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Comparison of International Codes for Ice Loads on Offshore Structures

PERD/CHC Report 11-20

Project 142211
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1.0 Introduction

1.1 BACKGROUND

Over the last three decades, oil and gas development activities in arctic and subarctic waters in many parts of the world have prompted designs of ice resistant offshore platforms. The understanding of ice mechanics, ice loads and structural reaction to ice action have made substantial advancement over the years, with the ultimate objective of rationalizing safe and economic ice resistant offshore structures.

In Canada, a number of offshore structures have been designed, fabricated and deployed in the Beaufort Sea and off the East Coast. The gravity-based platforms deployed in the Beaufort Sea in the early 1980's were designed and constructed without the benefit of a Canadian design code for offshore structures. In view of this, the Canadian Standards Association (CSA) was asked by the federal government and industry to develop a code for the design, construction and installation of fixed offshore oil and gas production structures. In response to this request, CSA prepared draft standards and oversaw the verification of these standards. The verification process achieved a number of principal objectives:

- To verify that the code allows the designer to produce acceptably safe and reliable structure designs;
- To ensure that designers have confidence in the structures designed to the code;
- To ensure that practicing engineers can apply the code with reasonable ease and without ambiguity;
- To allow the practicing engineering community to become familiar with the provisions of the new code.

Some fifteen code verification projects, each focusing on specific portions of the code such as ice load, earthquake load, steel design, concrete design and composite design, were completed between 1987 and 1989. These verification studies led to recommendations for further code editing, culminating in the publication of the CSA Standard for Fixed Offshore Structure in 1992. The CSA code, in parallel with the Russian SNiP and VSN codes, has been applied recently to the design of the first offshore platform in the Russian Sea of Okhotsk, offshore Sakhalin Island.

The American Petroleum Institute standards (the API RP series) have also undergone a verification process to produce a set of design guidelines based on the more modern Load Factor Resistance Design (LFRD) approach, an alternative to the traditional Working Stress Design (WSD) approach. At the same time, the section on ice loads was updated to reflect appropriately the recent advances in that discipline.

The current interests in the development of oil and gas reserves in the Canadian, American and Russian arctic and subarctic waters will continue to call for the design and construction of ice resistant offshore structures and the issue of code application will invariably arise. In view of this, the National Research Council of Canada (NRCC) has commissioned this study. It is considered that this work is very timely. In particular, by documenting the similarities and differences between the North American and the Russian standards for ice loads on structures, the study report will be an important reference for upcoming offshore structures designed by joint ventures of western and Russian companies for installation in Russian ice infested waters.

1.2 OBJECTIVE

The objective of this study is to compare the structural and ice design philosophy, and ice load determination on various structures using 4 international codes:

- the Canadian CSA code
- the American Petroleum API-RP-2N code
- the Russian SNiP code
- the Russian VSN code

1.3 SCOPE OF WORK

The scope of this study consists of three tasks:

- Similarities and Differences in the Philosophies and Approaches in the 4 Codes
- Ice Load Determination
- Report

Task 1 Similarities and Differences in the Philosophies and Approaches in the 4 Codes

The salient features regarding structural and ice design approaches and philosophies of the four codes are summarized in this task.

This task includes the provision to NRCC of up-to-date copies of each code, including English translations of the two Russian codes. These documents are included in the appendices to this report.

Task 2 Ice Load Determination

In this task, the provisions for ice load determination in each of the four codes are applied to estimate the expected ice loads for the following 3 scenarios:

- Scenario 1 - A level sheet of sea ice of 1.2 m thickness interacting with a fixed offshore structure in mid-winter. Assume that the ice is moving at a rate of 0.2 m/s, and the structure is vertical-sided with a width of 100 m and in deep water.
- Scenario 2 - A first-year ridge of total thickness 10 m interacting with the same structure. Assume a keel-to-sail ratio for the ridge of 4.4, a consolidated layer thickness of 1.5 m, and a width of 23 m. Assume that the ridge is embedded in an ice sheet with the same characteristics of Scenario 1.
- Scenario 3 - Open pack ice of 1.2 m thickness interacting with a multi-leg structure of 100 m width. Determine the expected load for pack ice concentrations of 0.4 and 0.8

for floe sizes of the order of 10 to 50 m in diameter moving at a speed of 0.5 m/s. Assume that the structure has four 20 m wide cylindrical supporting piers at the four corners.

The approach followed in each of the codes is described by:

- Noting the applicable code clauses that guided the ice load determination.
- Describing relevant ice strength parameters.
- Describing the mechanistic ice load model.
- Identifying any lack of guidance in the code that would have permitted an improved understanding of the ice load determination
- Identifying any assumptions made beyond code guidance.

Task 3 Report

The findings in Task 1 and Task 2 are presented in this report, which is organized into five sections:

Section 1	Introduction
Section 2	Structural Design Approach
Section 3	Ice Design Approach
Section 4	Ice Load Calculations
Section 5	Conclusions

2.0 Structural Design Approach

As indicated, the CSA code has been applied recently to the design of the first Russian offshore platform for deployment in the Sea of Okhotsk where sea ice will induce the dominant environmental loads through the winter seasons. In that design process, there was considerable debate on the different structural and ice design philosophies among the various interested parties - the foreign investor (Sakhalin Energy Investment Company Ltd.), the Russian investor, the foreign investor's engineer (Sandwell) and the Russian engineering body. The aim was to develop a design that would achieve certification by both western regulatory authorities, such as the American Bureau of Shipping, and the Russian Marine Registry Services, the Russian regulatory authority.

While the focus of this study is ice loading, it is important that the fundamental structural design philosophies in the different codes be examined at the same time because the specification of loads and the design of engineering components to accommodate these loads form the basis for all engineering developments.

This section summarizes the approaches in structural design, the specification of the recurrence interval of design loads, load factors and load combinations for each of the 4 codes.

2.1 CSA

The CSA code for the design of fixed offshore structures consists of 5 principal parts:

S471	**General Requirements, Design Criteria, the Environment, and Loads - Part I of the Code for the Design, Construction and Installation of Fixed Offshore Structures**
S472	Foundations - Part II of the Code for the Design, Construction and Installation of Fixed Offshore Structures
S473	Steel Structures - Part III of the Code for the Design, Construction and Installation of Fixed Offshore Structures
S474	Concrete Structures - Part II of the Code for the Design, Construction and Installation of Fixed Offshore Structures
S475	Sea Operations - Part II of the Code for the Design, Construction and Installation of Fixed Offshore Structures

The study focuses primarily on S471.

2.1.1 Objectives

The CSA code was developed with the aim to facilitate designs of offshore structures so that a low risk to the lives of people on or near the offshore structure and a low risk of environmental damage due to any accident or failure are ensured.

The code defines two safety classes for which the recurrence interval and load factors for certain design loads are different:

- *Safety Class 1 - failure would result in great risk to life or a high potential for environmental damage*
- *Safety Class 2 - failure would result in small risk to life and a low potential for environmental damage*

Appendix A of CSA S471 tabulates the following code intended annual reliability levels:

Ultimate limit state, Safety Class 1	$1 - 10^{-5}$
Ultimate limit state, Safety Class 2	$1 - 10^{-3}$
Serviceability limit state	$1 - 10^{-1}$

These are considered to be average values and are not met under all loading conditions. These values do not account for advantageous effects of structural redundancy, reserve capacity and ductility. Consequently, the reliability level in a structure designed in accordance with the code provisions may exceed these levels.

To achieve the design objective, the CSA code provides for the use of the limit states design method. This method incorporates load factors and material resistance factors in the design and the aim is to provide factored structure resistance (or capacity) that will exceed the factored loads. Alternatively, the code permits the designer to use known or postulated probabilistic distributions of loads and material resistances to formulate the design, provided that the designer can demonstrate that the level of safety intended by the code is satisfied.

Two categories of limit states are defined in the CSA code:

- Ultimate limit states

  Ultimate limit states are structural failure states that concern safety to personnel and the environment. These limit states include overturning, capsizing, sliding, sinking into water or ground, exceedance of structural strength in buckling, fracture, fatigue, fire or deformation, structural instability and progressive collapse.

- Serviceability limit states

  Serviceability limit states are behaviour states of the structure that hinder normal functions and reduce durability. These include unacceptable deflections, vibrations and local damage such as cracking and connection slippage.

2.1.2 Loads and Load Combination

The code specifies that offshore structures are to be designed to resist loads under four categories:

- Permanent loads, G

  Dead loads, G_D (structure weight, weight of permanent equipment and ballast, permanent hydrostatic loads).

  Deformation loads, G_R (prestressing, creep, shrinkage, temperature, differential settlement, foundation stiffness variation).

- Operational loads, Q

  Loads caused by occupancy and operation, storage, crane, helicopter, mooring, berthing, variable ballast and differential hydrostatic pressures.

- Accidental loads, A

  Loads caused by accidental events, events with an annual probability of occurrence of less than 10^{-4} need not be considered.

