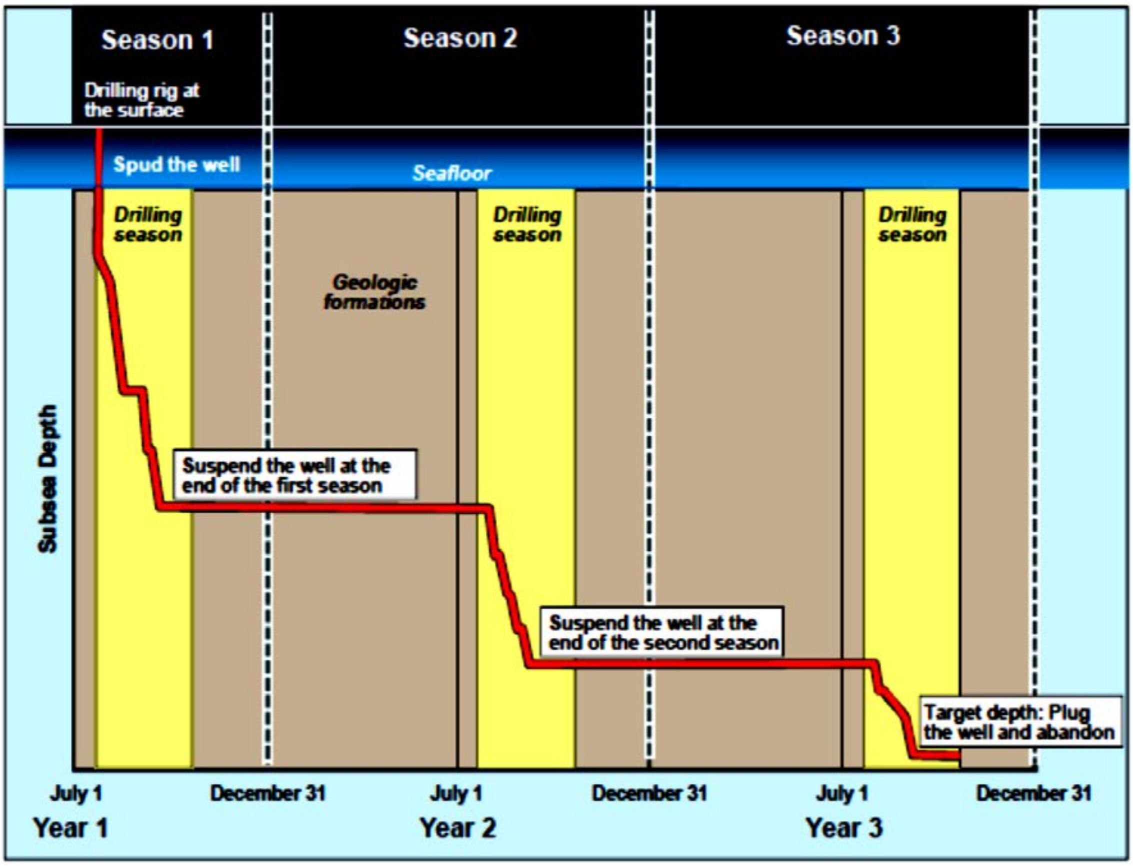


Figure 42 Example of Three-Season Drilling Program in the Beaufort Sea for One Well [59]

According to the strategy, drilling of one exploration well (from pre-drilling operations to plug and abandonment) can take up to three years for the Chukchi Sea, where the ice conditions are considered manageable in average about 120 days per year. This again illustrates how complex and expensive exploration drilling can be in Arctic. The possibility to complete drilling, well testing and P&A in one season can significantly reduce the exploration costs.

The ice capability of the new jack-up results not only in economic profits but also allows meeting the authority regulations. State regulations for Arctic areas are even stricter than for conventional offshore drilling. Since the possible consequences of oil spills are enormous and the methods to recover the oil from ice are not developed sufficiently, great attention is paid to the Contingency plan in case of uncontrolled release of reservoir fluids. According to “The National Energy Board Filing Requirements for Offshore Drilling in the Canadian Arctic”, the drilling company must be able to drill a relief well to kill an out-of-control well during the same drilling season (so called “The Same Season Relief Well Policy” [60]). The Ministry for Industrial and Natural Resources of Denmark announced even higher requirements for Arctic waters including a two rig policy that demands companies to make available two drill rigs for every well. The purpose of the second rig is to reduce the time needed to mobilize a rig to drill an emergency relief well [61].

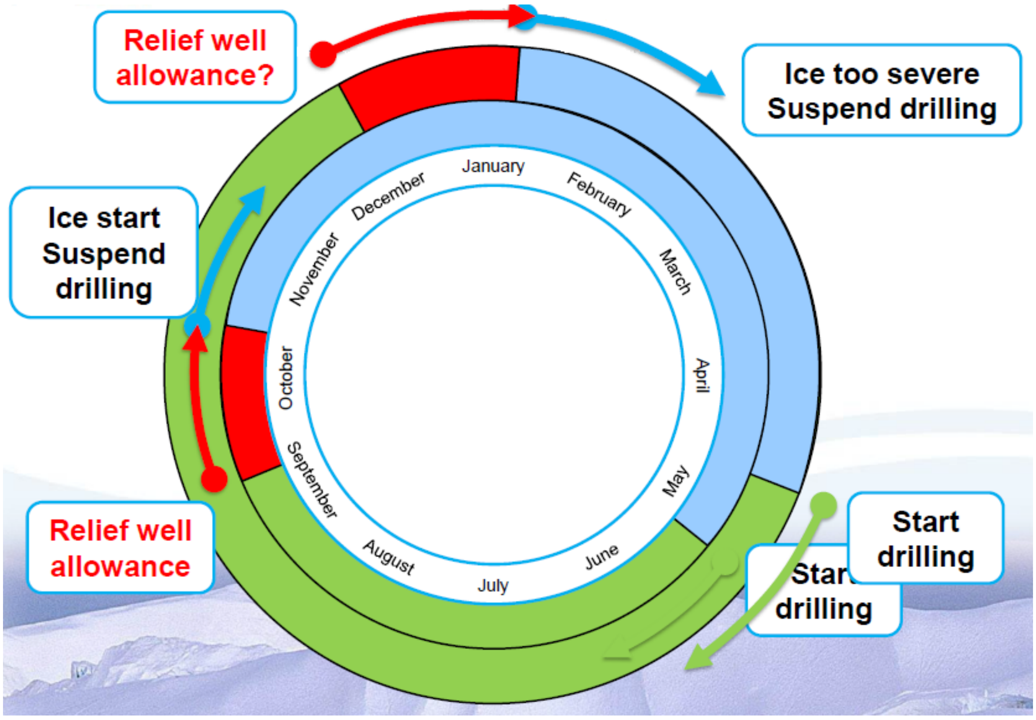


Figure 43 Extended drilling season [62]

The suggested jack-up can be used as an additional rig for drilling the relief well. In case of blowout on the neighbor drilling rig in the end of the drilling season, the ice-resistant jack-up can drill the relief well even in ice conditions. The situation becomes critical, however, when the drilling season is extended till winter and the ice conditions become harsh (see Figure 43). In case the relief well must be drilled from the jack-up in December - January, ice management must be implemented.

