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Assessment of the Wave-Iceberg Load Combination Factor

Ricardo Foschi and Michael Isaacson*
Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada

and

Norman Allyn and Ibrahim Saudy
Westmar Consultants Inc., North Vancouver, B.C., Canada

ABSTRACT

The present paper describes an extension to a recent study (Foschi et al., 1996), which was undertaken to determine the appropriateness of the recommended value of the load combination factor relating to the combined effects of wave and iceberg loads, as described in the Canadian Standards Association (1992) code for the design and construction of fixed offshore structures. The study examines the sensitivity of the load combination factor to various iceberg and wave parameters typical of three sites off the East Coast of Newfoundland. The methodology is based on a numerical analysis in which loads due to waves alone, an iceberg alone, and an iceberg and waves in combination, have been calculated for a range of iceberg and wave parameters, with the results applied to a first-order reliability analysis to study force levels corresponding to specified annual exceedence probabilities. The results indicate that the load combination factor is most sensitive to the wave angle relative to the current direction, and to the wave climate during the iceberg season — therefore, the load combination factor is site dependent. A load combination factor has been calculated conservatively as 0.20, applicable throughout the range of situations considered. This compares with the Code values of 0.8 or 0.4, for icebergs and waves which are taken to be stochastically dependent or independent, respectively.

INTRODUCTION

The selection of suitable environmental loads and load events is of critical importance in the design of offshore structures intended for operation in extreme environments. Such loads may include those due to wind, waves, earthquakes, ice floes and iceberg collisions. The CSA Offshore Structures Code CAN/CSA-S471-92 (S471) (Canadian Standards Association, 1992) describes the use of such loads in offshore design, and indicates the use of probabilistic methods on which the selection of load events and design loads should be based. The Code has been subjected to a comprehensive verification process, and this has identified several issues which warrant further study. One of these is an assessment of the combined effects of wave and iceberg collision loading. At present, this combination is treated by the use of a load combination factor which is used to determine a design value for the load due to a companion frequent environmental process (waves) acting in combination with a rare environmental event (iceberg collision). For combined iceberg-wave loading, the load combination factor γ is defined in the Code as follows:

$$E = E_r + \gamma E_f \tag{1}$$

where E is the load due to an iceberg with waves with an annual exceedence probability of 10^{-4}, E_r is the iceberg-alone load with an annual exceedence probability of 10^{-4}, and E_r is the wave load with an annual exceedence probability of 10^{-2}. Suitable values of γ are specified in the Code. The definition of load in Eq. 1 depends on the limit state under consideration, and includes the maximum iceberg load (in the presence of waves), applicable to a local damage limit state; and the maximum combined wave-iceberg load, applicable to a global sliding limit state.

Wave-structure interactions (in the absence of icebergs) and iceberg-structure interactions (in the absence of waves) have been studied extensively in the past (e.g. Sarpkaya and Isaacson, 1981, and Cammaert and Muggeridge, 1988, respectively), whereas the case of waves and an iceberg acting simultaneously on a fixed offshore structure has not been studied to the same extent. Isaacson (1987) considered the effect of waves on an iceberg up to the instant of impact, and described wave effects on the iceberg velocity and effective mass at the time of impact. Related studies include Lever, Attwood and Sen (1988), Lever, Colbourne and Mak (1990), and Isaacson and McTaggart (1990). In a recent study, Foschi et al. (1996) and Foschi and Isaacson (1996) described a numerical analysis in which loads due to waves alone, an iceberg alone, and an iceberg and waves in combination have been calculated for a range of iceberg and wave parameters. The corresponding results were applied to a probabilistic study of the load event using the first-order reliability method (FORM), with the objective of determining suitable values of the load combination factor.

In the present study, the method of Foschi et al. (1996) is extended to examine the sensitivity of the load combination factor γ to wave and iceberg parameters typical of three sites off the East Coast of Newfoundland. Loads due to waves alone, an iceberg alone, and an iceberg and waves in combination have been calculated for a range of iceberg and wave parameters. These results have been used to develop expressions for wave and iceberg loads which are then used in a probabilistic study of the load event.

*ISOPE Member.