- Environmental loads, E

  Frequent environmental processes, E_f (wind, waves, currents, sea ice, icebergs and bergy bits, tide, marine growth, snow and ice accumulation, storm surges)

  - Loads based on frequent environmental processes have annual probability of exceedance not greater than 10^{-2}

  Rare environmental events, E_r (earthquakes and related earthquake effects, icebergs and other rare ice features, sea ice and tsunamis)

  - Loads based on rare environmental events have annual probability of exceedance not greater than 10^{-2} for Safety Class 2 structure components and within the range of 10^{-3} and 10^{-4} for Safety Class 1 components.

Structures are to be designed to resist a number of combinations of factored loads:

Ultimate Limit States

Safety Class 1

$1.25\ G_D + 1.0\ G_R + 1.25\ Q + 0.7\ E_f$

$1.05 \text{ or } 0.9\ G_D + 1.0\ G_R + 1.0\ Q + 1.35\ E_f$

$1.05 \text{ or } 0.9\ G_D + 1.0\ G_R + 1.0\ Q + 1.0\ E_r$

$1.05 \text{ or } 0.9\ G_D + 1.0\ G_R + 1.0\ Q + 1.0\ A$

Safety Class 2

$1.05 \text{ or } 0.9\ G_D + 1.0\ G_R + 1.0\ Q + 0.9\ E_f$

$1.05 \text{ or } 0.9\ G_D + 1.0\ G_R + 1.0\ Q + 1.0\ E_r$

Serviceability Limit States

$1.0\ G_D + 1.0\ G_R + 1.0\ Q + 0.7\ E_f$

Guidelines for special design cases such as fatigue design (a particular case of ultimate limit states), design for cyclic loading and design for local concrete damage are also given in the code.

2.1.3 Method

The CSA code has been developed on the basis of the limit states design method incorporating load and material resistance factors.

The structure is proportioned to have sufficient strength and/or stability such that

$\Sigma\ \gamma_i F_i$ (effects of factored loads) $< \ \phi R$ (factored resistance)

where

Fi is the stress effect in a structure due to a specified load in a load combination

γ_i is the load factor for load type specified in the code

ϕ is the component resistance factor specified in the code

R is the nominal component strength or resistance

The code allows the use of alternative design methods that are based on theoretical analysis and recognized engineering practice in lieu of the design method stated in the code, provided that the design would achieve levels of safety and serviceability at least equal to those targeted by the code requirements. In this respect, the code is very clear in terms of design objectives and allows the code user to choose a design method to satisfy those objectives. Where new systems and materials or new hazards not contemplated by the code are encountered, this code provision is particularly useful and the designer may carry out risk analysis for the specific hazard, system or material in order to arrive at a structural design that would achieve the safety objectives.

2.2 API

The API code for the standardization of offshore structures consists of the following publications:

RP 2A	**Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms - LRFD**
Spec 2B	Specification for Fabricated Structural Steel Pipe
Spec 2C	Specification for Offshore Cranes
RP 2D	Recommended Practice for Operation and Maintenance of Offshore Cranes
Spec 2F	Specification for Mooring Chain
RP 2G	Recommended Practice for Production Facilities on offshore Structures
Spec 2H	Specification for Carbon Manganese Steel Plate for Offshore Platform Tubular Joints
RP 2I	Recommended Practice for In-Service Inspection of Mooring Hardware for Floating Drilling Units
RP 2L	Recommended Practice for Planning, Designing, and Constructing Heliports for Fixed Offshore Platforms
RP 2M	Recommended Practice for Qualification Testing of Steel Anchor Designs for Floating Platforms
RP 2N	**Recommended Practice for Planning, Designing and Constructing Structures and Pipelines for Arctic Conditions**
RP 2P	Recommended Practice for the Analysis of Spread Mooring Systems for Floating Drilling Units
Bul. 2S	Draft Bulletin on the Design of Windlass Wildcats for Floating Offshore Structures
RP 2T	Recommended Practice for Planning, Designing, and Constructing Tension Leg Platforms
Bul. 2U	Bulletin on Stability Design of Cylindrical Shells
Bul. 2V	Bulletin on Design of Flat Plate Structures
Spec 2W	Specification for Steel Plates for Offshore Structures, Produced by Thermomechanical Control Processing (TMCP)
RP 2X	Recommended Practice for Ultrasonic Examination of Offshore Structural Fabrication and Guidelines for Qualification of Ultrasonic Technicians
Spec 2Y	Specification for Steel Plates, Quenched-and-Tempered, for Offshore Structures

RP 2Z	Recommended Practice for Preproduction Qualification for Steel Plates for Offshore Structures

The API publications RP2A (for structural design philosophy) and RP2N (for ice design philosophy) are the primary focus in this study.

As mentioned previously, the standard API RP2A 'Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms' has undergone an extensive review process in the late 1980's to early 1990's. The review concluded that the then existing method of checking safety in structure components, the Working Stress Design (WSD) method, did not provide consistent component reliability. Subsequently, API decided to change the WSD method to the Load and Resistance Factor Design (LRFD) method, which, with its partial factors calibrated by a reliability model, will give structure designs a more consistent component reliability.

2.2.1 Objectives

The API code states that the Recommended Practices are published to facilitate the availability of proven, sound engineering and operating practices and that consideration is given to the safety of personnel, compliance with existing regulations, and prevention of pollution.

The design requirements given in API RP2A have been formulated on the basis of a reliability analysis, with the target safety indices established from a set of safety indices computed for the designs of a range of platform types developed from applying the earlier WSD method. Load factors in the LRFD format were then computed from these target safety indices. Although the code itself does not state explicitly the implied structural reliability, literature references report that the reliability analysis was based on component design practices in the Gulf of Mexico where wave is the primary environmental hazard, and that the probability of failure for structures designed to API RP 2A is about 0.001 in 20 years, a typical design life for platforms (Nevel, 1997). A probability of failure of 0.001 in 20 years translates into a probability of failure of 0.00005 in 1 year.

The LRFD method, in conjunction with calibrated load factors and resistance factors, is used to achieve the structural reliability objective. The aim in a design is to provide factored nominal structural strengths that are greater than the factored load effects. API refers to the American Institute of Steel Construction code entitled 'Load and Resistance Factor Design Specification for Structural Steel Buildings' for the calculation of nominal strengths of most types of steel components.

2.2.2 Loads and Load Combinations

API categorizes loads into five groups:

- Gravity loads, D and L

  Dead load 1, D_1 (self weight, weight of permanent equipment and ballast, hydrostatic forces).

Dead load 2, D_2 (weight of equipment and other objects that may change from one mode of operation to another but otherwise remain constant for long periods of time).

Live load 1, L_1 (weight of consumables).

Live load 1, L_2 (short duration loads such as lifting by cranes).

- Wind, Wave and Current loads, W and D

  Extreme Wind, Wave and Current load, W_e (combined action of the extreme wave (typically 100 year return period) and associated current and wind).

  Operating Wind, Wave and Current load, W_e (combined action of the operating wind, wave and current condition).

  Extreme or Operating Inertial load, D_n (inertial load at the time when the total global dynamic response is a maximum).

- Earthquake loads, E

  Strength Requirements, E (structure to be checked for strength to resist the inertially induced loads produced by the strength level ground motion that has a reasonable likelihood of not being exceeded during the life of the structure).

  Ductility Requirements (the global performance of the structure-foundation system must be demonstrated to be satisfactory in response to the rare intense earthquake).

- Fabrication and Installation loads

  Installation encompasses the operations of moving the platform components from the fabrication site to the offshore location, and installing them to form the completed platform.

Structure components are to be designed to resist the following factored load combinations:

$1.3\ D_1 + 1.3\ D_2 + 1.5\ L_1 + 1.5\ L_2$
1.1 or $0.9\ D_1 + 1.1$ or $0.9\ D_2 + 1.1$ or $0.8\ L_1 + 1.35\ (W_e + 1.25D_n)$
$1.3\ D_1 + 1.3\ D_2 + 1.5\ L_1 + 1.5\ L_2 + 1.2\ (W_o + 1.25D_n)$
1.1 or $0.9\ D_1 + 1.1$ or $0.9\ D_2 + 1.1$ or $0.8\ L_1 + 0.9\ E$ (1.15 E for deck supported structures)
Appropriate load combinations during fabrication and installation, and for fatigue design

2.2.3 Method

As in the CSA code, the API load and resistance factor design (LRFD) method calls for a design to satisfy the following criterion:

Resistance Factor x Nominal Strength > Effect due to the Sum of Factored External Loads where the load and resistance factors have been calibrated during code formulation using a reliability model. This format is consistent with that adopted by a number of codes in the United States such as the ACI for reinforced concrete, AISC for steel and AASHTO for bridges.

2.3 SNIP And vsn

The State Standard “Building Norms and Rules”, SNiP (Stroitelnye Normy i Pravila), is a regulating document and compliance of structural designs with this standard is mandatory. The “Building Norms for Industries”, VSN (Vedomstvennye Stroitelnye Normy) is a code for the Oil/Gas Ministry. It, in principle, must not contradict the SNiP code but supplements and clarifies the major provisions in SNiP. Both the SNiP and the VSN codes have been developed for the Russian offshore.