8. Conclusions and future work

8.1 Conclusions

The present research considers a new concept of a jack-up drilling rig for Arctic exploration. The study accounts for the specific Arctic conditions and investigates the important design issues relevant for these conditions. The main conclusions from the results obtained during the work are listed below:

- The growing Arctic exploration activity results in an increased demand for new drilling rigs suitable for the Arctic conditions. Several jack-up concepts proposed for this area were investigated during the study. The result shows that an upgraded jack-up drilling rig can be a very effective solution for drilling in shallow Arctic waters. Tubular reinforced leg design, modified hull shape, application of cold-resistive materials and ice protective shields are the solutions suggested to achieve the jack-up resistivity to the ice loads.
- The new jack-up design for Arctic exploration design comprises a strengthened ship-shaped hull with icebreaking capabilities and four tubular legs placed on outriggers. Specific concept features allowing operations in the beginning of the ice season, i.e. ice protective collars, winterized drilling unit, telescopic leg design etc., have been discussed.
- The potential wave loads on the jack-up legs during operations have been calculated. The design wave load, calculated for the Pechora Sea conditions and the jack-up legs with rack teeth, is found equal to *2.4 MN*.
- An air gap required for this area has been estimated as ≈*16 m* from the mean water level to the jack-up hull.
- An optimal geometry of the ice protective collars has been determined. Cone shape has been chosen in order to reduce the ice actions on the jack-up legs. A cone height of *4 m* has been suggested accounting for the water level variation on the considered drilling location. An optimal sloping angle is found (from the sensitivity analysis to environmental loads) being equal to *60°*. One possible system for the protective cone installation and fixation on the jack-up leg has been proposed. The size of buoyancy elements for the cones has been determined.
- A new drilling method through one of the jack-up legs has been suggested in order to protect the drill string from the ice impact. The telescopic leg design, comprising inner and outer sections, locking mechanism and a double pinion system, has been developed. Such a design provides the possibility to adjust the leg height above the deck and allows drilling in various water depths.
- The acceptable ice thickness for the jack-up operations has been determined by plastic method and elastic beam bending method. The design wave load has been set as a limitation for the design ice load. The design ice thickness obtained is equal to *0.54 m*. An ice thickness of *0.3 m* has been suggested as a target ice thickness when the jack-up should start demobilization.
- Based on the meteorological data from 2012, the possible extension of the drilling season has been estimated as *4-5 weeks* after the ice has started to form.
- An applicability of the new jack-up in the context of the specific regulations for drilling in Arctic has been discussed. Due to the ice load capacity, the jack-up can be applied to drill an emergency relief well in case of a blowout in the end of the drilling season. The ice thickness may in this situation be allowed to grow beyond the values sited above in case ice management is introduced to reduce the ice loads on the jack-up legs.

8.2 Future work

The present research represents the first step of a preliminary concept study. It is focused on the design issues which are, in the author's opinion, critical for the operations in Arctic. The main purpose of the present work is to estimate the feasibility of the new concept suggested. However, the scope of this Master Thesis apparently does not cover all the important parts of the jack-up rig design and can be considered only as an introduction to the future detailed and comprehensive design process. The following work is necessary to be carried out:

- A thorough design of the hull shape should be performed including the design of the icebreaking bow, midbody and stern of the vessel; determination of the vessel response in waves and ice and the jack-up stability during transportation; calculation of the permanent loads, variable functional loads, environmental and accidental loads etc.;
- A proper design of the tubular jack-up legs is needed taking into account the ice actions on the legs and possible ice induced vibrations; material behavior under low temperatures; bearing capacity of the outrigger arms; the mud mat capacity etc.;
- Evacuation, escape and rescue analysis is crucial and still very challenging due to the scarcity of evacuation techniques and equipment applicable for the ice conditions;
- Topside layout should be designed properly since the ship-shaped hull has a limited deck space; winterization of the topside is necessary;
- A possibility to increase the jack-up efficiency, for example by installation of dual cantilever drilling facilities, can be considered.

Based on the design results, the drilling season extension can be determined more accurately for the different locations, so that the full technical and economic efficiency of the proposed design can be evaluated.

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Appendix A

Protective cone geometry (MATLAB scripts)

Wave loads on protective cones

```
H=14.25 %wave height, m%
T=11.5 %peak period, s%
lambda=190 %wave length, m%
w=2*3.14/T %wave angular frequency, rad/s%
k=2*3.14/lambda %wave number, rad/m%
d=51.25 %high water depth with tide, m%
p=1030 %water density, kg/m^3%
g=9.81 %gravity acceleration, m/s^2%
A=g*H/(2*w*cosh(k*d))
B=3*(H^2)*k*g/((2^5)*w*coth(k*d))*(coth(k*d)^2-1)^2
C=(H^3)*(k^2)*g/((2^9)*w*cosh(3*k*d))*(coth(k*d)^2-
1)*(coth(k*d)^2+3)*(9*coth(k*d)^2-13)
syms z
for alpha=20:20:80
D=4.1+2*(-z+0.75)/tan(alpha*3.14/180) %cone diameter, m%
ua=k*A*cosh(k*(z+d))+2*k*B*cosh(2*k*(z+d))+3*k*C*cosh(3*k*(z+d)) %amplitude
water particle velocity, m/s%
fda=0.6*p.*D*(ua)^2 %amplitude drag force per unit length, N/m%
Fda=int(fda,z,-3.25,0.75) %amplitude drag force on the cone, N%
Fda=double(Fda)
t=0:1:12
Fd=Fda.*cos(w.*t).*abs(cos(w.*t)) % drag force on the cone, N%
%amplitude water particle acceleration, m/s^2%
aa=-k*A*w*cosh(k*(z+d))-2*k*B*w*cosh(2*k*(z+d))-3*k*C*w*cosh(3*k*(z+d))
fia=3.14/4*p*(2.16-0.04*ua*T/D)*D^2*aa %amplitude inertia force per unit
length, N/m%
Fia=int(fia,z,-3.25,0.75) %amplitude inertia force on the cone, N%
Fia=double(Fia)
Fi=Fia.*sin(w.*t) %inertia force on the cone, N%
F=Fd+Fi %total wave force on the cone, N%
max(F) %total wave force amplitude, N%
end
```

