OTC 27429

Modelling Iceberg-Topsides Impacts Using High Resolution Iceberg Profiles

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Abstract

Platforms operating in arctic and subarctic regions such as the Grand Banks, Labrador Sea, Barents Sea and offshore Greenland are exposed to the risk of iceberg impacts. These structures must be designed to withstand the impact from an iceberg or be designed to disconnect and move offsite to avoid the impact. Offshore Newfoundland, gravity based structures (GBS) such as the Hibernia and Hebron platforms are designed to withstand an impact from an iceberg. However, current accepted practice is not to design the topsides for impact, but to reduce impact risk to an acceptable level by varying the facility geometry (i.e., topsides elevation or footprint).

An analytical model was developed to estimate the frequency of icebergs impacting the topsides using three dimensional (3D) models of the platform and the icebergs. Random shapes and sizes are simulated for each iceberg and 3D shapes are generated using a database of measured 2D iceberg profiles. The iceberg shapes are placed randomly in close proximity to the structure and are set to drift towards the structure in a straight line. The initial point of contact between the iceberg and the structure is determined. Crushing of the iceberg against the platform caisson is considered. The process is repeated a large number of times and the total number of contacts with the topsides are determined.

In 2012, Hibernia Management and Development Company Ltd. (HMDC) sponsored a field program in which high resolution iceberg profile data were collected. The high resolution iceberg profiles contain detailed 3D information of the above water and below water shape of the iceberg. This paper describes updates to the existing-topsides impact model to take full advantage of the detailed 3D iceberg profiles. These updates include new iceberg shape databases for simulation, and the addition of a detailed iceberg management model and a graphical user interface (GUI) to improve the functionality of the software.

Introduction

Icebergs can pose a significant risk to oil and gas exploration, development and production facilities operating on the Grand Banks, off Canada's east coast. The Terra Nova and White Rose floating production storage and offloading (FPSO) vessels are designed to disconnect and move off location to avoid impacts for icebergs which cannot be managed. The Hibernia GBS was designed with an outer ice wall capable of resisting impacts from large icebergs (Hoff et al. 1994; Huynh, Clark, and Luther 1997). The Hebron GBS is also designed to withstand impacts from large icebergs (Widianto et al. 2013). With both GBS platforms, the caisson can withstand large impact forces. However, it is not practical or feasible to design the various components of the topsides structure (e.g. walkways, lifeboat stations, generators, etc.) to withstand such large impacts forces. Instead, the topsides layout and elevation above the sea surface are designed such that the risk of iceberg impact is minimized.

The Iceberg-Topsides Impact Model was developed to provide guidance to designers. This software tool can be used during the early concept selection stage of a project to optimize the basic GBS-topsides configuration such that the risk of an iceberg impact with the topsides is minimized. The tool can also be used later during detailed engineering design to verify that a particular design meets ISO 19906: 2010 guidelines.

During the summer of 2012, HMDC sponsered an extensive field program to collect high resolution iceberg profiles (Younan et al. 2016). Multibeam sonar was used to collect below water iceberg shape information and a photogrammetry system was used to collect above water information. The data were combined resulting in complete 3D iceberg profiles.

This paper provides a brief overview of the existing iceberg-topsides impact model and describes the updates and enhancements to the model using the new high resolution iceberg profiles. Example simulations are performed using the updated software.

ISO 19906 Design Criteria

When designing a platform for operations in arctic and subarctic regions, guidance can be obtained from the International Standard ISO 19906:2010 – Petroleum and natural gas industries – Arctic offshore structures (ISO, 2010). This standard ensures the performance of arctic structures through reliability targets associated with various limit states. Structures are assigned an Exposure Level based on:

- life safety categories that consider whether the facility is manned but not to be evacuated (S1), manned with provision for safe evacuation given extreme environmental events (S2), or unmanned with occasional visits for maintenance or inspection (S3); and
- the consequences of failure that consider the risk to persons onboard or near the facility, the environment, and anticipated loss to the owner – consequences are referenced as high (C1), medium (C2) and low (C3).

Life safety and consequence categories and the corresponding exposure levels are given in Table 1.

Table 1. Structure exposure level (ISO 2010)

Life safety category	Consequence category		
	C1 High consequence	C2 Medium consequence	C3 Low consequence
S1 Manned non-evacuated	L1	L1	L1
S2 Manned evacuated	L1	L2	L2
S3 Unmanned	L1	L2	L3

Each exposure level is assigned a reliability target expressed as an annual failure probability, as defined in Table 2. In a limit state design for iceberg impacts, the ultimate limit state (ULS) is defined as the extreme-level ice event (ELIE) which has a representative action that does not exceed an annual probability of 10^{-2}. The abnormal (or accidental) limit state is defined as the abnormal-level ice event (ALIE) which has a representative action which does not exceed 10^{-4} for L1 and 10^{-3} for L2.

Table 2. Reliability target levels (ISO 2010)

Exposure level	Reliability target expressed as annual failure probability
L1	1.0×10^{-5}
L2	1.0×10^{-4}
L3	1.0×10^{-3}

For example, an L1 structure will have a reliability target of 10^{-5} per annum. For the ULS design check, an abnormal level ice event (the ALIE design load) is defined at 10^{-4} with a load factor of 1. Calibration of ISO 19906 ensures that this, when combined with the fact that the factored structure resistance has reserve capacity at the design load level, leads to the final safety level of 10^{-5} per annum. In other words, when load and resistance are combined, the desired safety level is achieved. However, the topsides of a GBS consist of many different elements including large girders and beams which support the entire topsides, lifeboat stations and walkways. Typically many of these elements are not designed to withstand iceberg impacts and no credit is taken for any reserve structural capacity. Therefore the topsides are designed using a reliability target of 10^{-5} per annum.