For the design of marine structures, designers are obliged to follow these standards:

SNiP 2.06.01-86.	**Marine structures, general design provisions**
SNiP 2.01.07-85.	**Loads and influences**
SNiP 2.06.04-82*.	**Loads and influences on marine structures (from waves, ice and vessels), issued in 1996**
SNiP 2.02.02-85.	Marine structure foundations
SNiP 2.06.08-87.	Concrete and reinforced-concrete marine structures
VSN-41.88	**Design of fixed ice strengthened platforms**

This study focuses on SNiP 2.06.01-86, SNiP 2.01.07-85, SNiP 2.06.04-82* and VSN-41.88.

In principle, the VSN code is intended to supplement and elaborate on SNiP code provisions. However, on issues relating to ice load determination, these codes often contradict each other. In the years leading up to 1996, the SNiP and the VSN codes were accepted for ice load determination for non-overlapping ice speed regimes:

- SNiP is to be used for ice motion more than 0.5 m/sec
- VSN is to be used for ice motion less than 0.5 m/sec

This definition of applicable ice speed regimes for the two codes led to different ice loads calculated using the two codes for an ice speed of 0.5 m/sec. In 1996, this situation was rectified as the sections on ice loads in SNiP were revised to cover all ice speeds.

It is recognized that, because of the scarcity of field experience, the science of ice load determination is still controversial. Consequently, the State Expert Commission, who has the authority to approve projects, is able to accept ice loads determined on the basis of well substantiated mathematical rationale, particularly in the definition of certain parameters such as ice strength and ice ridge characteristics.

2.3.1 Objectives

Both the SNiP code (SNiP 2.06.01-86) and the VSN code provide for the use of the limit states design method, incorporating load factors and material resistance factors. The aim of the design is to achieve factored resistances (in strength and stability) in the structural elements that will be greater than the effects resulting from factored loads. However, structural reliability is not quantified because the codes do not state explicitly the target probability of structural failure.

The two categories of limit states are described in the SNiP code. VSN refers to the SNiP code on these requirements:

- The first group of limit states that would lead to a cessation in operation

  The strength and the stability of the structure-foundation system and its structural components are to be evaluated for failure states which would lead to a cessation in the platform operations.

  Examples of a limit state in this group is the loss of global structure stability due to a sliding of the platform on the foundation or the failure of structural elements which would lead to the total collapse of the structure.

- The second group of limit states that would not lead to a cessation in operation

  The strength and the stability of the specific structural elements and the local strength of the foundation are to be evaluated. The failure of these components would not lead to a cessation of the platform operations.

  An example of a limit state in this group is the loss of local strength in the hull plate on the platform.

2.3.2 Loads and Load Combination

The SNiP code (2.01.07-85 and 2.06.01-86) specifies the following categories of loads:

- Constant Loads

  These are loads that will always act on the structure. Examples are self weight and static soil pressure.

- Temporary Loads

  Temporary loads are divided into long term, short term and special loads.

  Long term temporary loads are operational loads.

  Short term loads are environmental (other than earthquake) loads of average magnitudes. For example, ice loads resulting from first year ice (characteristics are determined from many years of observation) of average thickness are classified as short term loads. In practice, short term environmental loads are annual maximum loads.

Special loads are environmental (including earthquake) and explosive loads of 'maximum' magnitudes. For example, ice loads resulting from first year ice of maximum (1 in 100 years) thickness are classified as special loads. The probability of exceedance of the special loads is not specified. Bolshev et al, 1997, discussed this issue and suggested the incorporation of a probabilistic model into the design process.

Loads determined in accordance with the guidelines in the code are called normative (or specified) loads. For use in design, these loads are to be multiplied by a coefficient of reliability. For example, SNiP 2.06.01-86 specifies that the coefficient of reliability for ice loads is 1.1. In comparison, VSN specifies a value of 1.1 for loads determined for the 100 year return period first year ice thickness and 1.0 for those determined for the average first year ice thickness. Values of this coefficient for various types of loads and limiting conditions are given in the code.

The principles for design load combinations are specified in SNiP 2.01.07-85 and SNiP 2.06.01-86. Load combinations reflecting realistic simultaneous influence of loads on the structure at the various stages in its design life are identified. The most unfavourable load combination would govern the design.

Two categories of load combination are to be considered:

- the main load combinations consisting of constant, temporary long term and short term loads
- the specific load combinations consisting of constant, temporary long term and only one of the special loads

The specified loads are to be factored by the appropriate coefficient of load reliability and then combined by applying the appropriate coefficients of load combination which account for the probability of simultaneous occurrence of the loads.

Main load combinations (from SNiP 2.01.07-85):

1.0 Constant load + 0.95 Temporary long term load + 0.9 Temporary short term load
1.0 Constant load + 1.0 Temporary long term load
1.0 Constant load + 1.0 First temporary load + 0.8 Second temporary load + 0.6 Third temporary load

Specific load combination:

1.0 Constant load + 0.95 Temporary long term load + 0.8 Special load

Ice loads should be considered as the Special load in the Specific load combination. In addition, in seismically active regions where earthquake would also be considered as a Special load in the Specific load combination, ice loads (or wave loads) should be included as a simultaneous temporary load in that Specific load combination.

These load combinations are to be considered for both categories of limit states during periods of normal operations. For periods of repair and construction, a reduced coefficient is specified in the code.

The VSN code refers to the SNiP code on the subject of load combinations.

2.3.3 Method

Similar to the CSA and the API approaches, the SNiP code follows a limit state design method with the following design criterion:

$$\Sigma \gamma_{1c} \gamma_f F_i < R \gamma_c / \gamma_m \gamma_n ,$$

where

Fi	is the stress effect in a structure due to a specified load in a load combination
γ_{1c}	is a coefficient of load combination (described above)
γ_f	is a coefficient of reliability for the specified load (described above)
R	is the specified strength of the material (or foundation bearing capacity)
γ_m	is a coefficient of reliability for the material
γ_n	is a coefficient of structural reliability
γ_c	is a coefficient of working conditions

and for foundation design, the coefficient of reliability for the foundation (ground), γ_g, is used instead of γ_m .

The coefficient of working conditions, γ_c, is specified by the code for various components of the structure and takes into consideration the effects of humidity, environmental aggressiveness and other factors not directly accounted in the design. For major structural elements, this coefficient varies from 0.8 to 0.95.

The coefficient of structural reliability, γ_n, takes into consideration the consequences of structural failure. Four classes of structure or structural components are defined with the coefficient of structural reliability ranging from 1.25 for Class 1 structures whose failure would have the most serious consequences to 1.1 for Class 4 structures whose failure would have the least serious consequences. For offshore structures, this coefficient is 1.25 for the first group of limit states (that would lead to a cessation of operations) and 1.0 for the second group of limit states (that would not lead to a cessation of operations). All offshore structures are considered to be Class 1 structures.

Material strength is treated in a similar manner. Normative (specified) design values for the material characteristics are associated with a probability of exceedance of 95%. For use in design, the specified material values are divided by a coefficient of material reliability, γ_m. The material reliability coefficient for steel is 1.1 and, for the various concrete classes suitable for structures in ice, 1.3.

Specified ground (soil foundation) characteristics are the statistical average values derived from field and laboratory tests. For use in design, these specified characteristics are to be divided by a coefficient of ground reliability, γ_g , that depends on the number of field and laboratory tests. A typical value for γ_g is 1.15. Alternatively, instead of the use of the coefficient of ground reliability, a design value can be determined by the 95% non-exceedance level in the test results. The treatment of ground strength is therefore seen to be different from the treatment of building material strength.

There are no provisions in the VSN code for material characteristics or principles on design loads.

2.4 Summary Comparison

Of the four codes, the CSA code is the most explicit, numerically, in stating its intended level of structural safety for the design. The limit states design method is presented in the code as a method for proportioning a structure so that the target level of safety would be achieved. The return periods for design loads are also clearly specified. The code also states clearly that, should the designer choose to use an alternative design method, the intended level of safety must be achieved.

The API LRFD code was developed when it was recognized that its predecessor, the API Working Stress Design (WSD) code, did not provide structure designs with consistent component reliability. It was also recognized that the historical use of the API WSD code did produce designs with levels of reliability that were acceptable to industry. Consequently, the load and resistance factors in the recommended limit states method were developed by calibrating against historical experience so that designs provided by the API LRFD method will have, on average, structural reliabilities similar to those implicit in the designs provided by the API WSD method. A discussion on this topic is given by Nevel in his 1997 publication entitled “Comparison of API and CSA Design Ice Forces”. The return period of design loads is clearly stated in the code.

The SNiP and the VSN codes are, in essence, not separate codes as the VSN code is intended to supplement and clarify the intentions of the SNiP code. The target level of reliability is not mentioned in these codes and the return period of extreme loads is likewise not specified. The VSN code contains no descriptions of limit states, load combinations and provides no guidance with respect to material characteristics and principles on design loads. However, the VSN code does contain recommended values for the coefficients for ice loads which are different from those given in the SNiP code. The limit state method given in the SNiP code is given in a format different from that in the CSA or the API codes in that it contains additional load and material coefficients. It is not clear whether these coefficients, or factors, have been developed with a target level of structural reliability.