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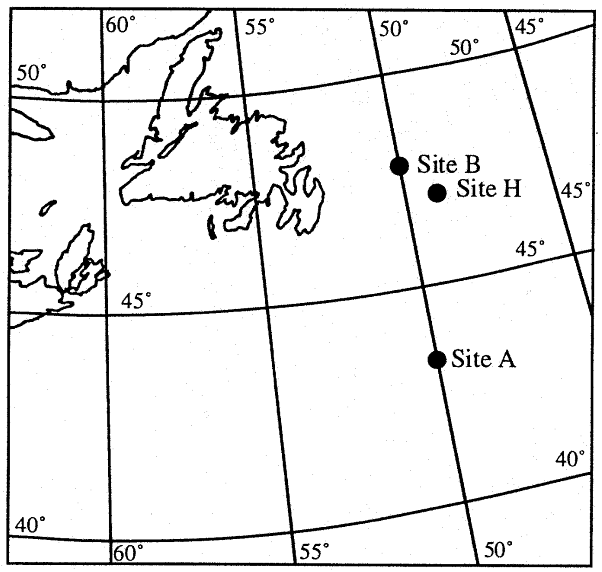

Fig. 1 Location sketch

The force exceedence probability is studied using FORM. For a given structure size, the influence of water depth, iceberg arrival rate, wave climate, wave direction and mean current on the loads and on the load combination factor are examined. The study thereby makes recommendations for the load combination factor applicable to combined wave-iceberg loading under fairly general conditions.

In practice, the predominant wave direction may differ from the direction of iceberg motion, so that the effect of an oblique wave direction should be taken into account when calculating the combined wave and iceberg loads. In this work, the wave-plus-iceberg load results for various wave directions are considered and a parametric fit is made to the corresponding results. Different values of the relative angle between the incident wave direction and the iceberg trajectory are considered. In addition, a wave climate description based on the use of a specified recording interval is adopted. Finally, it is recognized that there is a seasonal difference between the annual wave climate and the wave climate occurring during the iceberg season.

The structure is taken as a fixed vertical circular cylinder 100 m in diameter and extending from the seabed to above the water surface. Water depths, iceberg conditions and wave conditions corresponding approximately to three sites off the East Coast of Newfoundland have been selected. The three sites are indicated in Fig. 1, and are denoted Sites H, A and B. Site H corresponds to the location of the Hibernia platform; Site A is at the tail of the Grand Banks in 60-m water depth and located at 50° West, 43° 20' North; and Site B is near the north end of the Grand Banks in 100-m water depth and located at 50° West, 47° 47' North.

ENVIRONMENTAL CONDITIONS

In this study, data were required for both waves and icebergs for the three sites under consideration. Statistical distributions for the waves and the icebergs for the Grand Banks off the coast of Newfoundland are taken from Fuglem et. al. (1996), Jordaan (1996) and MacLaren Plansearch (1991), and are discussed below.

Icebergs

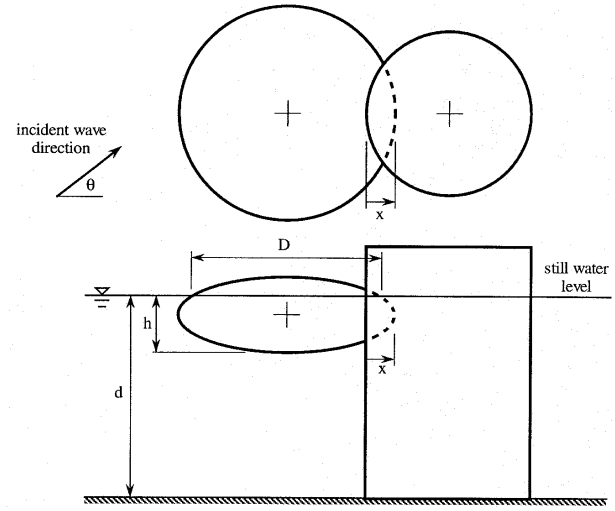

Fig. 2 Definition sketch

Site	Depth (m)	Max width (m)	Length parameter L		Draft	
		Mean	Mean (m)	S.D. (m)	Mean (m)	S.D. (m)
A	60	80.97	61.75	13.43	50.47	7.27
H	80	110.90	88.50	24.07	63.09	11.37
B	100	131.23	107.19	35.60	70.89	15.41

Note: Maximum draft equals water depth.
Table 1 Summary of iceberg statistics at three sites

Following Det Norske Veritas (1988), each iceberg is assumed to be circular in plan and ellipsoidal in elevation as shown in Fig. 2. From statistical data for the Grand Banks off the coast of Newfoundland, all iceberg dimensions are expressed in terms of a single random variable L which is represented by a Gamma probability distribution. In particular, the iceberg diameter at the waterline D, the iceberg radius R, and the iceberg draft h may readily be related to L. However, icebergs capable of colliding must have a draft smaller than the water depth, and consequently h has been fitted by a suitable Beta distribution ranging from a minimum of 0 m to a maximum equal to the water depth. Statistics for each site are shown in Table 1. The table is based on an iceberg waterline length with a mean of 120 m and a standard deviation of 50 m, as provided by Jordaan (1996).