Review of Modelling Iceberg-Topsides Impacts

An analytical model to estimate the probability of an iceberg impacting the topsides of a GBS is described in Stuckey et al. (2014), and is briefly reviewed here. A Monte Carlo simulation technique is used to sample a large number of iceberg shapes, sizes, orientations and offsets and the initial point of contact is determined for each impact. The iceberg-topsides impact frequency is determined based on the number of impacts with the topsides, average drift speed and iceberg areal density. The model flowchart is shown in Figure 1.

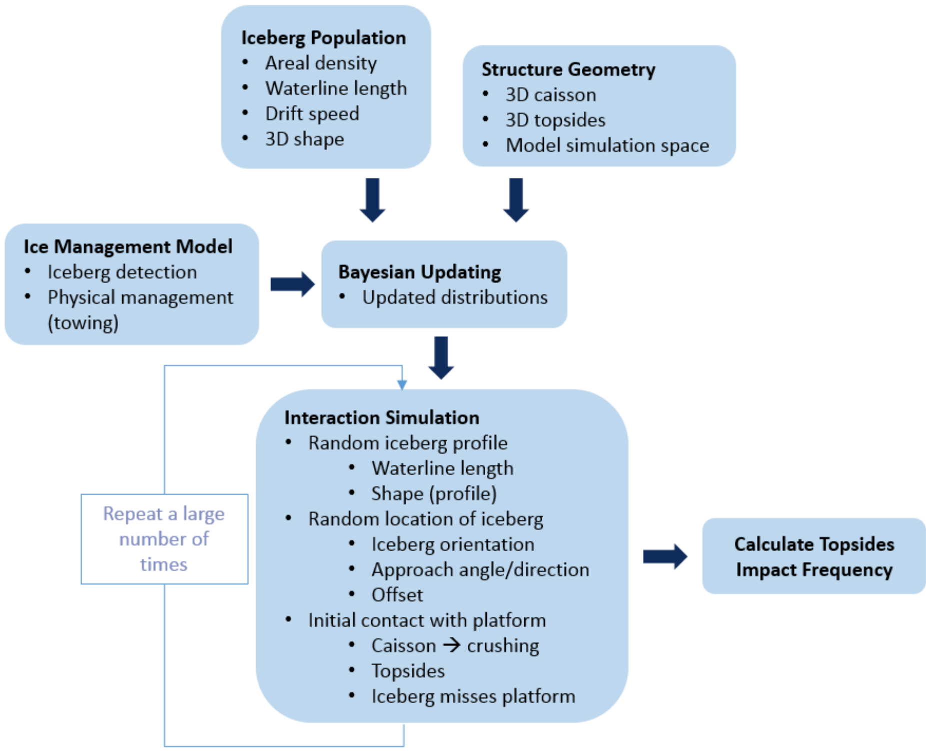


Figure 1. Iceberg-topsides impact model

Iceberg Population

The iceberg population is modelled in terms of frequency of occurrence, waterline length, drift speed and shape. The iceberg population includes all icebergs with lengths greater than 5 m. Ice islands have a relatively low sail height and are not included in the overall iceberg population when considering topsides risk.

Iceberg frequency is described in terms of average areal density, defined as the number of icebergs expected in an area at any given instant in time, averaged over a specified time span. In the past, areal density values for the Grand Banks were calculated using data collected by the International Ice Patrol (IIP) and reported in the form of bulletin charts. These charts contain an estimate of the number of observed and modeled icebergs in each degree square (one degree of latitude by one degree of longitude). Recent work by Habib et al. (2016) have shown that areal density values calculated using the IIP data are conservative when compared to data collected during aerial reconnaissance flights.

Iceberg waterline length is the maximum projected width of an iceberg at the water surface, and is one of the most easily measured dimensions of an iceberg. For the Grand Banks, the overall iceberg waterline length distribution is represented using a combined distribution in which the larger icebergs (L > 16 m) are modeled using an exponential distribution with a mean of 59 m. Bergy bits and growlers are added to the population using an exponential distribution with a mean of 2.7 m. The cumulative density function is expressed as:

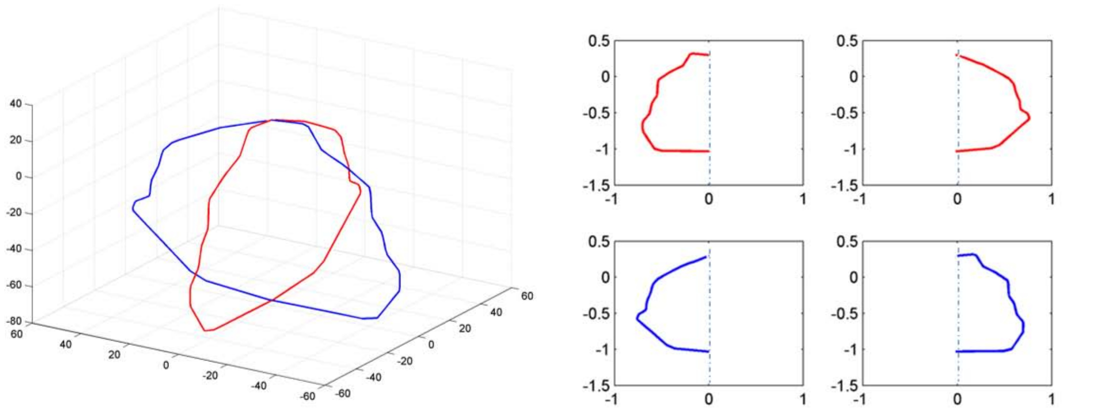
$$F_L(L) = 1 - 2.28 \exp\left(-\frac{l}{2.7}\right) - 0.70 \exp\left(-\frac{l}{59}\right) \tag{1}$$

A gamma distribution is typically used to model the iceberg drift speed, with the cumulative density function defined as:

$$F_v(V) = \frac{1}{\alpha\Gamma(\alpha)} \int_0^v v^{\alpha-1} \exp\left(-\frac{v}{\beta}\right) dv \tag{2}$$

A large database of recorded times and locations for icebergs on the Grand Banks is used to calculate a mean drift speed of 0.34 m/s and a standard deviation 0.35 m/s. Alternatively, a probabilistic iceberg drift speed model based on the same database can be used. See Stuckey (2008) for details.

