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Environmental Loading Studies for The CSA Offshore Structures Code

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EXECUTIVE SUMMARY

In 1992 the Environmental Studies Research Funds financed a study on the verification of the CSA/CAN S474 Code for Fixed Offshore Concrete Structures. During the course of the verification process, several issues relating to environmental loading and to the combined effects of ice/structure interaction were identified as being important and requiring further study. In particular, the load factors on rare environmental events and load combination factors for rare environmental events occurring along with frequent environmental required further study. The work on examining these issues was divided into two phases as follows:

- Phase I: examine the appropriateness of the 1.35 load factor specified for use on the 1 in 100 year iceberg for the design of the concrete strength.
- Phase II: examine the load combination factors specified in the code for rare environmental events occurring along with companion frequent environmental events.

In addition, as part of the research project, several reliability based computer programs were written to determine environmental loads on structures. The following programs were written for this project:

- ICELOAD calculates the force imparted on a structure by an iceberg upon impact between the iceberg and the structures. Results are presented as Force vs. Return Period.
- WLOAD calculates the force imparted on a structure by storm waves. Results are presented as Force vs. Return Period.
- ICEWLOAD calculates the force imparted on a structure by an iceberg upon impact between the iceberg and the structure when the iceberg is combined with storm wave action. Results are presented as Force vs. Return Period.
- EWLOAD calculates the force imparted on a structure by a seismic event when the seismic event is combined with storm wave action. Results are presented as Force vs. Return Period.

The major findings and recommendations from Phase I of the project are as follows:

- Designing to a lower ultimate limit states design load factor increases the risk of local damage to the structure and the possibility of environmental damage due to breaching of oil shafts, but slightly decreases the possibility of global structure failure;

- Designing a gravity based structure to a lower load factor is economical according to an expected cost analysis.

- Assuming that the structure is infinitely rigid when determining the iceberg load on a structure is conservative.

- The form of the iceberg pressure versus area curve is not important for the outcome of iceberg load evaluations. The most important parameter in iceberg load evaluations is the minimum contact pressure that the iceberg ice can sustain;

- The ultimate limit state load factor is recommended to be decreased from 1.35 to 1.1; and,

- Greater emphasis should be placed on determining the properties of iceberg ice.

The major findings and recommendations from Phase II of the project are as follows:

- icebergs and storm waves should be considered as stochastically dependent for the purposes of combining the effects of the two loads;

- load combination factors calculated for icebergs in combination with storm waves at the study location are lower than those recommended in the code if the two events are taken as stochastically dependent;

- load combination factors calculated for earthquakes in combination with storm waves at the study location are much lower than those recommended in the code;

- load combination factor "γ" is location dependent and must be calculated for each location of concern;

- *Table 6.1(a)* in S471 is recommended to be modified to reflect stochastic dependence between storm waves and icebergs;

- *Table 6.1(b)* in S471 is recommended to be modified to incorporate location dependent load combination factors; and,

- create separate load combination factors for the combination of different environmental loads (i.e. load combination factors will be different for earthquakes with storm waves than icebergs with storm waves.

RÉSUMÉ

En 1992, le Fonds pour l'étude de l'environnement a financé une étude de vérification de la norme CSA/CAN S474 "Code for Fixed Offshore Concrete Structures". Le processus de vérification a permis de déterminer que plusieurs questions relatives aux charges environnementales et aux effets combinés de l'interaction glace/structure étaient importantes et nécessitaient un examen plus poussé. En particulier, il fallait étudier plus à fond les facteurs de charge portant sur des événements environnementaux rares et les facteurs de combinaison de charges pour des événements environnementaux rares qui se produisent en même temps que des conditions environnementales fréquentes. Les travaux sur ces questions ont été divisés en deux phases:

* Phase I: examen du facteur de charge de 1,35 prescrit dans le cas de l'iceberg qui se produit une fois en cent ans pour le calcul de la résistance du béton.

* Phase II: examen des facteurs de combinaison de charges prescrits dans le code pour des événements environnementaux rares se produisant en même temps que des événements environnementaux fréquents.

De plus, plusieurs programmes informatiques basés sur la fiabilité ont été conçus dans le cadre de ce projet pour déterminer les charges environnementales qui s'exercent sur les structures. Ces programmes sont les suivants:

* ICELOAD Calcule la force exercée sur une structure par un iceberg lors du choc contre cette structure. Les résultats sont donnés en termes de force en fonction de la période de récurrence.

* WLOAD Calcule la force exercée sur une structure par les vagues d'une tempête. Les résultats sont donnés en termes de force en fonction de la période de récurrence.

* ICELOAD Calcule la force exercée sur une structure par un iceberg lors du choc contre cette structure lorsque l'action des vagues d'une tempête doit aussi être prise en compte. Les résultats sont donnés en termes de force en fonction de la période de récurrence.

* EWLOAD Calcule la force exercée sur une structure par un événement sismique combiné à l'action des vagues d'une tempête. Les résultats sont donnés en termes de force en fonction de la période de récurrence.

Les principales conclusions et recommandations de la Phase I du projet sont les suivantes:

* le calcul aux états limites avec une limite ultime inférieure accroît le risque de dommages locaux à la structure et la possibilité de dommages environnementaux par la rupture de

colonnes de pétrole, mais diminue légèrement le risque de ruine de la structure;

* l'utilisation d'un facteur de charge inférieur pour une plate-forme à embase-poids est économique selon une analyse de prévision des coûts;

* supposer que la structure est infiniment rigide pour la détermination de la charge de l'iceberg est une hypothèse prudente;

* la forme de la pression de l'iceberg par rapport à la courbe de la surface n'est pas importante pour les évaluations de la charge de l'iceberg, le paramètre le plus important étant la pression de contact minimale que la glace de l'iceberg peut absorber;

* il est recommandé d'abaisser de 1,35 à 1,1 le facteur de charge de l'état limite ultime, et

* on devrait davantage mettre l'accent sur la détermination des propriétés de la glace de l'iceberg.

Les principales conclusions et recommandations de la phase II du projet sont les suivantes:

* les icebergs et les vagues des tempêtes doivent être considérés comme stochastiquement dépendants dans la combinaison des effets des deux charges;

* les facteurs de combinaison de charges calculés pour les icebergs avec vagues de tempête à l'endroit de l'étude sont inférieurs à ceux qui sont recommandés dans le code si on considère que les deux événements sont stochasliquement dépendants;

* les facteurs de combinaison de charges calculés pour les tremblements de terre combinés à des vagues de tempête sont bien inférieurs à ceux qui sont recommandés dans le code;

* le facteur de combinaison de charges "y" dépend de l'emplacement et doit être calculé pour chaque endroit concerné;

* on recommande de modifier le *tableau 6.1(a)* de la norme S471 pour tenir compte de la dépendance stochastique entre vagues de tempête et iceberg;

* on recommande de modifier le *tableau 6.1(b)* de la norme S471 pour y ajouter les facteurs de combinaison de charges qui dépendent de l'emplacement, et

* créer différents facteurs de combinaison de charges pour la combinaison des différentes charges environnementales (par ex. facteurs différents pour des tremblements de terre avec vagues de tempête et pour des icebergs avec vagues de tempête).

NOTATION

d	water depth
D	structure diameter
d_i	duration of event *i*
F_d	drag force on iceberg
F_i	iceberg force on structure
F_m	maximum force
F_o	user defined force level
$F_w^{(i)}$	wave force on iceberg
$F_w^{(s)}$	wave force on structure
F_{wd}	wave force on iceberg
G	performance function
h	iceberg draft
H_s	significant wave height
H	wave height
L	iceberg waterline diameter
M	iceberg mass
ρ_i	ice density
ρ	water density
P	probability of occurrence
R_o	radius of icewall
R_{ni}	random variable *i*
T_R	return period
t	time
T	wave period
T_p	wave peak period
U	current velocity
μ	iceberg added mass
V_i	iceberg impact velocity
V_i	iceberg velocity
V_f	standard deviation
W	weight of structure
x	iceberg displacement
Z_w	structure depth

1.0 INTRODUCTION

1.1 Background

The CSA Offshore Structures Code CAN/CSA-S471-92 (S471) was finalized in early 1992 and is currently in use. The Code was subjected to a comprehensive verification process which identified several issues, related to environmental loading and to the combined effects of ice/structure interaction, as being important and requiring further study. However, the schedule for publication of the Code did not permit these issues to be examined in sufficient detail prior to its issuance.

The verification work performed by Westmar Consultants in projects G-2A and G-2B on the Code identified the need to more closely examine the load factors on rare environmental events, especially those pertaining to icebergs, and load combination factors for rare environmental events occurring along with frequent environmental events. A study on these load factors is presented in this report.

The overall study is comprised of two phases, as described below.

1.2 Scope of Study

The work on examining the load factors for icebergs and load combination factors for rare environmental events occurring along with frequent environmental events has been divided into two phases, as follows:

- Phase I: an examination of the appropriateness of the 1.35 load factor on the 1 in 100 year iceberg for the design of the concrete strength of offshore structures.

- Phase II: an examination of the load combination factors specified in the code for rare environmental events occurring along with companion frequent environmental events.

The work for each phase is discussed in greater detail in the following sections.

1.3 Summary of the Following Sections

The work completed for Phase I of the report is described in Sections 2 to 7. The contents of each section is discussed briefly in the following text:

- Section 2 introduces the methodology and scope of work for Phase I of the project;

- Section 3 discusses the principles used to determine iceberg loadings on offshore structures and introduces the computer programs currently available for calculation of iceberg loading. The iceberg movement characteristics and the final calculated loads used to design the study models are also introduced in this section;

- Section 4 covers the overall functional design of the study models, the development of the analysis model, the subsequent force analysis of the structure using the iceberg forces calculated in Section 3, and the structural design of the structure;

- Section 5 contains the analysis of the structure for the reliability level under iceberg loads, including a description of theory used, the analysis procedures and the setup of the problem;

- Section 6 contains the economic analysis for the different load factors; and,

- Section 7 presents the conclusions and recommendations amassed for Phase I of the project.

The work completed for Phase II of the report is described in Sections 8 to 12. The contents of each section is discussed briefly in the following text:

- Section 8 introduces the load combination factors currently used in S471 and discusses the methodology used to conduct the study on the appropriateness of the factors given in the code;

- Section 9 contains the theory used to calculate the environmental loads and summarizes the final relationships for use in environmental load calculations;

- Section 10 introduces analysis methods used to perform the analysis. Computer programs written for the study are introduced and explained;

- Section 11 contains the results of the analysis including final calculated environmental loads and the resulting calculated load combination factors;

- Section 12 presents the conclusions and recommendations amassed for Phase II of the project; and,

- Appendix A contains the references used for this study.

2.0 PHASE I

2.1 Methodology

The methodology for Phase I of the work was to design a gravity base structure (GBS) to withstand iceberg impacts, using three different load factors on the 1 in 100 year iceberg, i.e. three different designs of the structure were made with varying strength requirements. Two aspects of the resulting structures were then examined, namely:

- Reliability: The effect of the load factor on the target reliability against loss of life or damage to the environment of 10^{-5} per year for a Safety Class 1 structure.

- Cost: The effect of the load factor on the cost of the structure. The cost of the structure is taken as the capital cost added to the present value of the expected repair costs from damage due to iceberg impacts. Only the costs of the ice wall and outermost support walls were used in the analysis as these are the main items affected by iceberg impacts.

2.2 Scope of Work

The work undertaken to complete Phase I included the following:

- a literature search to determine what previous work has been done by others on calibration of load factors for:

  - iceberg loading
  - combined rare events and frequent environmental processes
  - calculation of seismic, iceberg, and wave loads on a GBS
  - wind, wave and current loads on an iceberg.

- determination of the iceberg loads as a function of return period;

- development of a finite element model of a typical GBS Test Structure. Gear teeth present in typical GBS structures were omitted to create as general a model as possible;

- structural design of the ice wall and the supporting walls for the GBS;

- analysis of the reliability level of the structural elements and the global resisting system due to iceberg loading;

- analysis of damage to the structural system under iceberg loading;

- capital cost estimates for the three designs using the three different load factors;

- estimates of the expected repair costs for the damaged structure after an iceberg impact;
- economic analysis of the designs for the three different load factors; and,
- recommendations for the load factor on the 1 in 100 year iceberg event for designing gravity based structures.

As part of the work two computer programs were written. The first computer program ICELOAD was used to conduct calculations for the probability of different force levels for iceberg impacts. The second computer program SIMCOST was used to conduct a probabilistic economic analysis of the damage caused by iceberg impacts.

3.0 DESIGN ICEBERG LOADS

Computer programs have been written and are available for use in determining the forces caused by iceberg impacts. The global iceberg loads stemming from the iceberg impacts were required to determine the forces that would be imparted on a gravity based structure in the event of a collision. These forces were used to design the test structure and to load the test structure for determining damage levels.

The computer programs used to determine iceberg impact loads generally assume that a rigid structure is impacted by an iceberg and upon impact, the iceberg crushes. The energy dissipated through the crushing of the iceberg is balanced with the initial kinetic energy in the iceberg. By using the principles of energy balance and an assumed minimum average ice crushing pressure versus area (P versus A) curve, to model the crushing of the iceberg ice, the final force imparted on the structure is determined. The equation for energy balance is given in Equation 3.1:

$$\frac{1}{2} * M * (1 + C_m) * V^2 = E_d \tag{3.1}$$

where M = Mass of Iceberg
C_m = Added Mass Coefficient
V = Iceberg Velocity
E_d = Energy Dissipated in the Crushing of the Ice

The left hand side of Equation 3.1 represents the kinetic energy of the iceberg and the right hand side represents the energy dissipated in crushing of the ice.

The energy dissipated in the crushing of the ice is the area under the ice force verses penetration curve. The general form of the ice force versus penetration curve is shown in *Figure 3.1.*

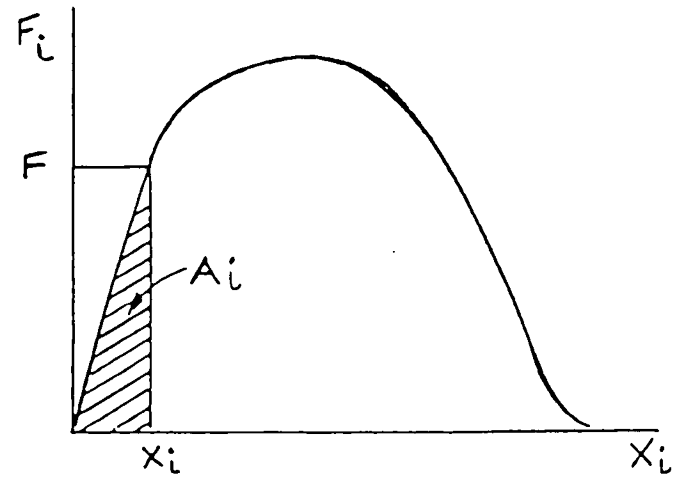

Figure 3.1: Ice Crushing Force versus Penetration

Where:

F = Iceberg Force
X = Penetration of Structure into Crushing Ice
A = Energy Dissipated by Crushing Ice

The iceberg load for this study was initially to be calculated using the BOREAS Version 3.1 probabilistic framework computer program by C-FER. Limitations with the program for the requirements of this project were identified in the initial stages of this study. It was decided that BOREAS could not be used for this project without making modifications to the program. Modifications to the program were requested from C-FER but, in order to avoid excessive delay to the project, iceberg loads calculated previously in the CSA Verification Projects G-2A and G-2B were used to design the new GBS. These iceberg loads were calculated using the DNV probabilistic framework computer program, a predecessor to the BOREAS program. The results from the DNV probalistic framework program were checked against those calculated using BOREAS once the BOREAS program was amended. Amendments to BOREAS were made by C-FER in a separate project stemming from the identification of the limitations to the program.

The iceberg loading from the DNV probabilistic framework analysis showed that the 1 in 100 year return period iceberg force was 555 MN. The results from the modified BOREAS program showed a 1 in 100 year return period iceberg force of 480 MN, 14% lower than the force determined by the DNV program. The structural design of the test structure was not modified for the lower force from BOREAS.

Iceberg loads for the 1 in 200, 1 in 500, 1 in 1000, 1 in 10000 and 1 in 100000 year return periods were also determined for analysis. Loads were again calculated previously for CSA Verification Project G-2A and G-2B. These values were checked against those calculated in BOREAS. The loads calculated from both computer programs are shown in *Table 3.1.* The relative difference between the two values is also shown.

Table 3.1: Comparison of Iceberg Forces from BOREAS and DNV Probabilistic Framework Programs

	Iceberg Force (MN)					
Iceberg Return Period	**1/100**	**1/200**	**1/500**	**1/1,000**	**1/10,000**	**1,100,000**
DNV	555	725	970	1090	1470	1760
BOREAS	480	640	860	1000	1400	1590
% Difference	-14	-12	-11	-8	-5	-10

The results show that BOREAS consistently produces forces lower than those calculated using the DNV probabilistic framework program. The forces from BOREAS are from 5% to 14% smaller than those used in this study for design and analysis of the GBS. The differences in the load calculated using the two programs was not deemed to be significant for this study.

The results were only used for initial design of the test structure. A new computer program was subsequently written specifically for this study and is explained in Section 5.

Iceberg parameters which were used in the DNV Probabilistic Framework program for the calculation of iceberg forces were:

- flux
- velocity
- length
- crushing pressure

All of the parameters were input as statistical distributions. A summary of the iceberg statistics used to calculate the iceberg forces in both computer programs is given in *Table 3.2.*

Table 3.2: Iceberg Statistics Used in the BOREAS and DNV Probabilistic Framework Programs

Parameter	Units	Mean	Standard Deviation	Distribution Type
Flux	Bergs/km	0.49	0	Deterministic
Velocity	m/s	0.36	0.25	Numerical
Length	m	63.5	54	Numerical
Crushing Pressure	MPa	6	1.25	Lognormal

The iceberg flux, velocity and length statistical values were determined from data obtained from the Centre for Cold Ocean Resources Engineering (C-CORE) as reported by D.F. Dickins.

4.0 STRUCTURE ANALYSIS AND DESIGN

4.1 Test Structure Layout

The general layout of the overall test structure was agreed upon by the National Energy Board and Westmar Consultants in a pre-project meeting. This layout is thought to be a representative shape which will give typical results for a cylindrically shaped gravity base structure. The overall dimensions of the structure are based on the dimensions of a typical Grand Banks GBS.

The diameter of the cross section was set at 100 m. The overall height of the structure was set at 85 m. *Figure 4.1* shows a plan view cross section of the test structure.

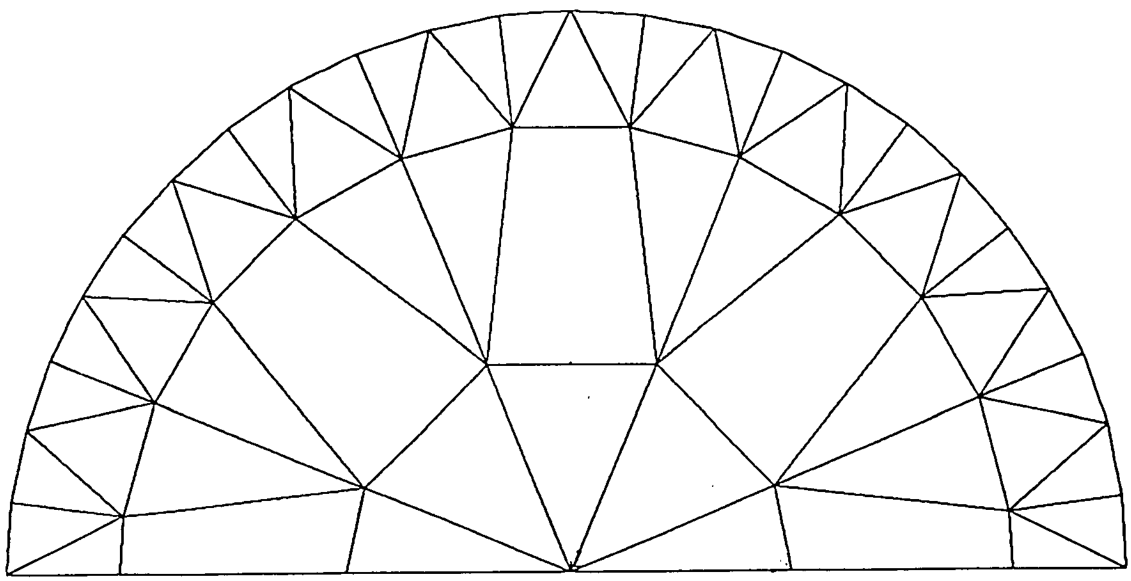

Figure 4.1: Cross-section of GBS.