In summary, all four codes follow a limit states design method which calls for the proportioning of the structural components such that the factored component resistance is greater than the effects of the sum of the factored loads. In both the CSA and the API formulation, it is clear that a target structural reliability was used in the derivation of the various partial factors and the specified return periods for the design loads. In the SNiP and the VSN codes, with the use of multiple factors on both the component resistance and the loads, for which a return period is not specified, the targeted level of structural reliability is not apparent, nor is the uniformity in component reliability.

Table 2.1 presents a summary comparison of the structural design approach of the codes.

Table 2.1 Comparison of Structural Design Approach

Item	CSA	API LRFD	SNiP and VSN
Safety Objective	• Low risk to the human safety • Low risk of environmental damage • Definition of Safety Classes for structures and components	• Safety of personnel • Prevention of pollution	• Not explicitly stated
Reliability Objective	• Annual reliability of 0.99999 for Safety Class 1 • Annual reliability of 0.999 for Safety Class 2	• Annual reliability of 0.99995*	• Not explicitly stated
Design Method	• Limit state design method • Ultimate limit states • Serviceability limit states	• Limit state design method	• Limit state design method • First group of limit states associated with operation cessation • Second group of limit states not associated with operation cessation
Design Environmental Loads	• Loads from frequent environmental processes are associated with a 100 year return period for both Safety Classes • Loads from rare environmental events are associated with a 1,000 to 10,000 year return period for Safety Class 1 and 100 years for Safety Class 2	• Extreme wind, wave and current loads are associated with a 100 year return period • Strength level earthquake has a reasonable likelihood of not being exceeded during the life of the structure • Ductility level earthquake is a rare intense earthquake	• Short term environmental loads are annual maximum loads • Special loads are environmental loads associated with a 100 year return period
Load Combinations	• Defined for all loads for both limit states and both Safety Classes	• Defined for all loads	• Defined for all loads
Load Factors	• Single factor applied to each load type in each combination	• Single factor applied to each load type in each load combination	• Each load type is factored by a coefficient of reliability and then by a coefficient of load combination in each load combination
Component Resistance Factors	• Single factor applied to the component resistance	• Single factor applied to the component resistance	• The component resistance is multiplied by a coefficient of working condition, divided by a coefficient of reliability and further divided by a coefficient of structural reliability

* based on component design practices in the Gulf of Mexico, the probability of structure failure is about 0.001 in 20 years (Nevel 97)

3.0 Ice Design Approach

3.1 CSA

As discussed in Section 2, the reliability based CSA code clearly specifies that the design rationale is to relate design loads to the target reliability as defined by an annual probability of failure of 10^{-5} for Safety Class 1 structure components and 10^{-3} for Safety Class 2. The annual exceedance probabilities for the corresponding environmental loads (which include ice loads), together with the load factors to be used in conjunction, are defined to achieve these target reliability levels. For frequent environmental processes (e.g. formation of first year sea ice), the annual probability of exceedance is 10^{-2}. For rare events (e.g. ice islands), the annual probability of exceedance is 10^{-4}.

CSA S471 also states, in Clause 4.5.2, that *if loading hazards can be predicted sufficiently ahead of time to carry out a pre-defined emergency response plan that ensures personnel safety and environmental protection, then, for that particular loading condition, the structure may be Safety Class 2*. This statement has particular significance in the design against ice hazards that can be reasonably monitored for the benefit of an offshore operation. An example of such a measure would be the identification of extreme stamukhas, whose characteristics and proximity to the platform, when compared with a set of design criteria, would trigger safety procedures to preserve human safety (e.g. by early evacuation) and damage to the environment (e.g. by well shut-down). This is one method by which the designer might adopt to deal with rare environmental loads. The concept of a structure being Safety Class 2 for a particular loading condition is an important one – the structure may be Safety Class 1 for earthquakes or other rare environmental loads which cannot be readily monitored or predicted.

In Clause 4.11, the code further states that *where ice management measures are to be used to reduce global or local design ice loads, the reliability of the procedures shall be consistent with the intended safety for the structure or for the particular structural element*. This statement emphasizes the importance of evaluating ice management measures, an example would be icebreaker support, in accordance with the code intended reliability levels.

3.1.1 Ice Features

Clause 5.4 of CSA S471, supplemented by Appendix E to the code, provides a check list of ice data necessary to characterize the regional ice regime. The ice types to be considered include:

- First year sea ice
- Multi-year sea ice
- Glacial ice

Ice features to be considered include:

- Ice floes
- Ice ridges

- Rafted ice
- Hummock fields
- Icebergs
- Bergy bits
- Growlers
- Ice islands

Mechanical and physical properties of these ice features are be to be determined, including:

- Compressive strength
- Flexural and tensile strengths
- Shear strength
- Fracture toughness
- Elastic modulus
- Salinity
- Temperature
- Brine volume and porosity
- Density
- Crystallography

In addition, regional characteristics are to be determined on the basis of field data and, if required, by analyzing the influences from wind, wave and current, on a seasonal and year-to-year basis, on the ice hazards. These characteristics include:

- Ice thickness
- Ice flux and concentration
- Ice velocity

The distribution statistics of these ice parameters are to be generated so that ice loads for the code specified probabilities of annual exceedance can be rationally computed.

3.1.2 Structure Types

Recommendations are provided for the determination of ice loads on a full range of structural shapes:

- Vertical sided structures, narrow or wide
- Slope sided structures, narrow or wide, upward breaking or downward breaking
- Structures founded on a soil berm

Guidance is also given for considering slender structures for which cyclic ice loading is identified as a phenomenon for which the design must accommodate. The potential for liquefaction of the foundation material under cyclic ice loading is also identified as a major design consideration.

3.1.3 Ice Loads

CSA S471 states that ice loads should be determined for the specified return periods on the basis of field data, physical model data or theoretical methods and by considering a number of factors, including:

- environmental driving force
- geometry of the ice feature and of the structures
- mechanical properties of the ice feature
- ice speed
- geometry of the ice/structure contact
- ice clearing around the structure
- inertial effects in both the ice and the structure
- hydrodynamic effects
- effects of ice rubble

Appendix E of CSA S471 gives an introduction to a comprehensive set of current ice determination methods.

It is recognized in the code that it is usual to determine the peak global ice load on a structure, which is then applied as a quasi-static design load for the proportioning of the structure. Such global ice loads are established by one of three limiting conditions:

- **Limit stress**
  Ice load is governed by the failure of the ice.

- **Limit energy (or momentum)**
  Ice load is governed by the available kinetic energy in the ice feature. This energy is continuously dissipated as the ice crushes against the structure.

- **Limit force**
  Ice load is governed by the available environmental forces (wind, current, waves or ice) driving the ice feature against the structure.

Three approaches are presented for the calculation of limit stress ice loads on vertical sided structures:

- **Indentation equation**
  At high ice speeds, ice load is characterized by ice crushing. Ice pressure is given by the crushing strength of ice factored by coefficients that take into consideration of confinement, strain rate in the ice, temperature, crystal structure, the presence of brine and air in the ice. This is based on Korzhavin's work.

- **Creep analysis**
  At slow strain rates, ice failure against a structure can be characterized by creep behaviour using numerical or reference stress methods.

- **Empirical treatment of large-scale data**
  It is suggested that empirical treatment of large scale data is the most promising approach to ice load determination.

On sloping structures, a number of ice load models are referenced for the simulation of level ice or ridged ice riding up onto the structure's surface and fails in a flexural mode. Considerations for potential adfreeze and rubble formation are recommended.

A qualitative description of the methodology for deriving limit energy or limit momentum ice loads is given. Similarly, methods for determining limit force ice loads are described and referenced.

Discussions on cyclic ice loads associated with structural vibrations are also given in Appendix E. It is recommended that a thorough analysis be made when dynamic structural response appears to be possible, taking into consideration of

- ice failure structure attributes such as the mass, stiffness and damping of the structure
- ice feature characteristics such the thickness, speed and strength
- potential modes such as crushing, flexural, flaking and buckling

A number of references are cited for local ice pressures and their relationship with contact area and the aspect ratio of the contact area.

3.2 API

Similar to the CSA code, the API recommendations for designing an offshore structure for ice conditions are given on the basis of a target structural reliability. Ice loads corresponding to a return period of 100 years (an annual probability of exceedance of 10^{-2}) are to be considered for structural design.

API recognizes that rare large ice features may cause an exceptional class of loading and accepts that the owner may decide to accept the risk of damage to the platform facility without loss of life or damage to the environment. To permit such eventuality, API calls for procedures to be implemented that would allow an orderly shutdown and abandonment of the platform. Such procedures would include a monitoring system and could involve active mitigative measures such as an ice management system.