Waves

Distribution of significant wave height. A simple representation of the long-term probability distribution of wave conditions is initially required. Various such representations are possible (e.g. Sarpkaya and Isaacson, 1981), and in the present study the significant wave height H_s based on a specified recording interval τ, is assumed to obey an Extreme Type I ("Gumbel") probability distribution as follows:

$$P(H_s) = \exp[-\exp(-a(H_s - b))] \qquad (2)$$

where $P()$ is the cumulative probability, and a and b are constants of the distribution. The constants a and b may be related to characteristic values of the distribution, such as the mean and standard deviation, or the slope and intercept of a straight line plot of the distribution.

Significant wave heights during iceberg season. Since iceberg impacts are not expected to occur year-round, it is not appropriate to consider the probability distribution of wave heights on the basis of annual data, but rather to use conditions corresponding to a typical iceberg season. This distinction was considered by Fuglem et. al. (1996), who provided information on the distribution of significant wave heights near site H during the iceberg season. These results have been fitted by Eq. 2 and the resulting wave height distribution, representative of an iceberg season taken to last for four months, has been obtained. In order to extend this distribution to the other two sites, the relevant Wave Climate Atlas (MacLaren Plansearch, 1991) has been used to obtain the relative wave heights at the appropriate time of year for zones in which sites A, B and H are located.

Distribution of wave period. A suitable description of the peak wave period is also required and is developed by adopting a simple assumption for the relationship between the peak wave period and significant wave height. In fact, it is assumed that T is fully correlated with the significant wave height and is given by:

$$T = 4.432\sqrt{H_s} \tag{3}$$

where T is the peak period in seconds and H_s is the significant wave height in metres. This relation has been found to be suitable for conditions in Canadian Atlantic waters (Neu, 1982).

Distribution of annual maximum significant wave height. The corresponding probability distribution of the annual maximum significant wave height, denoted $P_a(H_s)$, is required and can be obtained from the distribution $P(H_s)$ given in Eq. 2 (based on a recording interval τ), by raising the latter to the power of N, where N is the number of such intervals per year. Two values for N are considered; one for the whole year [$N = 365 \times 24/\tau$], and the other for a 4-month ice season [$N = 365 \times 24 / (3 \times \tau)$], where τ is in hours. It can thereby be shown that the probability distribution of annual maximum heights $P_a(H_s)$ is also given by Eq. 2, except that the constant b is replaced by $b + \ln(N)/a$.

Short-term distribution of individual wave heights. Individual wave heights within a sea state (during which Hs is taken as constant) are assumed to possess a Rayleigh distribution. The distribution of maximum individual wave height within a sea state is obtained by taking into account that there are $(3600 \times \tau / T)$ wave in the record of length τ. The distribution of annual maximum individual wave height is obtained by considering the maximum within the anual maximum sea state.

RELIABILITY MODEL

Probabilistic analyses have previously been used in offshore engineering problems (e.g. Fuglem et. al., 1991; Det Norske Veritas, 1988; and Maes and Jordaan, 1984), including the calibration of the Canadian Code for offshore structures (e.g. Maes, 1986).

The estimation of conditional probabilities associated with a load event is conducted here using a computer program RELAN (Foschi et. al., 1990), which implements standard FORM and SORM algorithms (First and Second Order Reliability Methods) to calculate the probability that a "performance function" G of the vector of a set of random variables $\mathbf{x}$ is negative. In order to equate this result to a force exceedence level in the present context, the function $G(\mathbf{x})$ is written as follows:

$$G(\mathbf{x}) = F - F_M(\mathbf{x})R_{n1} \tag{4}$$

where $F_M(\mathbf{x})$ is the maximum force developed on the structure due to waves, iceberg impact, or waves and iceberg impact in combination, as appropriate; $\mathbf{x}$ denotes a set of specified random variables characterizing the structure, the iceberg and the wave conditions; F is the sliding or local failure load level; and R_{n1} is a random variable associated with model inaccuracy in the calculation of F_M (Bea, 1992).

The probability of the event $G < 0$ corresponds to the probability that the load level F is exceeded. Three specific programs were extended for this study. The program ICELOAD calculates forces due to iceberg collisions only; the program WLOAD calculates forces due to waves alone; and the program ICEWLOAD calculates forces due to an iceberg collision in the presence of waves.