The structure is a prestressed reinforced concrete system. An exterior ice wall is 2.2 m to 2.4 m thick and is supported by a series of interior support walls. The support walls are 0.7 m thick. The layout of the interior walls is such that the clear span of the ice wall is approximately 6.5 m. A grillage of the support walls carry the loads on the ice wall to the core of the structure. The support walls directly adjacent to the ice wall have a length of approximately 10 m. The support walls further towards the core have a length of approximately 20 m. The layout was created solely for the purposes of this study for the analysis of the structural elements and in no way reflects the demands for the functionality of the structure such as oil storage, drill shafts, etc.

The concrete used for analysis is a normal weight concrete with a 28 day concrete compressive strength of 70 MPa. This is based on the concrete strength used for typical GBS structures. Concrete properties used for the analysis model are based on this concrete compressive strength. Reinforcement steel with a specified yield strength F_y of 400 MPa was used to determine section strength.

4.2 Finite Element Model

The finite element model based on the above system was constructed using COSMOS/M Version 1.70. To reduce the size of the model and thus the required analysis time only one half of the structure was modelled. Experience from modelling the Hibernia GBS - 1986 update structure in Verification Project G-2B showed that the structure is very stiff. Because the structure is very stiff, the remaining one half of the structure was assumed to create full fixity for the structure at the centre line of symmetry.

The model was divided into three levels so that the iceberg loading and resulting stresses in the structure could be accurately simulated without making the model too large. The three levels of the structure represent the following zones:

- 0 to 46 m above the ground level is the portion of the structure below the iceberg impact zone.
- 46 m to 72 m above ground level is the zone in which the icebergs are assumed to impact.
- 72 m to 85 m is the zone which is assumed to be above the impact zone.

The model was created with a different finite element mesh configuration at the different levels to represent the different accuracies required for the results at the different levels of the structure. The mesh was approximately two times finer for the iceberg impact zone as compared to the non-impact zone. *Figure 4.2* shows a perspective view of the model.

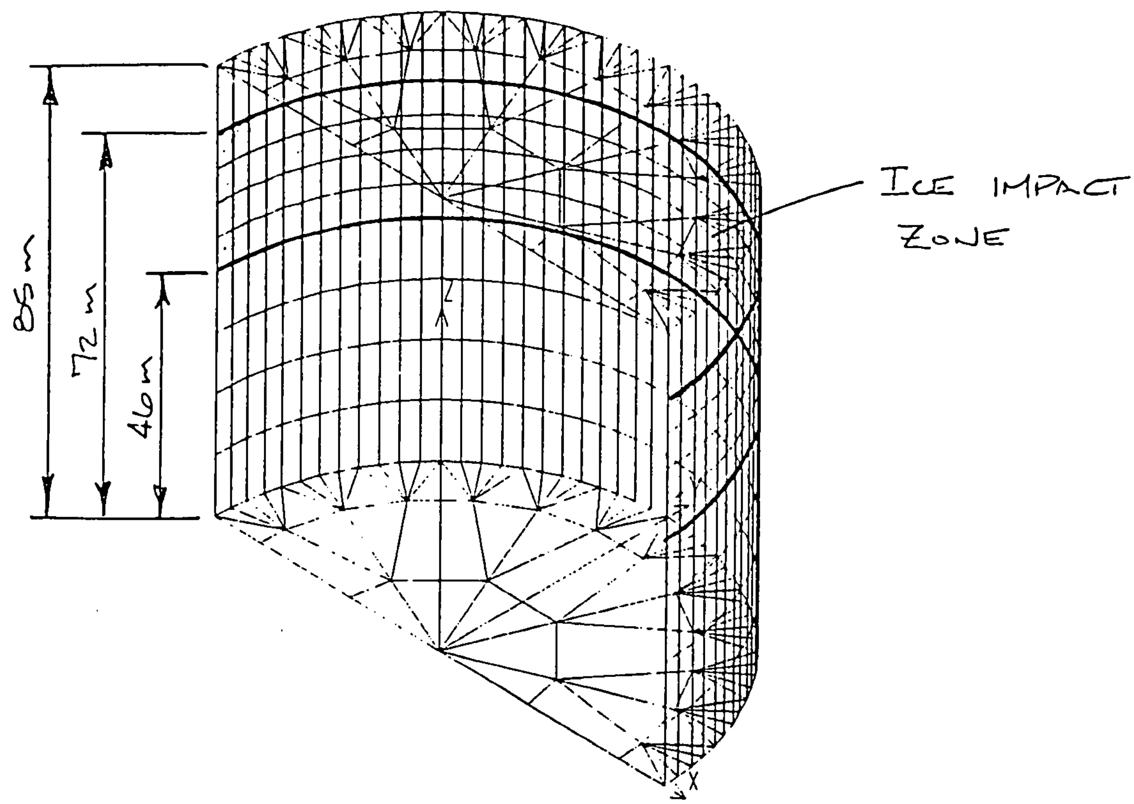

Figure 4.2: Perspective view of GBS Model.

The finite element model has the following attributes:

- 700 nodes
- 1274 elements
- 4032 degrees of freedom

4.3 Structure Analysis

Maximum member design forces were obtained from the results of the finite element analysis using the 1/100 year return period iceberg load determined in Section 3. The design loading patch for the structure was based on a constant ice pressure of 6 MPa. The constant pressure generally corresponds to the P versus A curve used to design the Hibernia GBS. The size of the design loading patch was determined by a total ice loading of 555 MN. The area of the load patch was spread over the ice wall in several different patterns to obtain the worst case load for design. The final design iceberg loading pattern for the 1/100 year iceberg loading is shown in *Figure 4.3.*

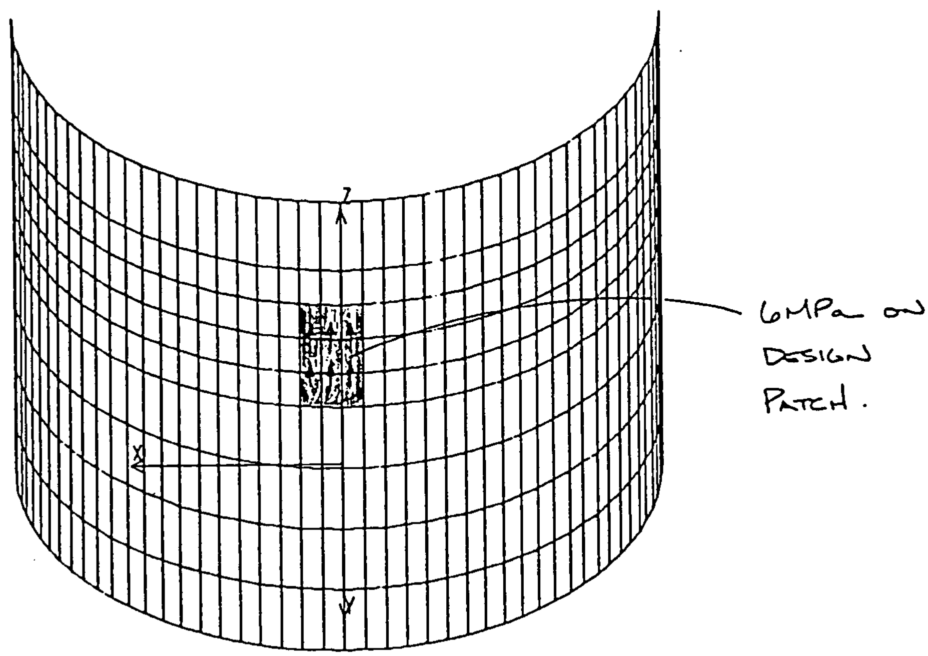

Figure 4.3: Design loading pattern for 1/100 year iceberg.

All analysis and design material properties, material factors, and detailing requirements were based on the recommendations of the CSA S474-M1989 Concrete Offshore Structures code.

4.4 Structure Design

Reinforcing steel levels in the concrete ice wall required to meet the strength criteria for the given loading were determined using the computer program SHELL474. The design was based solely on the ultimate limit states condition for the 1 in 100 year return period iceberg. This condition was found to be the governing factor in the previous CSA verification project G-2B when the iceberg load factor was greater than 1.11. If the load factor was less than 1.11, the local damage criteria governed the design.

Designs for the ice wall and the support walls were carried out for three load factors on the 1 in 100 year iceberg. The three load factors used for design were 1.1, 1.35 and 1.6. The 1.35 factor is the load factor currently in S471 while the other two load factors represent a range of load factors used to determine the sensitivity of the safety level of the structure on the load factor.

The final designs showed that the amount of reinforcing steel required for each separate design condition ranged from 186 kg of steel/m^3 of concrete for a load factor of 1.1 to 230 kg steel/m^3 of concrete for a load factor of 1.6 for the ice wall. The reinforcing steel required for the support wall ranged from 239 kg steel/m^3 of concrete for a load factor of 1.1 to 307 kg steel/m^3 of concrete for a load factor of 1.6. A summary of the reinforcing steel requirements for the separate design conditions is shown in *Table 4.1.*

Table 4.1: Summary of Reinforcing and Prestressing Steel Weights for Each Load Factor Design

Element	Load Factor					
	1.1		1.35		1.6	
	Reinforcing (kg/m^3)	Prestressing (kg/m^3)	Reinforcing (kg/m^3)	Prestressing (kg/m^3)	Reinforcing (kg/m^3)	Prestressing (kg/m^3)
Ice Wall	186	49	222	49	230	53
Support Wall	239	26	271	26	307	26

The final reinforcing configurations for the different load factors for the ice wall and the support walls are shown in *Figure 4.4* to *Figure 4.9*. The layouts include the requirements of minimum reinforcement and constructability.