3.2.1 Ice Features

The code provides descriptions and cites references for the possible ice feature types:

- first year floes
- rafted ice
- first year ridges
- rubble features
- multi-year floes and ridges
- icebergs
- natural ice islands

Similarly, the physical and mechanical properties of the ice features to be considered are described:

- crystal structure
- temperature
- salinity
- porosity and brine volume
- specific gravity
- friction
- elastic properties
- strengths, including tensile, flexural, compressive, shear and adfreeze

References are cited for descriptions of ice climate for the Alaskan offshore, including the Beaufort Sea, the Chukchi Sea and the Bering Sea. Ice condition is described by ice coverage and ice movement for three ice zones the Alaskan offshore:

- landfast ice zone where semi-stable ice is attached to the shore
- pack ice zone where ice moves continuously
- transition zone where rough ice occurs between the landfast and the pack ice

The potential for the ice to become adfrozen to the structure, as well as other thermal effects, also needs to be considered.

The code recognizes the large variability of ice feature geometry and recommends, in accordance with the reliability concept, that probability distributions be established to describe ice feature geometry and ice conditions:

3.2.2 Structure Types

Similar to the CSA code, the API provisions cover a full range of structures. The code recognizes that

- jackets
- gravity based structures
- gravel islands
- caisson retained islands
- spray ice islands

have been deployed in ice covered waters. The code tabulates the relevant ice design considerations for three structure types:

- vertical
- multi-leg
- conical

The code recognizes that dynamic ice crushing may induce high forces and that the dynamics of both the structure and its foundation should be taken in to consideration.

3.2.3 Ice Loads

API RP2N and its commentary give a comprehensive description of a procedure for calculating ice loads probabilistically and its rationale in a structural reliability framework. Even so, the code allows for the deterministic determination of ice loads.

The parameters that determine the ice load arising from a particular ice event include:

- type of ice feature
- size, shape, orientation and speed of ice feature
- ice properties
- ice failure mode
- size, shape and stiffness of the structure

Similar to the CSA, ice loads are categorized into three groups:

- loads limited by driving forces
- loads limited by ice momentum
- loads limited by ice failure

For ice loads limited by driving forces, provisions are given for driving forces arising from three factors:

- water current
- wind
- ice cover, frequently taken as the ridge building force

A description of ice loads limited by the momentum or energy in the ice feature is given, including considerations for mechanical properties consistent with rapidly occurring loads, hydrodynamic added mass and eccentric hits.

Descriptions of ice failure modes are provided for the determination of ice loads limited by ice failure. Four fundamental failure modes are states:

- crushing, which can be further divided into creep crushing, intermittent crushing and continuous crushing
- bending
- buckling
- splitting

Descriptions of theoretical models of these failure modes are provided and suggestions for the use of ice pressures measured in the field for design are made. The use of model tests to verify theoretical models or to serve as design tools is also discussed.

Similar to the CSA code, references and discussions are provided for the consideration of dynamic crushing loads and local ice pressures.

3.3 snIp and VSN

Ice design approaches are given in both SNiP 2.06.04-82* and VSN-41.88. While the VSN code is intended to supplement the SNiP code, there are differences in the ice design provisions in these two codes.

The annual probability of exceedance (or return period) of the design ice load is not specified in these codes. However, the annual probability of exceedance for some ice characteristics is specified to be 10^{-2}, these characteristics being ice thickness and the ice floe dimensions. As different ice hazards/features are characterized by different parameters, the ice loads resulting from these ice hazards/features do not appear to have a uniform risk.

3.3.1 Ice Features

The SNiP and the VSN codes consider only two types of ice formation, namely first year level ice and ridged ice, and that these ice features may impart loads on offshore platforms in the following manners:

- Pack ice moving against the structure
- Stationary ice pack being driven by wind and current
- Thermal expansion of a consolidated ice pack
- Adfreeze effects under tidal influence

Both codes use semi-probabilistic methods for the determination of ice characteristics for computing ice loads. Probabilistic distributions are used to describe these characteristics and a value at a prescribed probability of annual exceedance is selected for load determination. For example, to compute loads from level ice, the following characteristics are used:

- the level ice thickness at the 1% probability of annual exceedance level
- an ice floe area at its 1% probability of annual exceedance level
- to determine ice strength, VSN specifies the use of the average temperature on the coldest 6 day period over a 5 year observation period whereas SNiP recommends the use of an average temperature over a few days before the day for which the ice loads are to be determined; this period depends on the ice thickness

From this, it is evident that the probability of exceedance for the ice load thus computed is not explicitly established. Furthermore, VSN's recommendation for the simultaneous consideration of the 'maximum' ice thickness and the 'minimum' air temperature (thus 'maximum' ice strength) is unreasonably conservative.

The codes do not contain any provisions for other ice features such as:

- rafted ice
- broken ice
- icebergs
- stamuchas
- ice rubble

3.3.2 Structure Types

The codes contain provisions for determining ice loads on the following structure types:

- Vertical sided structures, monopods (e.g. columns, piles, piers) and wide structures
- Slope sided structures

The effect of structure width on ice loads is taken into consideration by the use of the aspect ratio parameter. The SNiP code divides vertical sided structures into monopods and wide structures but strict definitions of these structure types are not given. As the specified formulae for computing ice loads on these structure types are different, the designer must exercise judgment as to which formula is applicable.

3.3.3 Ice Loads

As mentioned previously, the codes consider only two types of ice features, namely level ice and ice ridges. However, the recommendations for determining ice loads due to ice ridges consist only of a ridge coefficient which is to be applied to ice loads calculated for level ice conditions. The magnitude of the ridge coefficient ranges from 1.3 to 2.0, depending on the geographic location. For the Arctic seas and the seas of the russian Far East (Bering Sea and the Sea of Okhotsk), SNiP permits the use of a ridge coefficient of 2.0 if it is substantiated.

SNiP provides guidance on the determination of global ice load only whereas VSN contains a contact area dependent local ice pressure recommendation. Ice speed is reflected in SNiP by incorporating a strain rate dependent ice strength. In VSN, the condition on ice speed is that it must be less than 0.5 m/s. Ice induced vibration is not treated in the codes.

VSN considers only limit stress ice loads. SNiP considers also ice loads limited by the available momentum in the ice feature and driving force by wind and current only. Driving force due to ridge formation is not treated in the code.

The limit stress method provisions in SNiP and VSN are based on Korzavin's formula, as referenced also in the API code. Ice load is given by:

$$p = P / A = k_o \, k_v \, R_c$$

and

$$A = b \, h$$

where:

p	is ice pressure over contact area
P	is the ice load
R_c	is ice strength
A	is the ice/structure contact area
b	is the width of the contact area, taken as the width of the structure
h	is the ice thickness
k_v	is a coefficient accounting for strain rate in VSN, the value is 1 (but ice speed must be less than 0.5 m/s)

in SNiP, the value is dependent on the characteristic strain rate ε, with strength value peaking at a strain rate between 10^{-4} and $5\text{x}10^{-4}$, as opposed to 10^{-3} as suggested in studies by Timco, Michel and others

k_o is a coefficient accounting for the aspect ratio of the contact zone
in VSN, the value ranges from 6.0 to1.0
in SNiP, the value ranges from 5.7 to 1.5

Size effect is not taken in consideration in the SNiP and VSN provisions.

The limit momentum method provisions in SNiP are similar to those in the API code although the equations are somewhat different.

The provisions for determining ice loads on sloping structure faces are based on Ralston's method as described in the API code.

3.4 Summary comparison of the code provisions for ice design

Both the CSA and the API codes provide discussions on and references to what appears to be a full range of state-of-the-art ice load calculation models. The recommendations in these two codes tend to be very similar although there are subtle differences (this difference in the interpretation of information for the determination of global ice load due to ice crushing is demonstrated in Section 4 Ice Load Calculations). This is not surprising as the developments of the CSA code and the API code in the LRFD format, and the update of the API RP2N, were undertaken by essentially the same community of arctic offshore experts. The API code includes many details of alternative ice load models and cautions the designer to exercise judgment in his selection of the appropriate model for the design at hand. In contrast, the CSA code cites publications and concentrates on giving advice on the overall approach. Since both codes are formulated on the basis of structural reliability, probabilistic ice load models are recommended by both codes. API, however, allows for the use of deterministic methods although little guidance is provided in this respect.

In comparison to the ice design provisions in the CSA and the API codes, the provisions in the SNiP and the VSN codes appear to be limited. The SNiP and the VSN codes consider only two types of ice features, namely level ice and ice ridge, and contain limited provisions for ice load determination. Topics such as ice induced structural vibrations and driving force due to ice ridge formation are not covered in these codes. The semi-probabilistic methods given in these codes for establishing design ice characteristics do not lead to a consistent probability of annual exceedance for the resulting ice loads. In the absence of a consistently quantified risk of the design ice hazard, the level of structural reliability cannot be established.

Table 3.1 presents a summary comparison of the ice design approach of the codes.