Iceberg shape is modeled using a database of 2D iceberg profiles collected by Ice Engineering during the early 1980s (Ice Engineering Ltd. 1981; Ice Engineering Ltd. 1982; Ice Engineering Ltd. 1983). To date, this series of iceberg profiles is the largest database of below and above water iceberg shapes, and it contains a range of different iceberg sizes. Below water iceberg shapes were measured at four positions around the iceberg and above water information (projected views) was recorded from two positions. The complete iceberg shape was represented by combining the four underwater profiles with the two above water projections. The final product is shown in Figure 2(a). Each iceberg profile is divided into four half profiles using a vertical line through the origin, and is normalized using the measured iceberg waterline length (see Figure 2b).



(a) Complete iceberg profile

(b) Four half profiles, scaled by measured waterline length

Figure 2. Typical Ice Engineering profile (Ice Engineering Ltd. 1981)

Structure Geometry

The structure geometry is modelled in 3D space using a series of *x*, *y*, *z* coordinates. The caisson must be modeled as a series of axisymmetric shapes and extends from the seabed to the underside of the topsides structure. The topsides geometry can range in complexity from a simple rectangular prism enclosing all components of the topsides (Figure 3, left) to a complex 3D model which includes the actual geometry of the various components (Figure 3, right). A cylindrical model simulation space is defined enclosing the entire platform. The diameter of the model simulation space is equal to the maximum projected width of the platform, including the topsides, plus the maximum iceberg waterline length (nominally set to 400 m) as shown in Figure 4. The model simulation space is used to calculate a preliminary impact frequency based on simplified geometry.

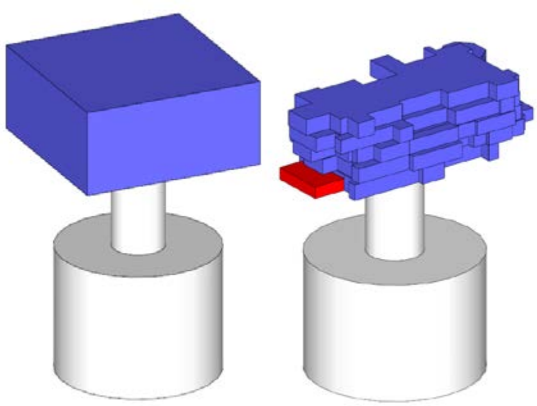


Figure 3. Illustration of 3D models for platform caisson and topsides

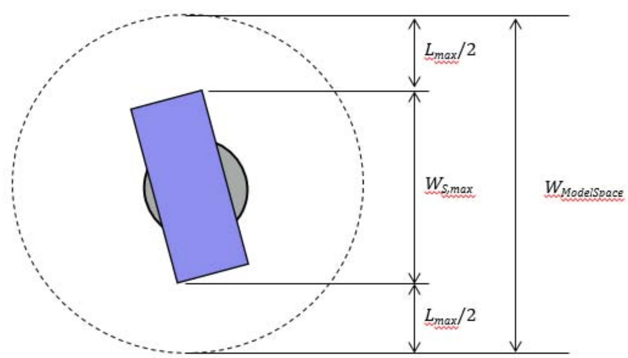


Figure 4. Illustration of 3D models for platform caisson and topsides (plan view)

Iceberg-Structure Interaction

A large number of iceberg-structure interactions are modelling using Monte Carlo simulation. The following random parameters are considered:

- iceberg waterline length: empirical cumulative distribution function described above;
- iceberg profile: random selection of half profile from database; scaled using sampled waterline length;
- iceberg approach direction: uniform distribution between 1° and 360°;
- iceberg orientation: uniform distribution between 1° and 360°; and
- iceberg offset: uniform distribution between $-\left(W_S + \frac{L}{2}\right)$ and $+\left(W_S + \frac{L}{2}\right)$.

The iceberg is assumed to drift towards the platform in a straight line and the initial point of contact is determined. Three impact scenarios are possible.

1. The iceberg misses the platform (caisson and topsides) completely. The impact is counted as a miss and the event simulation is over.
2. The iceberg impacts the topsides. The impact is counted as a topsides hit and the event simulation is over.
3. The iceberg impacts the caisson. A nominal amount of ice crushing, say 5 m, is assumed to occur in the same direction of motion as the iceberg. If the iceberg contacts the topsides during the additional crushing, it is counted as a topsides hit. If there is no contact with the topsides, the event is counted as a miss. The event simulation is over.

The expected number of iceberg encounter events based on the model simulation space $\eta_{ModelSpace}$ is estimated using the following expression:

$$\eta_{ModelSpace} = \rho\left(L_{max} + W_{S,max}\right)\overline{V_D}K \tag{3}$$

where ρ is the iceberg areal density per m^2, L_{max} is the nominal maximum iceberg waterline length (m), $W_{S,max}$ is the maximum projected width of the structure (m), $\overline{V_D}$ is the mean drift speed (m/s), and K is a time constant (number of seconds in a year). The impact frequency with just the topsides is calculated as a percentage of the model space impact frequency, given as:

$$\eta_{Topsides} = \eta_{ModelSpace} \times N_{TS} \tag{4}$$

where $\eta_{Topsides}$ is the expected number of iceberg encounters with the topsides and N_{TS} is the ratio of the number of icebergs contacting the topsides to the total number of icebergs sampled.