In the case of an iceberg impact, with or without waves present, the force exceedence probability is first obtained conditional on the occurrence of an impact. In such a case, the programs allow for the estimation of the corresponding annual risk, denoted P_a, using the hypothesis that the events (i.e., iceberg impacts) follow a Poisson pulse process with a given mean rate of annual occurrence (events per year), denoted ρ. Thus, if the conditional exceedence probability of the event is P_e, the annual risk is given as:

$$P_a = 1 - \exp(-\rho P_e) \tag{5}$$

Collision arrival rates ρ have been calculated for combinations of three mean currents and the three water depths at the sites. The corresponding iceberg densities ν (icebergs / degree square) and arrival rates are shown in Table 2. In each of the three cases, the maximum force F_M developed during the event requires an appropriate mechanics model for its calculation. The approach that has been used to assess the loads due to waves alone, an iceberg alone, and waves and an iceberg acting in combination are described in detail by Foschi et al. (1996) and summarized by Foschi and Isaacson (1996) for the case of wave directions and iceberg trajectories which are colinear. For convenience, a brief summary is given here.

WAVE FORCE ON STRUCTURE

Regular Wave Forces

The loads due to regular waves interacting with a structure (in the absence of an iceberg) are obtained on the basis of linear diffraction theory. Results have been obtained using a computer program WELSAS, which is based on three-dimensional linear diffraction theory using a boundary element method (e.g. Sarpkaya and Isaacson, 1981). The program involves a discretization of the submerged structure surface into quadrilateral elements, and employs a suitable Green's function. Although a closed-form solution is available for a vertical circular cylinder (e.g. Sarpkaya and Isaacson, 1981), WELSAS is used for the case of waves alone, since it is needed for the subsequent case of combined

Mean current (m/s)	Site A (d = 60 m, n = 0.31)	Site H (d = 80 m, n = 0.74)	Site B (d = 100 m, n = 0.74)
0.14	0.03	0.08	0.09
0.28	0.06	0.16	0.18
0.42	0.09	0.24	0.27

Table 2 Collision arrival rates at three sites for various mean current values

wave-iceberg loading. For regular waves of height H and period T, the wave force on the structure varies sinusoidally in time with an amplitude F proportional to H. Since the wave forces are ultimately required for application in a probabilistic model, a simple expression has been fitted to numerical results obtained for a range of wave periods and for the three water depths.

Random Wave Forces

Loads due to random waves may be obtained as a direct extension to the case of regular waves. Since linear diffraction theory is used to calculate wave loads, the wave force amplitude is proportional to the wave height, so that the force amplitude F is taken as random with a Rayleigh probability distribution and with a significant value that can be obtained by applying diffraction theory to a regular wave train of height H_s.

ICEBERG FORCE ON STRUCTURE

Attention is now directed to the maximum force exerted on the structure due to an iceberg impact in the absence of waves. In this context, Sanderson (1988) provides a suitable background to ice mechanics and risks to offshore structures.

Ice Crushing Pressure

During the process of ice crushing against the structure, the area of contact A is continuously changing and the pressure p required to crush the ice depends on A. On the basis of previous studies and data, it is assumed that the crushing pressure p has a lognormal distribution, with mean μ_p and coefficient of variation $V_p = 0.50$. The size effect for the mean pressure μ_p is represented by:

$$\mu_p = Max.\begin{cases} \dfrac{9.0}{\sqrt{A}} \\ p_o \end{cases} \tag{6}$$

where A is in m^2 and μ_p in MPa. p_o represents a lower bound for μ_p which appears in observed data. In contrast to the earlier approach of Foschi et. al. (1996) in which specified values of p_o were used, p_o is instead represented here as a random variable to account for the uncertainty in ice crushing pressure for large areas A. Thus, p_o has been taken to possess a normal distribution with a mean $\mu_{po} = 4$ MPa and a standard deviation $\sigma_{po} = 1$ MPa.

Force-Penetration Relationship

For a given iceberg penetration x due to ice crushing, the iceberg force $F(x)$ acting on the structure can be calculated from an integration of the crushing pressure p over the area of contact $A(x)$ on the basis of the specific geometry assumed here and assuming that the pressure is uniformly distributed over the area. In general, it is found that, for the cases of interest, the iceberg will be stopped after a few metres of penetration, allowing for a linearization of the force-penetration relationship.