Table 3.1 Comparison of Ice Design Approach

Item	CSA	API LRFD	SNiP and VSN
Probability of Annual Exceedance (Return Period) for Ice Loads	• 10^{-2} (100 year return) for frequent loads • 10^{-4} (10,000 year return) for rare loads	• 10^{-2} (100 year return)	• not specified for ice loads • annual probability of exceedance specified at 10^{-2} for some ice characteristics to be used in ice load calculation
Ice Types	• first year sea ice • multi-year sea ice • glacial ice	• first year sea ice • multi-year sea ice • glacial ice	• first year sea ice
Ice Features	• floes • ridges • rafted ice • hummock fields • icebergs, bergy bits and growlers • ice islands	• floes • rafted ice • ridges • ice rubble • icebergs • natural ice islands	• level ice • ridges
Structures	• vertical • slope sided • structures on soil berm	• vertical • multi-leg • conical	• vertical, narrow and wide • slope sided • multi-column
Quasi-Static Global Ice Loads	• limit stress • ***limit energy (or momentum)*** • limit force from wind, current or ice • use of field data suggested	• limited by driving force from wind, current or ice • limited by ice momentum • limited by ice failure • use of field data suggested	• limit stress • limit driving force from wind and current only (SNiP only) • limit momentum (SNiP only)
Dynamic Global Ice Loads	• provisions given	• provisions given	• no specific provisions
Local Ice Loads	• provisions given	• provisions given	• provisions given in VSN only

4.0 Ice Load Calculations

In this section, selected provisions the North American and Russian codes are applied to estimate the ice loads for the following 3 scenarios:

Scenario 1 A level sheet of sea ice of 1.2 m thickness interacting with a fixed offshore structure in mid-winter. Assume that the ice is moving at a rate of 0.2 m/s, and the structure is vertical-sided with a width of 100 m and in deep water.

Scenario 2 A first-year ridge of total thickness 10 m interacting with the same structure. Assume a keel-to-sail ratio for the ridge of 4.4, a consolidated layer thickness of 1.5 m, and a width of 23 m. Assume that the ridge is embedded in an ice sheet with the same characteristics of Scenario 1.

Scenario 3 Open pack ice of 1.2 m thickness interacting with a multi-leg structure of 100 m width. Determine the expected load for pack ice concentrations of 0.4 and 0.8 for floe sizes of the order of 10 to 50 m in diameter moving at a speed of 0.5 m/s. Assume that the structure has four 20 m wide cylindrical supporting piers at the four corners.

Since these scenarios are specified, the provisions in the codes pertaining to the probabilistic determination of ice parameters are not exercised.

The ice loads in the following subsections have been determined by interpreting and applying the provisions in the various codes as an offshore structure designer might if he were requested to estimate ice loads using only the information given in the codes or their commentaries. This approach was taken because any shortcomings in the codes would be demonstrated readily.

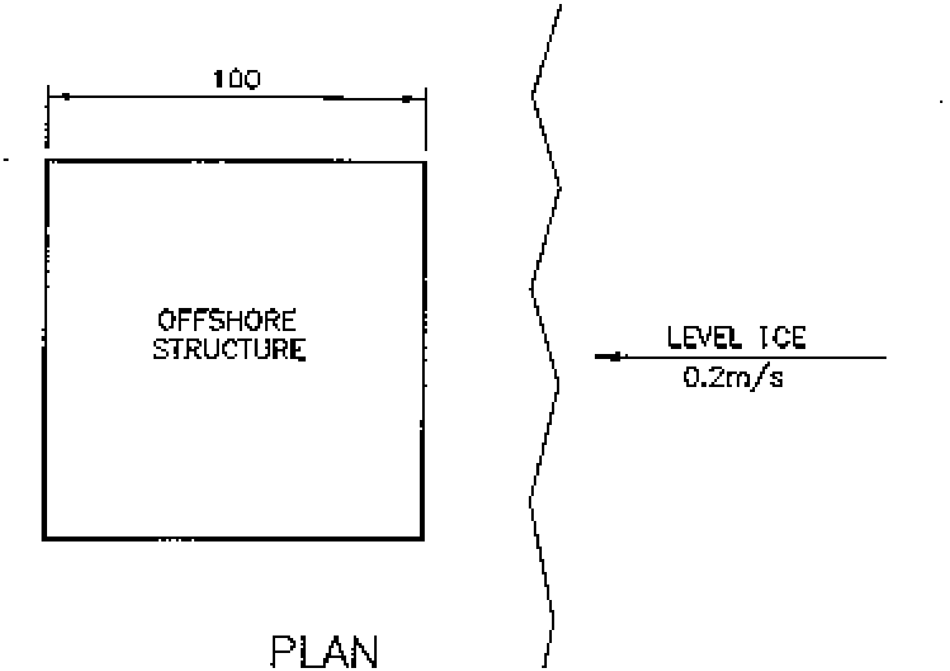
4.1 Scenario 1 – Level Sheet Ice

Figure 4.1 shows this scenario as described by "*A level sheet of ice of 1.2 m thickness interacting with a fixed offshore structure in mid-winter. Assume that the ice is moving at a rate of 0.2 m/s, and the structure is vertical-sided with a width of 100 m and in deep water.*"

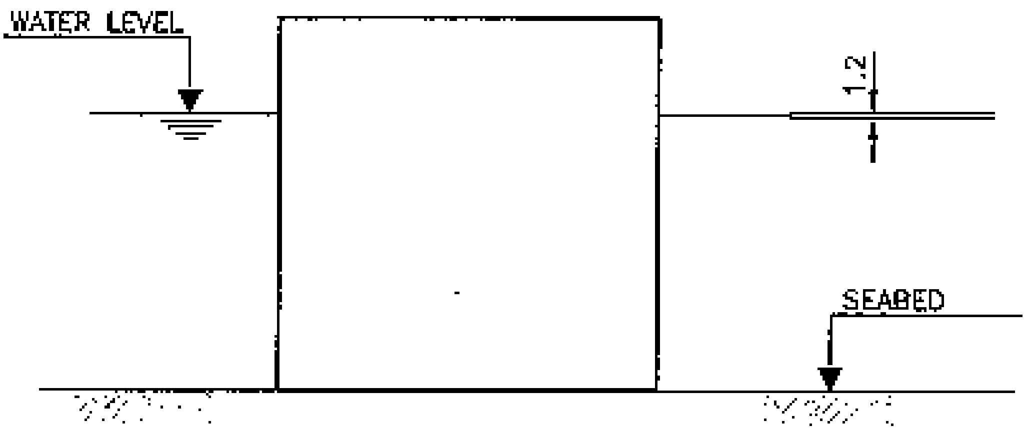
4.1.1 CSA

The CSA code addresses the determination of ice loads in Appendix E of the code, page 60. Approach to the issue is discussed, followed by a brief discussion of a probabilistic framework for determining ice loads. Ice load scenarios are then described for various regions, followed by lengthy descriptions of ice regimes in the Arctic and offshore Labrador. There follows a general discussion on the mechanical properties of ice.

Figure 4.1 Scenario 1 – Level Ice



PLAN



ELEVATION

Section E5.1.2 addresses quasi-static loads, giving the first limit to ice force as limit-stress, defined by:

$$F = pDt$$

where

p is the ice failure pressure
D is the structure diameter
t is the local ice thickness

The contact area is 100 m x 1.2 m = 120 m^2. It is stated that both p and t should be treated as random quantities. Statements are made regarding limited environmental driving force and limited momentum of the ice. There is also discussion of the effects of structural shape, buckling, strain rate, ice pile-ups etc.

In Section E5.2.1.2 there is a discussion of Korzhavin's indentation equation, which is given. However, this equation cannot be used without making assumptions about indentation coefficients and the effect of strain rate on ice pressure. There is no guidance, other than references, to assist in the use of these equations.

Under empirical treatment of large-scale data, Sanderson's curve of ice pressure vs. area is presented in Figure E2. The effective ice pressure is given in Section E5.2.1.2 as:

$$p = \sigma\sqrt{\frac{A_o}{A}}$$

where

p is the mean peak pressure in MPa
A is the contact area in m^2
A_o is the reference area of 100 m^2
σ is 0.92 MPa

The above equation forms an upper bound envelope to the data of Figure E2 in the code Appendix. For a contact area of 120 m^2, the effective ice pressure is 0.84 MPa. Thus the expected force is:

$$F = 100 \text{ MN}$$

Section 6 on loads and load combinations, gives factors in Table 6.2 for all types of loads in various combinations. Combination 2, for a Safety Class I structure, would require the ice load to be factored by 1.35. This considers the calculated load to have a probability of recurrence of 10^{-2}. Thus the design ice load from the CSA code is:

$$F = 1.35 \times 100 \text{ MN} = 135 \text{ MN}.$$

4.1.2 API

API RP2N is a comprehensive document that covers various aspects of pack ice loading on structures in considerable detail. Section 5.4 contains the procedures and equations for ice load determination.

Following through the procedures in sub-sections 5.4.2, 5.4.3, 5.4.4 and 5.4.5, the following is evident.

The probability of the structure interacting with the ice is 1 since the ice cover is continuous and the level ice sheet is assumed infinite and constant thickness.

There is no limit to the driving force since the ice sheet is infinite and thus wind and current drag are more than sufficient to initiate movement and to sustain it.