Ice load on protective cones

Elastic beam bending method

```
angle=20:5:80 %cone angle, degrees%
alpha=3.14.*angle/180 %cone angle, radians%
w=4.1+2*2./tan(alpha) %cone width at the level of interaction with ice, m%
mu=0.15 %kinetic friction coefficient between the ice and the cone%
sigmaf=400000 %flexural strength, Pa%
pw=1025 %water density, kg/m^3%
g=9.81 %gravity acceleration, m/s^2%
E=5*10^9 %elastic modulus, Pa%
nu=0.33 %Poisson ratio%
hr=7 %rubble height, m%
mui=0.03 %ice-to-ice friction coefficient%
pi=910 %ice density, kg/m^3%
e=0.3 %keel porosity%
teta=3.14.*(angle-10)/180 %angle the rubble makes with the horizontal, rad%
fi=3.14*20/180 %friction angle of the ice rubble, rad%
c=6000 %cohesion of ice rubble, Pa%
h=0.5 %ice height, m%
```

```
Lc=(E*(h^3)/(12*pw*g*(1-(nu^2))))^0.25
ksi=(sin(alpha)+mu.*cos(alpha))./(cos(alpha)-mu.*sin(alpha))
Hb=0.68.*ksi*sigmaf*((pw*g*(h^5)/E)^0.25).*(w+(3.14^2)*Lc/4) %breaking
load, N%
Hp=w*hr^2*mui*pi*g*(1-e).*((1-tan(teta)./tan(alpha)).^2)/(2.*tan(teta))
%load to push the sheet ice through the ice rubble, N%
P=0.5*mui*(mui+mu)*pi*g*(1-e)*(hr^2).*sin(alpha).*(1./tan(teta)-
1./tan(alpha)).*(1-tan(teta)./tan(alpha))+0.5*(mui+mu)*pi*g*(1-
e)*hr^2.*cos(alpha)./tan(alpha).*(1-
tan(teta)./tan(alpha))+hr*h*pi*g.*(sin(alpha)+mu.*cos(alpha))./sin(alpha)
Hr=w.*P./(cos(alpha)-mu.*sin(alpha))%load to push ice blocks up the slope,
N%
Hl=0.5.*w*(hr^2)*pi*g*(1-e).*ksi.*(1./tan(teta)-1./tan(alpha)).*(1-
tan(teta)./tan(alpha))+0.5.*w*(hr^2)*pi*g*(1-e).*ksi*tan(fi).*(1-
tan(teta)./tan(alpha)).^2+ksi*c.*w*hr.*(1-tan(teta)./tan(alpha))
%load to lift the ice rubble on the top, N%
Ht=1.5.*w*(h^2)*pi*g.*cos(alpha)./(sin(alpha)-mu.*cos(alpha))%load to turn
the ice block at the top, N%
lc=w+3.14^2/4*Lc %total length of the circumferential crack, m%
Fh=(Hb+Hp+Hr+Hl+Ht)./(1-Hb/(sigmaf.*lc*h)% horizontal ice load, N%
Fv=Fh./ksi %vertical component of ice load, N%
F=(Fv.^2+Fh.^2).^0.5 %total load from drift ice, N%
plot(angle,F)
```

Plastic method

```
angle=20:5:80 %cone angle, degrees%
alpha=angle*3.14/180 %cone angle, radians%
syms n
e1=(1-sin((alpha)).^2*(sin(n))^2).^(-0.5)
E1=int(e1, n, 0, 3.14/2)%complete elliptical integral of the first kind%
e2=(1-sin((alpha)).^2*(sin(n))^2).^0.5
E2=int(e2, n, 0, 3.14/2) %complete elliptical integral of the second kind%
mu=0.15 %kinetic friction coefficient between the ice and the cone%
f=sin(alpha)+mu.*E1.*cos(alpha)
gr=(sin(alpha)+alpha./cos(alpha))./(3.14/2.*sin(alpha).^2+2*mu.*alpha.*cos(
alpha))
hv=(f.*cos(alpha)-mu.*E2)./(3.14/4.*sin(alpha).^2+mu.*alpha.*cos(alpha))
pi=910 %ice density, kg/m^3%
g=9.81 %gravity acceleration, m/s^2%
h=0.5 %ice thickness, m%
hr=2*h %ice ride-up thickness, m%
w=4.1+2*2./tan(alpha) %cone width at the level of interaction with ice, m%
wt=4.1 %the top diameter of the cone, m%
W=pi*g*hr.*(w.^2-wt^2)/4/cos(alpha)
Hr=W*(tan(alpha)+mu.*E2-mu.*f.*gr.*cos(alpha))./(1-mu.*gr) %horizontal
ride-up action%
Vr=W.*cos(alpha).*(3.14/2.*cos(alpha)-mu.*alpha-f.*hv)+Hr.*hv %vertical
ride-up action, N%
sigmaf=4*10^5 %flexural ice strength, Pa%
Y=2.711 %Tresca yielding%
G=(pi*g.*w.^2)/4/sigmaf/h
x=1+(3.*G+Y/2).^(-0.5)
Hb=sigmaf*h^2/3*tan(alpha)/(1-mu.*gr).*((1+Y.*x.*log(x))./(x-1)+G.*(x-
1).*(x+2))%horizontal breaking action, N%
Vb=Hb.*hv %vertical breaking action, N%
Fh=Hb+Hr %total horizontal component, N%
Fv=Vb+Vr %total vertical component, N%
F=(Fh.^2+Fv.^2).^0.5 %total ice action, N%
double(F)
plot(angle,F)
```

