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Influence of Hydrodynamic Effects on Ice Design Loads for FPSOs in Regions with Icebergs

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ABSTRACT

In determining ice strengthening required for moored floating structures operating in regions with icebergs present, the wave induced motions and added masses at impact, including hydrodynamic interaction are important. Present design approaches incorporate both simplified models, based on tank tests and diffraction analysis with idealized iceberg shapes, and computational fluid dynamics. For example, the Iceberg Load Software (ILS^{TM}), a probabilistic tool for determining design iceberg loads on fixed and floating structures, derives iceberg drift speeds and wave-induced motions from field observations as well as open water Response Amplitude Operators (RAOs) determined from tank tests of idealized iceberg shapes. Impact added masses are modelled based on an approximate open water solution for different body shapes. The impact motions and impact added masses could be improved by considering multi-body hydrodynamic interactions and more detailed consideration of iceberg shapes. To achieve this, a numerical study was conducted using diffraction-radiation analysis of three different sizes of idealized tabular and non-tabular iceberg shapes, both in open water and near an FPSO. The iceberg added masses and responses were determined for regular waves at relevant frequencies. This paper provides the results of the new study, and describes the methods to extrapolate the results to more general iceberg shapes. The new response models have been incorporated into the ILS^{TM}, and the influence of the new models on the abnormal-level loads and on FPSO disconnection criteria are presented.

KEY WORDS: Hydrodynamic; Iceberg Loads; Iceberg; FPSO; Serviceability.

INTRODUCTION

Design of structures in regions where icebergs are present is always a challenge, especially for floating concepts when an iceberg is present in high seas. Both the floating structure and the iceberg would move in six degrees of freedom, hence, the relative motions defining the added mass and velocity during impact are also dynamic. Iceberg design loads are currently estimated from simplified models in open water and there is limited research done for icebergs nearby floating structures. To understand the motions of both objects nearby each other is important for estimating iceberg loads. Better estimation of impact velocities, accounting for hydrodynamic damping and motions of the icebergs in vicinity of the floating structure would reduce uncertainty and conservatism associated with the loads and load effects.

The iceberg and the floater will mainly influence each other in the near-field region via disturbance of the wave field. The degree of such influence depends on relative sizes of the floating bodies. Sayeed (2017) and Sayeed et al. (2017) have shown that smaller icebergs tend to drift away from a large structure in moderate sea states. However, in higher sea states, small and moderate glacial ice may enter the near-field region with increased kinetic energy and impact with the floater. Hence, the hydrodynamics of the two objects must be solved as a multi-body problem for such considerations.

This paper focuses on studying the influence of hydrodynamic interaction between an iceberg and a generic ship-shape floating production storage and offloading (FPSO) unit on iceberg design loads. The effect of accommodating the updated response models (RAOs) into ILS^{TM} is demonstrated with case studies.

This paper is part of the series of study for guidance on FPSO design in regions with icebergs.

ICEBERG DESIGN LOADS

ISO 19906 (2019) provides guidance for estimating global and local ice design loads for the ultimate limit state (ULS) and abnormal limit state (ALS). Probabilistic methods, such as Monte-Carlo, can be used to estimate ice design loads, and are recommended in ISO 19906 (2019). Iceberg Load Software (ILS^{TM}) is one of the major tools that utilizes the Monte-Carlo method, which groups icebergs and environmental conditions by iceberg waterline length (L) and significant wave height (Hs). Therefore, to include wave-induced velocity, hydrodynamic response provided with RAOs and translated to significant response is required. Stuckey et al. Stuckey et al. (2008, 2016) have detailed the ILS^{TM} methodology as illustrated in Figure 1.

