Evaluating stress analysis and failure criteria for offshore structures for Pechora Sea conditions

S Nesic1*, Y Donskoy2 and A Zolotukhin2,3,4

1NIS GAZPROM Neft, Novi Sad, Serbia,  
2Gubkin Russian State University (NRU) of Oil and Gas, Moscow, Russia  
3Northern Arctic Federal University, Arkhangelsk, Russia  
4University of Stavanger, Stavanger, Norway

* Contact Author: slavkonesic@yahoo.com

Abstract. Development of Arctic hydrocarbon resources has faced many challenges due to sensitive environmental conditions including low temperatures, ice cover and terrestrial permafrost and extreme seasonal variation in sunlight. Russian offshore field development in Arctic region is usually associated with annual ice cover, which can cause serious damage on the offshore platforms. The Pechora Sea has claimed as one of the most perspective oil and gas region of the Russian Arctic with seven discovered oil and gas fields and several dozens of structures. Our rough assessment, based on in-place hydrocarbon volumes and recovery factor evaluation concept, indicates that Pechora Sea alone has in-place volumes amounting to ca. 20 billion barrel oil equivalent (BOE). This quantity is enough to secure produced volumes by 2040 exceeding 3 billion BOE [1] that indicates huge resource potential of the region. The environmental conditions are primarily function of water dynamics and ice cover. The sea is covered by the ice for greatest part of the year. In this article, the ice load simulations were performed using explicit dynamic analysis system in ANSYS software to determine best shape and size of an offshore platform for the Pechora Sea ice conditions. Different gravity based structures (GBS) were analyzed: artificial island, hollow cylindrical and conical concrete structures and four-leg GBS. Relationships between the stress, deformations and time were analyzed and important observations from the simulation results were a basis for selecting the most preferable structures.

1. Introduction
In the Arctic conditions, the ice is presented in a form of ice floes, packs, ridges and icebergs. The ice forces can be static and dynamic, depending of the weather conditions. Moving of ice and collision with offshore structures can create damage or destroy a platform. Offshore structure must be dimensioned with high strength and stability to avoid issues with ice moving and collision. Hence, the offshore platforms are over dimensioned, and construction of platforms requires large quantities of steel and concrete as well as construction costs. To optimize platform construction, maximum ice loads must be evaluated and present a base parameter for design of the offshore structure. Analytical, numerical and simulation methods can be used for prediction of ice loads [2]. Field measurements are the best practice to investigate full scale ice loading and results present a reliable image of whole process [3]. Ice loading measurements has started in 1970’s by installing special panels on the offshore
structures and recording ice loads and measure interaction between ice and offshore structures [4-17]. Finite elements analysis (FEA) solvers are in commercial use like ANSYS and ABAQUS. Simulations from those software’s have very reliable results [18]. In FEA, ice properties present a critical factor for evaluation of the ice interaction with offshore structures [19]. To simulate ice floe collision on the offshore structures, FE simulation is used in this article. The ice collision will create non-linear deformation of the concrete offshore structure. ANSYS FEA software is used with explicit dynamic solver of AUTODYN.

2. Pechora Sea conditions

Development of Arctic hydrocarbon resources has faced with many challenges due to sensitive environmental conditions [20]. Characteristic of Arctic climate are:

- low temperature,
- ice cover and terrestrial permafrost and
- extreme seasonal variation in sunlight

The forming of ice in the Pechora Sea is depended by the season. The most extensive ice period is from March to April when covers the whole sea. Ice cover duration is from the end of October/mid November until the end of July/early August [21-23]. Pechora Sea ice parameters are shown in Table 1 [24].