Appendix B

Environmental loads on the jack-up legs and protective cones

Wave force

```
H=14.25 %wave height, m%
T=11.5 %peak period, s%
lambda=190 %wave length, m%
w=2*3.14/T %wave angular frequency, rad/s%
k=2*3.14/lambda %wave number, rad/m%
d=51.25 %high water depth with tide, m%
p=1030 %water density, kg/m^3%
g=9.81 %gravity acceleration, m/s^2%
Dleg=4 %leg diameter, m%
A=g*H/(2*w*cosh(k*d))
B=3*(H^2)*k*g/((2^5)*w*coth(k*d))*(coth(k*d)^2-1)^2
C=H^3*k^2*g/((2^9)*w*cosh(3*k*d))*(coth(k*d)^2-
1)*(coth(k*d)^2+3)*(9*coth(k*d)^2-13)
alpha=60 %cone angle, degree%
syms z
t=0:0.1:12
D=4.1+2*(-z+0.75)/tan(alpha*3.14/180) %cone diameter, m%
ua=k*A*cosh(k*(z+d))+2*k*B*cosh(2*k*(z+d))+3*k*C*cosh(3*k*(z+d))%amplitude
water particle velocity, m/s%
fda1=1/2*1.89*p*Dleg*ua^2 %amplitude drag force on leg per unit length,
N/m%
fda2=0.6*D*p*(ua)^2 %amplitude drag force on cones per unit length, N/m%
Fda1=int(fda1,z,-51.25,-3.25) %amplitude drag force on legs from sea bottom
to cone bottom, N%
Fda2=int(fda2,z,-3.25,0.75) %amplitude drag force on the cone, N %
Fda3=int(fda1,z,0.75,H/2*(1+3.14*H/2/lambda)) %amplitude drag force on legs
from cone top to wave crest, N %
Fd=(Fda1+Fda2+Fda3).*cos(w.*t).*abs(cos(w.*t)) % drag force on the leg and
cone N %
%amplitude water particle acceleration%
aa=-k*A*w*cosh(k*(z+d))-2*k*B*w*cosh(2*k*(z+d))-3*k*C*w*cosh(3*k*(z+d))
fia1=p*3.14*Dleg^2/4*aa %amplitude inertia force on leg per unit length,
N/m%
fia2=3.14/4*p*(2.16-0.04*ua*T./D).*D.^2*aa %amplitude inertia force on cone
per unit length, N/m%
Fia1=int(fia1,z,-51.25,-3.25) )%amplitude inertia force on legs from sea
bottom to cone bottom, N%
Fia2=int(fia2,z,-3.25,0.75) ) %amplitude inertia force on the cone, N %
Fia3=int(fia1,z,0.75, H/2*(1+3.14*H/2/lambda)) %amplitude inertia force on
legs from cone top to wave crest, N %
Fi=(Fia1+Fia2+Fia3).*sin(w.*t) % inertia force on the leg and cone N %
F=Fd+Fi % total ice load on the leg and cone N %
double(F)
plot(t,F)
```

Ice thickness investigation

Elastic beam bending method

```
angle=60 %cone angle, degree%
alpha=3.14*angle/180 %cone angle, rad%
w=4.1+2*2/tan(alpha) %cone width at the level of interaction with ice, m%
mu=0.15 %kinetic friction coefficient between the ice and a cone%
sigmaf=400000 %flexural ice strength, Pa%
pw=1025 %water density, kg/m^3%
```

```
g=9.81 %gravity acceleration, m/s^2%
E=5*10^9 %elastic modulus, Pa%
nu=0.33 %Poisson ratio%
hr=7 %rubble height, m%
mui=0.03 %ice-to-ice friction coefficient%
pi=910 %ice density, kg/m^3%
e=0.3 %keel porosity%
teta=3.14*(angle-10)/180 %angle the rubble makes with the horizontal, rad%
fi=3.14*20/180 %friction angle of the ice rubble, rad%
c=6000 %cohesion of ice rubble, Pa%
h=0.1:0.01:1 %ice thickness, m%
Lc=(E.*h.^3/12/pw/g/(1-nu^2)).^0.25
ksi=(sin(alpha)+mu*cos(alpha))/(cos(alpha)-mu*sin(alpha))
Hb=0.68*ksi*sigmaf.*((pw*g.*h.^5/E).^0.25).*(w+(3.14^2).*Lc/4) %breaking
load, N%
Hp=w*hr^2*mui*pi*g*(1-e)*(1-tan(teta)/tan(alpha))^2*1/2/tan(teta) %load to
push the sheet ice through the ice rubble, N%
P=0.5*mui*(mui+mu)*pi*g*(1-e)*hr^2*sin(alpha)*(1/tan(teta)-
1/tan(alpha))*(1-tan(teta)/tan(alpha))+0.5*(mui+mu)*pi*g*(1-
e)*hr^2*cos(alpha)/tan(alpha)*(1-
tan(teta)/tan(alpha))+hr.*h*pi*g*(sin(alpha)+mu*cos(alpha))/sin(alpha)
Hr=w.*P/(cos(alpha)-mu*sin(alpha))%load to push ice blocks up the slope, N%
Hl=0.5*w*hr^2*pi*g*(1-e)*ksi*(1/tan(teta)-1/tan(alpha))*(1-
tan(teta)/tan(alpha))+0.5*w*hr^2*pi*g*(1-e)*ksi*tan(fi)*(1-
tan(teta)/tan(alpha))^2+ksi*c*w*hr*(1-tan(teta)/tan(alpha))
%load to lift the ice rubble on the top, N%
Ht=1.5*w.*h.^2*pi*g*cos(alpha)/(sin(alpha)-mu*cos(alpha))%load to turn the
ice block at the top, N%
lc=w+3.14^2/4.*Lc %total length of the circumferential crack, m%
Fh=(Hb+Hp+Hr+Hl+Ht)./(1-Hb/sigmaf./lc./h)%the horizontal load from drift
ice, N%
Fv=Fh/ksi %vertical ice load component, N%
F=(Fv.^2+Fh.^2).^0.5 %total load from drift ice, N%
plot(h,F)
```