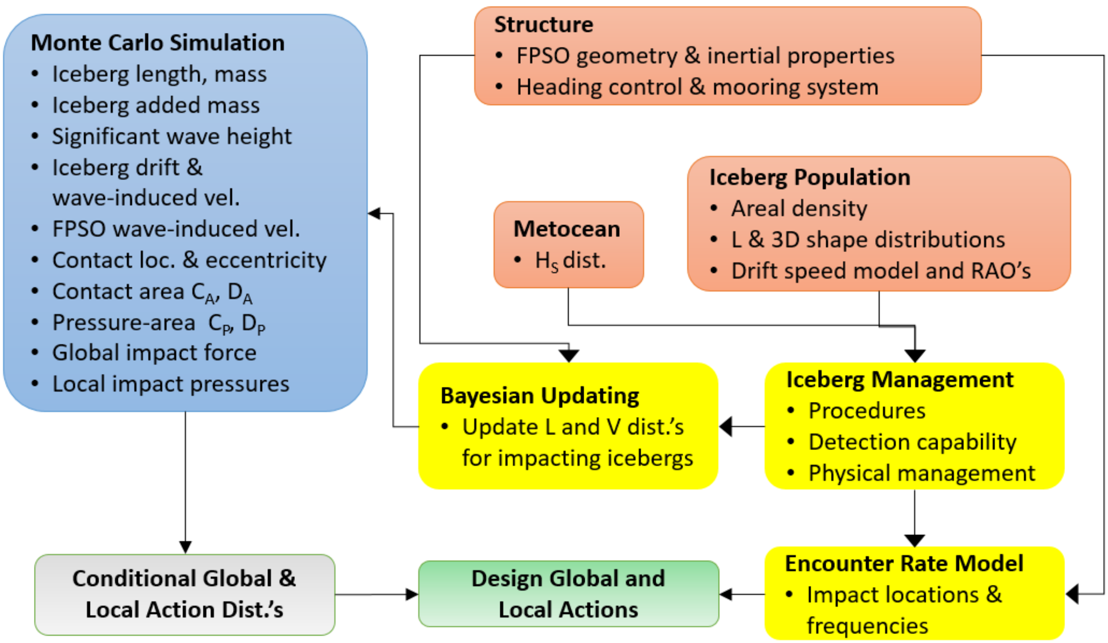

Figure 1. Schematic of ILS^{TM} methodology, after Stuckey et al. (2008, 2016)

ILS™ has been used to develop iceberg design loads on FPSOs for various projects (e.g., Bay du Nord, Wisting, White Rose and Terra Nova). In these studies, iceberg motions were modeled using idealized shapes in open water. A more comprehensive modeling approach has been carried out including the interactive motion between two bodies, the iceberg and FPSO for different iceberg shapes in different sea conditions.

WAVE INDUCED MOTION OF ICEBERG AND FLOATER

The hydrodynamic interaction between a generic FPSO and an iceberg is assessed in the frequency domain with the program Wadam from Sesam™ HydroD (DNV GL, 2017, 2018). Both single body (iceberg and FPSO far apart) and multi-body (iceberg and FPSO in close proximity) analyses are conducted for wave periods between 3 and 40 seconds. Both cases are solved within the assumption of potential flow. The viscous effects due to flow separation and skin friction drag are added as a percentage of the critical damping level.

The FPSO has an overall length of 305 m and displaced mass of 350,760 tonnes. Iceberg shapes resemble tabular and non-tabular iceberg according to the classification suggested in (White et al., 1980). Shapes in such classification are characterized by the ratio between representative horizontal and vertical dimensions. The shapes of the iceberg have a super-ellipsoidal geometrical form and are depicted in Figure 2. The standard linear potential flow solvers usually do not deal accurately with the large variation of the water plane area. In this study, the shape and size of the glacial ice are chosen in a way to avoid this complication. The key parameters of the icebergs considered as listed in Table 1. The super-ellipsoidal icebergs are tested in two orientation, 0° (head-on as show in Figure 2) and 45° (oriented by 45°).

