POAC'23
Glasgow, United Kingdom

Proceedings of the 27th International Conference on
Port and Ocean Engineering under Arctic Conditions
12-16 June 2023, Glasgow, United Kingdom

Glacial Ice Impact Loads on Floating Production Facilities

Paul Stuckey[1], Jørn Birknes-Berg[2], Ole-Christian Ekeberg[2], Mark Fuglem[1]
[1] C-CORE, St. John's, Canada
[2] DNV, Oslo, Norway

ABSTRACT

In areas where iceberg impact shall be considered for design, it is important to estimate iceberg actions and action effects with confidence and without unnecessary conservatisms. The Hibernia GBS was the first facility to be installed on the Grand Banks in 1997, and the first to be designed to withstand iceberg impacts. Since that time, there have been significant improvements in the field of ice mechanics and in design approaches used for ice loads, as a result of new field data and development of better modelling techniques. C-CORE and DNV previously completed a scoping study focusing on global and local iceberg loads and local structure response of a moored floating structure due to an iceberg impact. As a result of this scoping study, a joint industry project "Glacial Ice Impact Loads on Floaters" was established, bringing together stakeholders to discuss issues and work towards solutions. The overall goal of the project was to remove unnecessary conservatisms in models and assumptions and to increase confidence and clarity in the procedures used for estimating actions and action effects due to iceberg impacts with a moored floating platform. In this paper, the authors describe the background and motivation for the project, provide an overview of a probabilistic methodology which can be used for determining design global and local iceberg actions, and summarize improvements made during the project.

KEY WORDS: Icebergs; Design loads; Local hull response; Global loads, Hydrodynamic properties of icebergs; Repeated impacts.

BACKGROUND AND MOTIVATION

Background

When designing a production facility to be operated in areas where icebergs may be encountered, consideration of global and local ice actions and action effects are required. The severity of the interaction will depend on many factors, including the shape and size of the iceberg, the strength of the ice, how fast the iceberg is moving and the shape of the structure itself. Given that iceberg impacts cannot be avoided with 100% reliability, it is important to estimate iceberg actions and action effects with confidence and without unnecessary conservatisms. During the past 30-40 years, design methods have been established, and to date, four production facilities are operating in the harsh environment off the east coast of Canada.

The Hibernia GBS was the first facility to be installed on the Grand Banks in 1997, and the first to be designed to withstand iceberg impacts. To deal with impacts from large icebergs, the "ice wall" was designed with 16 "teeth" to help dissipate the impact energy. The teeth were connected to the inner structure by a series of complex, interconnecting XVT walls. Design iceberg loads were determined using a semi-probabilistic approach, with an ice pressure-area relationship derived using data collected during medium scale indentation tests at Pond Inlet; a lower bound ice pressure of 6 MPa was established for larger contact areas (Huynh, Clark, and Luther 1997).

Installed in 2002, the second facility, the Terra Nova FPSO was the first moored floater designed for operation on the Grand Banks. The Terra Nova FPSO is a double hulled, ice-reinforced vessel which relies on iceberg management (early detection, monitoring and iceberg towing) to reduce the risk of iceberg impact. The Terra Nova FPSO also includes a quick disconnect turret system designed such that the FPSO can disconnect and move offsite to avoid impacts from icebergs not successfully managed. Ice pressures were modelled based on data collected during the Grappling Island Experiments (Ralph et al. 2004); global ice pressures were limited to about 4 MPa for larger contact areas, a 33% reduction compared to the value used for the Hibernia GBS design.

The Sea Rose FPSO was the second moored floater to be designed for operation on the Grand Banks (at the White Rose field). Similar to the Terra Nova FPSO, the Sea Rose is a double-hulled, ice-reinforced vessel which has a quick disconnect turret system, and relies on iceberg management to mitigate the risk of iceberg impact. For this study, global and local ice pressures were based on the probabilistic models which are now described in ISO 19906:2019. This led to a reduction of more than 50% in global pressures compared to previous projects. Note the comparisons are made using mean values from the probabilistic model.

The second GBS constructed for operation on the Grand Banks was the Hebron GBS. This platform was designed as a stepped structure such that the larger icebergs would contact deeper in the water column, thus reducing the overturning moment, and reducing wave loads at the water surface. With improved understanding of ice failure and further data analyses, the global ice strength was modelled as an equivalent 1.5 MPa (Widianto et al. 2013), and local pressures were based on the model currently described in ISO 19906:2019.