Plastic method

```
angle=60 %cone angle, degree%
alpha=angle*3.14/180 %cone angle, rad%
syms n
e1=(1-sin((alpha))^2*(sin(n))^2)^(-0.5)
E1=int(e1, n, 0, 3.14/2)%complete elliptical integral of the first kind%
e2=(1-sin((alpha))^2*(sin(n))^2)^0.5
E2=int(e2, n, 0, 3.14/2) %complete elliptical integral of the second kind%
mu=0.15 %kinetic friction coefficient between the ice and a cone%
f=sin(alpha)+mu*E1*cos(alpha)
gr=(sin(alpha)+alpha/cos(alpha))/(3.14/2*sin(alpha)^2+2*mu*alpha*cos(alpha)
)
hv=(f*cos(alpha)-mu*E2)/(3.14/4*sin(alpha)^2+mu*alpha*cos(alpha))
pi=910 %ice density, kg/m^3%
g=9.81 %gravity acceleration, m/s^2%
h=0.1:0.01:1.2 %ice thickness, m%
hr=2.*h %ice ride-up thickness, m%
w=4.1+2*2/tan(alpha) %cone width at the level of interaction with ice, m%
wt=4.1 %the top diameter of the cone, m%
W=pi*g.*hr*(w^2-wt^2)/4/cos(alpha)
Hr=W*(tan(alpha)+mu*E2-mu*f*gr*cos(alpha))/(1-mu*gr) %horizontal ride-up
action, N%
Vr=W*cos(alpha)*(3.14/2*cos(alpha)-mu*alpha-f*hv)+Hr*hv %vertical ride-up
action, N%
sigmaf=4*10^5 %flexural ice strength, Pa%
Y=2.711 %Tresca yielding%
```

```
G=(pi*g*w^2)/4/sigmaf./h
x=1+(3.*G+Y/2).^(-0.5)
Hb=sigmaf.*h.^2/3*tan(alpha)/(1-mu*gr).*((1+Y.*x.*log(x))./(x-1)+G.*(x-
1).*(x+2))%horizontal breaking action, N%
Vb=Hb*hv %vertical breaking action, N%
Fh=Hb+Hr %total horizontal component, N%
Fv=Vb+Vr %total vertical component, N%
F=(Fh.^2+Fv.^2).^0.5 %total ice action, N%
double(F)
plot(h,F)
```

Appendix C

JACK-UP DRILLING RIG FOR ARCTIC CONDITIONS

Inventors: **Ove Tobias Gudmestad,** Søylandsvegen 61, 4365 Nærbø (NO); **Maria Urycheva,** Jernalderveien 57, 4041 Stavanger (NO)

ABSTRACT

The invention represents a self-propelled jack-up drilling rig for operations in the Arctic and subarctic areas. The jack-up has an extended drilling season when working in the Arctic compared to traditional jack-ups due to an ice resistive configuration.

The deck house acts as a hull with icebreaking capabilities achieved by inclined sides, icebreaking bow and reinforced design. Tubular jack-up legs are placed on the outriggers and are not exposed to ice loads during transportation. Protective collars are lowered down along the legs to reduce ice loads on the legs when the ice starts to form. The derrick is placed on skid beams in the middle of the deck during transportation. Drilling is to be performed through one of the jack-up legs that has an adjustable length due to telescopic design.

FIG.1

JACK-UP DRILLING RIG FOR ARCTIC CONDITIONS

FIELD OF THE INVENTION

[0001] The invention relates to self-elevated mobile drilling units (jack-ups) which are utilized for drilling in shallow waters.

[0002] In particular, this invention relates to improved mobile drilling system able to operate in Arctic and subarctic areas.

BACKGROUND OF THE INVENTION

[0003] Hydrocarbon resources of the Arctic are very attractive but still poorly explored due to considerable challenges created by harsh Arctic conditions.

[0004] Currently, jack-up drilling rigs are widely utilized for shallow water drilling during the open-water summer season (about 45-90 days). None of them are designed to withstand ice loads from drift ice.

[0005] A self-elevating unit, or jack-up, is a mobile drilling unit having a flotation hull with sufficient buoyancy to transport the jack-up to the drilling location. The jack-up legs can be lowered down to the seabed and the hull can be jacked up to the required height in the operational mode.

[0006] The installation of the conventional drilling jack-up can be performed only after the ice cover has been cleared sufficiently for the jack-up to be maneuvered to site. Towards the end of the drilling season the jack-up shall move out before the sea freezes up and the jack-up could get stuck in the ice cover. Extension of the drilling season can reduce exploration costs and make drilling operations in the Arctic more efficient. Furthermore, it may be possible to drill and test complex wells in one drilling season.

[0007] Several attempts have been made to design a drilling rig suitable for ice conditions.

[0008] WO 2007/126477 describes a Mobile Year Round Artic drilling system. The invention comprises the hull and the cylindrical legs made of an outer plate and an inner plate with a bonding agent filled between them. Drilling is to be performed through one of the legs.

[0009] US 2012/0128426 A1 discloses an ice worthy jack-up drilling unit comprising ice-resistive hull and open-trussed legs. The jack-up operates in the conventional mode during the open-water season. In case of ice presence the hull is lowered down into the water bending the ice and protecting the legs and the drill string.

[0010] US 2012/0247830 A1 describes a mobile drilling unit composed of gravity based foundation member with ballast tanks and floating jack-up top member. After the completion of the drilling, the foundation member either can be left on the site to support a production facility or can be de-ballasted and towed to another location.

[0011] It should be noticed that all concept described need to be towed to and from the drilling site.

[0012] According to what has been mentioned above there has been a desire for the improved jack-up drilling system for the Arctic conditions which is self-sufficient, has an extended drilling season, is easy to install and to transport and is able to withstand some ice loads from drift ice. It should be noticed that the jack-up is not intended to operate in heavy ice conditions but is supposed to leave the drilling site safely after the ice cover starts to form.

OBJECTIVES OF THE INVENTION

[0013] The main objective of the invention is to provide a new type of the drilling jack-up rig suitable for Arctic and subarctic areas.

[0014] Another objective is to provide the jack-up with extended drilling season, i.e. the jack-up can be transported through ice-infested areas to the site and start drilling before the ice cover has been fully cleared; can operate in open waters as a conventional jack-up; is able to continue drilling operations even after some ice cover has been formed; and can move away through ice-infested areas.

[0015] It is also an objective of the present invention to provide an installation method of the jack-up which allows protection of the drill string from drift ice loads during drilling.

BRIEF SUMMARY OF THE DISCLOSURE

[0016] According to one embodiment of the present invention, a mobile jack-up drilling rig is provided. It comprises the jack-up deck, four legs and a drilling unit.