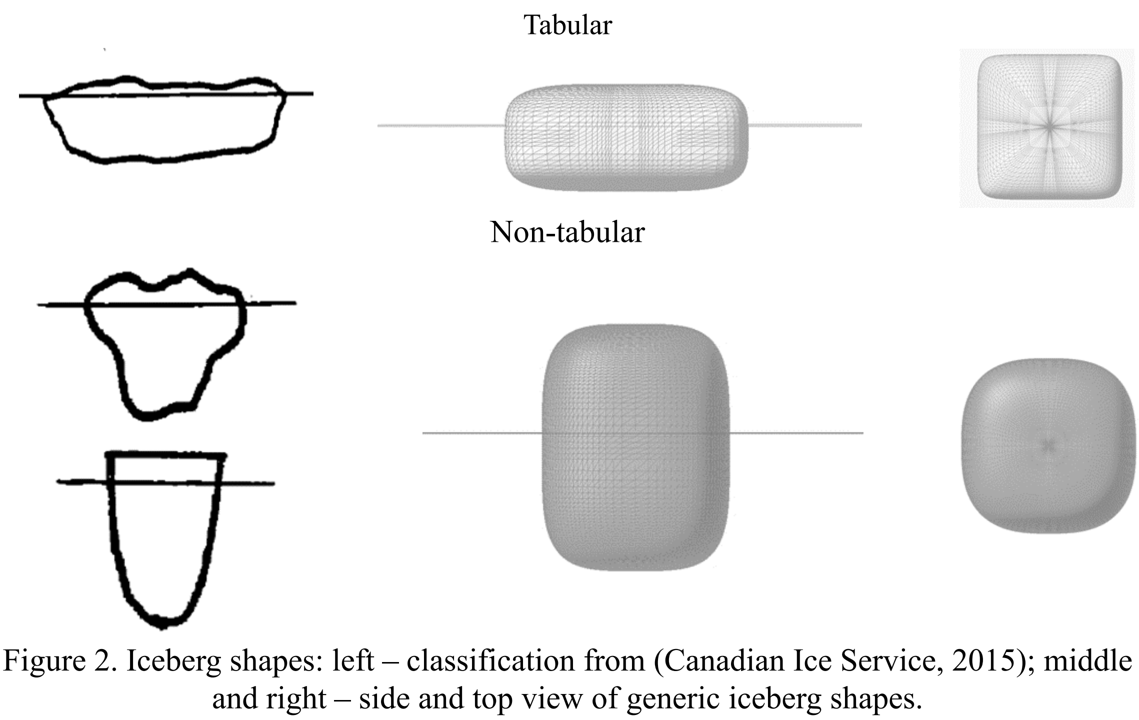

Figure 2. Iceberg shapes: left – classification from (Canadian Ice Service, 2015); middle and right – side and top view of generic iceberg shapes.

Table 1. Key parameters for super-ellipsoidal icebergs

Shape	Size*	Waterline Length (m)	Draft (m)	Mass (1000 tonnes)
Tabular	small iceberg	43	12	20
Tabular	medium iceberg	94	26	200
Tabular	large iceberg	130	36	538
Non-Tabular	small iceberg	32	23	20
Non-Tabular	medium iceberg	70	51	200
Non-Tabular	large iceberg	98	71	539

* Classification according to (Canadian Ice Service, 2015)

Figure 3 shows the surge RAOs for the FPSO and icebergs of different size from multi-body analysis in comparison with single-body (open water) analysis. The multi-body analysis has shown that the FPSO has the most significant effect on motions of the small iceberg. This is observed for both the tabular and non-tabular shapes. To be noted, the FPSO is not affected significantly by the presence of the iceberg; even large icebergs lead to only minor changes in the FPSO motions.