Maximum Iceberg Force

In calm water, the calculation of the maximum iceberg force F_M is implemented through consideration of an energy balance, which requires the initial kinetic energy of the iceberg to be equated to the energy dissipated through ice crushing up to the time the iceberg is brought to rest. Thus:

$$\frac{1}{2}M(1+C_a)V^2 = \int_0^{x_m} F(x)dx \tag{7}$$

where M is the iceberg mass, C_a is an added mass coefficient, and V is the impact velocity. The right-hand side corresponds to the energy dissipated through ice crushing up to a penetration x_m, obtained from the force-penetration relationship. An additional term on the right-hand side, corresponding to the energy dissipated through local structural damage, was considered by Foschi et. al. (1996), but is omitted here. Given the iceberg geometry, its impact velocity, added mass, and the crushing pressure parameters, Eq. 7 can be solved to obtain x_m. Once this is found, the maximum force F_M is obtained from the force-penetration relationship.

Impact Velocity

As indicated in Eq. 7, the iceberg's impact velocity V influences the magnitude of the maximum iceberg force on the structure. V is generally influenced by both the prevailing current U and waves. However, in calm water (iceberg alone, no waves), the impact velocity V is taken to be equal to the current velocity U. This approximation is only needed with respect to the statistical descriptions of V and U, and is reasonably consistent with dynamic models of iceberg drift (e.g. El-Tahan et al., 1986, and Isaacson, 1988) when applied in the absence of waves and wind. Following data from Det Norske Veritas (1988), the current U is assumed to possess a lognormal distribution. Three mean values for U are considered here: 0.14, 0.28 and 0.42 m/s, with corresponding standard deviations of 0.1, 0.2 and 0.3 m/s.

Added Mass

The added-mass coefficient at impact, C_a, needed in Eq. 7, is determined by solving the boundary value problem corresponding to an iceberg oscillating in otherwise still water. A description of the calculation procedure has been given by Isaacson and Cheung (1988). The added-mass coefficient depends on the submerged geometry of the iceberg and of any neighbouring structure (and thus it is a function of the iceberg distance from any such structure), the water depth and the oscillation frequency. The zero-frequency added-mass coefficient is suitable in the present context and has been estimated for a range of iceberg parameters, both in open water and when in contact with the structure. However, for the range of iceberg sizes of interest, the added mass is not strongly influenced by proximity to the structure. The numerical results have been used to develop a simple expression for the added-mass coefficient in terms of D/d and h/d for application to the probabilistic model.

Eccentric Collisions

The preceding description of the force-penetration relationship and the associated maximum force on the structure is based on the assumption of a head-on collision, whereas in practice an eccentric collision is likely to occur. In order to account for this possibility, the maximum force F_M calculated in the manner described above is multiplied by an eccentricity reduction factor $K_e \le 1$. Data from Salvalaggio and Rojansky (1986) have been utilized to develop a suitable probability distribution of K_e, such that K_e varies from 1 for a head-on collision, to 0 in the limit of the iceberg just making glancing contact with the structure.

Modifications to Probability Distributions for *U* and *L*

Finally, it is noted that available statistics for U and L correspond to all icebergs in open water. However, these differ from the corresponding statistics for impacting icebergs, since an iceberg's speed and size influence its probability of collision with the structure. Sanderson (1988) has investigated this difference and has shown that the speed and size probability distributions for colliding icebergs can be obtained as modifications of the corresponding distributions of all icebergs in open water. These modifications skew the original distributions so as to increase the chances of collision of bigger and faster icebergs.

COMBINED WAVE AND ICEBERG FORCES ON STRUCTURE

Attention is now given to an iceberg collision in the presence of waves. The preceding descriptions of iceberg shape and size, crushing pressure, and iceberg added mass continue to apply. However, the maximum iceberg force on the structure is altered, partly because the iceberg impact velocity is changed, and partly because the wave force on the iceberg influences the iceberg force on the structure. Also the maximum combined force on the structure, if required, should also account for the wave force which now acts on the structure. Furthermore, the description of wave parameters must now reflect the sea state at the moment of collision, so that more commonly occurring wave conditions should be accounted for, rather than wave conditions corresponding to annual maxima as is used in the case of waves alone. Finally, the influence of waves which are not colinear with the iceberg trajectory should be accounted for. These various aspects are now considered.

Wave Parameters

The description of waves under more commonly occurring conditions during which an iceberg impact occurs has already been summarized. The corresponding probability distribution of the significant wave height H_s, based on a recording interval of several hours, is assumed to be given by Eq. 2. As already indicated, the corresponding wave period is assumed to be proportional to $H_s^{1/2}$.