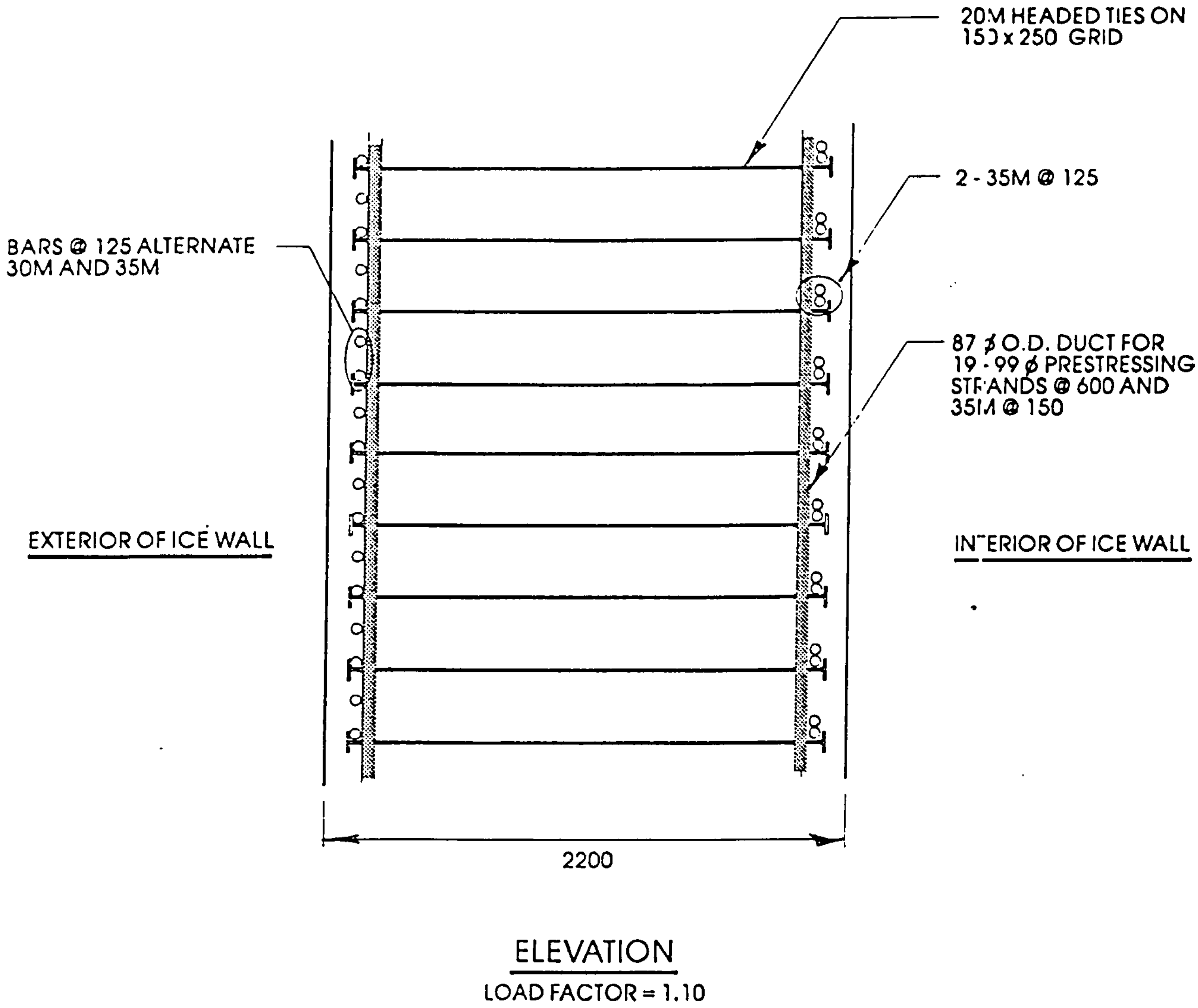

Figure 4.4: Ice Wall Design, Load Factor = 1.10

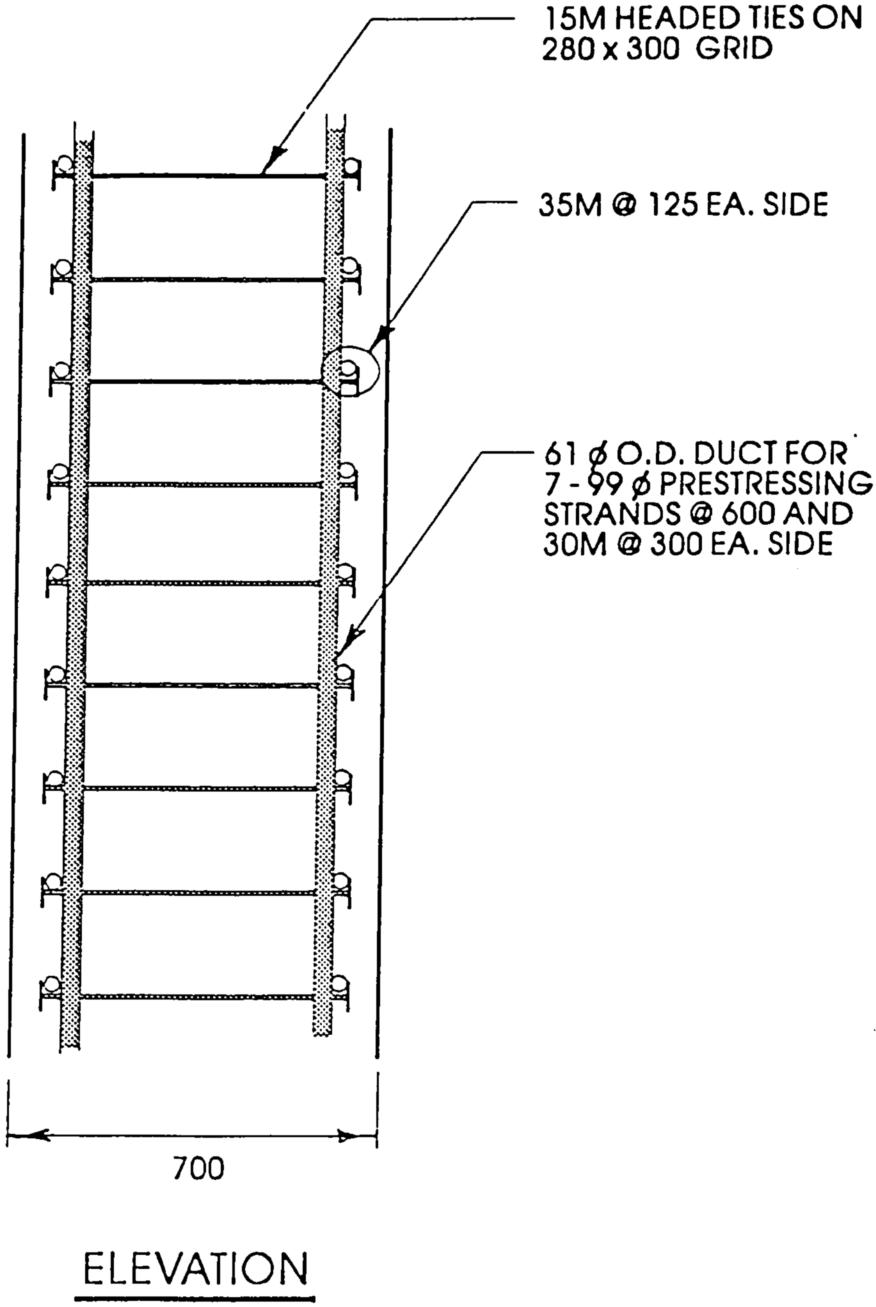

Figure 4.5: Support Wall, Design Load = 1.10

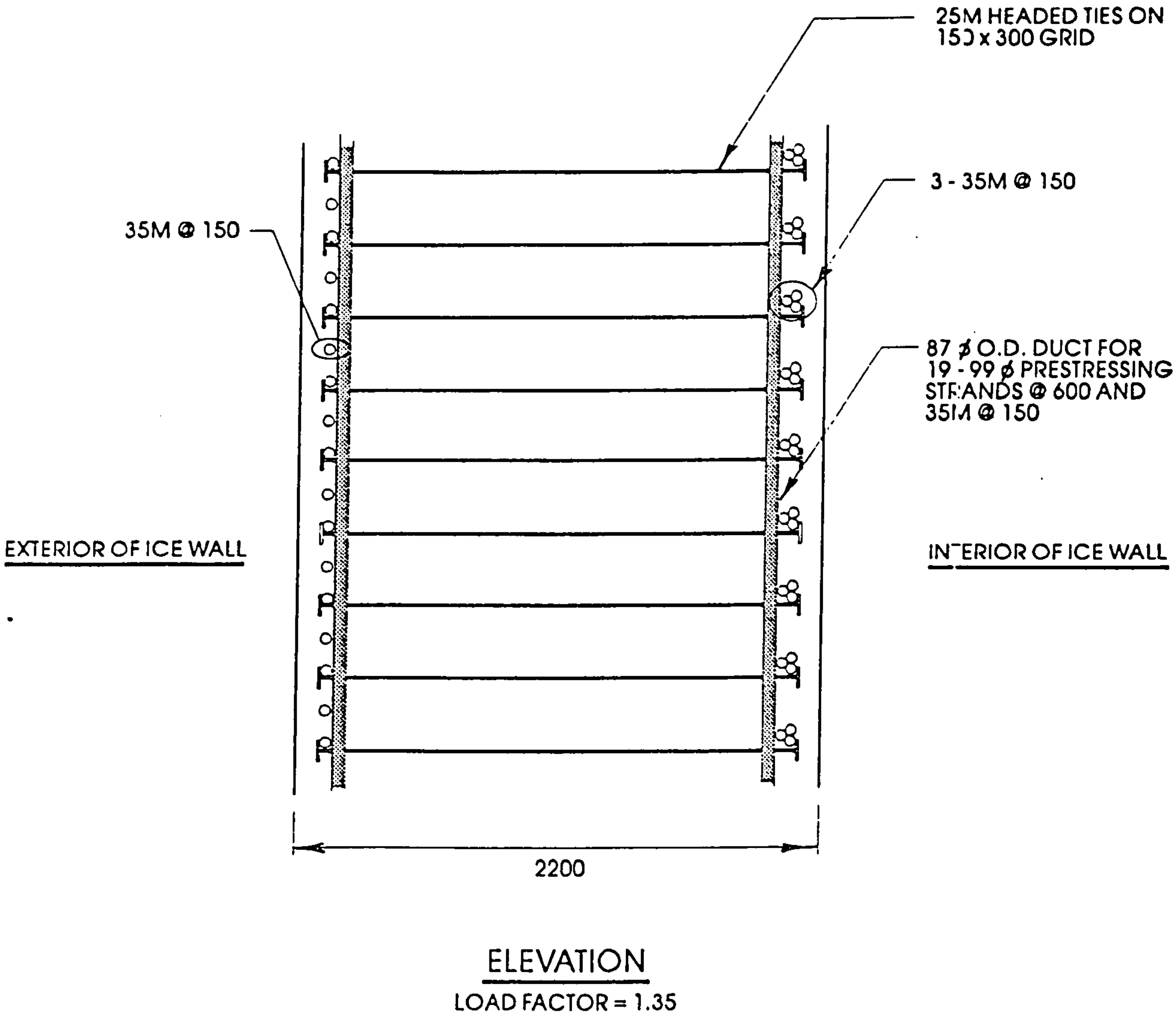

Figure 4.6: Ice Wall Design, Load Factor = 1.35

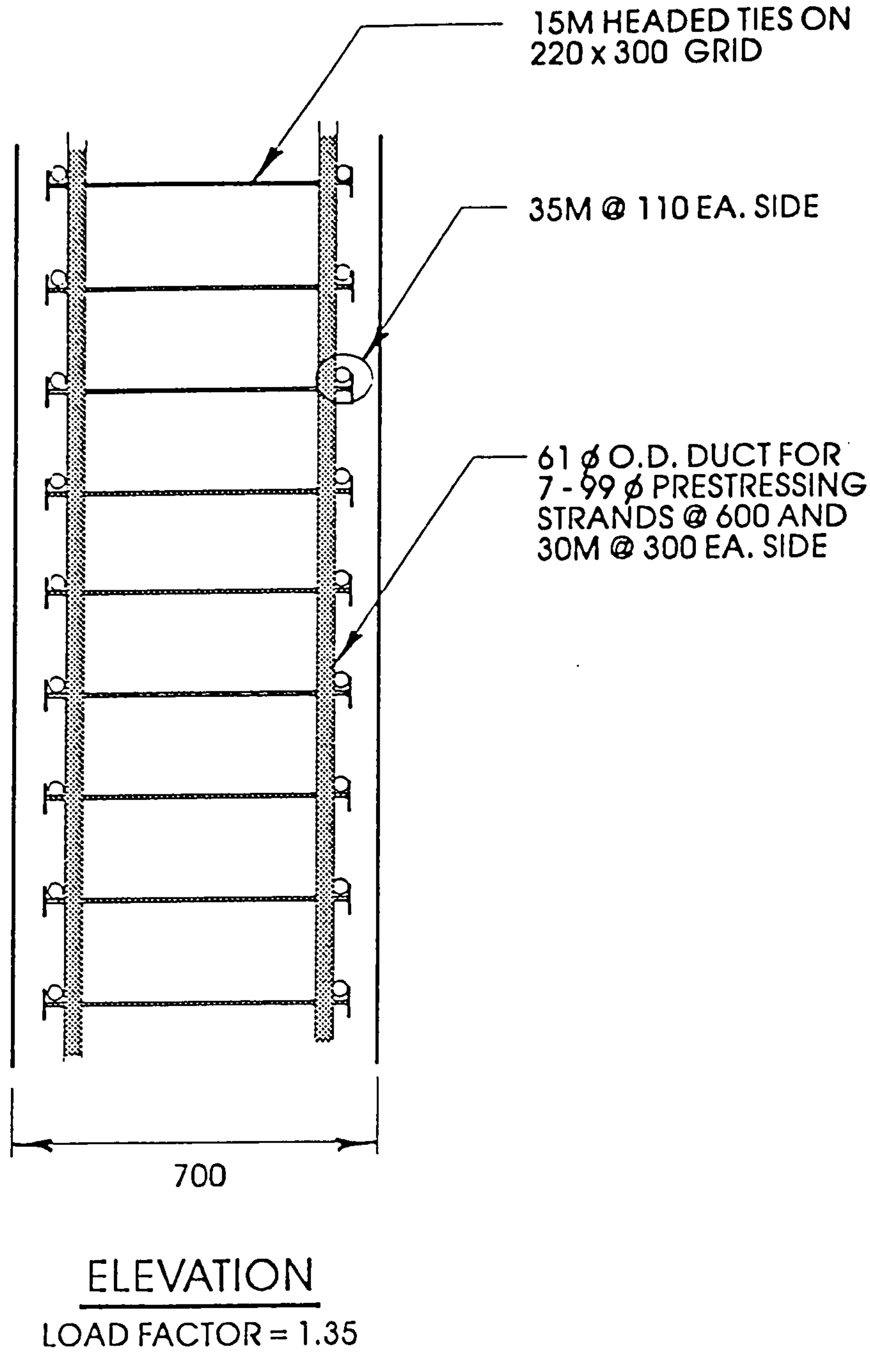

Figure 4.7: Support Wall Design, Load Factor = 1.35

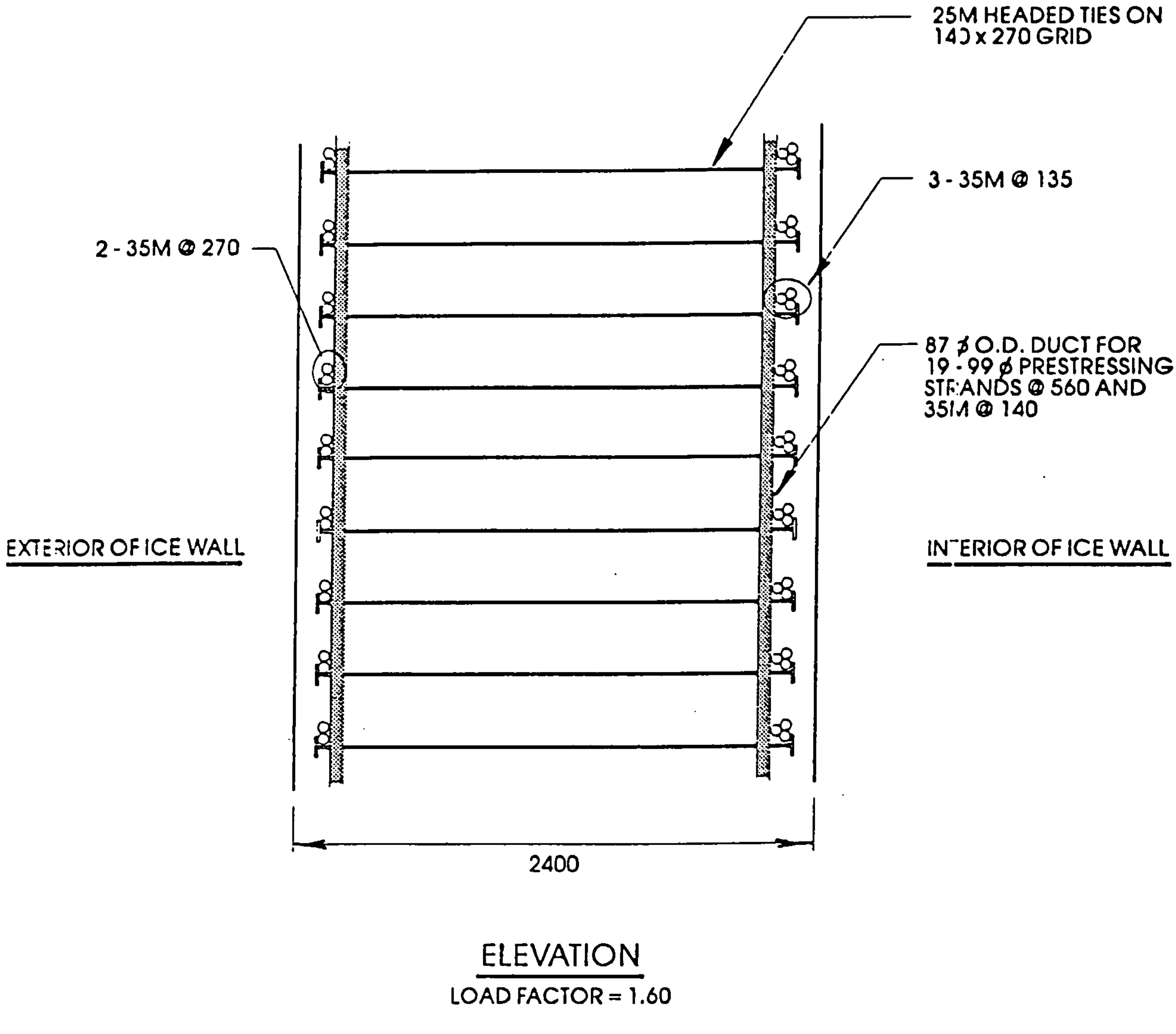

Figure 4.8: Ice Wall Design, Load Factor = 1.60

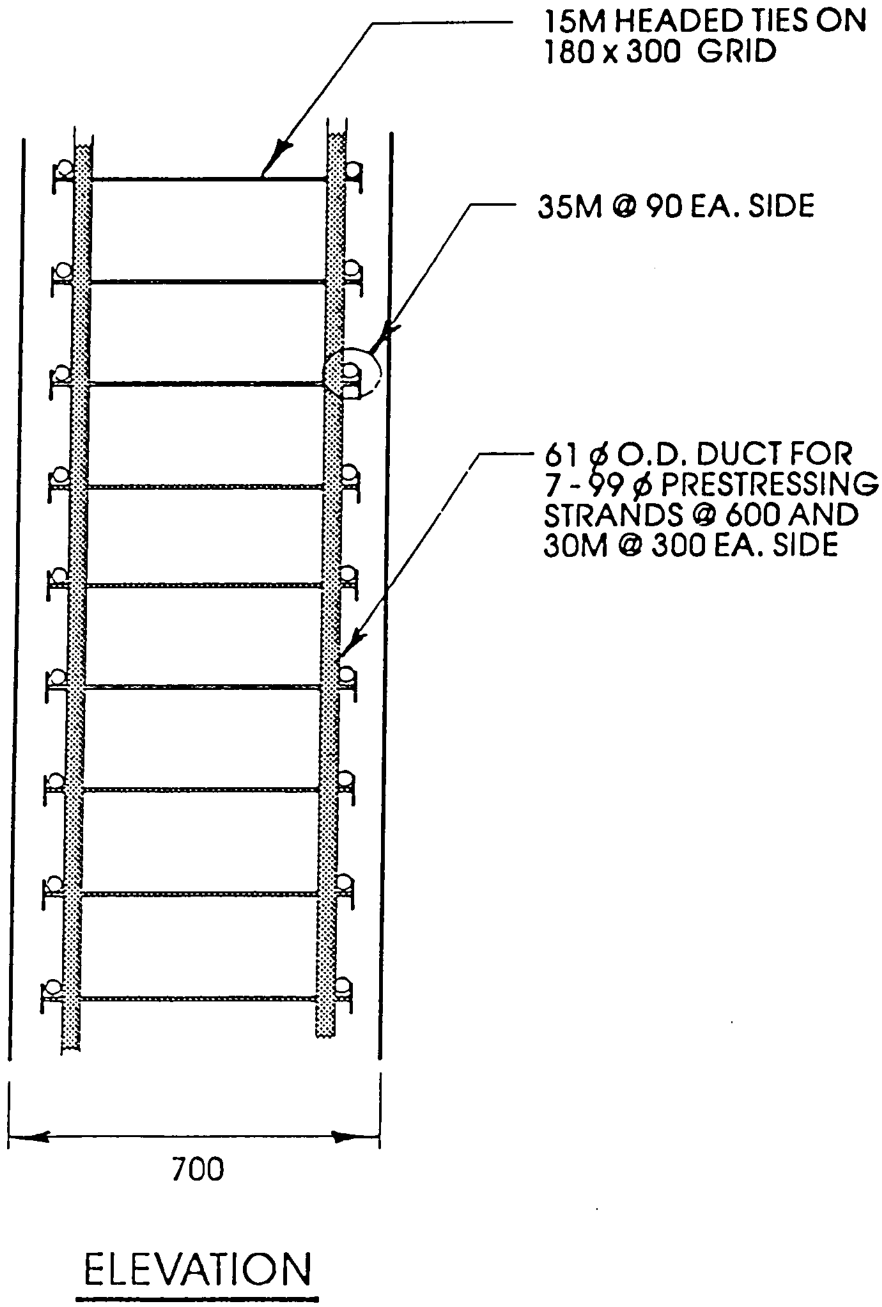

Figure 4.9: Support Wall Design, Load Factor = 1.60

5.0 STRUCTURE RELIABILITY

5.1 Background

A procedure to determine the reliability of a GBS under iceberg loading was developed for this project to check whether or not the target reliability of 10^{-5} against loss of life or damage to the environment was achieved in the design.

The margin of safety (reliability), that a structure has is estimated by comparing the maximum force developed through iceberg impact with the point of failure of the structure. The point of failure of the structure can be either the point of local failure, global failure, or the point where there is a damage condition that can cause loss of life or damage to the environment.

For the purposes of this portion of the study, the point of failure was taken to be situations where there is global failure or a damage condition which could cause loss of life or damage to the environment. These situations include global sliding of the structure and penetration of oil cells by an impacting iceberg. Local failure was not considered to be a point of failure.

As explained in Section 3, it is standard practice to calculate iceberg forces on a structure by using the principle of energy balance. The structure is assumed to be rigid and impact forces are assumed to be independent of global strength of the structure. Impact forces on a structure due to iceberg collisions are, in fact, partially dependant on the global strength of the structure and are thus limited by the load carrying capacity of the structure. For this reason, the calculation of iceberg loads cannot be separated from the structural response of the structure. Iceberg impact forces are thus more accurately determined by taking into account the strength and ductility of the structure rather than assuming a rigid structure.

5.2 Methodology for Determining Structure Reliability

For the purposes of this study, the computer program ICELOAD was written to calculate the iceberg forces on the structure as part of the structure reliability analysis package. The general methodology used for ICELOAD and the required input and resulting output of the program are discussed here. The program was used in lieu of using the probabilistic framework programs, which do not account for structure strength and ductility. ICELOAD was developed to incorporate the effects of the deformation of the structure on the forces developed by impacting icebergs. The incorporation of the effects of the structure deformation on the ice loads developed was not deemed to be possible with the existing programs with in-house programming without obtaining the original code.

Using ICELOAD, the probability of the iceberg force exceeding the global capacity of the structure was calculated. In addition, the ultimate penetration of the iceberg into the structure was determined using derived force versus structure deformation/damage (F versus d) curves. The calculation of iceberg penetration into the structure provided an evaluation of whether critical sections of the structure such as oil storage cells and drilling shafts were penetrated by the iceberg. Using these results, the reliability of the structure against both global failure and environmental damage was determined.

5.2.1 Incorporation of Structure Response for Calculation of Iceberg Forces

To incorporate the effects of the structure on the development of iceberg forces it was necessary to create F versus d curves for input to ICELOAD. F versus d curves were created for each of the structure designs. Determination of iceberg impact forces was then performed by balancing the iceberg kinetic energy with the energy dissipated in structure damage in addition to iceberg damage. The equation for energy balance is similar to Equation 3.1 and is given in Equation 5.1.

$$\frac{1}{2} * M * (1 + C_m) * V^2 = E_{di} + E_{ds} \qquad (5.1)$$

Where:
M = Iceberg Mass
C_m = Added Mass Coefficient
V = Iceberg Velocity
E_{di} = Energy Dissipated in the Crushing of the Ice
E_{ds} = Energy Dissipated in the Deformation of the Structure.

The left hand side of the equation is the kinetic energy of the iceberg and the right hand side of the equation is the energy dissipated in crushing of the ice and deformation of the structure. Calculations of the energy dissipated in the crushing of the ice is the same as explained in Section 3, while the energy dissipated in the crushing of the ice is the area under the ice force versus structure deformation curve. The determination of the F versus d curve is discussed below.

5.2.2 Calculation of Force Versus Structure Deformation Curve

To develop the F versus d curves, many broad assumptions had to be made including the following:

- The damaged area caused by the iceberg is circular to match the shape of an assumed, approximately circular iceberg. The radius of the iceberg is assumed to be 75 m.
- Energy is dissipated through the plastic bending of the ice wall as well as crushing of the support walls.
- Energy dissipation capabilities of the structure are assumed to increase linearly with the area of the damage patch.
- Energy dissipation through damage of the structure only begins to occur after the ice loads surpass the expected strength of the ice wall.

The geometry of the assumed impact and damage area is shown in *Figure 5.1*. The results of the force versus indentation analysis used in this analysis is summarized in tabular form in *Table 5.1*.

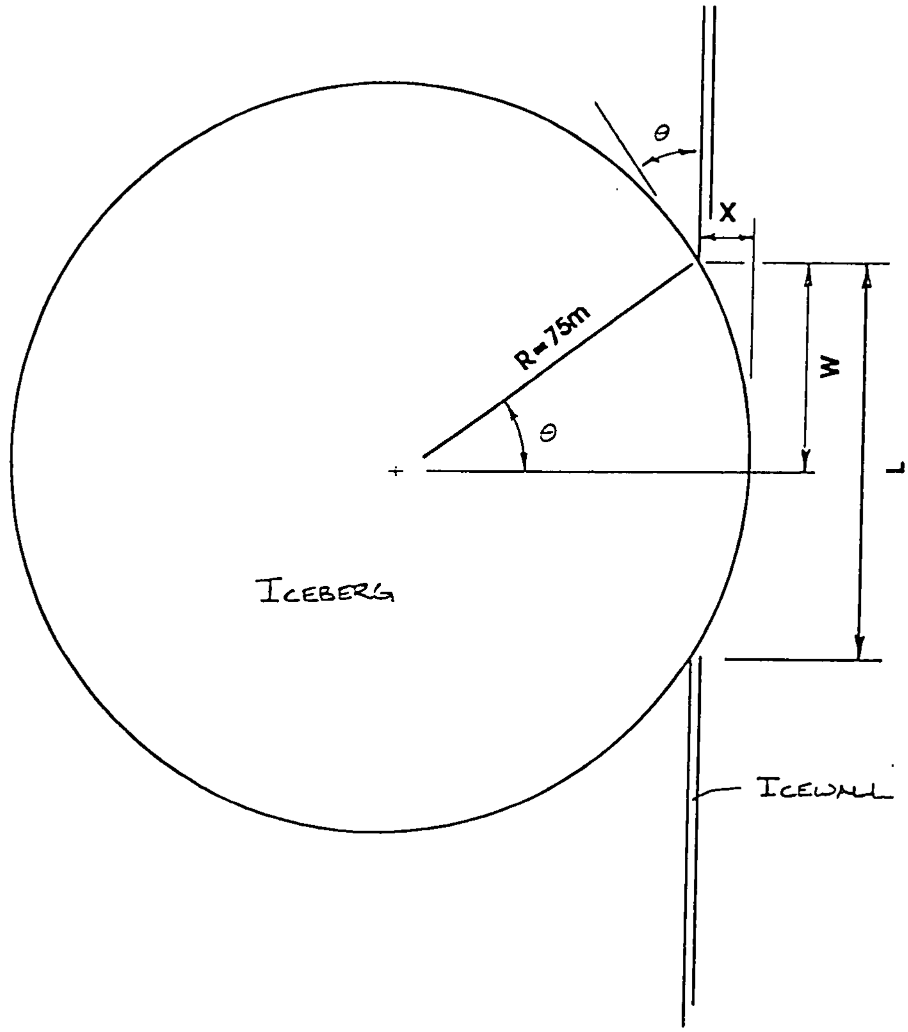

Figure 5.1: Geometry of Assumed Impact and Damage Area

Table 5.1: Force versus Structure Deflection Curves

Structure Deflection (m)	Load Factor		
	1.1 (MN)	1.35 (MN)	1.6 (MN)
0	610	750	890
0.05	690	830	970
0.1	765	905	1050
0.2	925	1065	1215
0.3	1080	1220	1380
0.4	1235	1375	1545
0.5	1395	1535	1710
0.75	1785	1925	2115
1.0	2175	2315	2525
1.5	2960	3180	3345
2.0	3745	3880	4165

The F versus d curves were incorporated into the computer program ICELOAD as discussed below.

5.2.3 Computer Program: ICELOAD

The computer program ICELOAD like the probabilistic framework programs uses the principles of energy balance to determine the iceberg forces on a structure. The equation for energy balance used for ICELOAD was given in Equation 5.1. The energy dissipated in the crushing of the ice is the area under the ice force verses ice penetration curve. The energy dissipated in the crushing of the structure is the area under the ice force versus structure deflection curve.

ICELOAD uses a First Order Reliability Method (FORM) to solve for the iceberg forces while the probabilistic framework programs use a Monte Carlo simulation to obtain the same results. The program RELAN (RELiability ANalysis) written at the University of British Columbia (Foschi 1988) forms the basis for the ICELOAD program. The FORM method of probability calculations is much more efficient than the Monte Carlo method.