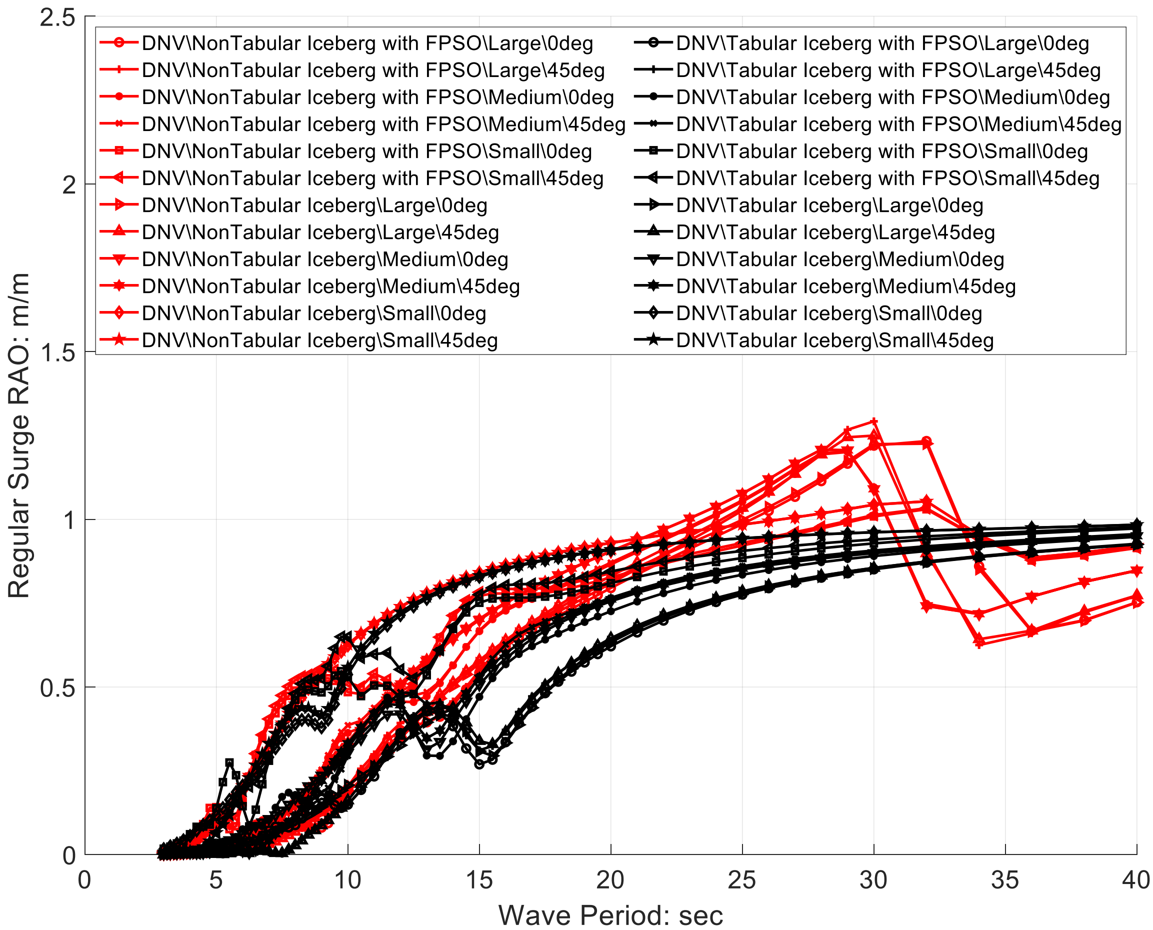

Figure 3. Regular surge RAOs of super-ellipsoidal icebergs.

The added mass in surge for all super-ellipsoidal iceberg shapes and sizes are summarized in Figure 4. Isaacson and McTaggart (1989) suggest using infinite-frequency added mass for short impact durations and zero-frequency added mass for longer impact durations.

The current added mass used in ILS™ are estimated from ellipsoids and vertical cylinders at zero-frequency for corresponding iceberg sizes. However, the new study of super-ellipsoidal icebergs on added mass at infinite-frequency will be incorporated into ILS™, considering most iceberg and floater impacts are short duration impacts. The effects of such change will be assessed.