Analyzing the 2012 High Resolution Iceberg Profiles

During the summer of 2012, HMDC sponsored a large field program with the objective to collect high resolution 3D iceberg profiles. A multi-beam sonar was used to collect below water iceberg shape information and a photogrammetry system was used to collect above water information. The data were combined resulting in 28 high resolution 3D iceberg profiles.

Generating Iceberg Profile Shapes using 2D Data

For comparison purposes, the high resolution iceberg profiles were processed to generate a series of 2D profiles similar to the Ice Engineering profiles. Vertical sections were taken through the origin at 1° intervals for each HMDC iceberg, as illustrated in Figure 5.

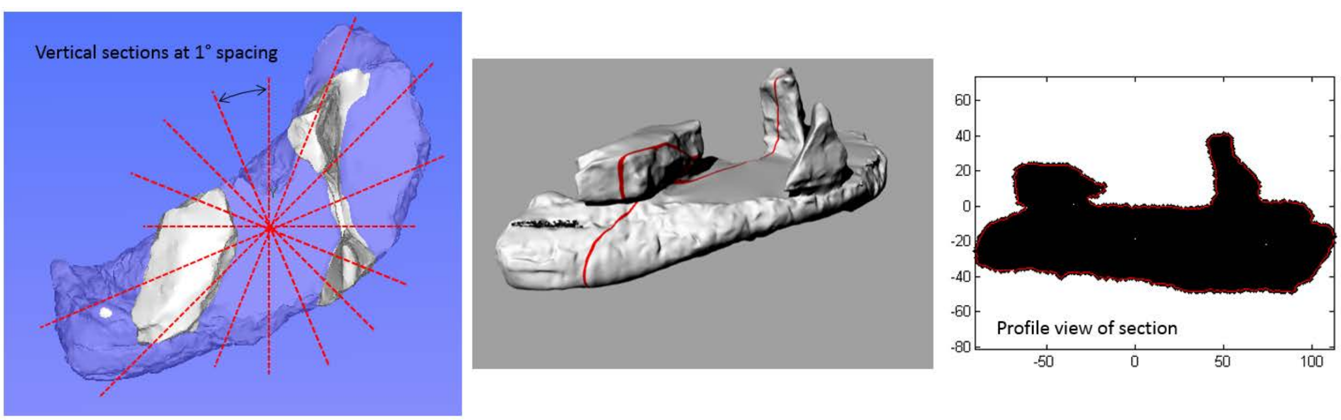


Figure 5. Generation of 2D contours using 3D high resolution iceberg profile

The Ice Engineering database consists of two vertical 2D profiles per iceberg. A sensitivity analysis was conducted to determine how the selection of profiles within an iceberg (i.e. which 2D profiles to choose and how many to choose) can affect the number of anticipated topside impacts. The following four key orientations, with two contours each, were selected:

1. North-South-East-West (NSEW): In this dataset, profiles with orientations in the North-South (0°) and East-West (90°) headings were chosen.
2. 45 Degree (NE-SW/NW-SE): In this dataset, profiles with orientations at 45° and 135°, as measured clockwise from north, were chosen.
3. Maximum project width: In this dataset the first profile was chosen to correspond with the orientation with the longest projected width, including the underwater portion of the iceberg. The second profile is orthogonal to the first.

4. Maximum sail height: In this dataset the first profile was chosen to correspond with the orientation with the maximum sail height. The second profile is orthogonal to the first. This will be a very conservative dataset relative to the other options.

Using the four key orientations listed above as starting positions, the number of vertical sections chosen per iceberg varied from two up to 16 sections per iceberg. One million iceberg-topsides impact simulations were performed for each case. The results are shown in Figure 6. These results were generated using the same structure, iceberg length distribution and physical ice management model inputs, only the iceberg profile database is different. The results from using the Ice Engineering dataset are also included in Figure 6 for comparison. As expected, option four (maximum sail height) produced the highest impact frequency due to the nature of choosing the highest point in the iceberg as the starting point for generating 2D profile shapes. The other three options were relatively close, except for the 45° case using four vertical profiles per iceberg. The difference reduces considerably and the trend stabilizes when using eight or more 2D profiles per iceberg.

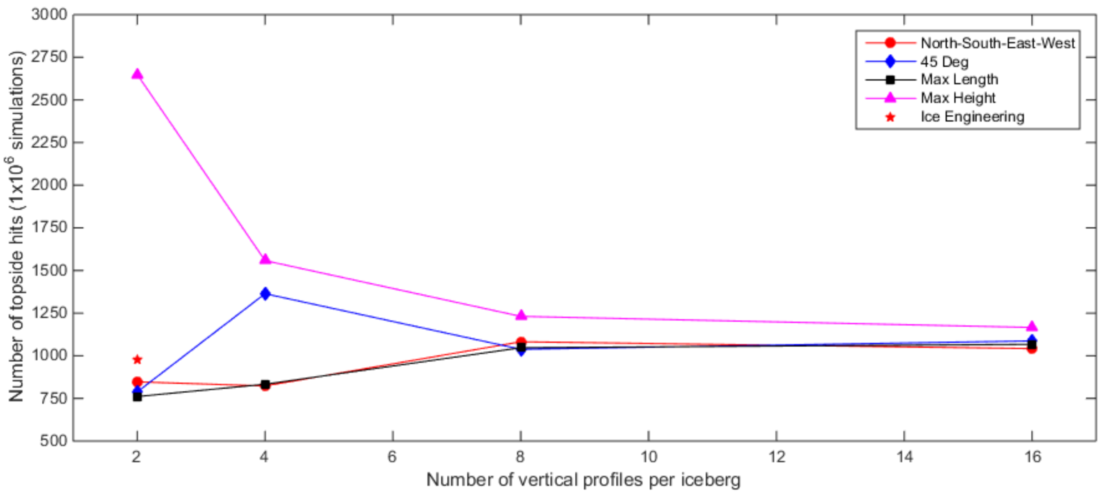


Figure 6. Number of topside contacts vs. number of vertical profiles extracted per iceberg, based on the 2012 high resolution iceberg profiles

The authors are unsure of how the two Ice Engineering profiles were chosen during the profiling exercise, nor how the above water and below water data was combined to form a pair of vertical profiles for each iceberg. Overall, the 2D Ice Engineering profiles compare well with 2D sections through the 2012 high resolution iceberg profiles.