[0017] More particularly, the hull resembles the geometry of an icebreaker, i.e. has icebreaking bow, inclined sides and rounded stern. The hull has four outrigger arms, two along each side, designed to support the jack-up legs and jacking equipment. The hull may have reinforced structure to be able to withstand ice loads during transportation.

[0018] According to another aspect of the invention, the jack-up comprises four legs of tubular shape mounted on the outriggers. Each leg is equipped with individual mud mat. During transportation the mud mats are located above the mean waterline and do not experience any ice actions. In the operational mode the legs are lowered down to the sea floor by means of the jacking system. Tubular shape allows the legs to withstand ice loads from drift ice.

[0019] According to yet another aspect of the present invention, the propulsion system can be preferably presented by being an azipod propulsion system with side thrusters. Protection of the rudders and propulsion system in the stern part of the hull can be achieved by implementing ice horns, ice skirts or deflectors.

[0020] According to further aspect of the invention, the legs are equipped with protective collars of preferably conical shape. During transportation they are placed in the outriggers. In the operational mode, when the ice is present on the drilling site, the protective collars should be lowered down along the legs to the ice level in order to protect the jack-up legs from the ice impact. The collars can be jacked down on the jacking rails by means of the separate jacking system.

[0021] According to still another aspect of the invention, at least one jack-up leg has a telescopic design, i.e. the length of the leg is adjustable for every particular location to allow drilling rig to be skidded above the leg.

[0022] According to the second embodiment of the present invention, the method of installing the jack-up drilling rig for the Arctic conditions is provided. Self-propelled jack-up drilling rig for the Arctic conditions comprises the jack-up deck with icebreaking capabilities; four tubular legs, equipped with mud mats and protective collars, with at least one of the legs having telescopic design; and a drilling unit. The derrick is placed on the skid beams in the middle of the hull. The method further includes orientation of the jack-up on the site in such way that the telescopic leg is placed over the drilling location; lowering the legs to the sea floor; thereafter penetration of the mud mats into the seabed; lowering the protective collars to the ice level if necessary; elevating the hull to the required height above the sea level; adjusting the height of the telescopic leg above the deck; and positioning the derrick over the telescopic leg. The drilling is supposed to be performed through the telescopic leg that allows the protection of the drill string from drift ice loads.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] A more accurate and detailed description of the present invention will be given in the following with reference to accompanying drawings, in which:

[0024] FIG 1 shows a 3D drawing of the rig while FIG.1A, 1B and 1C illustrate the first embodiment of the present invention.

[0025] FIGS. 2 A-E show the second embodiment of the invention and schematically represent the installation method of the jack-up drilling rig for the Arctic conditions.

DETAILED DESCRIPTION OF THE INVENTION

[0026] The following describes the invention more accurately with reference to accompanying figures. The scope of the invention is not limited to the embodiments described and illustrated. It is only limited by the scope of claims that follow.

[0027] FIGS. **1A**, **1B** and **1C** accompanying the first embodiment illustrate the front, side and top views of the present invention, respectively. The self-propelled jack-up drilling rig for the Arctic conditions comprises the jack-up deck **1** designed with an ice-resistive hull**.** The hull is supposed to withstand ice loads during the jack-up's transportation to and from the drilling site. Ice resistance is achieved by the icebreaking design comprising ice-breaking bow, inclined sides and rounded stern of the hull. The hull may have reinforced structure, i.e. stiffened steel plates, to be able to withstand ice loads during transportation.

[0028] The propulsion system is preferably presented by an azipod propulsion system. The azipod resembles an outboard motor with good maneuverability. Furthermore, use of side thrusters will enable sidewise movements even in ice conditions. Protection of the rudders and propulsion system in the stern part of the hull can be achieved by implementing ice horns, ice skirts or deflectors.

[0029] The hull accommodates four tubular legs **2**. The legs are placed on four outrigger arms **3** as shown on FIG. **1C**. Outrigger arms are located along the sides of the hull (two along each side) as illustrated by FIGS. **1A** and **1B**. The outrigger arms are elevated high above the water level avoiding the leg interaction with ice during transportation. In addition to the jack-up legs, the outriggers house four protective ice collars **7**, one for each leg. Necessary jacking equipment **5** is also placed on the outrigger arms. Due to the unconventional hull shape described above, the jack-up is expected to have significant roll motion during transportation in the open waters. According to that, the outrigger arms must be designed for possible wave-in-mudmat conditions.

[0030] The jack-up legs **2** may have cylindrical shape and reinforced structure. The jack-up foundation may be presented by four independent mud mats **4** of rectangular shape placed on the end of each leg. During transportation the mud mats are located high above the mean waterline and do not experience any ice actions. At least one leg **9** of the jack-up has telescopic design. It comprises outer upper and inner lower parts of tubular shape and locking mechanism. The length of the telescopic leg is adjustable for each particular drilling area. The location of the telescopic leg **9** can be determined during the design phase and is specified on FIGS. **1A-1C** only as an example.

[0031] Each leg of the jack-up is equipped with the ice protective collar **7**. The protective collars **7** are intended to protect the jack-up legs from lateral ice loads in case the ice is present on the drilling site. The protective collars **7** should have upward conical shape with the angle in the range of 30-60° and a sufficient height to protect the jack-up legs **2** and **9** from the interaction with drift ice. During transportation the collars **7** are placed in the outrigger arms **3**. When necessary, the protective collars **7** are lowered along the legs to the ice level. The collars **7** can be jacked down on the jacking rails by means of the separate jacking system.

[0032] The hull also accommodates the drilling unit with the derrick **6**. The drilling unit and the derrick **6** are winterized for the Arctic conditions. The derrick **6** may have totally enclosed structure formed by wind walls. The wind walls are utilized for the protection of the derrick **6** and drilling equipment from the spray ice accretion. The derrick **6** is placed on the skid beams **8**. During transportation, the derrick **6** is located in the middle of the deck as illustrated by FIG. **1C**. After installation on the site, the derrick **6** can be mounted over the telescopic leg **9** by means of skid beams **8**. The drilling is supposed to be performed through the telescopic leg **9**.