It is apparent from reviewing past projects that with more data, increased knowledge and innovated solutions, uncertainty is reduced (especially with respect to global ice pressures) and cost savings increased, all without sacrificing safety of personnel and the environment. Where actual data is unavailable, the model(s) and assumptions tend to be more conservative in nature.

Motivation

In design, it is imperative to develop effective concepts without compromising human safety and the environmental protection (i.e., satisfy safety first, then economics). Careful consideration is required when dealing with uncertainty, as making too many conservative assumptions can make a project needlessly unfeasible. Recent research, exploration and project activities have demonstrated a need and a potential in reducing uncertainties related to iceberg interaction with floating mooring structures. Conservative assumptions were used in past FPSO designs. For example, iceberg impact forces for the Sea Rose were derived assuming the platform was a fixed body, i.e., the vessel would not move from the equilibrium moored position due to the iceberg impact. Equinor (Statoil at the time) approached C-CORE and DNV to perform a scoping study and to answer the question: “Where are we now and where do we want to be?” regarding the design of floating moored structures. To answer this question, C-CORE and DNV conducted a scoping study to evaluate the current methodology for determining iceberg impact loads on a moored floating production system and to identify gaps (C-CORE and DNV GL 2017). The study focused on five topics: i) iceberg area-penetration, ii) global and local ice pressures, iii) wave-induced motions of the iceberg and the FPSO, iv) iceberg and structure dynamics during interaction, and v) iceberg interaction with mooring lines. A generic shaped FPSO was used for the analyses, and impact forces were determined for two iceberg sizes and three iceberg impact scenarios (refer to Figure 1). It was concluded that, although C-CORE and DNV used different tools to perform the analyses, the impact forces were generally similar for the different iceberg sizes and impact scenarios, and differences in forces could be explained based on different model assumptions. Four key areas were identified for further investigation: i) modelling of global and local ice pressures, ii) modelling the motions of icebergs in close proximity to the platform given hydrodynamic interaction effects, iii) accounting for the possibility of multiple impacts during an interaction and iv) clarification of the probabilistic approach for handling natural variability in environmental parameters and model uncertainty.

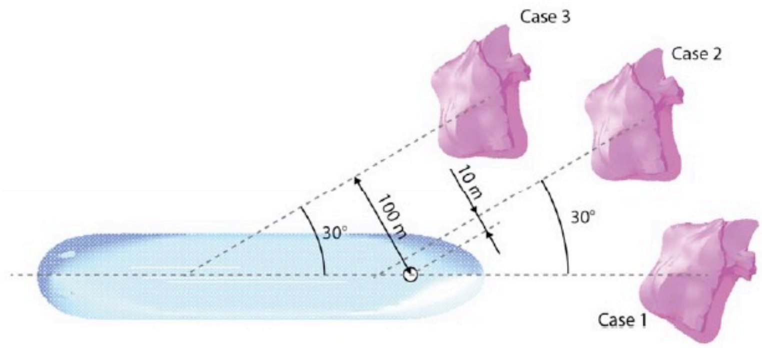

Figure 1. Iceberg-FPSO impact scenarios

Glacial Ice Impact Loads on Floaters Joint Industry Project

A joint industry project “Glacial Ice Impact Loads on Floaters” (Floaters JIP) was launched in 2018, bringing together stakeholders to discuss these four key areas and work towards solutions. The objectives of the JIP were to discuss, learn and disseminate information related to designing FPSOs for operation in regions where icebergs exist.

Six tasks were formulated based on the recommendations from the scoping study. Figure 2 shows the relationship between the different tasks. The first task consisted of defining case studies for the project, and also includes defining acceptance criteria to be used when modelling local hull deformation (Task 5b). The second task focused on modelling global and local ice pressures. The third task involved an investigation into hydrodynamic effects of the iceberg and the iceberg-FPSO. The fourth task centred on the possibility of multiple impacts from a single iceberg as it drifts past the FPSO. The fifth task focused on methods for determining design global and local iceberg loads and performing local hull analyses due to iceberg impacts. The main deliverable (Task 6) was a documentation of procedures for estimating design global and local iceberg loads for a FPSO, and for assessing the local hull response (given a hull design) to the applied iceberg loads. The methodology generally fulfills the requirements of ISO 19906:2019 and other governing standards and regulations.