The mechanics of ICELOAD is given in Section 11.2 along with three other programs written for environmental loads. The basic mechanics of ICELOAD are also discussed here.

- **Input to Iceload**

ICELOAD accepts statistical input for the following iceberg variables:

- velocity at impact
- length
- draft
- average pressure at which iceberg ice crushes
- model uncertainty (similar to Category II uncertainty, see Bea 1992)
- uncertainty in the force versus structural deformation curve (only if structural damage option is chosen)

As noted previously in Section 3, the probabilistic framework programs accept statistical input for the following:

- flux
- velocity
- length
- average pressure at which iceberg ice crushes

While ICELOAD does not incorporate the iceberg flux as a statistical distribution, it is accounted for deterministically as an input for average annual probability of iceberg impact. The average annual probability of iceberg impact is calculated using the iceberg flux data.

The extra input distribution for iceberg draft required for ICELOAD, which is not included in the probabilistic framework program, accounts for the possibility that the draft of the iceberg is water depth limited, in other words, the draft cannot be greater than the water depth.

In the Probabilistic Framework programs, the draft is related to the iceberg length through the following relationship by Hotzel and Miller, 1982:

$$h = 3.781\ L_r^{0.63} \tag{5.2}$$

where,

h = Iceberg draft
L_r = Iceberg length at waterline

Using this relationship gives the possibility of the iceberg draft exceeding the water depth. The other extra inputs, model uncertainty and uncertainty in the force versus structural deformation curve, account for any additional uncertainties in the iceberg impact model from the assumption and for the uncertainty in the structural damage due to iceberg impact model.

An additional option for modifying the velocity and length statistical distributions to account for the fact that icebergs with higher velocity and bigger size are more likely to impact the structure (Sanderson 1988) is also available. This modification is implemented by setting a flag during execution of the program.

For the purposes of the reliability analysis the inputs to ICELOAD were again taken from data obtained from C-CORE as reported by D.F. Dickson. The inputs are summarized in *Table 5.2.*

Table 5.2: Summary of Inputs Taken from C-CORE

Parameter	Units	Mean	Standard Deviation	Distribution Type
Velocity	m/s	0.36	0.25	Lognormal
Length	m	63.5	54	Gamma
Ice Crushing pressure (about the mean pressure versus area curve)	n/a	0	1	Standard Normal
Uncertainty in Force versus Structure Damage Model	n/a	1	0.5	Lognormal

In addition to the inputs for the above variables ICELOAD accepts input for P versus A curves. These curves can be input in one of two general models:

1. $P = S_0 * A^{S_k}$

2. $P = C_1 * (C_2 + C_3 / A)^{C_4}$

where,

S_0, S_k, C_1, C_2, C_3, and C_4 are constants.

- **<u>Output from Iceload</u>**

ICELOAD creates either three or four output files depending on the analysis options chosen. If it is assumed that no structural damage is caused by the iceberg, the three files ICE.SUM, ICEA.SUM, and ICET.SUM are output. ICE.SUM is a summary of the probability of exceedance ($P_e(F)$) of a particular iceberg load for the input, given the fact that an iceberg impact has occurred. ICEA.SUM is the annual $P_e(F)$ for a particular iceberg load. ICET.SUM is the $P_e(F)$ over the total life of the structure of a particular iceberg load.

If it is assumed that there is structural damage caused by the iceberg, a file DAM.SUM is created in addition to the above three output files. DAM.SUM is a summary of the expected distance of penetration of the iceberg into the structure for a given iceberg load level.

In addition to these four files, a user named output file is created by ICELOAD. This file contains a summary of the results of the probabilistic based analysis for each force level. Included in the summary of results is:

- the force level
- the probability of exceedance:
  - assuming that an event occurs
  - annually
  - over the lifetime of the structure
- the expected value of each variable to achieve the given force
- the sensitivity of each variable to changes in value
- the sensitivity of each variable to change in its mean and standard deviation values
- the penetration of the structure into the ice at the given force level
- the penetration of the ice into the structure at the given force level

Also output is the value for beta at the design point. Beta represents the number of standard deviations away from the mean value that the design point is if the family of design points is a normal distribution.

The larger the values for sensitivity the more important the variable is to the calculation of the design point of the analysis. The sensitivity values give an indication of how the design point will change for a given change in the variable. This allows a sensitivity analysis to be done without making numerous runs.

For a design point near the 1 in 10,000 year iceberg load, the sensitivity of the variables shows that the order of importance of the variables is as follows:

- velocity
- length
- model error
- ice crushing strength variability
- draft
- impact eccentricity variability
- structural damage curve error

These results show that the general order of importance of the variables go from those affecting the iceberg kinetic energy (velocity, length, draft) to those affecting the energy dissipation in the iceberg (ice crushing strength) to those affecting the energy dissipation in the structure (structure damage curve).

5.3 Failure Analysis

Failure analysis of the test structures was carried out using six different iceberg P versus A curves for input into ICELOAD. By using six different P versus A relationships, the sensitivity of iceberg loads to the P versus A relationship could be determined.

For the purposes of this portion of the project, the three test structure designs were as originally designed even though the original designs were based on a 6 MPa minimum average ice crushing pressure and not the different P versus A curves used for this analysis. The six P versus A curves used in the study are listed below in *Table 5.3.*

Table 5.3: Pressure versus Area Curves

Item	Pressure versus Area Curve	Minimum Average Ice Crushing Pressure (MPa)	Notes
1	$10\ A^{-0.4744}$	2	Upper bound to the S471 global ice pressure data.
2	$4\ A^{-0.4709}$	2	Mean of the S471 global ice pressure data.
3	$8.1\ A^{-0.572}$	2	Upper bound of the S471 local ice pressure data.
4	$3.8\ A^{-0.6212}$	2	Mean of the S471 local ice pressure data.
5	$11\ A^{-0.5}$	2	Sanderson's curve.
6	6 (constant)	6	Ice pressure curve used in the design of the GBS.

ICELOAD was run for each of the three load factors as well as for a rigid structure for each of the six pressure versus area curves. Computer runs were made for two situations, the case where the velocity and length statistical distributions were input as per *Table 5.3* and the case where the velocity and length distributions were modified using Sanderson's criteria. A total of 48 computer runs were made. A summary of the results are shown in *Table 5.4.*

Table 5.4: Summary of Failure Analysis Results

Design Level	Velocity and Length Distributions Not Modified for Sanderson's Criteria			Velocity and Length Distributions Modified for Sanderson's Criteria		
	Force		Probability of Exceeding Global Resistance (Sliding Force - 3650 MN)	Force		Probability of Exceeding Global Resistance (Sliding Force - 3650 MN)
	1 in 100 (MN)	1 in 10,000 (MN)		1 in 100 (MN)	1 in 10,000 (MN)	
$P = 10A^{-0.4744}$						
LF = 1.10	450	2405	2.3 (10^{-5})	835	4560	2.3 (10^{-5})
LF = 1.35	450	2520	2.3 (10^{-5})	845	4646	2.3 (10^{-5})
LF = 1.60	450	2560	2.5 (10^{-5})	850	4683	2.5 (10^{-5})
Rigid Structure	450	2835	4.4 (10^{-5})	850	5415	4.4 (10^{-5})
$P = 4A^{-0.4709}$						
LF = 1.10	450	2405	2.3 (10^{-5})	835	4560	2.3 (10^{-5})
LF = 1.35	450	2520	2.3 (10^{-5})	845	4646	2.3 (10^{-5})
LF = 1.60	450	2560	2.5 (10^{-5})	850	4683	2.5 (10^{-5})
Rigid Structure	450	2835	4.4 (10^{-5})	850	5415	4.4 (10^{-5})
$P = 8.1A^{-0.572}$						
LF = 1.10	450	2405	2.3 (10^{-5})	835	4560	2.3 (10^{-5})
LF = 1.35	450	2520	2.3 (10^{-5})	845	4646	2.3 (10^{-5})
LF = 1.60	450	2560	2.5 (10^{-5})	850	4683	2.5 (10^{-5})
Rigid Structure	450	2835	4.4 (10^{-5})	850	5415	4.4 (10^{-5})
$P = 3.8A^{-0.6212}$						
LF = 1.10	450	2405	2.3 (10^{-5})	835	4560	2.3 (10^{-5})
LF = 1.35	450	2520	2.3 (10^{-5})	845	4646	2.3 (10^{-5})
LF = 1.60	450	2560	2.5 (10^{-5})	850	4683	2.5 (10^{-5})
Rigid Structure	450	2835	4.4 (10^{-5})	850	5415	4.4 (10^{-5})

Design Level	Velocity and Length Distributions Not Modified for Sanderson's Criteria			Velocity and Length Distributions Modified for Sanderson's Criteria		
	Force		Probability of Exceeding Global Resistance (Sliding Force - 3650 MN)	Force		Probability of Exceeding Global Resistance (Sliding Force - 3650 MN)
	1 in 100 (MN)	1 in 10,000 (MN)		1 in 100 (MN)	1 in 10,000 (MN)	
$P = 11A^{-0.5}$						
LF = 1.10	450	2405	2.3 (10^{-5})	835	4560	2.3 (10^{-5})
LF = 1.35	450	2520	2.3 (10^{-5})	845	4646	2.3 (10^{-5})
LF = 1.60	450	2560	2.5 (10^{-5})	850	4683	2.5 (10^{-5})
Rigid Structure	450	2835	4.4 (10^{-5})	850	5415	4.4 (10^{-5})
P = 6 (constant)						
LF = 1.10	771	3577	9.3 (10^{-5})	1246	6625	7.5 (10^{-4})
LF = 1.35	776	3611	9.6 (10^{-5})	1285	6700	7.5 (10^{-4})
LF = 1.60	776	3677	1.0 (10^{-4})	1345	6765	7.9 (10^{-4})
Rigid Structure	776	5000	2.8 (10^{-4})	1470	9400	1.2 (10^{-3})

The results of the analyses show that the coefficients which change the form of the P versus A curves is not significant in the final force developed by an iceberg, but the minimum average ice pressure developed in the ice after crushing is significant. As can be seen for P versus A curves 1 to 5, the final iceberg force for the 1 in 100 year iceberg and 1 in 10000 year iceberg is the same in all five cases. These five P versus A curves have the same minimum average ice pressure of 2 MPa. P versus A curve 6 produces significantly higher forces. The minimum average pressure generated in P versus A curve number 6 is 6 MPa.

The reason that the coefficients for the P versus A curves are not significant is that the average ice crushing pressure very quickly goes to the minimum value as the area of iceberg contact with the structure increases. Only very small icebergs are affected by the form of the ice crushing pressure curves. The above results also show that the modification of the velocity and length distributions has a very significant effect on the expected force imparted on a structure by an iceberg. In fact the force is almost doubled when the velocity and length distributions are modified according to Sanderson's criteria.

The results also show that the iceberg forces calculated using ICELOAD are very high and in fact show that the structure is likely to fail in global sliding with higher probability than that allowed. The target reliability level for Safety Class I is 10^{-5}. It is also evident from the results that a conservative penetration of approximately 1.0 m into the structure for the 1 in 10000 year iceberg does not endanger the oil containment cells or drilling shafts. The probabilities of failure can be seen in *Table 5.4* above. Using this analysis shows that the safety against environmental damage far exceeds that required for a Safety Class I structure.

6.0 ECONOMIC ANALYSIS

In addition to the failure analysis from the previous section, the sensitivity of the present value of the damage costs on a structure due to the pressure versus area curve was examined. Cost analysis was carried out for each of the three load factor designs using the two minimum average ice crushing pressures (2 MPa and 6 MPa) for each design.

6.1 Methodology

A computer program SIMCOST was written for the purposes of this project to carry out the damage cost analysis. SIMCOST was executed for each of the designs for each of the minimum average ice crushing pressures. The present value of the damage costs (damage costs) were calculated for five different real discount rates. The resulting damage costs were added to the initial capital cost of the structure to see which load factor design was most economical in each P versus A curve design case.

6.2 Computer Program: SIMCOST

SIMCOST is a program which simulates the life of the structure and determines the present value of the cost of repair when the structure is damaged by an iceberg. In the simulation, once the structure is damaged, it is assumed to be repaired immediately and the simulation is continued until the service life of the structure is completed. The results of several simulations are compiled and the mean value of the results along with the results from each simulation causing damage is output to file. The simulation is done using a Monte Carlo simulation. From the SIMCOST output the exceedance of any level of damage cost can be determined.

In order to use SIMCOST, a force versus damage cost relationship is determined for the structure to be analyzed prior to running SIMCOST. The force versus probability of exceedance relationship developed using ICELOAD is also obtained.

6.2.1 Developing the Force versus Cost Relationship

Damage to the structure was determined for several discrete iceberg return periods. The loads applied for the 1 in 500, 1 in 10,000 and the 1 in 100,000 year icebergs are given previously in Section 3. The loads for the different icebergs were applied to the structure using the same principles as used to determine the loading for the 1 in 100 year iceberg in Section 4. The iceberg pressure was set at 6 MPa. The load patch was varied in several different finite element computer runs to obtain the worst location for damage.

The damage criteria for the structure was based on a given element location failing the ultimate limit states criteria at a load factor of 1.0. Any areas damaged were assumed to be entirely demolished and were assumed to require complete rehabilitation. The size of the worst damage patches for each load factor is summarized in tabular form in *Table 6.1*.

Table 6.1: Summary of Iceberg Damage Areas

Iceberg Return Period (Years)	Damaged Area					
	Load Factor					
	1.1		1.35		1.6	
	Ice Wall (m^2)	Support Wall (m^2)	Ice Wall (m^2)	Support Wall (m^2)	Ice Wall (m^2)	Support Wall (m^2)
500	85	35	45	20	0	0
10,000	170	100	65	55	40	35
100,000	215	110	85	90	65	55

To estimate the repair cost for these damage patches, the following assumptions for cost were used:

Concrete	$500	/m^3
Rebar	$2,400	/Tonne
Diving Platform	$70,000	/Day
Diving Crew	$25,000	/Day

These prices are based on order of magnitude estimations obtained in telephone conversations with contractors currently involved in the construction and repair of offshore structures, and on in-house experience with this type of work. The time required to complete the repairs depends on the number of bars affected by the damaged area, therefore the estimated time to complete repairs depends on the design of the structure and the size of the impacting iceberg. The average time required for repairs is approximately 110 days. This again is an order of magnitude assessment to determine levels of cost for repairs. This may not be the most effective repair scheme. The repair costs for each design case are summarized for each design in tabular form in *Table 6.2.*

Table 6.2: Force versus Estimated Cost of Repair Data

Force (MN)	Cost ($ Millions)		
	LF = 1.10	LF = 1.35	LF = 1.60
610	0	-	-
750	-	0	-
890	-	-	0
970	14.1	10.7	5.0
1470	28.0	22.0	16
1760	29.3	24.8	20.3

The results of the cost analysis was matched with a best fit curve to create the Force versus Cost curves for input into SIMCOST.

6.2.2 Input to SIMCOST

SIMCOST accepts the following input:

- service life of structure
- arrival rate for collisions
- discount rate at which to calculate present value
- force versus damage cost relationship
- force at which damage begins
- the variability in the cost estimation
- force versus probability of exceedance relationship from ICELOAD

6.2.3 Output from SIMCOST

One file is output from SIMCOST. The file COSTS.SUM gives a summary of the present value of the damage cost, (given that damage has occurred), for different probability of exceedance levels. From this output file, the expected present value of damage costs can be determined for any exceedance level. In addition to the file COSTS.SUM, the statistical information for the damage costs, including the mean value and standard deviation, are output to screen along with the number of simulations in which damage occurs. The damage cost for the structure including the events in which no damage occurs can be determined by multiplying the results from COSTS.SUM by the number of simulations in which damage has occurred and then dividing by the total number of simulations.

The results of SIMCOST are summarized for total expected costs of repair *assuming* damage occurs for the case where the statistical distributions for the velocity and length variables *are not* modified in *Table 6.3* and for the case where they *are* modified in *Table 6.4*. The results are summarized for total expected costs of repair *not assuming* damage occurs for the case where the statistical distributions for the velocity and length variables *are not* modified in *Table 6.5* and for the case where they *are* modified in *Table 6.6*. The results are tabulated for a 20 year service life.

Table 6.3: Total expected cost of repairs assuming damage occurs at least once in the lifetime of the structure. Velocity and length distributions not modified.

Expected Repair Costs ($ Millions)					
Structure Design Level	Real Discount Rate				
	0%	2.5%	5.0%	7.5%	10.0%
2.0 MPa					
LF = 1.10	12.9	10.1	8.0	6.5	5.4
LF = 1.35	13.9	10.8	8.6	7.0	5.8
LF = 1.60	12.7	9.9	7.8	6.3	5.2

Expected Repair Costs ($ Millions)					
Structure Design Level	Real Discount Rate				
	0%	2.5%	5.0%	7.5%	10.0%
6.0 MPa					
LF = 1.10	15.5	12.1	9.7	9.2	6.5
LF = 1.35	15.5	12.2	9.7	7.9	6.5
LF = 1.60	14.9	11.7	9.3	7.6	6.3

Table 6.4: Total expected cost of repairs assuming damage occurs at least once in the lifetime of the structure. Velocity and length distributions modified.

Expected Repair Costs ($ Millions)					
Structure Design Level	Real Discount Rate				
	0%	2.5%	5.0%	7.5%	10.0%
2.0 MPa					
LF = 1.10	18.9	14.8	11.8	9.7	8.0
LF = 1.35	17.9	14.0	11.2	9.1	7.5
LF = 1.60	16.1	12.6	10.0	8.2	6.8
6.0 MPa					
LF = 1.10	25.2	19.7	15.8	12.9	10.7
LF = 1.35	22.9	18.0	14.4	11.7	9.7
LF = 1.60	19.9	15.6	12.5	10.2	8.4

Table 6.5: Total expected cost of repairs of damage not assuming damage occurs. Velocity and length distributions not modified.

Expected Repair Costs ($ Millions)					
Structure Design Level	Real Discount Rate				
	0%	2.5%	5.0%	7.5%	10.0%
2.0 MPa					
LF = 1.10	1.6	1.2	1.0	0.8	0.7
LF = 1.35	1.0	0.8	0.6	0.5	0.4
LF = 1.60	0.7	0.5	0.4	0.3	0.3
6.0 MPa					
LF = 1.10	4.2	3.3	2.6	2.5	1.8
LF = 1.35	3.1	2.4	1.9	1.6	1.3
LF = 1.60	2.3	1.8	3.1	1.2	1.0

Table 6.6: Expected cost of repairs of damage not assuming damage occurs. Velocity and length distributions modified.

Expected Repair Costs ($ Millions)					
Structure Design Level	**Real Discount Rate**				
	0%	**2.5%**	**5.0%**	**7.5%**	**10.0%**
2.0 MPa					
LF = 1.10	5.5	4.3	3.4	2.8	2.3
LF = 1.35	4.2	3.3	2.6	2.1	1.8
LF = 1.60	2.7	2.1	1.7	1.4	1.2
6.0 MPa					
LF = 1.10	11.8	9.2	7.4	6.1	5.0
LF = 1.35	9.2	7.3	5.8	4.7	3.9
LF = 1.60	7.2	5.7	4.5	3.7	3.1

The results from this analysis were added to the capital cost estimates to complete the economic analysis.

6.3 Capital Cost Estimate

An order of magnitude capital cost estimate of the portion of the structure that includes the ice wall and the support walls immediately adjacent to the ice wall was carried out for each of the load factor designs. Estimated costs are based on costs for structures built in similar conditions for other types of structures. Concrete was estimated to cost $300/m^3 and reinforcement steel was estimated to cost $1,900/Tonne installed. A summary of the capital cost for each design is given in *Table 6.7.*

Table 6.7: Capital Cost Estimates for the Ice Wall and Adjacent Support Walls

Design Load Factor	Capital Cost ($)
1.10	86,000,000
1.35	92,000,000
1.60	101,000,000

6.4 Expected Cost Analysis

The final expected costs for each structure was calculated by adding the capital costs to the present value of the damage costs. The results of the analysis is shown in *Table 6.8* to *Table 6.11.*

Table 6.8: Total expected project cost assuming damage occurs at least once in the lifetime of the structure. Velocity and length distributions not modified.