[0033] FIGS. **2A-2E** accompanying the second embodiment schematically illustrate the preferred sequence of the jack-up installation on the drilling site. In FIG. **2A,** the jack-up drilling rig for the Arctic conditions is oriented in such way that the telescopic leg **9** is placed over the drilling location and the jack-up legs **2** and **9** are lowered down to the seabed. Ice protective collars **7** are located in the outrigger arms **3**. The derrick **6** is placed in the middle of the hull **1**. In FIG. **2B**, the protective ice collars are lowered down the legs to the ice level in case the ice is present on the site. Further, as shown on FIG. **2C**, the hull 1 with all drilling equipment is raised up along the jack-up legs **2** to the required height. It should be noticed that due to the unconventional deck depth the required air gap must be evaluated properly for each location to avoid wave interaction with deck. In FIG. **2D**, the height of the telescopic leg **9** is adjusted in such way that the derrick **6** can be mounted over it. In FIG. **2E**, the derrick **6** is skidded over the telescopic leg **9**. After that the drilling can be performed through the telescopic leg **9.**

CLAIMS

[0034] The present invention including all modifications, alternatives and equivalents is intended to be as broad as the claims below.

1. A jack-up drilling rig for offshore drilling in potential Arctic and subarctic conditions comprising:

a flotation hull having reinforced structure and ice-resistive shape presented by ice-breaking bow and inclined sides;

four legs wherein the legs can be both extended down to the sea floor and further up to lift the hull out of the water and also can be raised up off the seabed for jack-up transportation;

a drilling unit including the derrick placed on the skid beams;

a jacking system associated with each leg to raise the legs from the sea bottom for transportation and push the legs down to the seafloor and push the hull out of water in the operational mode.

2. The jack-up drilling rig for the Arctic conditions according to claim **1**, wherein the jack-up legs and associated jacking equipment are placed on individual outrigger arms along the jack-up sides.

3. The jack-up drilling rig for the Arctic conditions according to claim **1**, wherein each jack-up leg has tubular shape and is equipped with an ice protective collar which is placed in the outrigger arm during transportation and is able to be lowered and lifted along the leg length by means of the jacking system.

4. The jack-up drilling rig for the Arctic conditions according to claim **1,** wherein each jack-up leg has an individual mud mat on the lower end acting as jack-up foundation.

5. The jack-up drilling rig for the Arctic conditions according to claim **1,** wherein at least one jack-up leg has a telescopic design comprising outer upper and inner lower cylindrical sections and locking mechanism.

6. The jack-up drilling rig for the Arctic conditions according to claim **1** and **5,** wherein the derrick placed on skid beams is located in the middle of the deck during transportation and also can be skidded over the leg with telescopic design prior to drilling.

MMARY

A jack-up drilling rig for the Arctic conditions, having an icebreaker hull and jack-up legs mounted on outrigger arms, the method of installation and use comprising the steps of:

a) orientation of the jack-up on the drilling site in such way that a leg with a telescopic design is placed over the drilling location;

b) lowering at least four jack-up legs to the seabed;

c) if necessary, lowering ice protective collars down the legs to the ice level by means of the jacking system;

d) lifting jack-up hull out of water to the required height by means of the jacking system;

e) if necessary, adjusting the height of the telescopic leg above the deck;

f) mounting the derrick over the telescopic leg by means of skid beams.

25th April 2013

Ove Gudmestad

Maria Urycheva

Notarius Publicus i Stavanger bekrefter at
The Notary Public of Stavanger certifies that

MARIA URYCHEVA

har undertegnet dette dokument
has/have signed this document

Stavanger tingrett og Notarius Publicus
Stavanger District Court and Notary Public

STAVANGER · NOTARIUS PUBLICUS

25.04.13

Notarius Publicus i Stavanger bekrefter at
The Notary Public of Stavanger certifies that

OVE TOBIAS GUDMESTAD

har undertegnet dette dokument
has/have signed this document

Stavanger tingrett og Notarius Publicus
Stavanger District Court and Notary Public