Impact Velocity

The impact velocity is influenced by the presence of waves, and so is no longer taken to be equal to the current U. A simple formulation for the iceberg impact velocity V may be developed by taking V to be proportional to the iceberg drift velocity in open water, denoted V_o, and adopting a suitable expression for the latter. Following Isaacson (1988), an expression for V_o may be developed by equating the wave drift force to the current drag, taking the wave drift force coefficient to be proportional to D/L (see Isaacson, 1988), where L is the wave length, and taking T to be proportional to $H_s^{1/2}$. When the wave direction and the iceberg trajectory are colinear, the above approach leads to $V = U+V_r$, where V_r is the iceberg velocity relative to the current, given by $V_r = \alpha g T\,(D/h)^{1/2}$, where α is a constant and g is the gravitational constant. The value of the constant α has been estimated by examining previous results and data for the open water velocity V_o (e.g. Lever and Sen, 1987); and using a numerical model to relate the impact velocity V to the open-water velocity V_o. Thus, a wave diffraction-radiation analysis has been carried out for a series of conditions corresponding to the iceberg approaching the structure, using an extension to the computer program WELSAS (see Isaacson, 1987). The foregoing procedure has indicated that $\alpha = 0.003$ should be suitable. When the wave direction makes an angle θ with the iceberg trajectory (see Fig. 2), an extension to the above approach yields instead:

$$V = V_r\cos\theta + \sqrt{U^2 - V_r^2\sin 2\theta} \tag{8}$$

with V_r given as before.

Wave Force on Iceberg

The force due to waves on the iceberg is now required in order to treat the iceberg's equations of motion, and this must account for the presence of the structure. As a reasonable simplification to the problem, only the equation of motion of the iceberg in the x direction is considered, and the iceberg's transverse (y-ward) and rotational (yaw) motions are not treated. Thus, only the wave force in the in-line (x-ward) direction, denoted $F_{wx}^{(i)}$, is used and the force in the transverse (y-ward) direction is not needed. This wave force component, which is oscillatory, is calculated by treating the wave diffraction problem for the combined submerged surface of the iceberg in contact with the structure with a pressure integration over the iceberg surface only used to provide the wave force on the iceberg. The force amplitude and phase angle have been calculated for the three water depths and a range of iceberg and wave parameters using an extension to WELSAS, and the numerical results are expressed in terms of relevant iceberg and wave parameters in order to be applied to the reliability model.

Equation of Motion of Iceberg

In the presence of waves, the iceberg force on the structure, $F(x)$, is influenced in part by the in-line wave force on the iceberg, $F_{wx}^{(i)}$, and thus the calculation of $F(x)$ is carried out by a direct integration of the equation of motion, rather than by a simple energy balance as in Eq. 7. Thus, dynamic equilibrium in the x direction of an iceberg of mass M gives rise to the following equation of motion:

$$M(1+C_a)\ddot{x} = -F(x) + F_{wx}^{(i)} \tag{9}$$

with initial conditions $x = 0$ and $\dot{x} = V$ at $t = 0$, where x is the iceberg displacement in the x direction, corresponding to its penetration into the structure. In this equation, the steady forces due to current and wind drag are ignored. In order to obtain a solution to Eq. 9, estimates of the added mass coefficient, C_a, the iceberg impact velocity, V, and the in-line wave force on the iceberg, $F_{wx}^{(i)}$, are needed. These have been summarized above and are described in detail by Foschi et al. (1996) for the case of colinear wave direction and iceberg trajectory. As already indicated, the iceberg force on the structure, $F(x)$, is a nonlinear function of x, but can be linearized as $F(x) = Kx$. With this linearization, the equation of motion, Eq. 9, can readily be integrated in closed form to provide the iceberg force on the structure as a function of time.

Wave Force on Structure

In calculating the overall maximum force on the structure, needed for the limit state of global sliding, the force due to waves acting on the structure itself is also required, and this must now account for the presence of the iceberg. Because the wave direction and iceberg trajectory are not colinear, both the in-line and transverse components of the wave force on the structure, denoted $F_{wx}^{(s)}$ and $F_{wy}^{(s)}$, respectively, are required. As described earlier, these force components are obtained by treating the wave diffraction problem for the combined submerged surface of the iceberg in contact with the structure, with a pressure integration over the structure surface now only used to provide the wave force on the structure. Once more, the wave force amplitude has been calculated for the three water depths and a range of iceberg and wave parameters using an extension to WELSAS. The numerical results are used to express the x-ward and y-ward force amplitudes and phase angles in terms of relevant wave, iceberg and structure parameters. The phase angles, which control the effect of the force components at time $t = 0$ (i.e., at the beginning of the collision), are found to be important in the calculation of the exceedence probability.