Two companion papers accompany this paper, and provide detailed descriptions of the work completed on modelling ice pressures (Fuglem et al. 2023) and hydrodynamics (Huang et al. 2023).

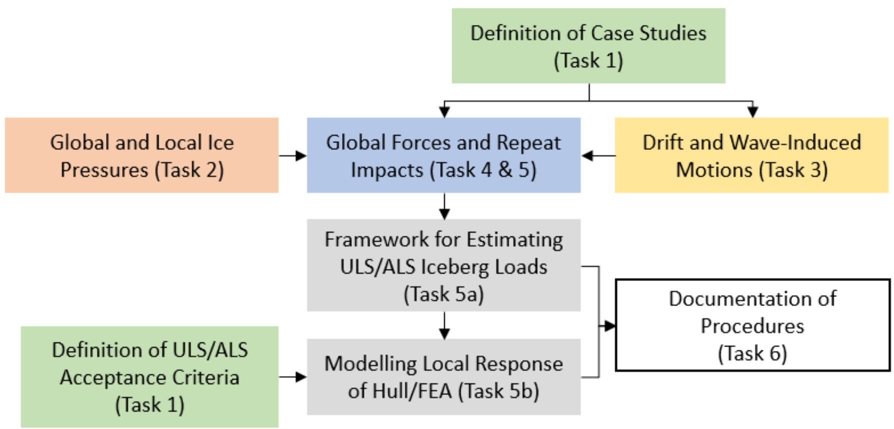

Figure 2. Relationship between project tasks

GLOBAL AND LOCAL ICEBERG LOADS

Design Criteria

ISO 19906:2019 – Petroleum and natural gas – Arctic offshore structures (ISO 2019) is a relevant standard for the design of FPSOs to be operated in regions with icebergs present. This standard ensures the performance of arctic structures through reliability targets associated with different limit states. The ultimate limit state (ULS) is defined to ensure the FPSO has sufficient strength and resistance to withstand extreme-level ice actions. Some localized inelastic behaviour of the structure and its components is acceptable, but the probability of significant deformation should be less than 10^{-2} per year over the design service life of the structure, where significant deformation is associated with impairment of structure function. Ice events associated with the extreme-level ice action are called extreme-level ice events (ELIE), and the corresponding ice forces are based on an annual probability of exceedance of not greater than

10^{-2}. The abnormal limit state (ALS) is defined to ensure the FPSO has adequate reserve capacity and energy dissipation capability to withstand abnormal-level ice actions, without leading to complete loss of integrity or performance of the FPSO. Ice events associated with the abnormal limit ice action are called abnormal-level ice events (ALIE), and the corresponding ice forces are based on an annual probability of exceedance of not greater than 10^{-4} for L1 structures (manned, non-evacuated platforms and high-consequence platforms, as per ISO 19906:2019). The fatigue limit state (FLS) is defined to ensure the FPSO has adequate endurance to withstand the accumulated responses due to cyclic or repetitive actions. The FLS is not an issue for iceberg impacts. An FPSO is likely to see at most one iceberg impact during its lifetime, and that impact will last for about 5-10 seconds. Even with multiple (repeated) impacts from the iceberg, there is not sufficient time for fatigue issues to develop. The serviceability limit state (SLS) is defined to ensure adequate performance under normal operating conditions. Minor, localized deformation (i.e., a small dent) is permitted, as long as the FPSO can continue to perform its functions without any impairment. Unless specified otherwise by the owner, ice actions are determined based on a 10^{-1} annual probability of exceedance. For FPSOs operating on the Grand Banks, the SLS takes on a new meaning since the annual iceberg impact frequency is much less than 10^{-1}. Fuglem et al (2020) describes how SLS can apply to an FPSO operating on the Grand Banks.