STAVANGER · NOTARIUS PUBLICUS

25.04.13

DRAWINGS

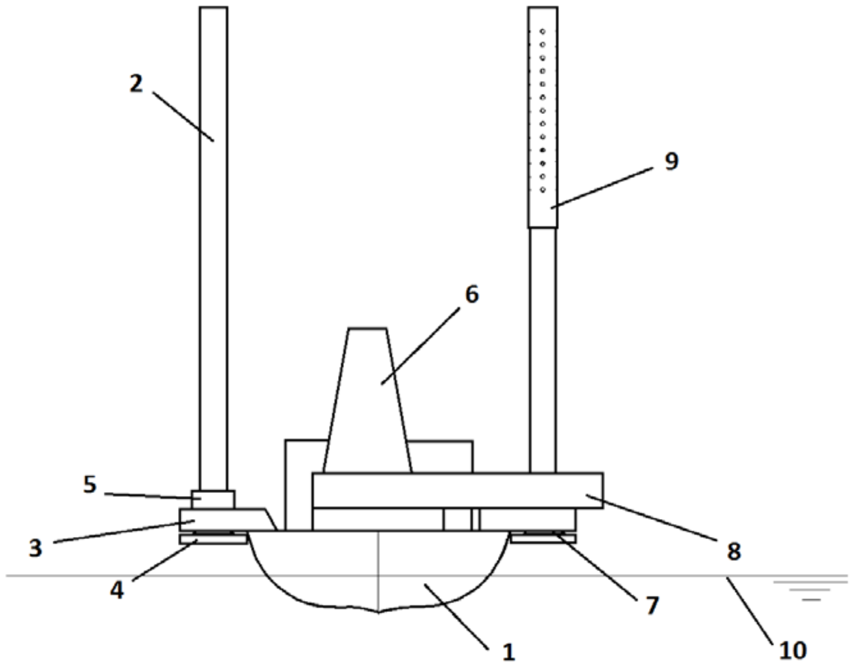

FIG. 1A

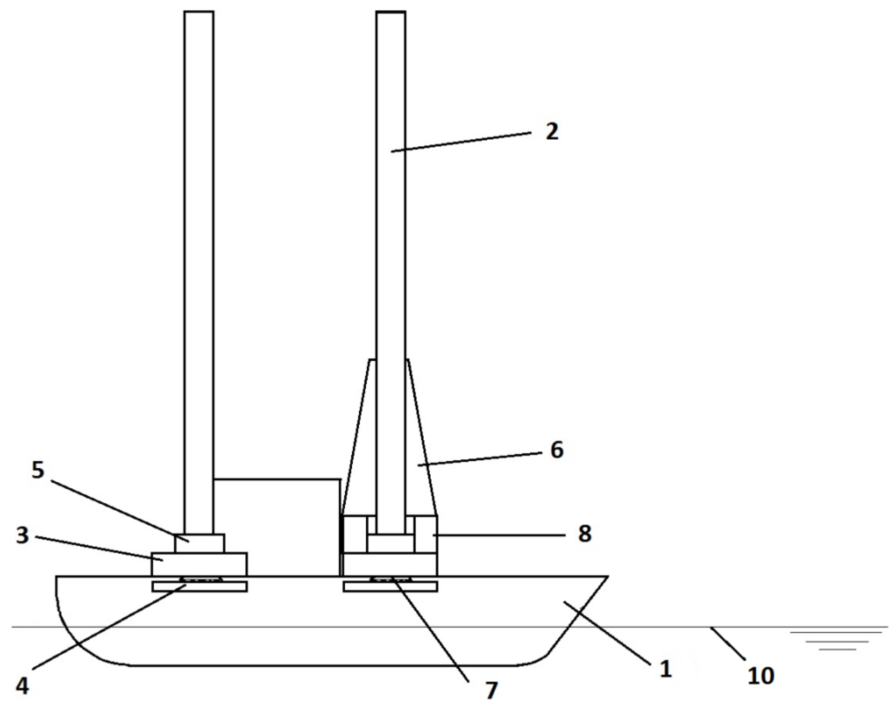

FIG. 1B

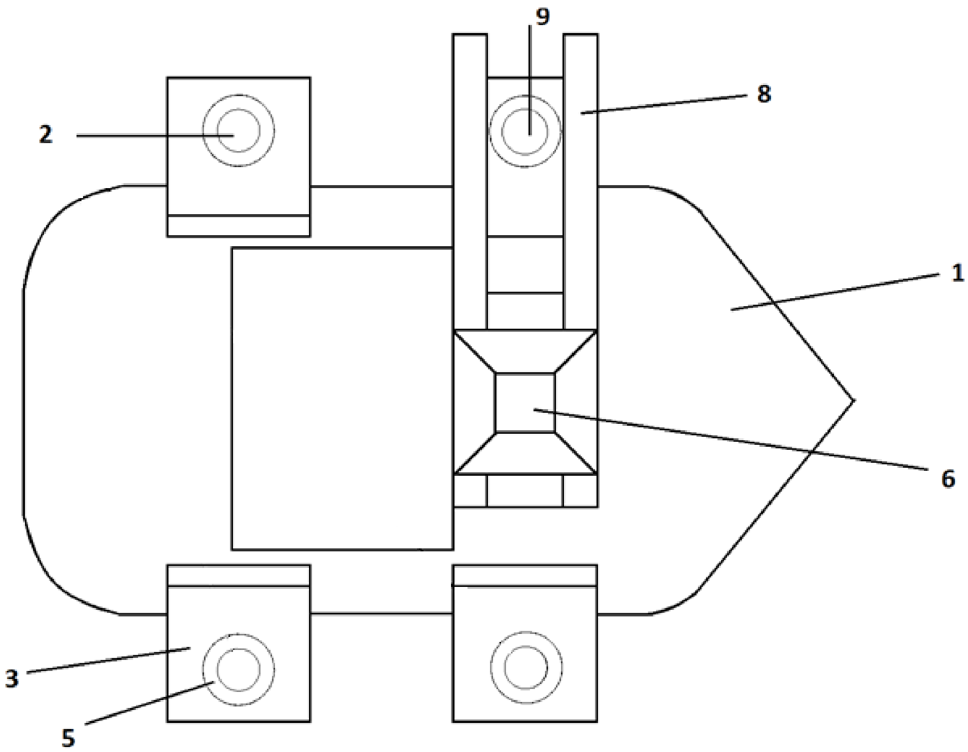

FIG. 1C

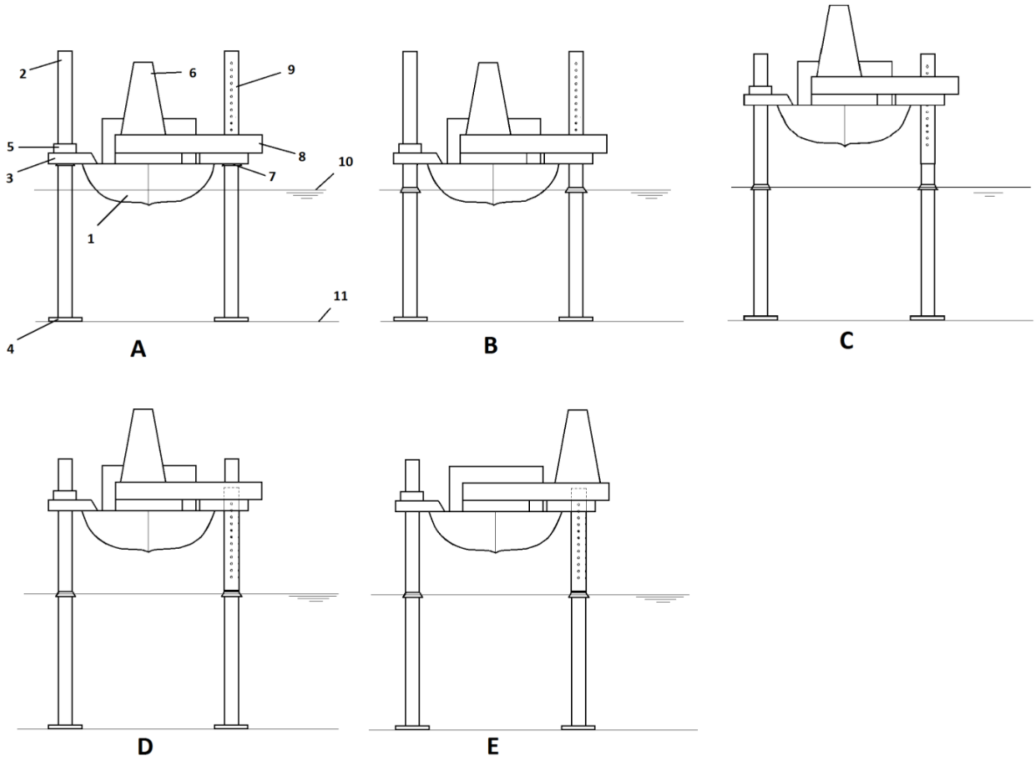

FIG. 2