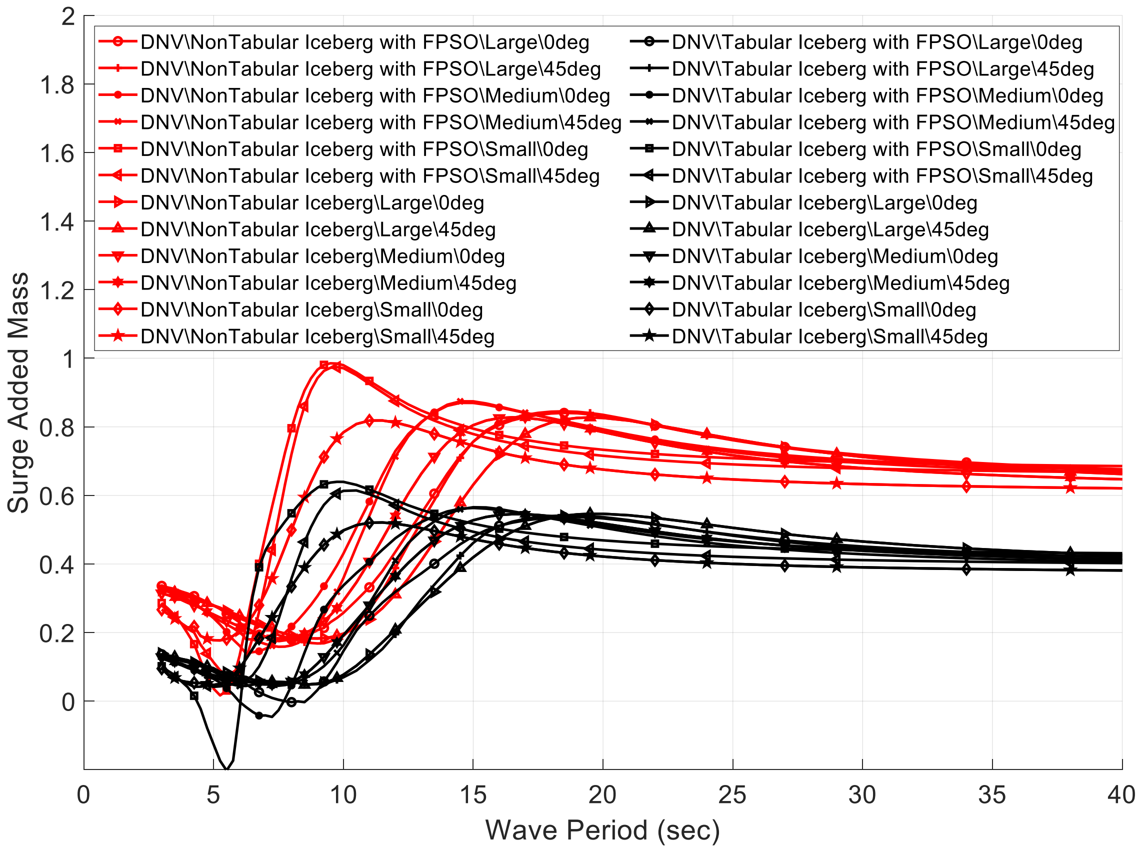

Figure 4. Surge added mass of super-ellipsoidal icebergs.

SIGNIFICANT RESPONSE

There is limited research on updating regular iceberg RAOs to iceberg significant response to waves. Lever et al. (1987, 1988a, 1988b, 1990a, 1990b) were the main references for previous ILS™ work. It will also be our main focus for this study.

The approach proposed by Lever et al. (1987, 1988b, 1990a, 1990b) was based on a JONSWAP (the Joint North Sea Wave Program) wave energy spectrum, $S_w(f)$, for the Hibernia area (i.e. spectra data curve fitted by (Hasselmann et al., 1973)), represented as

$$S_w(f) = \frac{A}{f^5} exp\left[-\frac{5}{4}\left(\frac{f_0}{f}\right)^4\right]\gamma^a \tag{1}$$

where,

$$a = exp[(f - f_0)^2/(2\sigma^2 f_0^2)]$$

$$\sigma = 0.07 \; for \; f \leq f_0$$

$$\sigma = 0.09 \; for \; f > f_0$$

$$A = 5H_s^2 f_0^4/(16\gamma^{1/3}) \; for \; 1 < \gamma < 4$$

Here, f is the wave frequency, H_s is the significant wave height. f_0 is the peak frequency equal to $1/T_p$ with $T_P = 4.43\, H_s^{1/2}$. The peak performance factor $\gamma = 2.2$ is based on LeBlond et al. (1982). The peak frequency factor, σ, was an independent value of fetch-limited wave.