A Probabilistic Method for Determining Iceberg Loads for Design

Probabilistic methods are permitted by ISO 19906:2019 and are ideal when determining iceberg loads corresponding to ELIE and ALIE. Probabilistic methods allow the designer to model the randomness observed in nature without introducing unnecessary conservatisms. The Iceberg Load Software (ILS™) is an example of a probabilistic tool that can be used to estimate global and local iceberg design loads. The ILS™ was developed by C-CORE to estimate design actions for the Hebron GBS. The original framework of the tool was established during the Canadian Design for Ice Environments (CODIE) projects at Memorial University (CODIE 1995; CODIE II 2003). Numerous improvements and enhancements have been made over the past three decades. A large database of high-quality 3D iceberg profiles were used to update distributions and relationships used to characterize iceberg shape (Stuckey et al. 2016; 2021). Dynamic interaction models (1D surge models) were developed to account for the inertial effects of an FPSO and restoring forces developed in the mooring system (Stuckey et al. 2009; Jordaan et al. 2014; Fuglem et al. 2020). A general description of the ILS™ is provided.

Significant wave height, H_S, is the primary variable used to model metocean conditions. Since the most severe wave heights occur during months with no icebergs, a seasonal distribution is developed by weighting the monthly H_S distributions by the number of icebergs present each month. A wind driven JONSWAP spectrum is assumed when modelling wave-induced motions of icebergs and the platform (if floating).

The iceberg population is characterized in terms of the number of icebergs and their associated sizes and shapes. The number of icebergs is defined in terms of areal density (the average number of icebergs per unit area for a given instant in time), and is used to determine how often the platform will be impacted by icebergs. Iceberg size is modelled in terms of waterline length (the largest projected width at the water surface), the most easily measured dimension. Other iceberg dimensions, such as width, draft, height and mass, are typically modelled as a function of waterline length, using relationships derived based on a large database of measured 3D iceberg profiles (Bruce et al. 2021). Iceberg shape plays an important role in the ILS^{TM}, with the global shape of the iceberg influencing the rotation of the iceberg about the contact point (i.e., a portion of iceberg kinetic energy is transferred to rotational energy) and the initial point of contact on the platform. The local shape of the iceberg at the point of contact dictates how the contact areas develops as the iceberg crushes against the platform. Iceberg impact speed consists of two components – drift and wave-induced velocities. Iceberg drift velocity is modelled using a probabilistic model accounting for the size of the iceberg and the significant wave height (Stuckey 2008) developed using a database of iceberg trajectories (consisting of dates/times and locations of iceberg, generally on an hourly basis). Iceberg motion is strongly influenced by the size of the iceberg and the sea state. Smaller icebergs or higher sea states will have a larger influence on the wave induced surge velocity component. Curves for significant surge response have been developed by Lever et al. (1990), and Fuglem (1997) further adapted the approach to account for Bayesian updating given the combined drift and wave-induced velocities.

Iceberg management can be included to mitigate the risk of iceberg impact with platforms. McKenna et al. (2003) developed a strategy for modelling iceberg management, and individual models for iceberg detection performance and iceberg tow success have been developed for application in the ILS^{TM} based on Grand Banks experience (Randell et al. 2009; Stuckey et al. 2016).

Monte Carlo simulation is used to generate a large population of impacting icebergs and associated impact forces. The complexities of ice mechanics are approximately captured using area-penetration and pressure-area models. A closed form solution for maximum impact force is adopted, in which the energy is dissipated through the crushing of the iceberg onto the structure, as well as from inertial rotations of the iceberg during impact. The method is outlined in Fuglem, Muggeridge and Jordaan (1999) and is based on the generalized model for rotation developed by Matskevitch (1996). The model assumes small iceberg rotation during the impact, zero friction and that the influence of hydrostatics can be neglected. For moored floating structures, the inertial properties of the platform and the restoring force in the mooring system are also considered, for example see Jordaan et al. (2014) and Fuglem et al. (2020) for dynamic models.

A parent distribution of impacts forces is determined by ranking the forces from smallest to largest and corresponding exceedance probabilities are calculated. The influence of the annual iceberg-structure contact rate is described by Jordaan (2005). For rare events, the annual maximum force distribution will have the same shape as the parent distribution but with reduced probabilities, and there will be a "spike" of probability at zero corresponding to years with no iceberg impacts. Design forces can then be determined for different annual probabilities of exceedance.

SCOPE OF WORK

Overview

Four technical tasks were defined for the project: i) modelling global and local pressures, ii) drift and wave induced motions, iii) repeated impacts and iv) estimating design loads and modelling of local hull response. A summary of activities is presented in the following section.