Ridge formation processes are not an issue and, if they do form as the ice moves, the level sheet ice force on the structure is not affected.

The load is not limited by momentum since the ice sheet is infinite.

The load is thus limited by ice failure (stress limited) as outlined in Section 5.4.6.

For crushing, equation 5.27 is applicable.

$$F = p_e D t$$

where

D is the width of the structure
t is the ice thickness
p_e is the effective crushing pressure

The contact area of the ice is 100 m x 1.2 m = 120 m^2. By Figure 8 in the API code, the effective ice pressure is 1.5 MPa at the mean plus 2 x standard deviation level. Thus the crushing force of the level ice is:

$$F = 180 \text{ MN}$$

Since the structure is vertical walled, bending failure in the ice is not considered possible. Buckling, Section 5.4.9 was checked. For the present situation, the dimensionless buckling load is as follows:

$$\frac{P}{B\gamma_w l^2} \approx 3$$

where

P = Buckling load

B = Width of beam

γ_w = water density

= $9.8\ \mathrm{kN/m^3}$

l = ice characteristic length

For this ice sheet the characteristic length is about 10 m. The value 3 for the dimensionless buckling load was taken from Figure 11 in the API code.

> If the width of the beam to be buckled is taken as the structure width, then the buckling load is 300 MN, greater than the crushing load. It should be noted that a “mixed mode” failure could occur, with a mixture of buckling and crushing. This would lead to a lower total load on the structure. However, experience with the Molikpaq structure has shown that simultaneous crushing across 100 m is possible and thus it is necessary to consider the global load as 180 MN.

Floe splitting is considered in Section 5.4.10. The effective pressure required to split a floe is given as:

$$p = K_{1C}\frac{\sqrt{L}}{b}F\left(\frac{W}{L}\right)$$

where:

$$K_{1C} = 0.1\ \mathrm{MPa\ m^{1/2}}$$

K_{1C}, the ice fracture toughness, is taken from the example in RP2N. Likewise, the floe length, L, is taken as 2,000 m. b, the contact width, is 100 m or less. F(W/L) is a function. From Figure 13 in the API code, the pressure required to split a floe of this size is about 1.5 MPa, making splitting or crushing equally likely. Larger floes will crush and as we are assuming that the ice sheet is infinite, crushing remains the most likely failure mode.

In summary, the crushing load of 180 MN was obtained using an expected ice thickness of 1.2 m and an effective ice pressure of 1.5 MPa which is the mean plus 2 standard deviation pressure vs. area curve with a truncation at 1.5 MPa. Section 6.5.7 of API RP2N specifies that the structure should be designed for strength using the load factors of Table 6 in the code. If the 180 MN is regarded as a frequent event, then this load would be factored by 1.35 to obtain the design load. If the load is regarded as an infrequent event, then the load factor is 1.0.

4.1.3 SNiP and VSN

Ice loads for this scenario using the provisions in the SNiP 2.06.04.82*-1996 and the VSN codes are given in this section.

The extent of the ice floe is assumed to be very large for the purpose of calculating ice loads. Also, the average air temperature is assumed to be -20°C and the sea ice salinity is assumed at 3‰. For a monopod structure, SNiP allows ice loads to be determined by the use of formula (121) or formula (122) in the case of elements of a wide structure. As the code does not specify the distinction criterion between narrow and elements of wide structures, both formulae will be applied for the purpose of illustration.

Formula (121) expresses the ice load, F_s, as follows:

$$F_s = m\, k_b\, k_v\, R_c\, b\, h,$$

where

b	is the width of the structure, equals 100 m
h	is the ice thickness, equals 1.2 m
m	is the shape coefficient; equals 1.0 as per Table 29
k_b	is the aspect ratio; equals 1.5 as per Table 30 for b/h = 83.3
k_v	is the coefficient accounting for strain rate, formula (120); for $\varepsilon = v / 2\,b = 0.2 / 200 = 1 \times 10^{-3}$ then k_v equals 0.8 as per Table 31
R_c	is ice strength as per clauses 5.3, 5.4:

$$R_c = \Big[\sum_{i=1}^{N} (C_i + \Delta_i)^2 / N\Big]^{1/2},$$

where:

N	is the number of layers in the ice thickness, equals 3 in this example, in general, 5 layers should be used
C_i	is the average strength value for uniaxial compression in the ith-layer at temperature t_i, MPa
Δ_i	is a confident limit on C_i, MPa.

The three layers within the ice thickness are given by

- upper layer is 0.2 h = 0.24 m
- middle and lower layer of 0.4 h = 0.48 m

The average strength of the individual layer is determined from the temperature and the brine volume in each layer. Using SNiP's Table 28 the strengths are obtained as follows:

Layer	Temperature, °C	Brine Volume, ‰	Ice Strength, MPa
1	-18.1	12.03	6.1
2	-11.4	17.4	3.2
3	-5.8	31.0	2.1

The strength of the ice sheet is then determined:

$$R_c = [\,(37.2 + 10.2 + 4.4) / 3\,]^{1/2} = 4.15 \text{ MPa}$$

The ice load on the structure is thus:

$$F^s = 1 \times 1.5 \times 0.8 \times 4.15 \times 100 \times 1.2 = 597.6 \text{ MN}$$

Alternatively, assuming that formula (122) is applicable (as in the case of elements of a wide structure), the ice load is given as follows:

$$F^s = k\, k_v\, R_c\, b\, h,$$

where

k is a coefficient that accounts for the aspect ratio; equals 0.4 as per Table 32

The global ice load is then given by:

$$F^s = 0.4 \times 0.8 \times 4.15 \times 100 \times 1.2 = 159.4 \text{ MN}$$

The VSN code is applicable to this scenario because the specified ice speed of 0.2 m/s is slower than the maximum speed of 0.5 m/s required by the code. Formula (1) in the VSN code gives an ice load F_v as follows:

$$F_v = m_1\, K_b\, R_c\, b\, h,$$

where

m_1 is the shape coefficient; equals 1.1 for rectangular structures

K_b is the aspect ratio coefficient; equals 1.0 as per Table 4, when adfreeze condition does not occur

R_c is ice strength; equals 1.3 MPa as per Table 2 at the assumed temperature and salinity (VSN gives ice strengths that are usually significantly lower than those determined in the field.)

The global ice load is then given by

$$F_v = 1.1 \times 1.0 \times 1.3 \times 100 \times 1.2 = 171.6 \text{ MN}$$

4.1.4 Comparison for Scenario 1

The ice loads for Scenario 1 (level ice) computed by using the different codes are tabulated below.

Code	Level Ice Load (MN)
CSA	100
API	180
SNiP	597.6 if structure considered as a monopod 159.4 if structure considered as a wide structure
VSN	171.6

There is substantial difference between the CSA and the API loads. Both the CSA and API codes allow for the use of alternate data sources for determining the effective pressure. The CSA code especially contains considerable discussion on the various approaches and the differences in treatment of data. However, if one is to use the codes directly for load determination, these are the results. The discussions of crystal structures and ice types ultimately have little relevance for the designer, who requires a load and, in the absence of other information, will obtain it from Figure E2 in the CSA code or from Figure 8 in the API Recommended Practice. The two are obviously not in agreement and the difference stems from the divergence in ice pressure versus contact area information presented. It is interesting to note that the same pressure versus area information is contained in the CSA code as in API as Figure E3. However, the CSA code indicates this information applies only to local ice pressures. At any rate, neither of the data bases should be used alone for ice load determination but should be supplemented with other, relevant data bases, a clear requirement of the CSA code.

Two ice loads can be calculated using SNiP. The ice load calculated using formula (121), applicable to monopods, is more than three times that calculated using the API code. The ice load calculated using formula (122), applicable to elements of a wide structure is similar in magnitude to the API load, despite that the Russian code does not take into consideration explicitly the effect of size on ice strength (Shkhinek et al, in their publication entitled “Comparison of the Russian and Foreign Codes and Methods for Global Load Estimations” also indicated that the Russian codes do not use a scale factor).

The ice load computed using the VSN code is almost identical to the API load. This is probably just co-incidental but at the same time, this result is not surprising as the assumed mode of ice failure is crushing in both cases.

This comparison shows that ice loads for level ice crushing against a structure calculated using formula (122) in SNiP (applicable to elements of a wide structure) and using VSN are comparable to those calculated using the ice pressure-area curve given in the API code. The load calculated using formula (121) in SNiP (applicable to monopods) is more than three times larger. Loads estimated by the referring to large scale field data, which both the CSA and API codes support, are lower.

The following table summarizes the areas in the various codes where there seems to be a lack of guidance and the assumptions needed beyond code guidance in order to calculate ice loads due to level ice.