Analyzing Iceberg Profiles – 3D

A total of 28 complete 3D profiles were available for analysis and implementation into the topsides risk model. These 3D profiles began as 3D point clouds which were later simplified into an assembly of horizontal contours generated at 0.5m intervals. A new iceberg shape database was created by normalizing all the measured profiles using the measured waterline for each iceberg.

Model Enhancements using 2012 High Resolution Iceberg Profiles

Several enhancements and additions were made to the Iceberg-Topsides Impact Model, including:

- a new iceberg shape database using the 2012 high resolution profiles;
- the addition of an enhanced ice management model, with various options; and
- the development of a GUI to improve the ease of setting up running a single case, or multiple cases to run in batch mode.

Enhanced Iceberg Management Model

An enhanced iceberg management component was added to the iceberg-topsides impact model. The influence of iceberg detection and management on the probability of an iceberg impacting a platform is illustrated in Figure 7. Of the encroaching icebergs, only those remaining undetected and unmanaged pose can a risk to the facility.

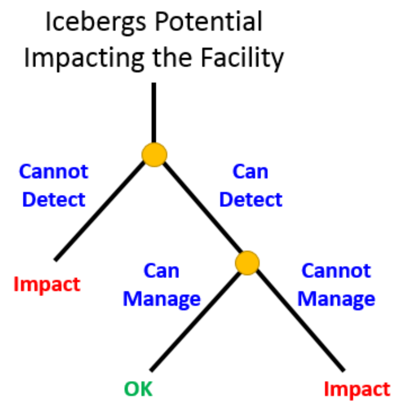


Figure 7. Iceberg management model strategy

Two options for iceberg detection are available. First, a performance model developed for the SeaScan radar by Sigma Engineering (Johnson and Ryan 1991; Sigma Engineering 1994) was used to derive detection probabilities for various combinations of iceberg sizes and sea state conditions. As an example, the performance of an X-band radar mounted 75 m above sea level, for an iceberg with a 50 m waterline length, for both single scan (Figure 8, left) and 16 scan averaging (Figure 8, right). Alternatively, a constant probability of detection can be assigned for all combinations of iceberg size and sea state.

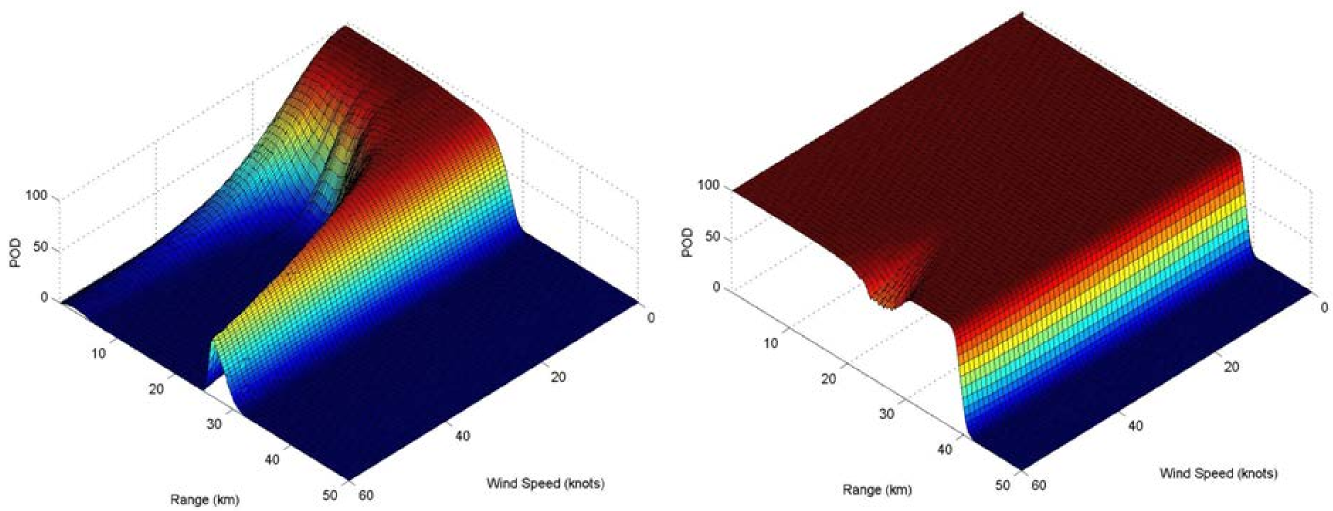


Figure 8. Modeled X-band detection of a 50 m iceberg, single scan (left) and average of 16 scans (right); (Randell et al. 2009)

Iceberg towing success is modeled as a function of iceberg waterline length and significant wave height. Tow success was assessed using data from the Panel of Energy Research and Development (PERD) Comprehensive Ice Management Database (PERD 2009). Tows in the database were classed as successful if the tow summary was referenced as:

- planned objective achieved;
- towed past the closest point of approach (CPA);
- suitable outcome; or
- the deflection angle was greater than or equal to five degrees.

The results were binned and averaged probabilities of success were determined. The tow success quantities are influenced by the time available for the towing operations. With more time available, the probability of success increases given more time for multiple attempts (if required) to successfully tow the iceberg. With less time available, the probability of success decreases. The results are shown graphically in Figure 9. As with iceberg detection, an alternative approach is to assign a constant probability of tow success for all combinations of iceberg size and sea state.