Modelling Global and Local Ice Pressures

Ice failure is a complex and dynamic process. During an impact, the ice undergoes an array of changes including microcracking, recrystallization and spalling of large pieces. Jordaan (2001) provides a good overview of the different processes involved in ice-structure interaction. During an iceberg-structure interaction event, the majority of the load from the ice is transferred to the structure through localized high pressure zones (*HPZ*). These *HPZ*s are surrounded by regions of lower (background) pressure. ISO 19906:2019 Clause A.8.2.4.3.5 describes a probabilistic model for global ice pressures that can be used to simulate ice pressures during an iceberg impact. ISO 19906:2019 Clause A.8.2.5.3.1 describes a probabilistic model which can be used to determine design local ice pressures as a function of local area and annual probability of exceedance.

The objective of this task was to review available models for ice contact pressures, provide clarification regarding the models and limitations, and where possible, identify potential improvements. Fuglem et al. (2023) describe the work performed in this task; they conclude that the models presently referenced in ISO 19906:2019 are largely sufficient for design of FPSOs in regions with low impact frequencies, although there are nuances on how to apply the models. Although it should be noted that when contact frequencies are high, results based on the global pressure-area model may be overly conservative.

Modelling Motions of Icebergs and FPSO

Iceberg impact velocities and forces may be influenced by hydrodynamics. Iceberg drift velocities are determined by current and water drag and wave drift forces. Currents vary with depth and smaller icebergs will be influenced more by winds and surface currents. Wave-drift forces will depend in part on the size of the iceberg relative to the predominant wave length. Icebergs and floating platforms will both have wave-induced velocity components; with greater velocities when the floating body is small relative to the predominant wave length. Before impact, the velocities of the two bodies will be influenced by hydrodynamic interaction forces, and during impact, forces may be increased as a result of fluid inertia effects (hydrodynamic added mass).

A challenge when determining design impact loads is the consideration of different combinations of environmental parameters and iceberg sizes and shapes. The project used a generic FPSO and a selection of iceberg shapes and sizes representing the conditions of interest for design iceberg loads. For the glacial ice, two different shapes and three different sizes is considered. The shapes correspond to tabular and non-tabular glacial ice. The ratio between mass of the glacial ice to the mass of the FPSO is 1:20, 1:2 and 3:2 for the small, medium and large icebergs as defined by the Canadian Ice Service (MSC 2005).

The hydrodynamic interaction between the FPSO and glacial ice is analysed with the software HydroD/Wadam (part of DNV's software suite) which is a general hydrodynamic analysis program for calculating wave structure interaction for fixed and floating structures of arbitrary shape (DNV 2023; 2022). Wave loads are based on potential and Morison theory.

The multi-body analysis resulted in added mass, drift velocity, horizontal velocity and relative vertical displacement, all of which are important when assessing the impact between an FPSO and an iceberg. These results are used in updating models in the ILS^{TM} software. Also, hydrodynamic damping and wave excitation forces are studied. A detailed description and summary of the main findings are presented in the accompanying paper by Huang et al. (Huang et al. 2023).

Modelling Repeated Impacts

Simulations in the scoping study indicated that some icebergs may impact the structure multiple times before clearing the structure and drifting away, especially when wave forces are included in the interaction model. While loads from secondary impacts may be expected to be lower than initial loads in general, this may not always be the case. The objective of this task was to investigate the possibility of multiple impacts occurring and to develop a methodology for addressing the issue. The task has been approached from a couple of different directions – direct modelling of the interaction, assuming different degrees of freedom, and from a probabilistic point of view.

The global dynamics of impact, including importance of force-deformation curves, wave induced motion and mooring system stiffness have been analyzed. In the analysis, the iceberg drifts slowly (due to wind, waves and current) towards the moored floater with wave induced motions superimposed on the steady drift. The moored FPSO undertakes wave-frequency and low-frequency motions in its mooring system. As the iceberg approaches the FPSO the wave induced motions of both objects will change as a result of hydrodynamic interaction between the two. Repeated impacts may occur, with gradually reduced wave induced velocities since wave induced motions are restricted by the presence of the FPSO. At the end the two bodies will be in contact, while first-order wave loads will be transferred to the contact area.