Maximum Force on Structure

Once a numerical solution to Eq. 9 has been obtained, the required force on the structure may be obtained. Two limit states are considered here. The first is the local damage limit state, for which the maximum iceberg force on the structure in the presence of waves is needed. The second is the global sliding limit state, for which the iceberg force on the structure must be combined with the overall wave force on the structure, in order to develop the maximum combined force. Since the case of an oblique wave direction is being considered here, the maximum combined force is given as:

$$F_M = Max\left\{\sqrt{\left(F(x)+F_{wx}^{(s)}\right)^2+F_{wy}^{(s)2}}\right\} \qquad \text{for } 0 \le t \le t_o \qquad (10)$$

The calculation of the maximum force F_M requires a search for the maximum combination of the iceberg force on the structure, $F(x)$, the in-line wave force on the structure, $F_{wx}^{(s)}$, and the maximum transverse wave force on the structure, $F_{wy}^{(s)}$, from the instant of initial impact, $t = 0$, until the iceberg is stopped, $t = t_o$, bearing in mind that at maximum penetration the wave force components may not be at their peaks.

RESULTS

Table 3 shows a summary of the deterministic and random variables specified in the numerical model.

Waves Alone and Iceberg Alone

The program WLOAD was first run to obtain the forces for waves alone at an annual exceedence probability of 10^{-2}. The program ICELOAD was then run to obtain the iceberg-alone forces at an exceedence probability of 10^{-4} for various values of the iceberg arrival rate μ, with the modifications to the U and L distributions described earlier. The results indicated that the iceberg collision forces are strongly dependent on both current speed and iceberg size (which is limited by water depth). The results are shown for waves and icebergs, respectively, in Tables 4 and 5.

Combined Waves and Iceberg

ICEWLOAD was then run to obtain the total force on the structure as a result of an iceberg collision in the presence of waves, and the corresponding results based on the local and global damage limit states are shown in Tables 6 and 7, respectively. For the local damage limit state, F_M is the maximum iceberg force on the structure in the presence of the waves; and for the global damage limit state, F_M is the maximum combined iceberg-wave force on the structure. The annual exceedence probability was set at 10^{-4}, as required by the Code. The tables show results based on the three water depths, three values of mean current, and four values of mean wave direction, the iceberg parameters considered in

Variable	Description	Site A	Site H	Site B
Depth, d (m)	Deterministic	60	80	100
Structure radius, a (m)	Deterministic	50		
Minimum crushing pressure, p_o (MPa)	Normal	$\mu = 4$, $\sigma = 1$		
Iceberg density, ν (no / deg^2)	Deterministic	0.31	0.74	0.74
Current velocity, U (m/s)	Log-normal	$\mu = 0.14, 0.28, 0.42$ $\sigma = 0.1, 0.2, 0.3$		
100 year sig. wave ht, H_s (m) - all year	Extreme Type I	19.70	19.50	19.50
100 year sig. wave ht, H_s (m) - ice season	Extreme Type I	12.60	9.80	9.80
Individual wave period, T (s)	Normal	$4.43\sqrt{H_s}$		$\mu = 1.0$, $\sigma =$ (input)
Wave direction, α (deg)	Normal	$\mu = 0$, $\sigma = 20$	$\mu = 0, 30, 60, 90$, $\sigma = 20$	$\mu = 0$, $\sigma = 20$
Recording interval, r (hr)	Deterministic	6		
R_{n1}, associated with model uncertainty	Normal	$\mu = 1.0$, $\sigma = 0.1$		
R_{n2}, associated with ice crushing pressure	Normal	$\mu = 0.0$, $\sigma = 1.0$		
R_{n3}, associated with collision eccentricity	Uniform	Min. = 0.0, Max. = 1.0		
R_{n4}, associated with Rayleigh distribution for wave height	Uniform	Min. = 0.0, Max. = 1.0		

Note: Parameters shown refer to all three sites unless otherwise indicated.