Structure Design Level	Expected Project Cost ($ Millions)				
	Real Discount Rate				
	0%	2.5%	5.0%	7.5%	10.0%
2.0 MPa					
LF = 1.10	98.9	96.1	94.0	92.5	91.4
LF = 1.35	105.9	102.8	100.6	99.0	97.8
LF = 1.60	113.7	110.9	108.8	107.3	106.2
6.0 MPa					
LF = 1.10	101.5	98.1	95.7	95.2	92.5
LF = 1.35	107.5	104.2	101.7	99.9	98.6
LF = 1.60	115.9	112.7	110.3	108.6	107.3

Table 6.9: Expected project cost assuming damage occurs at least once in the lifetime of the structure. Velocity and length distributions modified.

Structure Design Level	Expected Project Cost ($ Millions)				
	Real Discount Rate				
	0%	2.5%	5.0%	7.5%	10.0%
2.0 MPa					
LF = 1.10	104.9	100.8	97.8	95.7	94
LF = 1.35	109.9	106.0	103.2	101.1	99.5
LF = 1.60	117.1	113.6	111.0	109.2	107.8
6.0 MPa					
LF = 1.10	111.2	105.7	101.8	98.9	96.7
LF = 1.35	114.9	110.0	106.4	103.7	101.7
LF = 1.60	120.9	116.6	113.5	111.2	109.4

Table 6.10: Expected project cost not assuming damage occurs. Velocity and length distributions not modified.

Structure Design Level	Expected Project Cost ($ Millions)				
	Real Discount Rate				
	0%	2.5%	5.0%	7.5%	10.0%
2.0 MPa					
LF = 1.10	87.6	87.2	87.0	86.8	86.7
LF = 1.35	93.0	92.8	92.6	92.5	92.4
LF = 1.60	101.7	101.5	101.4	101.3	101.3
6.0 MPa					
LF = 1.10	90.2	89.3	88.6	88.5	87.8
LF = 1.35	95.1	94.4	93.9	93.6	93.3
LF = 1.60	103.3	102.8	104.1	102.2	102.0

Table 6.11: Expected cost of repairs of damage not assuming damage occurs. Velocity and length distributions modified.

Structure Design Level	Expected Project Cost ($ Millions)				
	Real Discount Rate				
	0%	2.5%	5.0%	7.5%	10.0%
2.0 MPa					
LF = 1.10	91.5	90.3	89.4	88.8	88.3
LF = 1.35	96.2	95.3	94.6	94.1	93.75
LF = 1.60	103.7	103.1	102.7	102.4	102.2
6.0 MPa					
LF = 1.10	97.8	95.2	93.4	92.1	91.0
LF = 1.35	101.2	99.3	97.8	96.7	95.9
LF = 1.60	108.2	106.7	105.5	104.7	104.1

Note that the most economical structure is consistently the structure designed to the lowest load factor. The expected cost of the structure increases with increasing load factor.

7.0 CONCLUSIONS AND RECOMMENDATIONS FOR PHASE I

The following conclusions were compiled during the course of the study:

- Designing a gravity based structure to a lower load factor is economical, even after the effects of damage costs are added to the economic analysis. The initial capital cost of the structure outweighs the added expected damage costs associated with iceberg impacts;

- Designing to a lower ultimate limit states design load factor increases the risk of local damage to the structure and the possibility of environmental damage due to breaching of oil shafts, but slightly decreases the possibility of catastrophic global structure failure;

- Assuming that the structure is infinitely rigid when determining the iceberg load on a structure is conservative. The assumption that the structure is infinitely rigid for the determination of iceberg loads is currently standard practice;

- Including energy dissipation through structure deformation gives more realistic iceberg load results;

- The form of the iceberg pressure versus area curve is not important for the outcome of iceberg load evaluations. The most important parameter in iceberg load evaluations is the minimum contact pressure that the iceberg ice can sustain;

- The main source of uncertainties in the design loads for icebergs are those relating to the uncertainties in the evaluation of the icebergs loads on a rigid structure. The uncertainties in the structure resistance factors and the load carrying capacity of the structure is not significant compared to the variability in the iceberg forces calculated using different minimum iceberg contact pressures;

- The computer program ICELOAD is an effective tool for determining iceberg loads; and,

- The computer program SIMCOST is an effective tool for determining the present value of damage to the structure.

The following recommendations were compiled upon completion of this study:

- Reduce the ultimate limit state load factor from 1.35 to 1.1. During the course of the study, it was determined that the load factor used for design has little influence on the total safety of the structure at the design levels used. In fact, higher rigidity of the structure due to the higher strength actually increases slightly the probability of global failure in the structure;

- Provide greater emphasis on determining the properties of iceberg ice; particular attention should be placed on determining the minimum average ice pressure that an iceberg can exert on the structure;

- Provide greater emphasis on determining the distributions of iceberg sizes and movement velocities;

- Provide greater emphasis on determining force versus structure deformation curves for structure failure modes found in Gravity Based Structures;

- Upgrade the ICELOAD computer program to include the effects of eccentric iceberg impacts, to add the ability to input numerical statistical distributions, and to make them more user friendly; and,

- Upgrade the SIMCOST computer program.

8.0 PHASE II

8.1 Methodology

The methodology for Phase II of the work was as follows:

- determine loadings associated with independent frequent and rare environmental events as a function of return period;
- determine loadings associated with combined rare and frequent environmental events as a function of return period;
- determine the force level required to attain a reliability level of 10^{-5} for the combined rare and frequent environmental events; and,
- compare loadings determined for combined rare and frequent environmental event loads with the load combinations given in S471 and back calculate the load combination factor.

8.2 Scope of Work

The work undertaken to complete Phase II of the work included the following:

- search of existing literature;
- development of relationships used for calculating environmental loads;
- development of reliability based computer programs for calculating environmental loads;
- determination of wave loads as a function of return period;
- summarization of earthquake loads from Verification Project G-2A;
- summarization of iceberg loads taken from Phase I;
- determination of wave and iceberg loads in combination as a function of return period;
- determination of wave and earthquake loads in combination as a function of return period; and,
- determination of actual load combination factors using data from environmental loads determined as above.

9.0 CODE SPECIFIED LOAD COMBINATION FACTORS FOR RARE AND FREQUENT ENVIRONMENTAL LOADS

9.1 Frequent and Rare Environmental Events

Frequent environmental events as listed in S471 include the following:

- wind
- waves
- currents
- sea ice
- icebergs and bergy bits (depending on location)
- tide
- marine growth
- snow and ice accumulation
- storm surges and seiches

Rare environmental events as listed in S471 include the following:

- earthquakes and related earthquake effects
- icebergs and other rare ice features
- sea ice
- tsunamis

Loads based on frequent environmental processes have an annual probability of exceedance (P_E) not greater than 10^{-2} for both Safety Classes 1 and 2. Safety Classes are explained in S471. Loads based on rare environmental events have an annual P_E not greater than 10^{-2} for Safety Class 2 and between 10^{-4} and 10^{-3} for Safety Class 1.

9.2 Code Specified Load Combination Factors

In determining both frequent and rare environmental loads, consideration must be given to the occurrence of companion frequent environmental events. Guidelines for the combination of environmental loads is given in S471. The companion load factors for frequent environmental loads in combination with rare environmental events given in the code is shown in *Table 9.1* below. The table is taken directly from *Table 6.1(b)* of CAN/CSA-S471-92.

Table 9.1: Values of Loads Due to Companion Frequent Environmental Process E_f - Specified Frequent Environmental Loads

Principal Process or Event	Companion Environmental Process	
	Stochastically Dependent	Stochastically Independent
Principal Environmental Process	E_f	0.6 E_f
Rare Environmental Event	0.8 E_f	0.4 E_f

Note in *Table 9.1* that the load factors are different for companion environmental processes which are stochastically dependent and for those which are stochastically independent. Companion load processes for the different combinations of environmental loadings and their level of dependence on each other is shown in *Table 9.2* below. *Table 9.2* is taken directly from *Table 6.1(a)* of S471.

Table 9.2: Companion Frequent Environmental Processes

Principal Environmental Process or Rare Environmental Event	Companion Frequent Environmental Processes		
	Stochastically Dependant	**Stochastically Independent**	**Mutually Exclusive**
Waves	Wind, wind-driven current	Tidal and background current	Sea ice
Wind	Waves, wind-driven current	Tidal and background current	Sea ice
Wind	Wind-drive current, sea ice	Tidal and background current	Waves
Current (tide and background)	Sea ice	Wind, wind-driven current	Waves
Sea Ice	Wind, wind-drive current, tidal current	-	Waves
Earthquake	-	Waves, wind, wind-driven current, tidal and background current	-
Icebergs or Isolated Ice Floes	Wind, wind-driven current, tidal and background current	Waves	-

For the purposes of this study, only waves were considered in determining loads for a frequent environmental process. Only earthquakes and icebergs were considered in determining loads for rare environmental events. The load combinations which were examined for the above load conditions were as follows:

- waves with earthquake, and
- waves with iceberg

The combination of earthquakes with waves were taken to be stochastically independent as shown in *Table 9.2*. Waves in combination with icebergs are also shown as stochastically independent in *Table 9.2*, but in a storm condition the iceberg can be driven by the same wind forces as the ones driving the waves of the storm. For this reason, the companion events were considered to be stochastically dependent for the purposes of this study.

9.3 Load Combination Factor Determination Methodology

The methodology for determining the appropriate load combination factor for combined frequent and rare environmental events is as follows:

- determine the loads due to waves alone and extract the load due to the 10^{-2} wave;
- determine the loads due to earthquakes alone and extract the load due to the 10^{-4} earthquake;
- determine the loads due to icebergs alone and extract the load due to the 10^{-4} iceberg;
- determine the loads due to earthquake in combination with storm waves and extract the load which would result in a probability of exceedance of 10^{-5};
- determine the loads due to icebergs in combination with wind and storm waves and extract the load which would result in a probability of exceedance of 10^{-5};
- back calculate the load combination factor for earthquake combined with waves; and,
- back calculate the load combination factor for iceberg combined with waves.

The processes for the determination of wave loads, iceberg in combination with wind and wave loads and earthquakes in combination with waves is presented in the following chapters. These processes involve the development of fundamental relationships for the environmental loads from first principles and incorporating the relationships into a reliability based computer program. Earthquake loads were previously calculated in Verification Project G-2A and iceberg alone loads were calculated in Phase I using a reliability based computer program.

The load which would result in a probability of failure of the structure of 10^{-5} (the failure load) could be based on any one of the following:

- global sliding of the structure;
- overturning of the structure;
- breaching of oil containment cells causing environmental damage.

In this study, the failure load was based on the load required to cause global sliding of the structure. Overturning of a typical Grand Banks GBS was found to have a higher factor of safety than global sliding in Verification Project G-2A and breaching of the oil containment cells was found to require a load considerably higher than the global sliding load. Note that significant amounts of energy can be dissipated by sliding of the structure in an overload situation, and so the structure is inherently safe. This method of improving the reliability has not been considered herein as it requires specific information on movement and ductility of the flow lines, which were not available for this study.

10.0 ENVIRONMENTAL LOADING

Environmental loading relationships were determined for waves alone, waves with icebergs and waves with earthquake. The theory used in the analysis and the development of formulae for use in determining environmental loads is given in the following sections.

10.1 Waves

An analysis is first carried out for the structure alone in order to provide results of wave loads in the absence of iceberg or earthquake loading. This analysis is intended in part to verify the corresponding computer model against available results, since the model is subsequently applied to the case of waves and an iceberg in combination; and in part to provide corresponding results for the structures alone which are needed to develop the required factors in *Table 6.2* of the CSA code.

10.1.1 Design Wave Conditions

Initially, a simple representation of the long-term distribution of wave conditions is required. These are represented here in terms of a single parameter, the peak period T_p (wave period corresponding to the peak of the wave spectral density). The significant wave height H_s (average height of the highest one third of the waves) is taken to be related to peak period T_p on the basis of the following formula which has been found to be suitable for conditions in Canadian Atlantic waters (Neu, 1982):

$$H_s = 0.0509 T_p^2 \qquad (10.1)$$

The probability distribution of T_p has been developed by assuming that it follows an Extreme Type I distribution such that T_p = 15 sec for T_R = 1.05 years, and T_p = 18 sec for T_R = 100 years (Westmar Consultants Inc., 1990). On this basis, the cumulative distribution function $P[T_p]$ of T_p is expressed as:

$$P[T_p] = \exp(-\exp[-1.9044(T_p - 15.5846)]) \qquad (10.2)$$

If required, the return period T_R may be expressed in terms of $P[T_p]$ as:

$$T_R = \frac{1}{1 - P[T_p]} \qquad (10.3)$$

The above expressions corresponds to the following specific wave conditions:

$$T_p = 15 \text{ sec}, \ H_s = 11.4 \ m \qquad for \ T_R = 1.05 \ years$$

$$T_p = 18 \text{ sec}, \ H_s = 16.5 \ m \qquad for \ T_R = 100 \ years$$

The significant wave heights given above differ somewhat from those given by Westmar Consultants Inc. (1990) since they have been obtained on the basis of the *Equation 10.1* from the previous page.

10.1.2 Regular Wave Forces

The loads due to regular waves interacting with the structure may be obtained on the basis of linear diffraction theory. This is based on the assumptions of a horizontal seabed, small amplitude waves (although such results are generally applied to all wave heights), and potential flow theory, which itself is based on the assumptions of an inviscid fluid and an irrotational flow. The corresponding boundary value problem may be treated by a computer model based on a boundary element method. A closed-form solution is also available (e.g. Sarpkaya and Isaacson, 1981) since the structure is assumed to correspond to a vertical circular cylinder. However, because a computer model based on the boundary element method is subsequently used for the case of combined wave-iceberg loading, it is appropriate to verify its results for the cylinder alone against those based on the closed-form solution.

The computer model employs a suitable Green's function and involves the solution of a surface integral equation in order to obtain the pressure distribution around the submerged surface of the structure. This pressure distribution is integrated to obtain the load components acting on the structure. Since the structure is a vertical circular cylinder, the only load components are the horizontal force acting in the wave direction, and the corresponding overturning moment. With regular waves of height H and period T, the wave force on the structure vary sinusoidally with the wave period, and thus are expressed as $F \cos(\omega t)$, where $\omega = 2\pi/T$, and F is the force amplitude. F is linearly proportional to the wave height H so that results for waves of unit height $H = 1$ m suffice.

A corresponding comparison between the results of the computer model and the closed-form solution is presented in *Table 10.1* for several wave periods. The results were obtained on the basis of a discretization of the cylinder surface into 48 facets. The table indicates that the agreement is generally very good, with the numerical results within about 2% of the closed-form solution.

Table 10.1: Comparison of numerical and closed-form predictions of the wave force and overturning moment on the structure (H = 1 m).

T (sec.)	Force (MN)	
	Numerical	Closed-form
10	28.8	29.3
12	46.3	46.8
14	62.2	62.6
16	72.5	72.5
18	77.1	76.7
20	77.6	76.8

Since the wave load results are ultimately required for application to a probabilistic model in the context of combined wave-iceberg loading and combined wave-earthquake loading, a simple expression for the wave force is required. The calculations indicated above have been carried out on the basis of the following parameters:

Water depths, d	80 m
Structure diameter, D	116 m
Water density, ρ	1025 kg/m^3
Regular wave period, T	10, 12, 14, 16, 18, 20 sec

The corresponding results for the wave force have been fitted by a suitable polynomial in order to express the wave force amplitude directly in terms of the wave period. This is:

$$F = H[-101.670 + 16.755\,T - 4.4083 \times 10^{-1}\,T^2] \tag{10.4}$$

where H is in m, T is in seconds, and F is in MN.

10.1.3 Random Wave Forces

The loads due to random waves may be obtained as an extension of the case of regular waves. When random waves of significant height H_s and peak period T_p are considered to act on the structure, the wave force may still be taken as $F\cos(\omega t)$. The frequency ω is now given as $\omega = 2\pi/T_p$, and the force amplitude F is now a random quantity which may be approximated by a Rayleigh distribution:

$$P[F] = 1 - \exp\left[\left(\frac{-2F}{F_s}\right)^2\right] \tag{10.5}$$

Here *P[F]* is the cumulative probability, and F_s is the significant value of the force (average of the highest one third of the force maxima) which may be used to characterize the distribution. The Rayleigh distribution gives rise to other characteristic values which may be related to the significant value F_s. For examples, the mode and median of F are $0.500F_s$ and $0.588F_s$ respectively.

In addition, the expected value of the largest value of F over a specified duration τ, denoted $E[F_{max}]$ is also of interest and may be estimated on the basis of the following formula:

$$E[F_{max}] = F_s \left[\frac{\ln(\omega\tau)}{2}\right]^{\frac{1}{2}} \tag{10.6}$$

Typically, this provides $E[F_{max}]/F_s \approx 1.8 - 2.0$

Since linear diffraction theory is used to calculate wave loads, the wave force is proportional to the wave height, so that the significant force can be obtained by applying diffraction theory directly to a regular wave train of height H_s. Because of this, the maximum force due to a random sea state corresponding to specified return periods may be obtained directly from the results given in *Table 10.2* or *Equation 10.4.*

Table 10.2: Predicted wave force on the structure for design wave conditions.

T_R (years)	T_p (sec)	H_s(m)	F_s(MN)
1.05	15.0	11.4	779
100	18.0	16.5	1,265

10.2 Waves and Iceberg

When an iceberg impacts the structure in the presence of waves, there are various hydrodynamic effects which arise and which may be taken into account in estimating the combined force due to both the iceberg and waves. These include the following:

- the added mass of the iceberg at impact may be different to that of an isolated iceberg;
- the impact velocity of an iceberg in the presence of waves may be different to that when waves are absent;
- the wave force on the structure while it is being impacted by an iceberg is different to that when an iceberg is absent; and,

- the wave force on the iceberg while it is impacting the structure affects the maximum force of the iceberg on the structure.

These aspects are considered further below.

10.2.1 Added Mass at Impact

The added mass of an iceberg is determined by solving the boundary value problem corresponding to an iceberg undergoing small amplitude oscillations in otherwise still water. In general, the added mass is frequency dependent, although it is customary to use a single value (usually the zero frequency value) when treating the iceberg impact problem. The added mass of the iceberg depends on the submerged iceberg geometry, the water depth and the submerged geometry of any neighbouring structure that may be present, and so is a function of the iceberg distance from the structure. The calculation of the added mass under such conditions may be made by solving a two body boundary value problem corresponding to the iceberg oscillating in otherwise still water in the vicinity of a fixed structure. A description of this has been given by Isaacson and Cheung (1988a, 1988b). On the basis of this approach, an assessment of the added mass μ 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, it turns out the added mass is not strongly influenced by proximity to the structure. A simple expression for the added mass for use in the probabilistic model is given in Section 10.2.4.

10.2.2 Impact Velocity

Although data for the open water drift velocity of icebergs is generally available, the iceberg's velocity may differ from such data when storm waves are present and when it approaches the structure. There are two reasons for the differing velocities. Firstly, the waves give rise to a wave drift force which causes an increase in the iceberg velocity. Secondly, since the wave drift force and iceberg added mass vary with distance from the structure, the iceberg velocity may be further modified through its equations of motion as it approaches the structure. Bearing these factors in mind, an outline of the calculation of the iceberg impact velocity is given below.

(i) Wave absent. In the absence of waves, the iceberg velocity V is approximately equal to that of the prevailing current U in order for the iceberg to be in equilibrium. There is then no net drag force on the iceberg, and hence it does not accelerate and moves at a steady velocity $V = U$.

(ii) Waves present, iceberg far from the structure. When waves are present, a wave drift force F_{wd} acts on the iceberg, and the iceberg velocity V is then increased above the current velocity U such that the wave drift force F_{wd} exactly counteracts the drag force F_d in order for the iceberg to be in equilibrium and hence not accelerate. This force balance may be expressed as $F_{wd} = F_d$, with F_d itself given as:

$$F_d = \frac{1}{2}\rho A C_d (V-U)^2 \tag{10.7}$$

where C_d is a drag coefficient, and A is the cross-sectional area of the submerged iceberg normal to its direction of motion. This equation can be used to provide the iceberg velocity V for a known current U and a known value of F_{wd} corresponding to a specified wave condition:

$$V = U + \frac{\sqrt{2F_{wd}}}{\rho A C_d} \tag{10.8}$$

(iii) Waves present, iceberg approaching the structure. When waves are present and the iceberg is approaching the structure, the iceberg added mass and the wave drift force both vary with distance from the structure, and therefore the iceberg velocity changes in accordance with the equation of motion of the iceberg. For a head-on impact, only a single equation of motion is needed and this is given as:

$$[m + \mu(x)]\frac{d^2x}{dt^2} = F_{wd}(x) - F_d(U) \tag{10.9}$$

where m is the iceberg mass, and x denotes the iceberg displacement in the direction of the structure. Using suitable initial conditions at some distance ahead of the structure, a time-stepping procedure can be applied to the above equation in order to calculate the impact velocity V_i of the iceberg. The influence of the drift force on the iceberg motion is described by Isaacson (1988).