Repeated impacts were further studied using a 1-degree of freedom (DOF) surge motion simulator. The tool includes both steady forces from wind and current and dynamic forces from the waves. The phasing of motions between the two objects have been accounted for as well as modified wave forces as the two objects are close to each other. The advantage of using a special purpose program instead of SIMO (SINTEF Ocean 2020) is that it is easier to implement special purpose models for the impact. The tool has been used for parametric studies where variables such as iceberg size, wave height, mooring stiffness and force-deformation curves, have been varied.

Two scenarios for environmental loading have been considered, i) current only and ii) combined wind, wave and current.

When current is the only environmental parameter, the analysis indicates that maximum impact loads are:

- proportional to mass and added mass of glacial ice and FPSO,
- proportional to impact force-deformation stiffness,
- proportional to steady current velocity, and
- independent of mooring stiffness, i.e. effect of mooring system is insignificant.

Further, the deformation energy is proportional to mass, $M_{ice}M_{FPSO}/(M_{ice} + M_{FPSO})$, and a function of the steady current velocity. M_{ice} and M_{FPSO} are the mass of the iceberg and FPSO, respectively.

For the combined wave, wind and current condition, repeated impacts are important due to additional environmental energy fed into the system. Due to the nonlinearities of the impact force model with area development during repeated impacts, conclusions are based on the results from the simulator. Impact forces with 10% exceedance probability (P90 based on 30 realisations) are calculated. A few of the main findings are listed below. The impact forces are:

- affected by mass and added mass of iceberg and FPSO, but not proportional as for the case with only current loading,
- affected by impact force-deformation stiffness,
- significantly influenced by waves and wind, through the increased steady drift velocity and wave frequency velocities, and
- independent of mooring stiffness, same as for the case of the current only environmental condition.

DynIIS is a full 3D time domain model that simulates the interaction between an iceberg and a fixed or floating platform in six (fixed platform) or 12 (floating platform) degrees of freedom (Fuglem and Younan 2016). Hydrostatic forces on the iceberg and the platform are considered. Wind and current forces are included, but not wave forces (currently being added to the tool). A matrix of cases has been set up for analysis using DynIIS. These cases cover a range of iceberg shapes (based on real 3D iceberg profiles), sizes, approach angles and offset from the platform centreline.

Modelling Local Hull Response

One of the objectives of the project is to improve the modelling of local hull response of moored floating platforms to iceberg impacts, and to provide a description of the methodology. As part of the scoping study, non-linear finite element analyses were applied to investigate the structural response to iceberg loads for an FPSO. In the present study, non-linear finite element analysis was used to: i) verify the of hull capacity for ultimate and abnormal limit states and ii) establish an operational decision basis applicable for an FPSO with disconnect capability. The objective of the second point was to come up with a procedure for when to disconnect or not when glacial ice is approaching the FPSO.

The contact pressure between the iceberg and the structure during their interaction was modelled by different methods; pressure area-models and impact analysis with a rigid as well as deformable, iceberg (with an implemented continuum model for the iceberg). The collision performance of the iceberg continuum model and the challenges to the use of such a model were also investigated.

The study indicated that the different methods to evaluate the ability of a structure to sustain ice loads presents some opportunities, limitations and challenges. Until ice constitutive models suitable for integrated analyses are available, as well as test data to calibrate such models, the main options to evaluate the structure's ability to resist glacial ice impact are to analyse the structure for iceberg interaction using:

- Local deformation analysis, only allowing small deformations ("strength design") combined with pressure area models describing the iceberg resistance, preferably with an associated area-penetration model;
- Impact analyses modelling the iceberg as a rigid object ("ductile design"); and
- A combination of the above methods used in a simplified "shared energy approach".

The two first methods are simplifications and assume that the structure and ice responses to the collision can be treated independently. When 'strength design' is the objective, simulating the ice load using pressure as a function of time is believed to be a good approximation. On the other hand, the impact with a rigid iceberg is a good representation for a 'ductile design' describing the maximum deformation to the structure that the iceberg can potentially (and conservatively) cause. A combination of these methods can be used in a simplified shared energy design approach when an area-penetration model is available for the ice. However, for large deformations, the accuracy of this approach is expected to be reduced due to the assumptions of the methods.

CONCLUDING REMARKS

A JIP was launched in 2018 to investigate issues related to design of moored floating platforms for operation in regions where icebergs occur. The project brought together stakeholders (owners/industry, designers/contractors, regulators and subject matter experts) with the objective to discuss relevant topics, learn about the various procedures involved in the process and to reach a general consensus on matters. As part of the project deliverables, a guidelines document was prepared describing a probabilistic methodology for determining design iceberg loads and how to assess the local response of the vessel hull to ensure it meets defined acceptance criteria.