### Table 1. Pechora sea ice parameters

|                  | Beginning of ice freeze-up | Duration of ice-covered season |
|------------------|----------------------------|-------------------------------|
|                  | early                      | average                       | late                          |
| Fast ice freeze-up| 25.X                      | minimum                       | 131 days                     |
| average          | 18.XI                     | average                       | 213 days                     |
| late             | 23.XII                    | maximum                       | 272 days                     |
| Fast ice freeze-up| 23.XII                   | extent                        | 3 to 15 km                   |
| average          | 22.II                     | average                       | 110 cm                       |
| late             | 11.IV                     | thickness                     |                               |
| Beginning of fast ice break-up| | Drift ice thickness |                               |
| early            | 5.IV                      | average                       | 80 cm                        |
| average          | 23.V                      | maximum                       | 145 cm                       |
| late             | 7.VII                     | continuity                    | 10                           |
| Total disappearance of ice cover| | hummocks                     | 60-90 %                      |
| early            | 10.IV                     | mass of hummocks              | 47-130 x10^3 t               |
| average          | 19.V                      | hummocks                      |                               |
| late             | 30.VIII                   |                               |                               |

The storm season in the Pechora Sea is from October until the end of December. The highest waves are spreading from northwest to eastern direction. Extreme waves may be 11.5 meters high at the depth from 20-30 meters during October and November [25]. Waves with 2-3 m during the storm season are very dangerous for ships and vessels carrying out offshore operations in the sea.

3. Explicit dynamics solver in ANSYS

Degree of finite element modeling, realized with the help of similar systems, depends on many factors: the degree of discretization of the simulated bodies; type (shell, membrane, volumetric) and the formulations (Lagrangian, Euler, arbitrary) elements; type of contact algorithm, etc. At the same time, the main conditions for the reliability of the calculations are the correct formulation of the defining relations for materials of bodies (mathematical description of the behavior of materials under load), criteria destruction and the task of physical and mechanical characteristics of materials. The physical and mechanical characteristics of ice are determined by its temperature, salinity, availability impurities, formation conditions, age. Therefore, in its natural state, ice is a material, extremely heterogeneous in its properties. There are several methods of ice modeling. One of the first CAD...
methods is described by Zhang and Hibler [26]. Due to this method sea ice motion is governed by the following momentum balance:

\[ m \frac{Du}{Dt} = -mfk \cdot u + \tau_s - mgV_p p(0) + F \]  

where \( u = u_i + v_j \) is ice velocity vector, \( m \) is the ice mass per unit area, \( F \) is the Coriolis parameter, \( g \) is the gravity acceleration, \( p(0) \) is the sea surface dynamic height, \( \tau_s \) is the force due to air stress, \( \tau_w \) is the nonlinear water drag, \( F \) is the ice interaction force, and \( i, j, \) and \( k \) are the unit vectors in the \( x, y, \) and \( z \) directions, respectively. The air stress and water stress terms are given by:

\[ \tau_s = \rho_s C_s (|U_0| - U_0) \cos \theta + \rho_s C_w (|U_w| - U_w) \sin \theta = \tau_s(u) \]

where \( U_0 \) is the geostrophic wind, \( U_w \) is the geostrophic ocean current, \( C_s \) and \( C_w \) are the air and water drag coefficients, \( \rho_s \) and \( \rho_w \) are the air and water densities, and \( \theta \) and \( \phi \) are the air and water turning angles, \( F \) is the force due to internal ice interaction is given by:

\[ F = \nabla \cdot \sigma \]

Here \( \sigma \) is the stress tensor \( \sigma_{ij} \), which for an isotropic system is related to the ice strain rate and strength via a nonlinear viscous-plastic constitutive law:

\[ \sigma_{ij} = 2\eta(e_{ij}, P)e_{ij} + \left[ \xi(e_{ij}, P) \right] e_{ij} + \frac{P}{2} \delta_{ij} \]

In the above equation, \( e_{ij} \) is the ice strain rate, given by:

\[ e_{ij} = \frac{1}{2} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] \]

Here \( P \) is the ice strength depending on the ice compactness and thickness, and \( \eta \) and \( \theta \) are nonlinear bulk and shear viscosities. These "viscosity" parameters are functions of the ice strain rate invariants and the ice strength and take on some maximum "creep" value when the deformation rate becomes very small. The idea here is to approximate a rigid behavior by a state of a very slow creep. For the elliptical yield curve used here, the nonlinear viscosities differ from each other by a constant factor.

For simplicity, the numerical method for solving is described in rectangular coordinate system. The method is however, applicable to the momentum equations in an arbitrary orthogonal curvilinear coordinate system. These curvilinear equations are briefly presented in the next section to demonstrate the structural similarity.