Based on Lever et al. (1987, 1988a, 1988b, 1990a, 1990b), LeBlond et al. (1982) and Sen (1983), the regular RAO can be converted to dimensionless irregular significant velocity response, $\widehat{V_s}$, specifically for surge that the current study is focused on. The following equations are taken from the above references directly.

$$\widehat{V_s} = \frac{V_s}{\pi H_s/T_P} \tag{2}$$

$$V_s = 2(m_0)^{1/2} \tag{3}$$

$$m_0 = \int_0^\infty S_v(f)\, df \tag{4}$$

$$S_v(f) = 4\pi^2 f^2 S_w(f) \cdot H^2(f) \tag{5}$$

The velocity response spectra $S_v(f)$ with respect to the JONSWAP spectrum $S_w(f)$, Eq. **Error! Reference source not found.**, is defined as Eq. (5), where $H(f)$ is the RAO for motion in the desired (surge) mode. Then, the significant velocity in a given mode can be estimated and made dimensionless as in Eq. (2).

With the data and method from Lever et al. (1987, 1988a, 1988b, 1990a, 1990b), the derived dimensionless irregular significant velocity response for the iceberg with associated waterline length and significant wave height are shown in Figure 5. The digitized values from Lever et al. (1987, 1988a, 1988b, 1990a, 1990b) are also recreated with above equations and illustrated in Figure 5.