The following concluding remarks are made.

- Models for global and local ice pressures, as described in ISO 19906:2019, are largely sufficient for design, although care should be taken to understand the nuances in the models. An approach for defining background pressures has also been developed using the existing local pressure-area model.

- Hydrodynamic interaction between an FPSO and glacial ice in the case of bow impact has been analyzed. Focus has been on hydrodynamic interaction forces, added mass and velocities of the two bodies just before impact. These results are important when addressing impact energy and are also important input to an analysis using ILS.
- Multiple impacts from a single iceberg (repeated impacts) are possible and should be considered in calculating design loads. It is expected to have a minimal effect (increase) on the design loads. Several different analyses have been completed to date, and work is ongoing at the time of publication.
- A procedure performing non-linear finite element of local hull response to verify that hull strengthening is sufficient was established.

In addition, there are plans to conduct laboratory experiments using the Rapid High-capacity Impact Test Apparatus (RHITA) load frame designed and installed at C-CORE (Macneill et al. 2023). The objective of the ice indentation tests is to investigate the distribution of ice pressures in the interaction zone. A specialized indentor is being designed and fabricated, and will be instrumented with the Tekscan pressure mapping system to measure the pressure distribution during an interaction event.

ACKNOWLEDGEMENTS

The authors would like to acknowledge funding from the JIP participants: Equinor, Aker Solutions, Cenovus, Kvaerner Canada, OilCo, Suncor, TechnipFMC; and from the Atlantic Canada Opportunities Agency (ACOA) and Department of Industry, Energy and Technology. They would also like to acknowledge significant initial input from Dr. Ian Jordaan.

REFERENCES

Bruce, J., R. Yulmetov, T. King, F. Ralph, and A. Younan. 2021. “Development of Iceberg Profiling Technology.” In *Proceedings of the 40th International Conference on Ocean, Offshore & Arctic Engineering*. Virtual Conference.

C-CORE, and DNV GL. 2017. “Improved Modelling of Iceberg Interaction with Floating Moored Structures: Project Summary.” Prepared for Statoil.

CODIE. 1995. “Canadian Offshore Design for Ice Environments.” Technical report prepared for Department of Industry, Trade and Technology. Ocean Engineering Research Center, Memorial University of Newfoundland.

CODIE II. 2003. “Canadian Offshore Design for Ice Environments - Phase II.” Technical report prepared for Department of Industry, Trade and Technology. Ocean Engineering Research Center, Memorial University of Newfoundland.

DNV. 2022. “Sesam User Manual – Wadam. Wave Analysis by Diffraction and Morison Theory.”

———. 2023. “Sesam User Manual – HydroD. Wave Load & Stability Analysis of Fixed and Floating Structures.”

Fuglem, M. 1997. “Decision-Making for Offshore Resource Development.” Ph.D. Thesis, St.