From the constitutive law, the ices for interaction force components in a Cartesian coordinate system are derived as:

\[ F_i = \frac{\partial}{\partial x} \left[ \eta + \xi \right] \frac{\partial u_i}{\partial x} + \xi \left( \frac{\partial u_i}{\partial y} - \frac{P}{2} \right) + \frac{\partial}{\partial y} \left( \eta \frac{\partial u_i}{\partial y} + \frac{\partial v_i}{\partial x} \right) \]

\[ F_j = \frac{\partial}{\partial y} \left[ \eta + \xi \right] \frac{\partial v_j}{\partial y} + \xi \left( \frac{\partial v_j}{\partial x} - \frac{P}{2} \right) + \frac{\partial}{\partial x} \left( \eta \frac{\partial v_j}{\partial x} + \frac{\partial u_j}{\partial y} \right) \]

The component equations can be organized and simply written as:

\[ \tau_s + C_{ij} \frac{\partial}{\partial x} \left[ \eta + \xi \right] \frac{\partial u_i}{\partial x} - \frac{\partial u_i}{\partial y} \left( \eta \frac{\partial u_i}{\partial y} + \frac{\partial v_i}{\partial x} \right) + m \frac{\partial u_i}{\partial t} + C_{ij} u_i F_i \]

\[ = \tau_s + C_{ij} \frac{\partial}{\partial x} \left[ \eta + \xi \right] \frac{\partial v_j}{\partial y} - \frac{\partial v_j}{\partial x} \left( \eta \frac{\partial v_j}{\partial x} + \frac{\partial u_j}{\partial y} \right) - \frac{\partial P}{\partial x} \]
\[
\begin{align*}
&- \frac{\partial}{\partial y} \left[ \eta + \zeta \right] \frac{\partial v}{\partial y} - \frac{\partial}{\partial x} \left( \eta \frac{\partial v}{\partial x} \right) + m \frac{\partial v}{\partial t} + C_d \mu \\
&= \tau_v - C_i \nu + \frac{\partial}{\partial y} \left[ \zeta - \eta \right] \frac{\partial u}{\partial x} + \frac{\partial}{\partial x} \left( \eta \frac{\partial u}{\partial y} \right) - \frac{\partial P}{\partial y} \\
\end{align*}
\]

where \( C_d \) and \( C_i \) are functions of the ice velocity and the viscosities, \( \zeta \) and \( \eta \) are functions of the strain rate invariants.

The application of ANSYS makes it possible to set the real properties of ice in analytic and graphical form, which makes it possible to accurately simulate the behavior of ice under different conditions.

### 4. Model properties

Since the ice floe play critical role in this article, determination of ice properties is very important. Special emphasize is on mechanical properties due to importance on the final results of simulations. Ice is very complex material because its temperature, salinity, age etc. can have significant effect on the mechanical properties [27]. Ice properties are defined based on the current results of comprehensive researches. Ice properties used in this article are listed in Table 2. For this article, the general properties of concrete defined in ANSYS database are used. Concrete does not have any steel or other reinforcements. Concrete properties are listed in Table 3.

| Table 2. Ice properties used in this study |
|------------------------------------------|
| Density (kg/m³) | 915 |
| Young’s modulus (GPa) | 10 |
| Poisson’s ratio | 0.3 |
| Bulk modulus (GPa) | 8.33 |
| Shear modulus (GPa) | 3,8462 |
| Compressive strength (MPa) | 7 |
| Tensile strength (MPa) | 2.5 |

| Table 3. Concrete properties used in this study |
|-----------------------------------------------|
| Density (kg/m³) | 2300 |
| Young’s modulus (GPa) | 30 |
| Poisson’s ratio | 0.18 |
| Bulk modulus (GPa) | 15,625 |
| Shear modulus (GPa) | 12,712 |
| Compressive ultimate strength (MPa) | 41 |
| Tensile ultimate strength (MPa) | 5 |

### 5. Simulation study

In this article, ice floe collision on the different shapes of the concrete offshore structure. Offshore structures are set as static and the ice floe will have initial velocity. Ice layer is set to be homogeneous with the 1m thickness and ice velocity is set to 1m/s. There are three objects to model, water layer, ice layer and concrete offshore structure. Water layer is used to be 25 m depth and offshore structures have 50 m height. Concrete offshore structures with cylindrical, conical and rectangular shape were considered in this study. The ice layer is moving in one direction except four-leg structures and rectangular structures where two directions of the ice flow were simulated. The focus of the simulation is a collision between the ice layer and offshore structure.