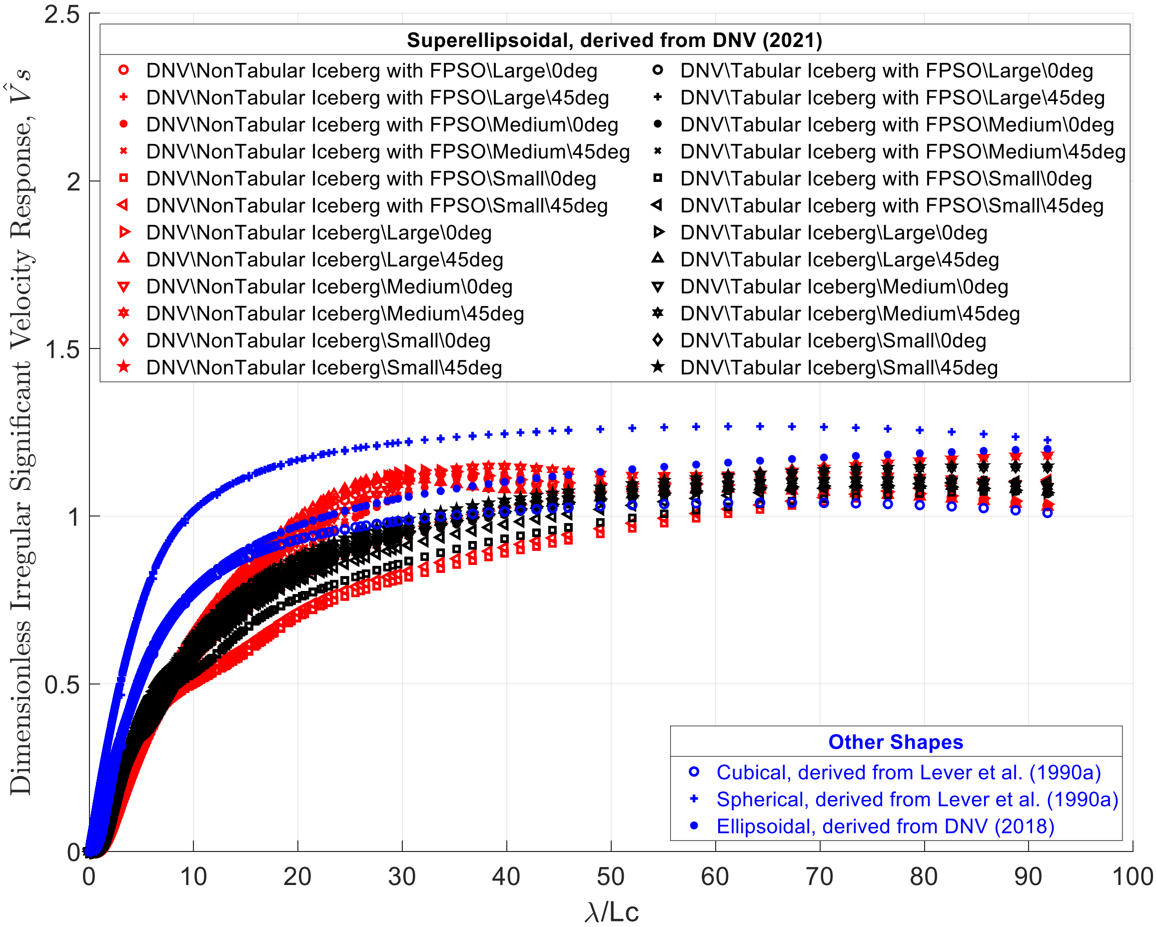

Figure 5. Summarized dimensionless irregular significant velocity responses in surge as function of wavelength scaled with characteristic iceberg dimensions

CASE STUDY

Design Iceberg Loads

The ILS^{TM} was used to perform a sensitivity analysis to assess the effect of the hydrodynamic interaction (specifically, the added mass and significant response velocity in surge) on the design iceberg loads. Comparison was made for the abnormal-level load and contributing impact velocity and kinetic energy. The following cases were assessed:

- *No Surge Response Case* – the iceberg impact velocity is set equal to the iceberg drift speed (i.e., there is no wave-induced surge component included) and the added mass model is based on an approximate open water solution for different body shapes.
- *Original ILS^{TM} Case* – the *No Surge Response Case* with wave-induced surge component included. This case will highlight the influence of the wave-induced surge velocity component.
- *Super-ellipsoidal Open Water Case* - modeled significant response and added mass in surge are taken from different super-ellipsoidal icebergs in open water;
- *Generic Open Water Case* - surge response and added mass are randomly selected from

spherical and super-ellipsoidal icebergs in open water; and

- *Super-ellipsoidal Multi-body Case* - modeled significant response and added mass in surge from super-ellipsoidal icebergs with the FPSO in close vicinity.

Metocean and iceberg conditions was based on typical Grand Banks data. Iceberg detection, management and FPSO disconnection was included. A generic mooring system (i.e., force-offset curve) was assumed. The simulation results are shown in Table 2.

Table 2. ILS™ outputs with different significant response and added mass models.

Parameters	No Surge Response	Original ILS™	Super-ellipsoidal Open Water	Generic Open Water	Super-ellipsoidal Multi-body
ALS Loads (MN)	13.9	20.0	18.4	18.1	17.7
Contributing Impact Speed (m/s)	0.56	0.73	0.55	0.62	0.53
Contributing Kinetic Energy (MJ)	10	17	11	11	11

The Original ILS™ Case illustrates the conservatism in the current ILS™. All new models to estimate significant response have shown 8% to 12% reductions in iceberg design loads when compared to the Original ILS™ Case. The contributing impact velocities are reduced between 14% to 27% and contributing kinetic energy reduced by 35%. These values might be changed for different examples, but the results have shown the reduction in iceberg design loads by incorporating a more comprehensive analysis of hydrodynamic interaction effects.

FPSO Disconnection Criteria

While an FPSO may have disconnect capability, if it can be shown that an impact from a very small iceberg in a mild sea state results in only minor deformation (i.e. local denting) that doesn't require repair, then the FPSO can remain on location and avoid disconnecting.

Operational criteria are required for such decisions. This requires determining the magnitude of local ice pressures which can be applied to the hull to ensure the deformation does not exceed some specified acceptance criteria. These local pressures can be represented as a function of iceberg waterline length and significant wave height. a single decision support curve can be defined to identify combinations of iceberg waterline length and significant wave height that may exceed the serviceability capacity of the FPSO hull.