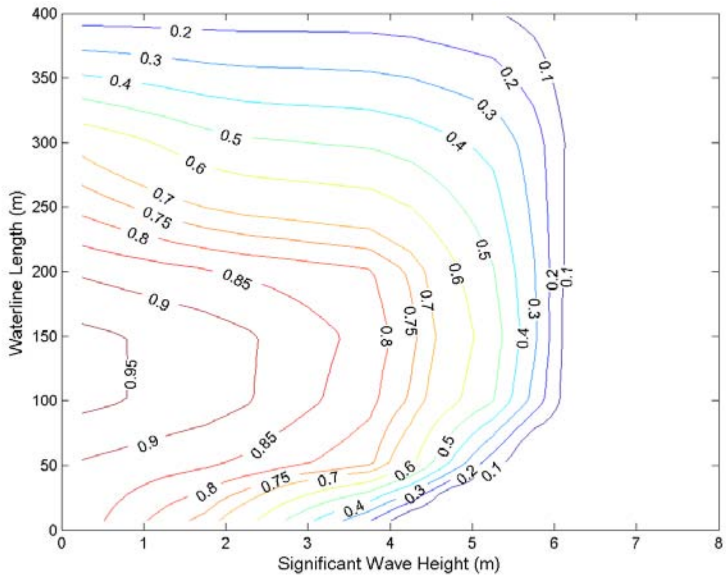


Figure 9. Probability of success iceberg towing

Graphical User Interface (GUI)

A GUI was added to make the software more user-friendly. The GUI allows the user to define all model input variables, create the structure and topsides 3D models using a series of coordinates, access the software documentation and run a single case or a number of cases in batch mode. The starting point is the main form, shown in Figure 10.

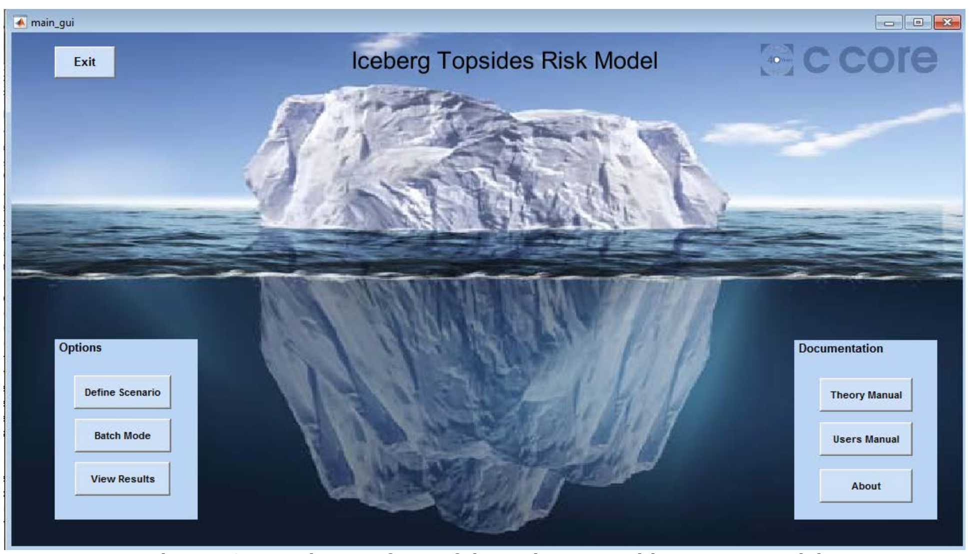


Figure 10. Introductory form of the Iceberg-Topsides Impact Model

In order to define a scenario, the user must define the structure geometry. The Structure Geometry (see Figure 11) form allows the user to input information to define the gravity based structure and the platform topsides. The caisson is defined as a series of axisymmetric shapes. The topsides is modeled using a series of x, y, z coordinates defining the footprint of each deck. The deck bulkheads are assumed to extend vertically between two consecutive deck plans.