In every simulation set (i.e., number of simulations performed for a specified type of structure) the first run is made for a solid concrete structure followed by runs for the same structure but with different wall thickness to determine the minimum wall thickness for the Pechora Sea conditions. The output of this simulation will be equivalent stresses vs time and potential deformations, visually detected in the graphical output of the software.
5.1. Cylindrical offshore concrete structure
Simulation setup for the cylindrical offshore concrete structure is shown in the Table 4. The wall thicknesses of the platform are 0.5 m, 1 m and 2 m. Simulation model of the cylindrical platform is shown in Figure 1.

Table 4. Simulation setup for the cylindrical platform used in this study

| Objects       | Material | Dimensions (m) |
|--------------|----------|----------------|
| Cylindrical platform | Concrete | r = 100, h = 50 |
| Ice layer    | Ice      | 200 x 200, h = 1 |
| Water layer  | Water    | 350 x 200, h = 25 |

Figure 1. Simulation model of the cylindrical platform

Figure 2. Equivalent stress vs time for different wall thicknesses of the cylindrical platform
Equivalent stress vs time for different wall thicknesses of the cylindrical platform is shown in Figure 2. For wall thicknesses of 0.5 m and 1 m, the platform is collapsed under the ice floe pressure. For wall thickness of 2 m there is no deformation of the platform for the whole 120 seconds of simulation. Different wall thicknesses vs stress for different wall thicknesses of the cylindrical platform is shown in Figure 3.
5.2. Rectangular offshore concrete structure – one side loading

For the rectangular offshore structure, the position of the ice layer will be guided directly to the one side of the platform and in second run, on the edge side of the model. The wall thicknesses of the platform are 0.5 m, 1 m, 2 m and 3 m. Simulation setup for the rectangular offshore concrete structure – one side loading is shown in Table 5.

Simulation model for the rectangular offshore concrete structure – one side loading is shown in Figure 4. Equivalent stress vs time for different wall thicknesses the rectangular offshore concrete structure – one side loading is shown in Figure 5.

Unlike cylindrical offshore structure, the rectangular structures show very unfavorable behavior because the ice layer collides with the platform with an angle of 90 degrees and there is no space for ice moving. A lot of ice is accumulated on the one side of the platform contributing on the cumulative stress. For wall thicknesses of 0.5m and 1m, the platform is collapsed under the ice floe pressure. For wall thickness of 2m there is a minor deformation of the platform and with the wall thickness of 3m there is no deformation for the whole 120 seconds of simulation. Different wall thicknesses vs stress for rectangular offshore concrete structure – one side loading is shown in Figure 6.

Table 5. Simulation setup for for the rectangular offshore concrete structure – one side loading

| Objects       | Material | Dimensions (m) |
|---------------|----------|----------------|
| Rectangular platform | Concrete | a =100, h = 50 |
| Ice layer     | Ice      | 200 x 200, h = 1 |
| Water layer   | Water    | 350 x 200, h = 25 |

Figure 4. Simulation model for the rectangular offshore concrete structure – one side loading
5.3. Rectangular offshore concrete structure – edge loading

In the second run, the ice floe is directed on the edge side of the structure. The wall thicknesses are 0.5 m, 1 m and 2 m. Simulation setup for the rectangular offshore concrete structure – edge loading is shown in Table 6. Simulation model for the rectangular offshore concrete structure – edge loading is shown in the Figure 7 and the equivalent stress vs time for the rectangular offshore concrete structure – edge loading is shown in Figure 8.

Table 6. Simulation setup for the rectangular offshore concrete structure – edge loading

| Objects               | Material | Dimensions (m) |
|-----------------------|----------|----------------|
| Rectangular platform  | Concrete | a = 100, h = 50 |
| Ice layer             | Ice      | 200 x 200, h = 1 |
| Water layer           | Water    | 350 x 200, h = 25 |

Figure 7. Simulation model for the rectangular offshore concrete structure – edge loading

Figure 8. Equivalent stress vs time for the rectangular offshore concrete structure – edge loading

Figure 9. Different wall thicknesses vs stress for the rectangular offshore concrete structure – edge loading
This direction of ice moving creates the smallest stresses on the platform. For wall thicknesses of 0.5m and 1m, the platform is collapsed under the ice floe pressure. For wall thickness of 2 m there is no deformation of the platform for the whole 120 seconds of simulation. Different wall thicknesses vs stress for the rectangular offshore concrete structure – edge loading is shown in Figure 9.