Table 3 Summary of specified variables and their statistics

Site	F_M (MN)	
	Ice season	All year
A	1,213	2,084
H	931	2,386
C	991	2,585

Table 4 Wave-alone forces for annual exceedence probability of 10^{-2}

Mean current (m/s)	F_M (MN)		
	Site A	Site H	Site B
0.28	1,254	2,693	3,788
0.14	534	1,161	1,631
0.42	2,053	4,381	6,166

Table 5 Iceberg-alone forces for annual exceedence probability of 10^{-4}

Table 3 (collision rate, and with the modifications to the U and L distributions), and to the limit state under consideration. The wave climate considered is that which occurs during the ice season, and is relatively mild when compared to the year-round annual maximum.

Load Combination Factors

Finally, the preceding results may be used to determine the load combination factor γ used in the CSA Code. γ is used to determine a design value for the load due to a companion frequent environmental process (waves) acting in combination with a rare environmental event (iceberg collision), and is defined in the Code by Eq. 1. The Code recommends that $\gamma = 0.8$ for stochastically dependent events/processes, and $\gamma = 0.4$ for stochastically independent events/processes, and that iceberg impact and waves should be considered stochastically independent (i.e., $\gamma = 0.4$).

Values of γ can be calculated from the results obtained for waves alone, an iceberg alone, and the wave/iceberg combination, and are included in Tables 6 and 7. As expected, although the actual loads are substantially influenced by the various parameters that are considered, the results shown suggest that the load combination factor itself is much more stable. As the wave direction changes, the value of γ changes quite significantly, and eventually approaches zero for a wave direction $\alpha = 90°$ as expected. Finally, the results do not change substantially when the limit state is changed from the local damage state to the global damage state.

The values of γ were calculated with the 10^{-2} annual wave load, which may not occur during the ice season. As a result the values of γ are found to be substantially smaller than the 0.4 level given in the code. If one were to use the 10^{-2} seasonal wave load, the value of γ would be larger (reaching the 0.4 level). Since the iceberg collision force is interrelated with the effect of the waves, it is recommended that the combined event should be classified as dependent rather than independent, and that a value of 0.20 could be conservatively used if a more detailed study cannot be conducted, and modified for different mean wave directions.

CONCLUSIONS

The analysis of loads due to an iceberg collision in the presence of waves, taking account of seasonal variations in wave climate and the influence of wave direction, is summarized. This analysis is based on mechanics models for the forces on an offshore structure due to waves alone, an iceberg alone, and the combination of waves with an iceberg, and these are combined with a reliability model in order to develop forces corresponding to specified risk levels.

A primary objective of this study has been to examine the load combination factor γ for combined iceberg-wave loads on large offshore structures. At present, the CSA Code recommends that iceberg impact and waves should be considered stochastically independent, with a load combination factor $\gamma = 0.4$. The results of the study suggest that iceberg impact and waves should instead

Mean current (m/s)	Wave direction (deg)		Site A		Site H		Site B	
	Mean	S.D.	F_M (MN)	γ	F_M (MN)	γ	F_M (MN)	γ
0.28	0	20	1,436	0.09	2,959	0.11	4,189	0.16
0.28	30	20	1,408	0.07	2,915	0.09	4,122	0.13
0.28	60	20	1,334	0.04	2,794	0.04	3,939	0.06
0.28	90	20	1,235	-0.01	2,630	-0.03	3,692	-0.04
0.14	0	20	734	0.10	1,469	0.13	2,097	0.18
0.42	0	20	2,226	0.08	4,623	0.10	6,529	0.14

Table 6 Maximum combined iceberg force F_M and load combination factor γ for annual exceedence probability of 10^{-4} and for various currents and mean wave directions (local damage limit)

Mean current (m/s)	Wave direction (deg)		Site A		Site H		Site B	
	Mean	S.D.	F_M (MN)	γ	F_M (MN)	γ	F_M (MN)	γ
0.28	0	20	1,439	0.09	2,960	0.11	4,190	0.16
0.28	30	20	1,419	0.08	2,916	0.09	4,123	0.13
0.28	60	20	1,345	0.04	2,794	0.04	3,948	0.06
0.28	90	20	1,248	0.00	2,637	-0.02	3,695	-0.04
0.14	0	20	742	0.10	1,471	0.13	2,098	0.18
0.42	0	20	2,228	0.08	4,624	0.10	6,530	0.14

Table 7 Maximum combined wave-iceberg force F_M and load combination factor γ for an annual exceedence probability of 10^{-4} and for various currents and mean wave directions (global damage limit)

be considered stochastically dependent, and that a value of γ of 0.20 could be conservatively used. This value may also be modified for wave direction as indicated here.

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