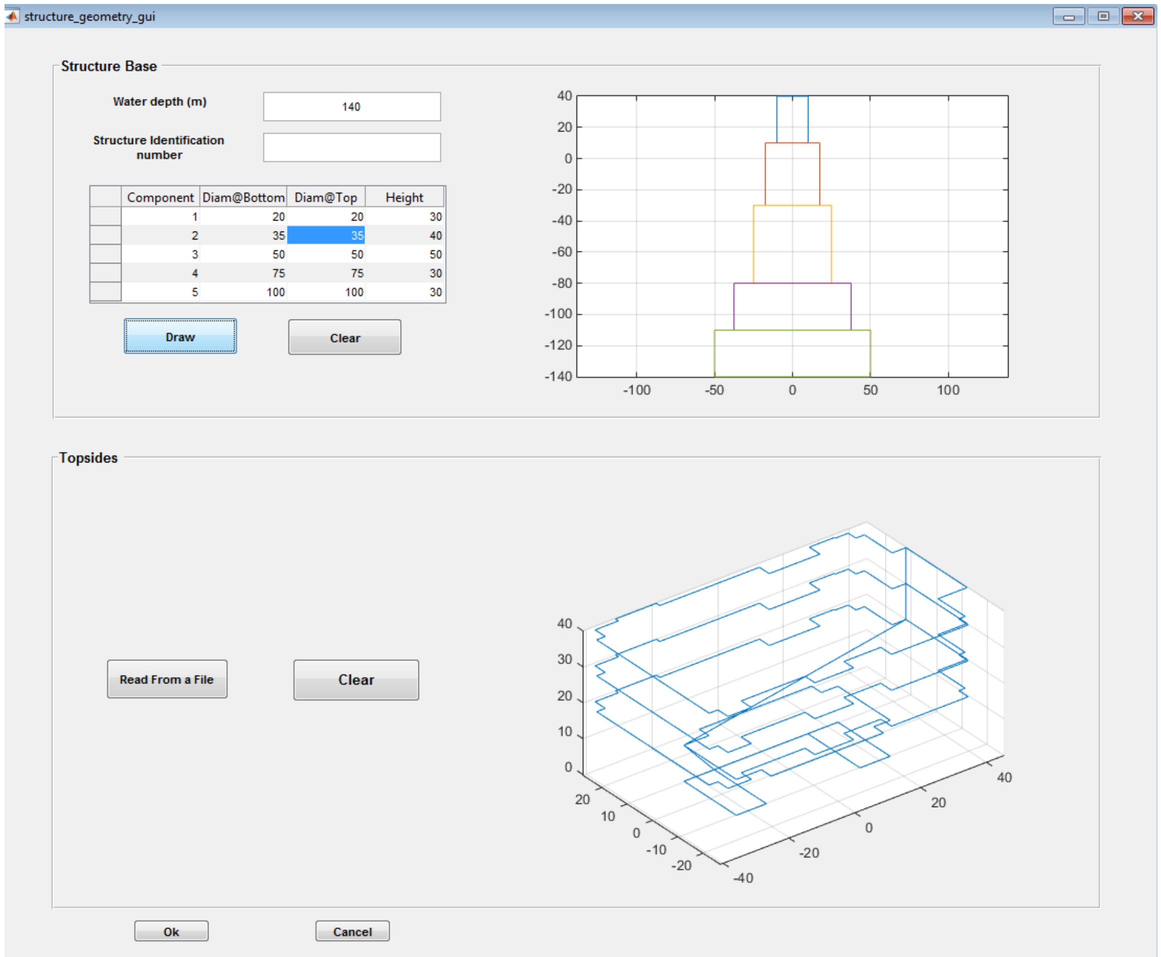
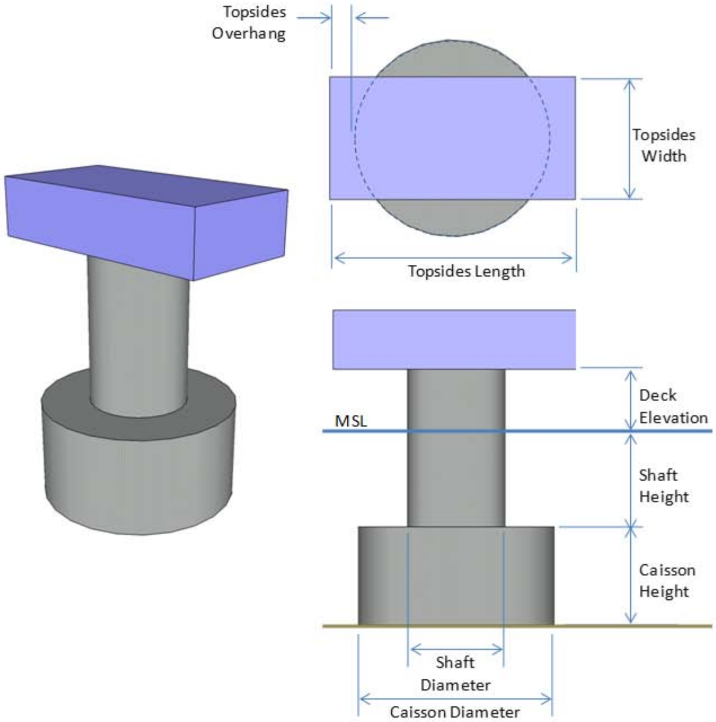


Figure 11. Structure Geometry form

Additional input information is entered using forms in the software. The location of the structure is specified using latitude and longitude coordinates, and appropriate distributions for iceberg waterline length and significant wave height are specified. Options for iceberg detection and towing are specified for the probabilistic models or constant probability values can be specified. An iceberg profile shape database is selected. All input parameter are saved in a scenario file. The user can run a single scenario, or can create multiple scenarios and run them consecutively using the batch mode.

Application of Model and Sensitivity Analyses

Here, a stepped GBS with a rectangular topside, as illustrated in Figure 12, is considered. The GBS consists of a 100 m diameter caisson which is 50 m high and a 50 m diameter shaft which extends from the roof of the caisson to the underside of the topsides. The topsides has a footprint of 125 m × 62.5 m and overhangs the caisson by 12.5 m on each end. The water depth is assumed to be 100 m and the iceberg areal density to be 2.0×10^{-4} icebergs/km^2. Assuming a L1 structure, the target impact frequency for the topsides is set at 1×10^{-5} impacts/year.



Component	Base Case Dimensions
Shaft diameter	50 m
Shaft height	50 m
Caisson diameter	100 m
Caisson height	50 m
Deck elevation	30 m
Topsides Length	125 m
Topsides Width	62.5 m
Topsides Overhang	12.5

Figure 12. Generic stepped GBS with basic structural dimensions

Several scenarios were simulated to highlight the various changes in the model and the results are summarized in Table 3. Using 2D profiles generated from the high resolution iceberg profiles resulted in a slightly higher (<5%) impact frequency when compared to the 2D Ice Engineering profiles. Using the new high resolution 3D profiles resulted in 120% increase in the topsides impact frequency.