On the basis of the foregoing considerations, the impact velocity V_i differs from the open water drift velocity and depends on the current magnitude U, the iceberg dimensions, characterized by its waterline diameter L and draft h, and the prevailing wave condition characterized by H_s or T_p. A wave diffraction-radiation analysis has been carried to for a series of conditions corresponding to the iceberg approaching the structure. For each such condition, the submerged surfaces of the structure and iceberg are discretized into a number of quadrilateral facets for application to a corresponding computer program; the program has been run for a series of appropriate conditions in order to obtain the trajectory of the iceberg and the impact velocity. This procedure is described in detail by Isaacson (1987) and Isaacson and Dello Stritto (1986). Because of the magnitude of the wave drift force, the impact velocity is generally significantly larger than the prevailing current magnitudes when storms are absent. This turns out to be an important factor in calculating the maximum force on the structure since the energy of the iceberg depends on V_i^2.

10.2.3 Wave Loads During Impact

During the iceberg impact process, the wave force on the structure differs from that on the isolated structure because of the presence of the iceberg. In addition, a wave force is also exerted on the iceberg and this affects the iceberg force on the structure.

Regular Waves. While the iceberg is impacting the structure, the wave force on the iceberg may be expressed as $F_w^{(i)}$ cos (ωt - ε), where $F_w^{(i)}$ is the amplitude of the oscillatory wave force on the iceberg, and ε is a phase angle corresponding to the phase of the wave force of the iceberg at the instant of impact. The wave force on the structure may be expressed as $F_w^{(s)}$ *cos(ωt - ε - ϕ),* where $F_w^{(s)}$ is the amplitude of the oscillatory wave force on the structure, and ϕ denotes a phase difference between the wave force on the iceberg and the structure.

Random Waves. Under random waves, the above formulation applies, except that $F_w^{(i)}$ and $F_w^{(s)}$ and ε are random quantities. The two force amplitudes $F_w^{(i)}$ and $F_w^{(s)}$ may each be approximated by a Rayleigh distribution characterized by the corresponding significant values. ε is now a random quantity and, to a first approximation, may be taken to possess a uniform distribution since for a large iceberg the wave-induced oscillatory velocity is small so that the impact may be expected to occur at any wave phase with equal probability. [For a smaller iceberg, for which the wave-induced oscillatory motion becomes more significant, the distribution of ε may not be uniform, since impact may be more likely to occur when the iceberg has a forward oscillatory velocity. However, such small icebergs need not be considered here as a design case.] Finally, the phase difference ϕ remains constant.

Because of the wave loading on the iceberg, its equation of motion during the impact process is given as:

$$(m+\mu)\frac{d^2x}{dt^2} = -F_i(x) + F_w^{(i)}\cos(\omega t-\varepsilon) \qquad (10.10)$$

where m is the iceberg mass, x is its displacement (which corresponds to its penetration into the structure), and $F_i(x)$ is the structure force of the structure on the iceberg, which is a function of the penetration x. The drag and wave drift forces have been omitted from *Equation 10.10* since these are small in relation to the F_i and the oscillatory wave force $F_w^{(i)}$.

Apart from the iceberg force on the structure, F_i, the structure also experiences a wave force which is expressed above as $F_w^{(s)}$ cos(ωt - ε - ϕ). The combined force on the structure due to both the iceberg and waves is thus given as:

$$F_c = F_i + F_w^{(s)}\cos(\omega t-\varepsilon-\phi) \qquad (10.11)$$

The maximum values of F_c may be obtained numerically by a suitable time-stepping procedure applied to the iceberg's equation of motion.

In order to carry out the above procedure in the context of a suitable probabilistic model for combined wave-iceberg loading, simple expressions for the various parameters are required and have been obtained. Thus, a wave diffraction analysis has been carried out for the two body problem of iceberg-structure contact for a series of iceberg parameters and wave conditions to provide the wave force on the structure and the iceberg. For each such configuration, the submerged surfaces of the structure and iceberg are discretized into a number of quadrilateral facets for application to the corresponding computer program. The structure is assumed to be a vertical circular cylinder extending from the seabed to the free surface. The iceberg is assumed to be an ellipsoid with a circular plan form. Computations for regular waves have been obtained for regular waves with height $H = 1$ m, since results for other wave heights may be obtained directly from these on the basis of the linearization assumption which is entailed in the radiation-diffraction theory.

10.2.4 Parametric Representations

The various calculations described in Sections 10.2.1 to 10.2.3, have been carried out on the basis of the following parameters:

Constant parameters

Water depth, d	80 m
Structure diameter, D	116 m
Water density, ρ	1025 kg/m^3
Ice density, ρ_i	895 kg/m^3

Variable parameters

Iceberg waterline diameter, L	80, 140, 200 m
Iceberg draft, h	20, 40, 75 m
Regular wave period, T	10, 12, 14, 16, 18, 20 sec
Open water velocity, U	0.1, 1, 2, 3 m/sec

The parameters required for application to the probabilistic model as follows:

ω wave angular frequency

$F_w^{(i)}$ amplitude of wave force on iceberg

$F_w^{(s)}$ amplitude of wave force on structure

ε phase of wave crest at iceberg centroid at the instant of impact

ϕ phase difference between the wave force on the iceberg and the structure

μ iceberg added mass

V_i iceberg impact velocity

The corresponding results have been fitted by suitable functions in order to express the required parameters indicated above directly in terms of the variable input parameters L, h, T and U, and these functions are provided below. In the following expressions, all parameters are in metric units, except where otherwise stated.

$$\omega = 2\pi/T \tag{10.12}$$

$$F_w^{(i)} = 0.01720h\, L^2 H \frac{C_{mi}}{T^2} \qquad (F_w^{(i)} \textit{ in MN}) \tag{10.13}$$

$$F_w^{(s)} = 0.01012 \frac{H\, C_{ms}}{T^2} \qquad (F_w^{(s)} \textit{ in MN}) \tag{10.14}$$

$$\varepsilon = 360.0\, R \qquad (\varepsilon \textit{ in deg}) \tag{10.15}$$

$$\phi = a_4 + a_5 \left[\frac{D}{1.16\lambda}\right] \qquad (\phi \textit{ in deg}) \tag{10.16}$$

$$\mu = C_{ma} m \tag{10.17}$$

$$V_i = U + C\sqrt{\frac{L}{h}} \tag{10.18}$$

where,

$$C_{ms} = [a_1 + a_2 \left(\frac{D}{1.16\lambda}\right) + a_3 \left(\frac{D}{1.16\lambda}\right)^2] \tag{10.19}$$

$$C_{mi} = [2.25 - 3 \left(\frac{L}{\lambda}\right) + \left(\frac{L}{\lambda}\right)^2] \; x \; [2.5255 \; x \; 10^{-1} + 4.0111 \; x \; 10^{-3} L - 5.6944 \; x \; 10^{-3} L^2] \tag{10.20}$$

$$C_{ma} = 0.2229 - 0.0998 \left(\frac{L}{d}\right) + 0.06386 \left(\frac{h}{d}\right) + 0.0833 \left(\frac{L}{d}\right) \left(\frac{h}{d}\right) \tag{10.21}$$

$$a_1 = [1.4756 + 3.8331 \; x \; 10^{-2} h - 3.8052 \; x \; 10^{-4} h^2] \tag{10.22}$$

$$x \, [1.9395 - 9.2436 \; x \; 10^{-3} L + 1.8093 \; x \; 10^{-5} L^2]$$

$$a_2 = [-4.1870 - 1.0847 \; x \; 10^{-1} h + 1.2662 \; x \; 10^{-3} h^2] \tag{10.23}$$

$$x \, [1.7296 - 6.7278 \; x \; 10^{-3} L + 1.0832 \; x \; 10^{-5} L^2]$$

$$a_3 = x \; [2.9091 + 1.0682 \; x \; 10^{-1} h - 1.3636 \; x \; 10^{-3} h^2] \tag{10.24}$$

$$x \, [1.6132 - 4.7543 \; x \; 10^{-3} L + 2.6709 \; x \; 10^{-6} L^2]$$

$$a_4 = [-248.87 - 1.7507 L + 4.0953 \; x \; 10^{-3} L^2] \tag{10.25}$$

$$a_5 = [-371.56 + 11.047 L - 1.9113 \; x \; 10^{-2} L^2] \tag{10.26}$$

$$H = H_s R_2 \tag{10.27}$$

$$H_2 = 0.0509 T^2 \tag{10.28}$$

R_1 is a uniform probability density:

$$R_1 = \begin{cases} 1 & \text{for } 0 < \varepsilon < 360° \\ 0 & \text{otherwise} \end{cases} \tag{10.29}$$

R_2 is the Rayleigh probability density:

$$R_2 = \begin{cases} \dfrac{2H}{H_r^2} \exp\left[-\dfrac{H^2}{H_r^2}\right] & \text{for } H > 0 \\ 0 & \text{otherwise} \end{cases} \tag{10.30}$$

$$H_r = 0.706\ H_s \tag{10.31}$$

λ *is the wave length given as:*

$$\lambda = \frac{160\pi}{k_d} \tag{10.32}$$

C is a constant which defines the level of contribution of storm waves to the iceberg impact velocity.

$$kd\ \tanh(kd) = 4\pi^2 \frac{d}{gT^2}$$

10.3 Waves and Earthquake

For the case of earthquake-induced motions of the structure, the hydrodynamic loads on the structure may be obtained using an approach which is closely related to that used for the case of waves interacting with the fixed structure. The corresponding boundary value problem is similar, with the primary difference associated with a different boundary condition on the structure surface, since this should now account for the structure's motion rather than an incident flow velocity. The analysis proceeds in a similar manner, and the corresponding closed-form solution for a vertical cylinder is described by Isaacson, Mathai and Mihelcic (1990).

When waves and an earthquake occur simultaneously, the CSA code indicates that the two forms of loading may be taken to occur independently. Since calculation methods for wave loading and earthquake loading are each based on linear theory, the flow field associated with each process may indeed by superposed, so that when both act together, the combined hydrodynamic load is simply the sum of those for the two separate cases. This is commonly adopted in problems involving linear diffraction-radiation theory, such as the prediction of the motions of ships and other floating structures. Thus, under conditions of combined wave and earthquake loading, the hydrodynamic loads involve an added mass associated with the seismic event, together with the wave forces on the structure due to the waves as would be acting on the structure if fixed.

11.0 PROBABILISTIC EVALUATION OF ENVIRONMENTAL LOADS

Computer programs using probabilistic methods were written for use in determining environmental loadings. The development of the programs are discussed below.

11.1 Introduction

The design of offshore platforms must take into account the forces produced by wave action, the possibility of earthquake occurrence and, in waters where icebergs are likely to be found, the rare event of iceberg collision with the structure. Furthermore, the design must take into account the possibility that two or more of these loads events could occur simultaneously. For each of the load effects (either by individual or combined action) it is necessary to develop models for the calculation of the maximum force on the structure, and the exceedance probability associated with a given force level. This probability needs to be computed conditional on the event actually taking place, and corrected to an annual risk basis taking into account the occurrence frequency of the event.

This section describes the theoretical and probabilistic approaches used, in each case, to calculate: 1) the force exceedance probabilities and 2) the associated reliability for the limit state of structure sliding on the seabed. The results were used to calibrate the load combination factor used in the CSA Code for Offshore Structures.

11.2 Probabilistic Framework

The estimation of conditional probabilities in the case of a load event was conducted using the program RELAN (RELiability ANalysis), developed at the Civil Engineering department of the University of British Columbia (Foschi *et al,* 1990). This program implements standard FORM and SORM algorithms (First or Second Order Reliability Methods) to calculate the probability that a performance function $G(x)$ of the vector of random variables x takes on negative values. To equate this result to an exceedance or failure probability, the function $G(x)$ was written as follows:

1. To compute exceedance probability of the load level F_o,

$$G = F_o - F_M R_{n2} \tag{11.1}$$

where, F_M is the maximum force developed through individual or combined action and R_{n2} is a random variable associated with model inaccuracy in the calculation of F_M. The probability of the event G $<$ 0 corresponds to the probability that the maximum load F_M exceeds the level F_o.

RELAN is a general reliability analysis program which must be supplemented with a specific description of the limit state to be analyzed. Thus, three computer programs were developed specifically for this portion of the project. The program ICELOAD developed for Phase I of the project, was also used for this phase of the project. The four programs used for this phase of the project are summarized below:

- ICELOAD: For forces due to iceberg collisions only (also discussed previously in Section 5.2).
- ICEWLOAD: For forces due to combination of waves and simultaneous iceberg collision;
- EWLOAD: For forces due to combination of waves and earthquakes;
- WLOAD: For forces due to waves alone.

Each program can be run under one of two options:

- **Option 1** Computes exceedance probability of force level *Fo*, assuming a rigid structure;
- **Option 2** Computes exceedance probability of force level *Fo*, taking into account structure ductility and damage.

After calculation of the probability conditional on the occurrence of the event, the program allows the estimation of the annual risk using the hypothesis that the events follow a Poisson pulse process, with a given mean rate of annual occurrence. Thus, if this rate is μ and the conditional probability of the event is P_e, the annual risk P_a is:

$$P_a = 1.0 - exp(-\mu P_e) \qquad (11.2)$$

In the case of two simultaneous events, the combined mean rate of occurrence μ_{12} was determined as:

$$\mu_{12} = \mu_1 \mu_2 \bullet (\bar{d}_1 + \bar{d}_2) \qquad (11.3)$$

where μ_1 and μ_2 are the occurrence rates for, respectively, events 1 and 2; and $\bar{d}_1$ and $\bar{d}_2$ are the corresponding mean durations for the events.

The maximum forces F_M required the development of appropriate models for their calculation. The following sections described these algorithms.

11.3 Forces Due to Iceberg Collision Alone or in the Presence of Waves

The force developed during and collision will vary during the process of ice crushing against the structure, since the area of contact is continuously changing and the crushing pressure exhibits a size effect (the greater the contact area, the lower the required pressure).

The force is also influenced by the damage deformation of the structure, which could have been designed to allow for local damage when the force exceeded a certain level.

This work has focused on the calculation of the c.d.f of maximum collision force for icebergs in the Grand Banks off the coast of Newfoundland. The sea, at the location of this gravity-based reinforced concrete structure, has a depth Z_w = 80 m. The structure will rest on the seabed and will be protected against collisions by a cylindrical ice wall with a radius R_o = 53 m.

The background of ice mechanics and risks to offshore structures have been amply discussed elsewhere (Sanderson, 1988). This work applied the basic ideas to the particular example of a typical Grand Banks GBS platform and extends the formulation to take into account the ice penetration due to local structural damage. The size effect in ice crushing pressure was also considered.

It is of course very difficult to accurately represent, in a mathematical equation, the three-dimensional shape of an iceberg. The approach used here followed that used by Det Norske Veritas (1988), the iceberg mass being assumed to be circular in plan and ellipsoidal in elevation *(Figure 11.1)*, with semi-axes R and B. From statistical data for the Grand Banks, all the iceberg dimensions were expressed in terms of a single random variable L_r (in m), in particular

$$R = 0.428L_r + 1.053L_r^{0.63} \tag{11.4}$$

The length L_r was represented by a Gamma distribution, with a mean value of 63.5 m and a standard deviation of 54.0 m. The draft h is also related to the length L_r according to

$$h = 3.781L_r^{0.63} \tag{11.5}$$

However, icebergs capable of colliding must have a draft smaller than the water depth of 80 m. Using the Gamma distribution for L_r, *Equation 11.5* was used to obtain the distribution of draft h in open water. After truncation to a maximum of 80 m, the data for h were fitted with a Beta distribution (minimum value 0.0 and maximum 80.0), resulting in a mean draft of 42.0 m with a standard deviation of 19.0 m.

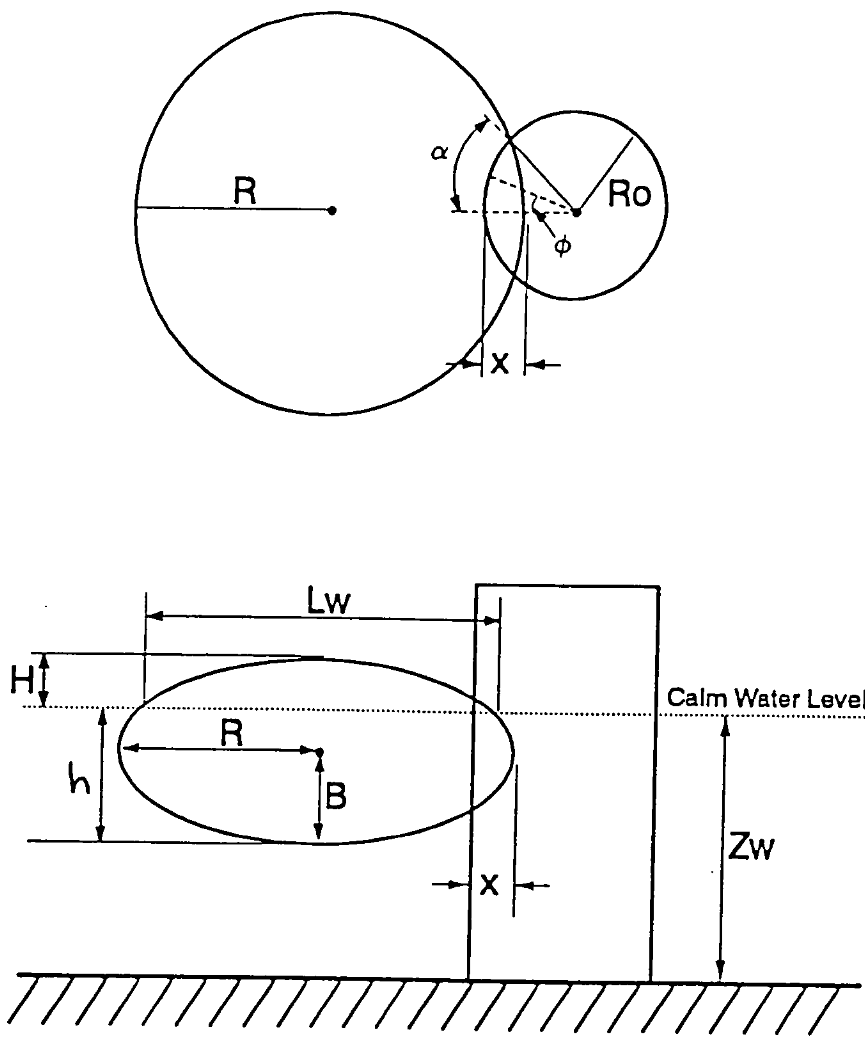

Figure 11.1: Definition Sketch of Iceberg/Cylinder Geometry

It can be shown that the semi-axis B is related to the draft h according to:

$$B = h/1.608 \tag{11.6}$$

and that the iceberg height above water, H, is:

$$H = 0.244h \tag{11.7}$$

Similarly, the iceberg diameter at the waterline L, is related to L_r according to:

$$L = 0.679L_r + 1.671L_r^{0.63} \tag{11.8}$$

For different penetrations x, as shown in *Figure 4.1*, it is possible to compute the area of contact as the intersection of the ellipsoid with the cylindrical ice wall of radius R_o.

Knowing the relationship between ice-crushing pressure and area, the force $Fi(x)$ can be obtained by integration over the area. The assumption is made that the pressure is uniformly distributed over the area.

The pressure required to crush the ice depends on the area of contact. Although laboratory experimental measurements have been obtained over small areas and in-situ observations have been collected for sea ice, not much information is available for icebergs. In general, the size effect trend is represented by an equation of the form

$$m_c = C_1 A^{C_2}$$

$$m_c > m_{co} \tag{11.9}$$

where m_c is the mean crushing pressure (MPa) associated with the contact area A (m^2). The value m_{co} is a lower bound for m_c. The data show substantial scatter around the regression *Equation 4.9*. It was assumed that the crushing pressure σ_c is lognormally distributed, with mean m_c and coefficient of variation V_c:

$$\sigma_c = \frac{m_c}{\sqrt{1 + V_c^2}} \, exp\left(R_{nl}\sqrt{1n(1 + V_c^2)}\right) \tag{11.10}$$

where R_{nl} is a Standard Normal variable (mean = 0.0, std.dev. = 1.0). The scatter in the available data is well represented with the following parametric values:

$$C_1 = 9.0\ MPa$$

$$C_2 = -0.5$$

$$m_{co} = 2.0\ MPa$$

$$V_c = 0.50 \qquad (11.11)$$

although some other values could be chosen for a more conservative estimate.