John’s, Canada: Memorial University of Newfoundland.
Fuglem, M., P. Stuckey, Y. Huang, J. Barrett, J. Thijssen, T. King, and F. Ralph. 2020. “Iceberg Disconnect Criteria for Floating Production Systems.” *Safety in Extreme Environments* 2 (1): 15–36. https://doi.org/10.1007/s42797-019-00007-4.
Fuglem, M., P. Stuckey, H. Shayanfar, F. Ralph, and J. Thijssen. 2023. “A Review of Global and Local Ice Pressure Models for Application to FPSO Design for Iceberg-Impacts.” In *Proceedings of 27th International Conference on Port and Ocean Engineering under Arctic Conditions*. Glasgow, United Kingdom.
Fuglem, M., and A. Younan. 2016. “A 3D Time-Domain Model for Iceberg Impacts with Offshore Platforms and Subsea Equipment.” In *Proceedings of Arctic Technology Conference*. St. John’s, Canada: OTC 27359.
Huang, Y., O. Shipilova, F. Mattson, and P. Stuckey. 2023. “Influence of Hydrodynamic Effects on Ice Design Loads for FPSOs in Regions with Icebergs.” In *Proceedings of 27th International Conference on Port and Ocean Engineering under Arctic Conditions*. Glasgow, United Kingdom.
Huynh, T.L., W.J. Clark, and D.C. Luther. 1997. “Structural Design of the Iceberg Resistant Hibernia Reinforced Concrete GBS.” In *Proceedings of Offshore Technology Conference*. Houston, USA: OTC 8398. https://doi.org/10.4043/8398-MS.
ISO. 2019. *ISO 19906 Petroleum and Natural Gas Industries - Arctic Offshore Structures*.
Jordaan, I. 2001. “Mechanics of Ice–Structure Interaction.” *Engineering Fracture Mechanics* 68 (17–18): 1923–60. https://doi.org/10.1016/S0013-7944(01)00032-7.
———. 2005. *Decisions under Uncertainty: Probabilistic Analysis for Engineering Decisions*. Cambridge: Cambridge University Press.
Jordaan, I., P. Stuckey, P. Liferov, and F. Ralph. 2014. “Global and Local Iceberg Loads for an Arctic Floater.” In *Proceedings of Arctic Technology Conference*. Houston, U.S.A.: OTC 24628. https://doi.org/10.4043/24628-MS.
Lever, J, D. Sen, and D Attwood. 1990. “The Influence of Shape on Iceberg Wave-Induced Velocity Statistics.” *Journal of Offshore Mechanics and Arctic Engineering* 112 (3): 263. https://doi.org/10.1115/1.2919865.
Macneill, A., J. Thijssen, T. King, and R. Ralph. 2023. “SIIBED: Rapid High Impact Test Apparatus (RHITA) for Modelling Ice Keel Interaction.” In *Proceedings of the Offshore Technology Conference*. Houston, USA: OTC 32241.
McKenna, R., F. Ralph, D. Power, I. Jordaan, and S. Churchill. 2003. “Modeling Ice Management Strategy.” In *Proceedings of the 17th International Conference on Port and Ocean Engineering Under Arctic Conditions (POAC03)*. Trondheim, Norway.
MSC. 2005. “MANICE: manual of standard procedures for observing and reporting ice conditions.” Meteorological Service of Canada. https://ec.gc.ca/glaces-ice/4FF82CBD-6D9E-45CB-8A55-C951F0563C35/MANICE.pdf.
Ralph, F., R. McKenna, G. Crocker, and K. Croasdale. 2004. “Pressure/Area Measurements from the Grappling Island Iceberg Impact Experiment.” In *Proceedings of the 17th IAHR International Symposium on Ice*. St. Petersburg, Russia.
Randell, C., R. Ralph, D. Power, and P. Stuckey. 2009. “Technological Advances to Assess, Manage and Reduce Ice Risk in Northern Developments.” In *Proceedings of Offshore Technology Conference*. Houston, U.S.A.: OTC 20264. https://doi.org/10.4043/20264-MS.
SINTEF Ocean. 2020. “SIMO 4.18.0 Theory Manual.”
Stuckey, P. 2008. “Drift Speed Distribution of Icebergs on the Grand Banks and Influence on Design Loads.” Master’s Thesis, St. John’s Canada: Memorial University of Newfoundland.

Stuckey, P., M. Fuglem, A. Younan, H. Shayanfar, Y. Huang, L. Liu, and T. King. 2021. “Iceberg Load Software Update Using 2019 Iceberg Profile Data Set.” In *Proceedings of the ASME 2021 40th International Conference on Ocean, Offshore and Arctic Engineering*. Vol. OMAE2021-63418. Virtual, Online.

Stuckey, P., F. Ralph, M. Fuglem, P. Moore, and I. Jordaan. 2009. “Probabilistic Iceberg Impact Loads on Floating Structures.” In *Proceedings of the 20th International Conference on Port and Ocean Engineering Under Arctic Conditions (POAC09)*. Luleå, Sweden.

Stuckey, P., A. Younan, G. Parr, M. Fuglem, and K. Habib. 2016. “Updating the Iceberg Load Software Using High Resolution Iceberg Profiles.” In *Arctic Technology Conference*. Offshore Technology Conference.

Widianto, W., J. Khalifa, A. Younan, T. Karlsson, P. Stuckey, and A. Gjorven. 2013. “Design of Hebron Gravity Based Structure for Iceberg Impact.” In *Proceedings of the 23rd International Offshore and Polar Engineering Conference*. Vol. 1. Anchorage, Alaska, USA.