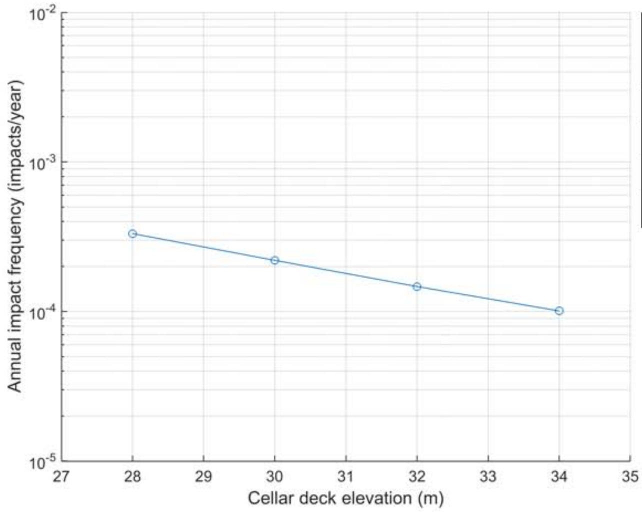
Table 3. Summary of scenarios

Profile Database	Ice Management	Annual Topsides Impact Frequency
2D Ice Engineering	No	1.0×10^{-3}
2D from High Resolution Profiles	No	1.1×10^{-3}
3D from High Resolution Profiles	No	2.4×10^{-3}
3D from High Resolution Profiles	Probabilistic model	2.2×10^{-4}

Sensitivity Analyses

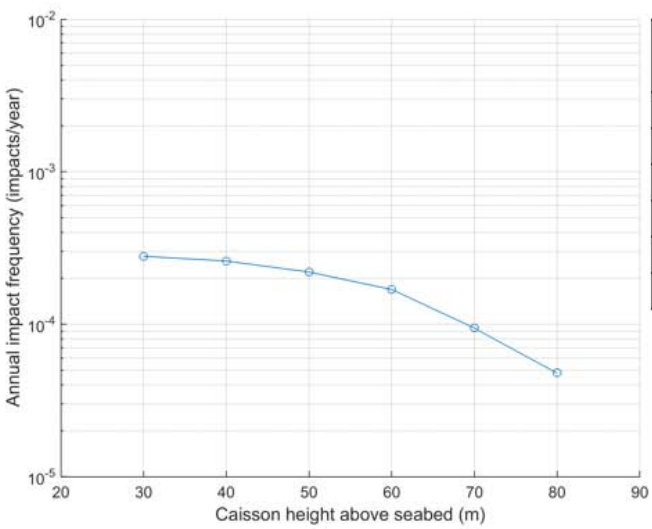
The deck elevation was varied from 28 m to 34 m above the water surface to investigate the effect on the topsides impact frequency. The results are summarized in Figure 13. As expected, the topsides annual impact frequency decreases as the height of the topsides above the sea surface increases. For this hypothetical structure, a deck height of approximately 50 m is required to reach the target impact frequency of 1×10^{-5}. A second sensitivity analysis was performed in which the caisson height was varied from 30 m above the seabed to 80 m above the seabed, and the results are shown in Figure 14. Increasing the caisson height has a significant effect on the impact frequency. A higher caisson height will shield the topsides from impacts with icebergs with deep keels; the keel will likely impact the caisson before the iceberg sail reaches the topsides. A structure with a caisson extending above the water surface will prevent a large proportion of the icebergs from reaching the topsides. However, there are other design criteria to consider such as iceberg and wave loading which factor into the overall decision.

These sensitivity analyses highlight the value of the simulation tool. During the early stages of a project, designers can use this tool to estimate the annual impact frequency for various GBS and topsides configurations. Initially the topsides layout can be represented using a rectangular prism enclosing all topsides components. Later during the final design stages when more information is available, the geometry can be updated and the annual impact frequency reassessed.



Cellar Deck Elevation above Sea Level (m)	Annual Topsides Impact Frequency
28	3.3×10^{-4}
30	2.2×10^{-4}
32	1.5×10^{-4}
34	1.0×10^{-4}

Figure 13. Annual topsides impact frequency as a function of deck elevation



Caisson Height Above Seabed (m)	Annual Topsides Impact Frequency
30	2.8×10^{-4}
40	2.6×10^{-4}
50	2.2×10^{-4}
60	1.7×10^{-4}
70	9.4×10^{-5}
80	4.8×10^{-5}

Figure 14. Annual topsides frequency as a function of caisson height

Conclusions and Recommendations

HMDC, C-CORE, Fugro Geosurveys and Pro-Dive conducted an extensive field program to collect high resolution iceberg profiles during the summer of 2012. The Iceberg-Topsides Impact Model was recently updated using information collected during the field program. A new iceberg shape database was created using the new profiles. A new GUI was added to the software to improve the functionality of the tool.

Several areas have been identified for future consideration.

- The consequences of iceberg-topsides impacts should be assessed. Presently any iceberg contact with the topsides is assumed to cause failure of the topsides and is included in the calculation of topsides impact frequency. Natural flaws in the iceberg may lead to failure of the pinnacle upon contact with the caisson or topsides before any significant force can be transferred to the topsides. Impact forces from glancing impacts with the topsides are likely to result in small forces being transferred to the topsides.
- Potential wave induced motions of the iceberg during the interaction should be assessed, especially pitch and heave. Refer to Talimi et al. (2016) for a preliminary assessment of iceberg hydrodynamics using the 2012 high resolution iceberg profiles.
- Iceberg motion after contact with the caisson should be further assessed.
- With deep water exploration continuing off the east coast of Canada, the option to model spars should be added to the software.

- 3D iceberg profiles should be collected on a regular basis to increase the size of the shape database. A rapid iceberg profile system has been developed (McGuire et al. 2016). This tool can be used to collect a large number of iceberg profiles on a regular basis. The HMDC 2012 dataset consists of 29 icebergs, with several icebergs having large pinnacles close to the perimeter of the iceberg. Additional data will confirm if this is the norm or if this is a result of a relatively limited data set.
- Ongoing work related to ice management (McGuire et al. 2016; Bruce, Younan, and MacNeill 2016) will likely lead to improvements in ice management efficiency. The database used to model the iceberg towing performance should be updated on a regular basis to capture any improvements in ice management operations.

Acknowledgements
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