For a given penetration x due to ice crushing *(Figure 4.1)*, the force $Fi(x)$ acting on the structure can be calculated from integration over the area of contact $A(x)$:

$$A(x) = 2R_o \int_o^{\alpha} h(x,\phi)d\phi$$

$$F(x) = 2R_O\sigma_C(x) \int_o^{\alpha} h(x,\phi)\cos\phi d\phi \qquad (11.12)$$

where the angles α and ϕ are shown in *Figure 4.1*. *Figure 4.2* shows two typical force-penetration relationships, for L_r = 50 m and L_r = 100 m. For a radius $R < R_0$, and assuming sufficient kinetic energy, the iceberg could eventually disintegrate against the structure; for $R > R_0$, the structure would split the iceberg in two. These two are, however, extreme events. In general it was found that, in the cases of interest, the iceberg will be stopped after a few meters of penetration, near the beginning of curves like those in *Figure 4.2*.

An iceberg of mass M will impact the structure with a velocity V. As discussed in Section 3.2.2, this is related to the sea state and it is influenced by both the current and the waves. The iceberg impact velocity can be represented by *Equation 3.18*.

Following data from DnV (1988), U was assumed to be Lognormally distributed, with a mean 0.36 m/sec and a standard deviation 0.25 m/sec. The wave period T was estimated from an Extreme Type 1 probability distribution as discussed in Section 3.1.1. The c.d.f. was given in *Equation 3.2*.

Equation 3.2 gives, at P = 0.99 (or exceedance probability 0.01), the value T_{100} = 18.0 sec.

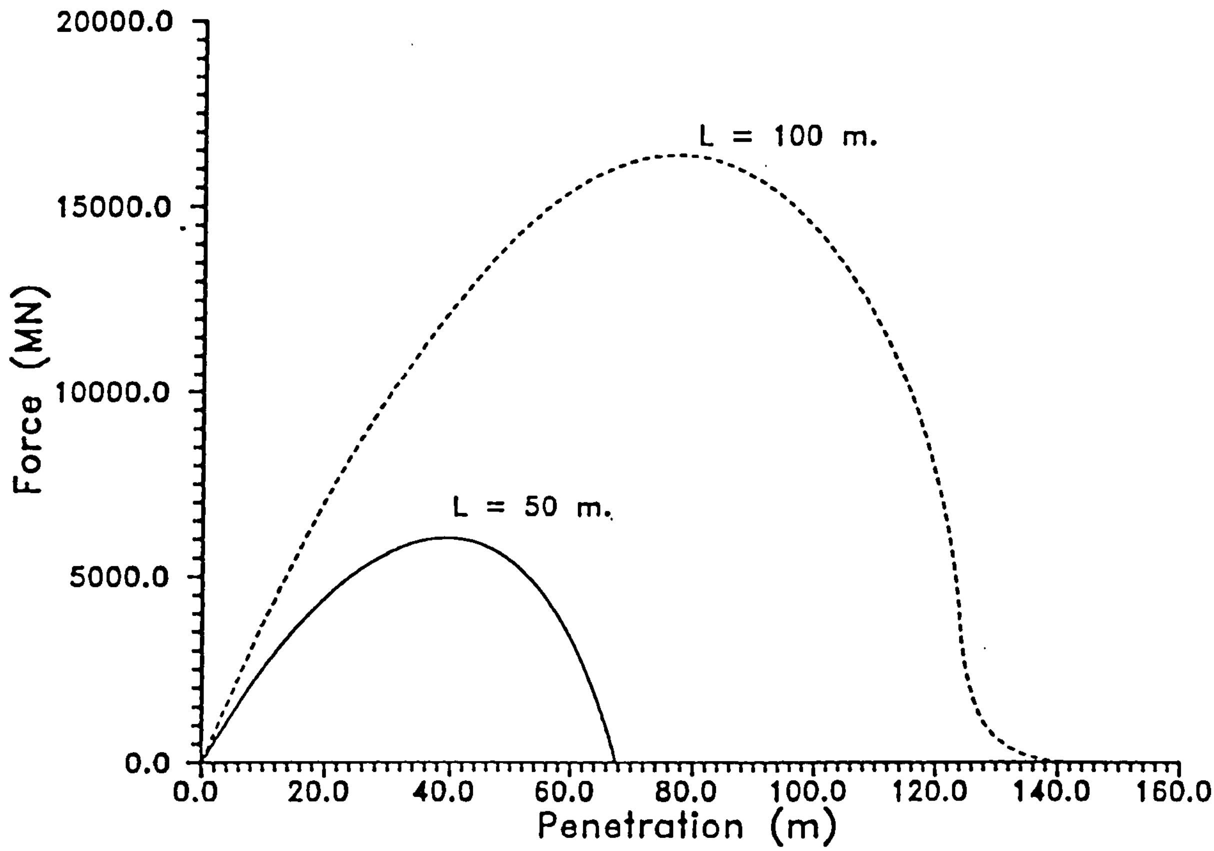

Figure 11.2: Iceberg Force Versus Penetration

In calm water, the calculation of the maximum force F_M was implemented through consideration of an energy balance. The iceberg will be stopped when its kinetic energy is fully dissipated through ice crushing and structural damage deformation. Thus, this energy balance requires.

$$\frac{1}{2} M(1 + C_m) V^2 = \int_o^{x_c} F_i(x) dx + \int_o^{x_d} F_i(x) dx \qquad (11.13)$$

where the mass M has been augmented by the added-mass coefficient C_m. The right-hand side represents the summation of the two cross-hatched areas in *Figure 4.3*. The first term corresponds to the energy dissipated through ice crushing up to penetration x_c, obtained from the force-penetration relationship. The second term corresponds to the energy dissipated through the local structural damage penetration x_d. The second term requires a minimum force F_o.

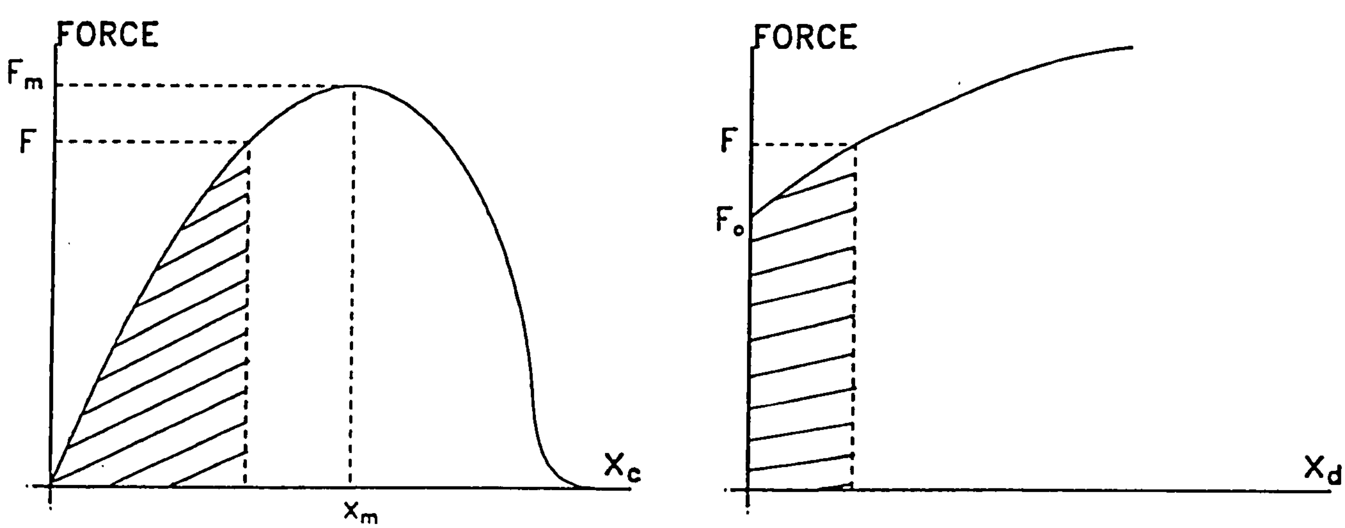

Figure 11.3: Force Versus Penetration for Ice Crushing and Structure Damage

The added-mass coefficient C_m was derived in Section 3.2.4 as *Equation 3.2.1.*

The relationship between damage penetration and force can be estimated using structural analyses of reinforced concrete elements at ultimate load. For the particular ice wall considered here, the results can be represented by a linear relationship up to a damage penetration of 1.5 m, according to:

$$F(x) = 610.0 + 156.70 x_d R_{n4} (MN) \tag{11.14}$$

where $F_o = 610.0$ MN. To account for the uncertainty in this estimate, the random variable R_{n4} is introduced, Lognormally distributed, with a mean = 1.0 and a standard deviation V_f.

The calculation of the maximum force F_M resulting from the collision requires the solution of *Equation 4.13* for the penetrations x_c and x_d. Once found, the maximum force is obtained from the force-penetration relationship. It should be noticed that the maximum force depends on whether the iceberg is stopped or not stopped at all. Thus, referring to *Figure 4.3*, if the iceberg is stopped after the penetration x_m, or if it is not stopped at all, the maximum force will be the peak F_m.

Given the geometry of the iceberg, its impact velocity, and the crushing pressure parameters, *Equation 4.12* can be solved iteratively to obtain the penetrations x_c and (if damage occurs) x_d.

In the presence of waves, the calculation of F_M was carried out by direct integration of the equation of motion. *Figure 4.4* shows the iceberg mass M under the force $F_i(x)$, due to ice-crushing, and the force $F_w^{(i)}$ due to the waves acting on the ice mass. Considering the dynamic equilibrium of this mass, the equation of motion is as given in *Equation 3.10.*

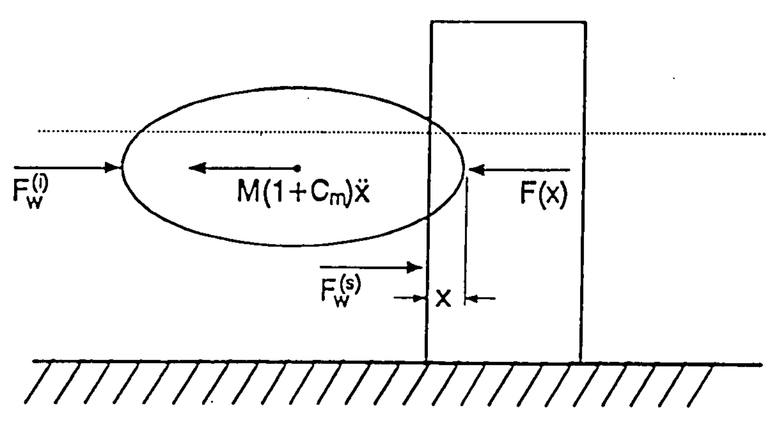

Figure 11.4: Definition Sketch of Forces on an Iceberg

As shown before in *Figure 11.2*, the force $F_i(x)$ is a nonlinear function of x. However, the iceberg will be stopped at values of x for which the function $F(x)$ can be linearized as follows,

$$F_i(x) = K_o x \tag{11.15}$$

where K_o is the initial slope of the force-penetration relationship. On the other hand, the wave force amplitude $F_w^{(i)}$ was expressed in *Equation 3.13.*

The wave height H_w is random within a storm and obeys a Rayleigh distribution, the c.d.f of which is:

$$R_{nS} = 1.0 - exp\left\{-\left[\frac{H_w}{0.706H_s}\right]^2\right\} \tag{11.16}$$

where R_{nS} is a random variable with a Uniform distribution between 0.0 and 1.0. H_s is the significant wave height, which is related to the period T according to *Equation 3.27.*

With the linearization of the force $F_i(x)$, the equation of motion can be easily integrated in closed form. Of particular interest is the calculation of the time t_o at which the velocity $\dot{x}$ first vanishes (iceberg stopped), and the corresponding maximum penetration x. For the calculation of force exceedance probabilities, the maximum force F_M on the structure was obtained from the force-penetration relationship at the maximum penetration.

For the sliding limit state, it was also required to calculate the force $F_w^{(s)}$ due to waves acting on the structure itself. This force must reflect, however, the presence of the iceberg. It was derived in Section 3 as:

$$F_w^{(s)} = 0.01012R_0^2\,\frac{H_w\lambda}{T^2}\,C_{ms}\cos(\omega t - \varepsilon + \phi) \tag{11.17}$$

where the factor C_{ms} obeys

$$C_{ms} = a_1 + a_2\left(\frac{D}{1.16\lambda}\right) + a_3\left(\frac{D}{1.16\lambda}\right)^2 \tag{11.18}$$

with coefficients a_1, a_2 and a_3 which are functions of the draft h and the waterline diameter L:

$$a_1 = (1.4756 + 3.8331 \times 10^{-2}h - 3.8052 \times 10^{-4}h^2)$$
$$\bullet\ (1.9395 - 9.2436 \times 10^{-3}L + 1.8093 \times 10^{-5}L^2)$$
$$a_2 = (-4.1870 - 1.0847 \times 10^{-1}h + 1.2662 \times 10^{-3}h^2)$$
$$\bullet\ (1.7296 - 6.7278 \times 10^{-3}L + 1.0832 \times 10^{-5}L^2) \qquad (11.19)$$
$$a_3 = (2.9091 + 1.0682 \times 10^{-1}h - 1.3636 \times 10^{-3}h^2)$$
$$\bullet\ (1.6132 - 4.7543 \times 10^{-3}L + 2.6709 \times 10^{-6}L^2)$$

Reflecting the interaction between the iceberg length and the wave length there is an additional phase angle ϕ between the forces $F_w^{(i)}$ and $F_w^{(s)}$. The value ϕ was obtained in Section 3 as:

$$\phi = a_4 + a_5\left(\frac{D}{1.16\lambda}\right) \qquad (11.20)$$

where the coefficients a_4 and a_5 depend on the iceberg's waterline diameter L:

$$a_4 = -248.87 - 1.7507L + 4.0953 \times 10^{-3}L^2$$
$$a_5 = -371.56 + 11.047L - 1.9113 \times 10^{-2}L^2 \qquad (11.21)$$

The calculation of the maximum force F_M for the sliding limit state requires a search for the maximum combination of the forces $F_i(x)$ and $F_w^{(s)}$ in the interval $t = 0$ to $t = t_o$, given that at maximum penetration the wave force $F_w^{(s)}$ may not be at its peak.

Because of the oscillatory character of the wave force $F_w^{(i)}$, it sometimes pushes the ice mass forwards and sometimes backwards. The phase angle ε, which controls the effect of this force at time $t = 0$ (beginning of the collision), has therefore a substantial importance in the calculation of the exceedance probability. To prevent oscillatory behaviour in the numerical FORM algorithm, the calculations were done conditional on specific values of the phase angle, with the total exceedance probability then calculated by integration over all phase angles from 0.0 to 2π. The integration was facilitated by the simple probability density function of the uniform distribution for ε, using a Gaussian scheme.

11.4 Forces Due to Waves Alone

For the case of waves alone, the maximum force $F_M = F_w$ on the structure can be obtained from *Equation 3.4* in Section 3.

11.5 Earthquake Forces

Maximum forces due to earthquakes were taken directly from past research (Westmar, 1990; Bea, 1992) and fitted with an Extreme Type I distribution. Earthquake forces were considered only in combination with waves. That is, the possibility of coincidence between iceberg collisions and earthquakes was assumed negligible during the lifetime of the structure.

11.6 Eccentricity in Collisions and Modifications to Probability Distributions for *U* and *L*

The "open water" statistics for U and L could be modified to account for the increased probability that faster and larger icebergs have of colliding with a structure of radius R_o. This modification has been discussed by Sanderson (1988) and has been introduced in the work reported here:

$$f^*(U) = f(U(U/\bar{U})$$

$$f^*(L) = f(L)(R_o + L)/(R_o + \bar{L}) \qquad (11.22)$$

where $f(U)$ and $f(L)$ are the corresponding probability density functions.

Finally, to account for the possibility of icebergs colliding with the structure in an eccentric manner (reducing the full impact), the force F_M in the case of icebergs alone or waves plus icebergs was reduced as follows:

$$F_M, \textit{reduced} = F_M[1.0 - \frac{2.0}{3.0} \bullet R_{n3}] \qquad (11.23)$$

where R_{n3} is a random variable Uniformly distributed between 0 and 1. Thus the maximum reduction possible is 2/3.

11.7 Comparison Between FORM Results and Montecarlo Simulations

It is useful to compare the accuracy of FORM results against straightforward Montecarlo simulations. *Figure 4.5* shows the exceedance probabilities associated with different load levels F_o, obtained using FORM or Montecarlo simulation, when only iceberg collisions are considered and neither structural damage nor the modifications of *Equation 4.22* are included. The ice crushing parameters were C_1 = 11.0 MPa, C_2 = -0.5, m_{co} = 2.0 MPa, V_c = 0.5. The model error variable R_{n2} was assumed normally distributed, with mean equals 1.0 and a standard deviation 0.15. At 500 MN, the design point included a velocity U = 0.55 m/sec and an iceberg of dimensions L = 143.0 m and h = 67.9 m. From higher to lower, the sensitivity of the results to variable uncertainty was ordered as follows: U, L, h, ice crushing variable R_{n1}, model uncertainty R_{n2}. *Figure 4.6* shows the results when structural damage is included (V_f = 0.5). It is apparent from *Figures 4.5 and 4.6* that FORM produces excellent results in comparison to simulation. FORM also resulted in very efficient and fast calculations (0.5 sec per load level in a 486 PC at 33 MHz).

As a comparison of *Figures 4.5 and 4.6* at low exceedance probabilities, *Figure 4.7* shows that structural damage introduces only small changes, reducing the probability for a given load level. This implies that the c.d.f of maximum load is mostly controlled by energy dissipation through ice crushing. Using a Poisson arrival process with mean rate 0.08 collision/year, the 100-year iceberg corresponds to an event exceedance probability of 0.126.

Finally, *Figure 4.8* shows the substantial effect of the corrections from *Equations 4.22.* The shift to faster and larger icebergs implies large changes to the c.d.f., emphasizing the importance of correctly modelling collision probability. The corresponding 100-year iceberg force becomes, 2in this case, 796 MN.