5.4. Sloped offshore conical structures
Based on the assumption that the tensile strength of the ice is much lower from compressive strength sloped structures were developed. In this study, cylindrical platform is modelled with 100m diameter of the base and three angles, 45°, 60°, 70°. Simulation setup for the sloped conical offshore concrete structure is shown in Table 7. Simulation model for the sloped conical offshore concrete structure is shown in Figure 10 and the equivalent stress vs time for a conical offshore concrete structure is shown in Figure 11.

Table 7. Simulation setup for the sloped conical offshore concrete structure

| Objects         | Material | Dimensions            |
|-----------------|----------|-----------------------|
| Conical platform| Concrete | r =100 m, h=50 m, α = 45°, 60°, 70° |
| Ice layer       | Ice      | 200 m x 200 m, h=1 m  |
| Water layer     | Water    | 350 m x 200 m, h=25 m |

Simulation results show that with an increasing the angle of the structure, the equivalent stress is increasing. With the inclined structures, the mechanisms of ice loading are very complex and present a combination of compressive and tensile stress because the ice floe tend to move up on the conical part of the structure. A solid sloped structure undergoes much lower stresses than hollow cylindrical structures with different wall thicknesses due to mechanism of ice loading because compressive
strength of the ice is much bigger than its tensile stress. Equivalent stress vs different cone angles for a conical offshore concrete structure is shown in Figure 12.

5.5. Four legs concrete structures

Four legs concrete offshore structure is modelled in rectangular pattern with 50 m distance between each leg. There are two directions of ice floe, one to first pair of legs and diagonally on the first leg. Simulation setup for the four leg offshore concrete structure is shown in Table 8.

| Objects       | Material | Dimensions (m) |
|---------------|----------|----------------|
| Conical platform | Concrete | r = 20, h = 50 |
| Ice layer     | Ice      | 200 x 200, h = 1 |
| Water layer   | Water    | 350 x 200, h = 25 |

Simulation model of the four legs offshore concrete structure where the ice floe is directed to the first pair of legs is shown in Figure 13. The equivalent stress vs time of the four legs offshore concrete structure where the ice floe is directed to the first pair of legs is shown in Figure 14.

From the stress analysis, it can be concluded that the first two legs receive most of the stress caused by ice floe loading. Simulation model of the four leg offshore concrete structure in case of the ice floe movement diagonally to the first leg is shown in Figure 15. Equivalent stress vs time of the four-leg offshore concrete structure for such a case is shown in Figure 16. In this configuration of the model, the first leg receives most of the stress caused by the ice floe loading.

Figure 13. Simulation model of the four legs offshore concrete structure where the ice floe is directed to the first pair of legs

Figure 14. Equivalent stress vs time of the four legs offshore concrete structure where the ice floe is directed to the first pair of legs
6. Conclusions
In this article, simulation results of the ice floe loading on different offshore structure are presented. The main goal was to determine an optimum shape and dimension of the offshore structure for the Pechora Sea conditions. Multiple simulation runs were performed for different gravity-based structures including cylindrical, rectangular, sloped cylindrical and four leg structures. The grid for ice model in this article is slightly coarse and there is an additional space for improving the modelling. Due to the size of the model, simulation time will be very long, up to seven days for one run and require very strong computer. However, the results of simulation in this article are very usable for understanding of the ice impact on different shapes of the offshore structures, analyzing of stresses and determination of minimum wall thickness for safe operations. Based on the simulation results, the critical thickness of the offshore structures in the Pechora Sea condition is found to be 2 m for pure concrete without any steel reinforcement. The critical wall thickness will be lesser in a case of steel-reinforced concrete. Based on the simulation results and Pechora Sea ambient data it can be concluded that gravity based fixed cylindrical and sloped offshore structures are recommended.

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