A sensitivity analysis was performed using the five cases defined above. For this analysis, the hull serviceability capacity was assumed to be 3.2 MPa for all structural areas; actual hull capacity is determined using nonlinear finite element analysis. The local ice pressures were modelled based on the Terry Fox ship ram database. Simulations were performed using the ILS™ and the results are shown in Figure 6. Each curve presented in Figure 6 defines disconnect criteria for the modelled FPSO. Using the figure, any combination of L and H_S occurring below this line will result in local ice pressures which is less than the 10^{-1} annual probability of exceedance serviceability criteria; for these cases the FPSO does not have to disconnect to avoid the impact. For combinations of L and H_S occurring above the line, the local pressures will exceed the 10^{-1} annual probability of exceedance serviceability criteria and the FPSO must disconnect to avoid potential hull deformations which would exceed the acceptable level and require repairs.

The No Surge Response Case and the Original ILS™ Case show similar disconnection criteria in low sea states, but the Original ILS™ Case allows for slightly larger icebergs in higher sea states. Including the added mass and significant surge response based on the super-ellipsoidal icebergs, the disconnection criteria curves shift upwards, with the multi-body case showing the largest increase. Hence, the disconnection criterion shows another aspect of the importance of hydrodynamic effects for designing FPSOs in regions with icebergs.

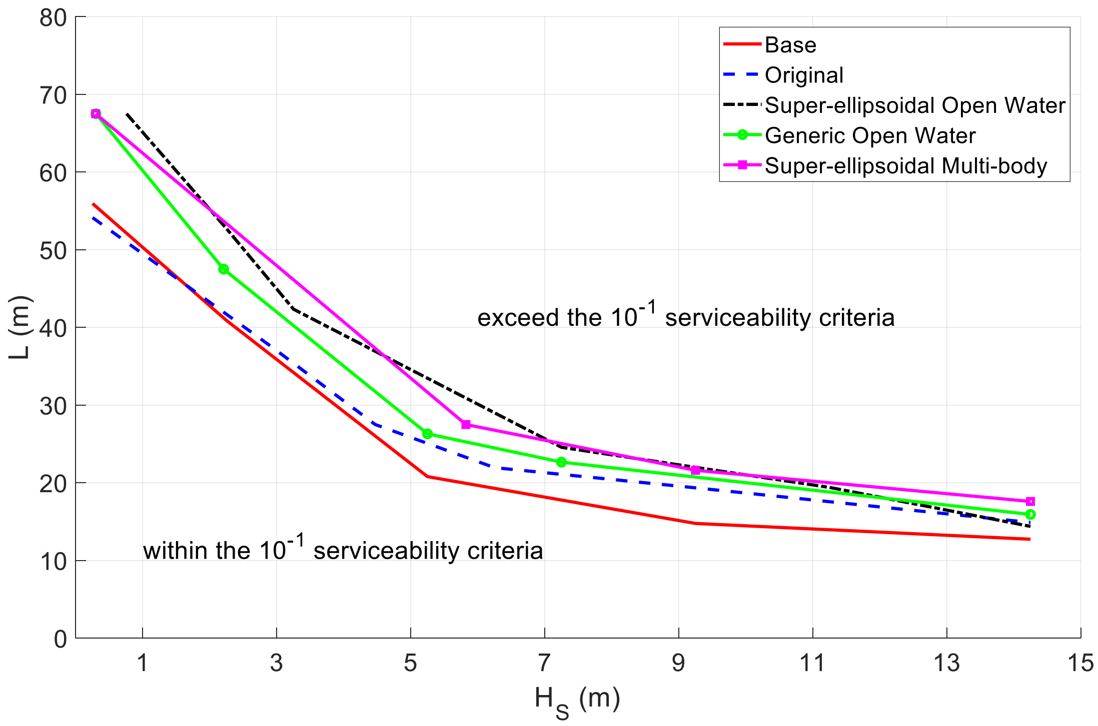

Figure 6. FPSO Disconnection Criteria Comparison
i.e. L-Hs scenarios above each curve exceed the 10^{-1} serviceability criteria.

CONCLUSION

The study has shown that hydrodynamic interaction between an iceberg and a FPSO has a significant effect on iceberg design loads. However, the degree of influence varies depending on hydrodynamic models utilized. Currently, there are only limited generic iceberg shapes and sizes are considered with or without FPSOs nearby. There are limited data to state which model to be considered for future design. Larger variety of iceberg shapes should be considered for further improvement of modeling and possibly reducing conservatism in iceberg design loads.

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