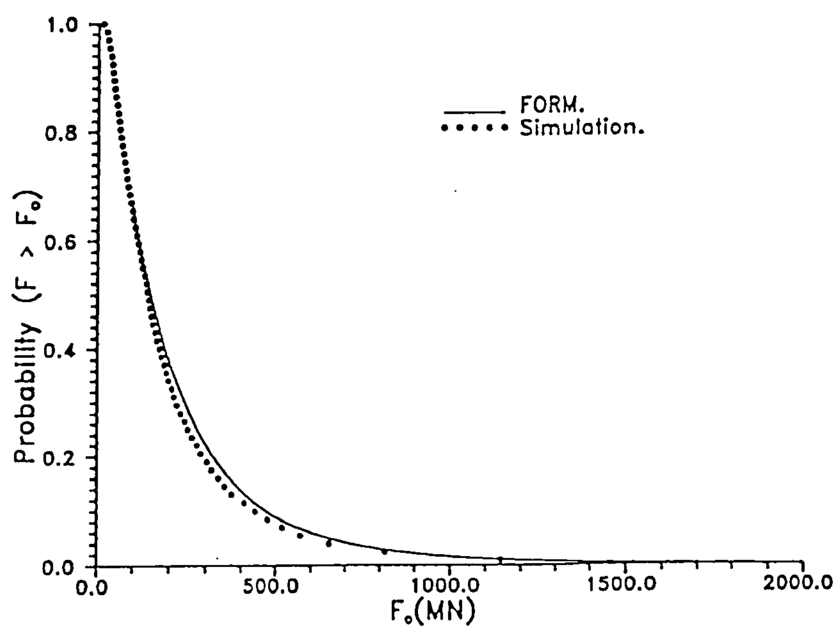

Figure 11.5: Force Probability Density Function for Two Models with No Damage

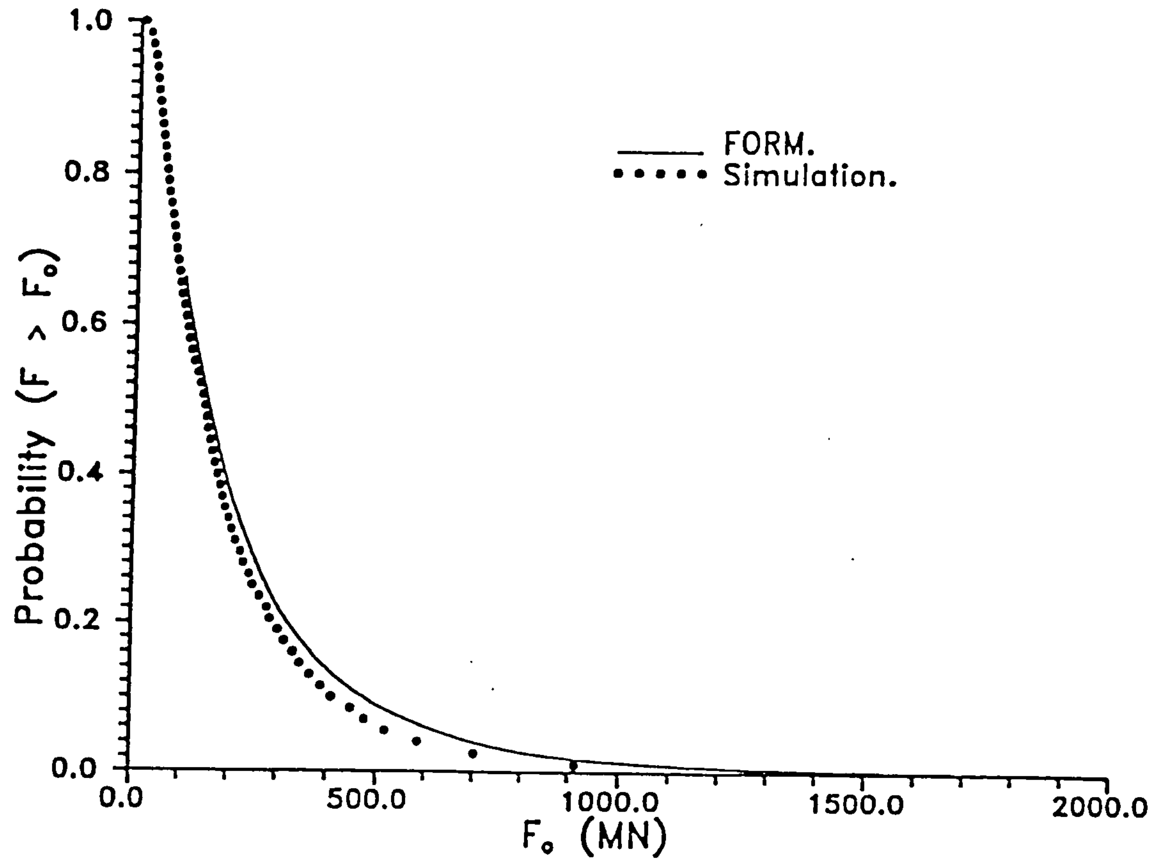

Figure 11.6: Force Probability Density Function for Two Models with Damage

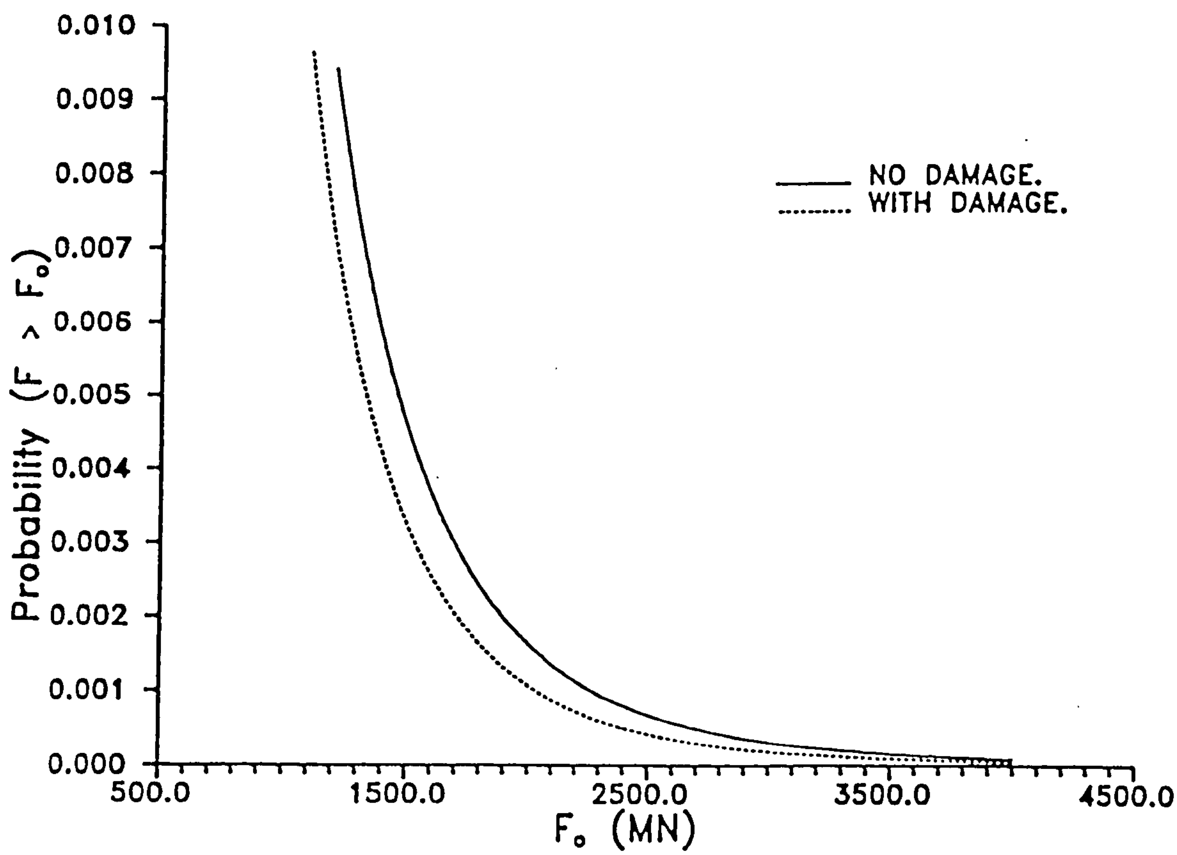

Figure 11.7: Force Probability Density function With and Without Structure Damage

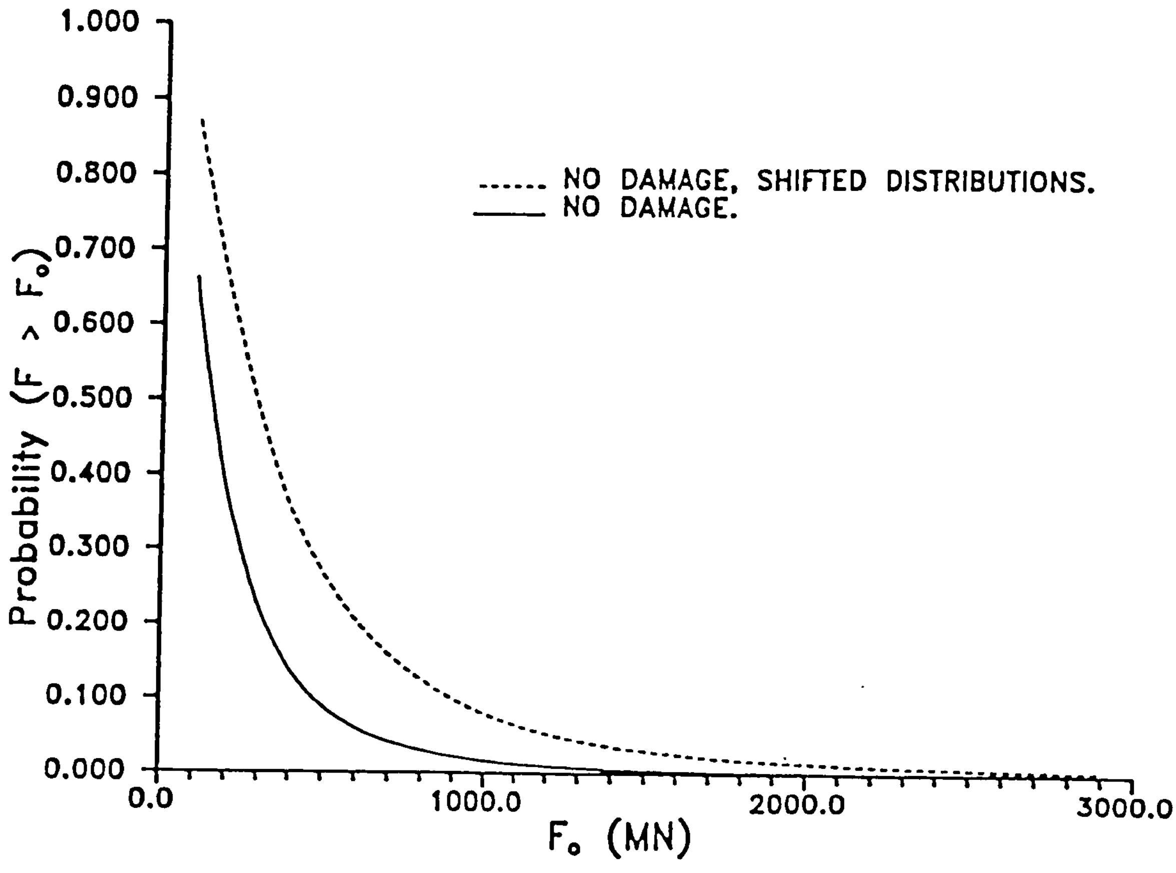

Figure 11.8: Shifted Force Probability Density Function With and Without Damage

12.0 CALCULATION OF LOAD COMBINATION FACTORS

The computer programs developed in the previous chapter were used to calculate load combination factors (γ) for the data available for the Grand Banks near Newfoundland. The input assumptions used in calculating (γ) and the results of the calculations are discussed below.

12.1 Environmental Load Calculations

The input random variables and associated statistical distributions (in parentheses) required for input into the computer programs discussed above were as follows:

- **ICELOAD**
  - iceberg of impact velocity (Lognormal)
  - iceberg length (Gamma)
  - iceberg draft (Beta)
  - minimum average ice crushing pressure (Normal)
  - modelling uncertainty (similar to Category II uncertainty, Bea 1992) (Normal)
  - distribution for location of iceberg impact on the structure (eccentricity of loading) (Uniform)
  - uncertainty in the force versus structural damage curve (only if structural damage option is chosen) (Normal)

The values of the random variables and their statistical distributions used for analysis are summarized in *Table 12.1* below.

Table 12.1: Statistical Distribution Input for ICELOAD

Variable	Distribution	Characteristics
Current Velocity, U	Lognormal	Mean = 0.36 m/sec Std. Dev. = 0.25 m/sec
Iceberg Length, L	Gamma	Mean = 63.5 m Std. Dev. = 54 m/sec
Iceberg Draft, D	Beta	Mean = 42 m Std. Dev. = 12 m Min. = 0.00 m Max. = 80.00 m
R_{n1}, associated with ice crushing pressure	Normal	Mean = 0.0 Std. Dev. = 1.0
R_{n2}, associated with model uncertainty	Normal	Mean = 1.0 Std. Dev. = 0.25
R_{n3}, associated with collision eccentricity	Uniform	Min. = 0.0 Max. = 1.0
R_{n4}, associated with slope of load-damage deformation relationship	Lognormal	N/A

The inputs given above for the iceberg impact velocity and length were taken from data obtained from C-CORE (1989). The velocity data from C-CORE was assumed to represent the iceberg drift velocity due to current forces. Subsequent discussions with Mona El-Tahan at C-CORE revealed that the iceberg velocity distributions include storm events, but do not include the most severe storm events. Under extremely severe storm conditions no velocity measurements could be taken. The periods during which iceberg velocities could not be measured varied from several hours up to 1 to 2 days in the most severe situations. The velocity data thus has some bias towards velocities higher than under calm conditions, but still does not include the most severe waves. Although the velocity distribution of the icebergs is overestimated, the data was considered applicable for use as the distribution for iceberg impact velocities. Iceberg draft information was calculated from the length data as discussed in Section 4.3.

Many different ice crushing pressure curves were available for use in this analysis from different sources. It was determined in the Phase I work that global safety of the structure is not dependent on the form of the curves, but is dependent on the minimum average ice crushing pressure. In performing the above analyses three different values for the minimum average ice crushing pressure were used. The values were 2 MPa, 4 MPa and 6 MPa. The annual probability of iceberg impact used was 0.08.

The results of the analyses performed using ICELOAD are summarized in *Table 12.2* below.

Table 12.2: Results from ICELOAD

Average Minimum Iceload Pressure (MPa)	Load for 10^{-4} Probability of Occurrence (MN)
2.0	2,350
4.0	3,350
6.0	4,100

- **ICEWLOAD**
  - iceberg current induced component of impact velocity (Lognormal)
  - iceberg length (Gamma)
  - iceberg draft (Beta)
  - minimum average ice crushing pressure (Normal)
  - modelling uncertainty (similar to Category II uncertainty, see Bea 1992) (Normal)
  - distribution for location of iceberg impact on the structure (eccentricity of loading) (Uniform)
  - uncertainty in the force versus structural damage curve (only if structural damage option is chosen) (Normal)
  - wave period (Extreme Type I)
  - random variable associated with the Rayleigh distribution of wave heights (Uniform)

The values of the random variables and their statistical distributions used for analysis are summarized in *Table 12.3* below.

Table 12.3: Statistical Distribution Input for ICEWLOAD

Variable	Distribution	Characteristics
Current Velocity, U	Lognormal	Mean = 0.36 m/sec Std. Dev. = 0.25 m/sec
Iceberg Length, L	Gamma	Mean = 63.5 m Std. Dev. = 54 m/sec
Iceberg Draft, D	Beta	Mean = 42 m Std. Dev. = 19 m Min. = 0.00 m Max. = 80.00 m
R_{n1}, associated with ice crushing pressure	Normal	Mean = 0.0 Std. Dev. = 1.0
R_{n2}, associated with model uncertainty	Normal	Mean = 1.0 Std. Dev. = 0.25
R_{n3}, associated with collision eccentricity	Uniform	Min. = 0.0 Max. = 1.0
R_{n4}, associated with slope of load-damage deformation relationship	Lognormal	N/A
T, Wave Period	Extreme Type I	Mean = 15.89 sec Std. Dev. = 0.67 sec.
R_{n5}, associated with wave height H_w Rayleigh distribution	Uniform	Min. = 0.0 Max.. = 1.0

The origin of the iceberg length and draft data is the same as discussed for iceload. The iceberg impact velocity is determined from *Equation 3.18*. In *Equation 3.18* the velocity distribution obtained from C-CORE was considered to be the velocity distribution for the current induced component of the iceberg impact velocity. This overestimates the current component of the impact velocity, but is not considered to be a significant overestimation. The constant used for the wave induced portion of the impact velocity was taken as 0.03 to best match the upper end of the velocity statistical distribution. The minimum ice crushing pressure values were again taken as 2 MPa, 4 MPa and 6 MPa. The wave period and wave height distributions were those calculated using the equations in Section 3.

The results of the analyses performed using ICEWLOAD are summarized in *Table 12.4* below.

Table 12.4: Results from ICEWLOAD

Iceberg Force for 10^{-5} Probability of Occurrence (MN)			
Minimum Average Ice Crushing (MPa) Pressure	**Storm Duration (Days)**		
	4	**8**	**16**
2.0	2,900	3,700	3,700
4.0	3,400	4,200	5,000
6.0	4,200	4,900	6,050

It must be noted that no consideration was given to the directionality of the waves. It was assumed that the waves and the icebergs move in the same direction. This would tend to cause an overestimation in the above loads from ICEWLOAD.

- **EWLOAD**
  - wave period (Extreme Type I)
  - random variable associated with the Rayleigh distribution of wave heights (Uniform)
  - force due to earthquakes (Extreme Type I)
  - modelling uncertainty (similar to Category II uncertainty, see Bea 1992) (Normal)

The values of the random variables and their statistical distributions used for analysis are summarized in *Table 12.5* below.

Table 12.5: Statistical Distribution Input for EWLOAD

Variable	Distribution	Characteristics
T, Wave Period	Extreme Type I	Mean = 15.89 sec. Std. Dev. = 0.67 sec.
R_{n1}, associated with wave height H_w Rayleigh distribution	Uniform	Min. = 0.0 Max. = 1.0
F_E, earthquake force	Extreme Type I	Mean = 148.59 MN Std. Dev. = 101.79
R_{n2}, associated with model uncertainty	Normal	Mean = 1.0 Std. Dev. = 0.25

The variables for wave load are taken as from previous page. The statistical distribution for earthquake load was determined from data taken from Verification Project G-2A.

The combined earthquake and wave load with a 10^{-5} probability of exceedance was calculated based on an earthquake annual probability of occurrence of 0.03. Based on this assumption, the design load was determined to be 1950 MN.

- **WLOAD**

    - wave period (Extreme Type I)
    - random variable associated with the Rayleigh distribution of wave heights (Uniform)

The values of the random variables and their statistical distributions used for analysis are summarized in *Table 12.6* below.

Table 12.6: Statistical Distribution Input for WLOAD

Variable	Distribution	Characteristics
T, Wave Period	Extreme Type I	Mean = 15.89 sec. Std. Dev. = 0.67 sec.
R_{nS}, associated with wave height H_w Rayleigh distribution	Uniform	Min. = 0.0 Max. = 1.0

The variables are again taken as above. Based on the above inputs, the wave load with a return period of 10^{-2} was determined to be 2870 MN.

In addition to the above determined loads, the earthquake load with a return period of 10^{-4} was extracted from Verification project G-2A. The 10^{-4} load was determined to be 1500 MN.

12.2 Load Combination Factor Calculations

Load combination factors were calculated based on the following equation:

$$E = E_r + \gamma E_f \tag{12.1}$$

where E is the load calculated to provide a reliability level of 10^{-5} against failure of the structure, E_f is a frequent environmental load E_r is a rare environmental load and γ is the load combination factor. Solving for γ in *Equation 5.1* gives:

$$\gamma = (E - E_r)/E_f \tag{12.2}$$

Load combination factors were tabulated for earthquakes in combination with waves and icebergs in combination with waves for three different values for significant storm days. The three values chosen to represent significant storm days were as follows:

- 4 days
- 8 days
- 16 days

These values for significant storm days represent the expected number of days each year that the wave height exceeds a value of 8 m, 7 m and 6 m respectively. These values are calculated based on wave data taken from different wave buoys between October 1981 and September 1985. The results of the calculation of load combination factors is summarized in *Table 5.7* below.

Table 12.7: Calculated Load Combination Factors

Load Combination Factors			
Minimum Average Ice Crushing Pressure (MPa)	**Storm Duration (Days)**		
	4	**8**	**16**
2	0.19	0.47	0.47
4	0.02	0.30	0.57
6	0.03	0.28	0.68
Earthquake	0.06	0.12	0.16

13.0 CONCLUSIONS AND RECOMMENDATIONS FOR PHASE II

The following conclusions were compiled during the course of the study:

- load combination factors calculated for icebergs in combination with storm waves at the study location, are lower than those recommended in the code if the two events are taken as stochastically dependent;
- icebergs and storm waves should be considered as stocastically dependent for the purposes of combining the effects of the two loads;
- load combination factors calculated for earthquakes in combination with storm waves are much lower than those recommended in the code;
- load combination factor "γ" is location dependent and must be calculated for each location of concern; and,
- the impact velocity of an iceberg is increased in the presence of waves and thus causes a significant increase in the energy that an iceberg possesses. This subsequently increases the load caused by the iceberg;
- the wave force on the structure while it is being impacted by an iceberg is different to that when an iceberg is absent;
- the wave force on the iceberg while it is impacting the structure affects the maximum force of the iceberg on the structure;
- the computer programs developed in this project for calculating loads and load combinations probabilistically, ICELOAD, ICEWLOAD, EWLOAD, and WLOAD are effective tools for determining environmental loads.

The following are recommendations resulting from this study:

- modify *Table 6.1(a)* in S471 to reflect stochastic dependence between storm waves and icebergs;
- modify *Table 6.1(b)* into an Appendix to the code with location dependent load combination factors;
- analyze all potential locations in which offshore structures can potentially be built such as to obtain environmental loads;

- use reliability based methods such as those developed in this study to create a table of location dependent load combination factors;

- in lieu of the above recommendation, a paragraph should be added to S471 and S471.1 noting the high dependency of wave drift velocity on iceberg load levels;

- create separate load combination factors for the combination of different environmental loads (i.e. load combination factors will be different for earthquakes with storm waves than icebergs with storm waves; and,

- upgrade ICELOAD, ICEWLOAD, EWLOAD and WLOAD to make them more user friendly.

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