Code	Comments on Code Guidance on Level Ice Load Determination
CSA	• Little guidance on the use of indentation coefficients and the effect of strain rate in Korzhavin's indentation equation • Ice pressure information provided in the Commentary, rather than the main body of the code • Calculated ice load assumes limit stress load
API	• Comprehensive guidance provided • Calculated ice load assumes limit stress load
SNiP	• Equations for monopods and elements of wide structures are given but the criterion to distinguish structure types is not given • Calculated ice load assumes limit stress load
VSN	• Straightforward guidance provided • Calculated ice load assumes limit stress load

4.2 Scenario 2 – First Year Ridge

Figure 4.2 shows this scenario as described by "*A first-year ridge of total thickness 10 m interacting with the same structure. Assume a keel-to-sail ratio for the ridge of 4.4, a consolidated layer thickness of 1.5 m, and a width of 23 m. Assume that the ridge is imbedded in an ice sheet with the same characteristics of Scenario 1*".

4.2.1 CSA

The CSA code provides a discussion of forces on sloping structures due to both first-year and multi-year ice ridges and, while doing so, alludes to vertical structures. No equations are given for the calculation of ridge loads but references are suggested which contain methodologies.

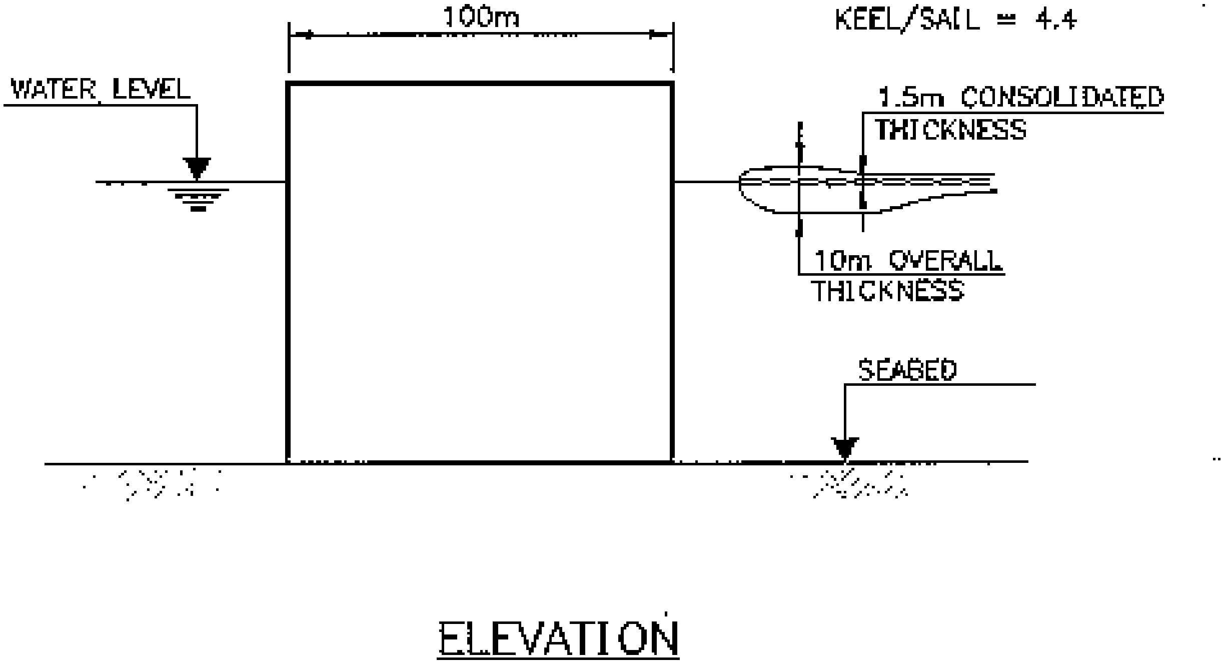
The force from the consolidated portion of the ridge can be calculated using the same general equation as for Scenario 1. Thus:

$$F_C = 0.92\,\{100/(1.5\mathrm{x}100)\}^{0.5} \mathrm{\ x\ } 100 \mathrm{\ x\ } 1.5$$
$$= 113 \mathrm{\ MN}$$

An additional 14 MN force can be calculated to account for the clearing of the ice rubble in the sail and the keel of the ridge. This calculation is shown in detail in the next section describing the API methodology. Therefore the CSA expected ridge force would be:

$$F = 127 \mathrm{\ MN}$$

Figure 4.2 Scenario 2 – First Year Ridge



4.2.2 API

The force from the ice ridge will be calculated in two parts, that due to the consolidated layer and that due to the rubble in the keel and sail.

The force from the consolidated layer is, using Figure 8 in the code:

F_C = 1.5 m x 100 m x 1.5 MPa
= 225 MN

Section 5.4.12, page 32, gives suggested equations, based on a Mohr-Coulomb material, for calculating the force from ice rubble and ridges. With a width of 23 m, the ridge is wide compared to its thickness and thus equations applicable to wide ridges have been used.

The force per length from the rubble in the sail is given as:

$$F_S = \frac{1 + \sin\phi}{1 - \sin\phi} (1 - n) \gamma_i t_S^2 + 2C \left(\frac{1 + \sin\phi}{1 - \sin\phi} \right)^{1/2} t_S$$

where

ϕ = friction angle of the rubble
n = rubble porosity
C = cohesion of the rubble in MPa
γ_i = ice density = 0.009 MN / m^3
t_S = sail thickness

Since the total ridge thickness is 10 m, then the sail and keel are 10 m – 1.5 m = 8.5 m thick. The sail is then 1.9 m thick and the keel is 6.6 m thick.

To calculate the force, the friction angle of the sail was taken as 40^o, a value being currently used in offshore designs, and C was taken as 0. Thus,

F_S = ½ x 4.6 x 0.8 x 1.9^2 x 0.009 x 100
= 6 MN

The force per length due to the keel is given as:

$$F_k = \frac{1 + \sin\phi}{1 - \sin\phi}(1 - n)(\gamma_w - \gamma_i)\, t_k^{\,2} + 2C\left(\frac{1 + \sin\phi}{1 - \sin\phi}\right)^{1/2} t_k$$

where

ϕ = friction angle of the rubble

n = rubble porosity

C = cohesion of the rubble in MPa

γ_w = water density = $0.01\ \mathrm{MN/m^3}$

γ_i = ice density = $0.009\ \mathrm{MN/m^3}$

t_k = keel thickness

Thus the keel force, for similar properties, is:

F_k = ½ x 4.6 x 0.8 x 6.6^2 x (.01 - .009) x 100
= 8 MN

Thus the total force due to the ridge is:

F = 225 MN + 6 MN + 8 MN
= 239 MN

Recognizing that the ridge must be pushed by the level ice behind it, the width of level ice required is:

W_{req} = (239 MN)/(1.5 MPa x 1.2 m)
= 133 m

A pressure ridge with a length of at least 133 m is very possible and it is reasonable to have a ridge length mobilized against the structure which is 33 percent greater than the structure width without having the ridge fail in shear at the structure edges.

Thus the expected ridge force is:

F = 239 MN

4.2.3 SNiP and VSN

Ridge loads, as per SNiP and VSN, are determined by level ice loads modified by a ridge coefficient of 1.5 for Arctic conditions. According to SNiP the coefficient may take on a value of 2 if there is appropriate justification. It is noted that, by this method, the loads due to ice ridges do not explicitly account for the thickness of the consolidated layer, the width or length of the ridge, and the presence of the ice rubble in the sail and the ridge of the ridge.

For a ridge coefficient, k_t, of 1.5 to 2., and using the level ice loads given for Scenario 1, the ridge loads according to SNiP are:

Using formula (121), which is applicable to monopod structures, the ice loads are:

F_t^s = 896.4 to 1195.2 MN

Using formula (122), which is applicable to elements of a wide structure, the ice loads are:

F_t^s = 239.1 to 318.8 MN

For a ridge coefficient of 1.5, the ridge load according to VSN is:

F^v = 257.4 MN

It must be noted that these calculations are performed by illustrative purpose only because the specified consolidated thickness of the ridged ice may have no correlation with the level ice thickness specified in Scenario 1. The ridge coefficient in the Russian codes is specified for the Russian arctic and implies a certain relationship between a design first year ridge and the design level ice thickness.

4.2.4 Comparison for Scenario 2

The ice loads for Scenario 1 (first year ridge) computed by using the different codes are tabulated below.

Code	Ridge Ice Load (MN)
CSA	127
API	239
SNiP	896.4 to 1195.2 (using formula (121), applicable to monopod structure) 239.1 to 318.8 (using formula (122), applicable to a wide structure)
VSN	257.4

Again, there is considerable difference between the force obtained from the API and the CSA codes. The difference is due to the information provided in each document regarding global consolidated ice pressures on vertical faced structures.

The provisions in the Russian codes do not contain guidelines for calculations that recognize the structure of the ridge – a consolidated layer sandwiched by ice rubble in the sail and the keel. Rather, the ridge load is given by applying a ridge coefficient (1.5 for both SNiP and VSN, 2.0 for SNiP is there is justification) to an ice load which accounts only for the crushing of the parent level ice (not the consolidated thickness within the ridge). This methodology, which appears to be empirical in nature, yields ridge loads derived from an application of formula (122) in SNiP that are comparable to that calculated on the basis of API provisions. However, this is purely coincidental because there is no implicit correlation between the specified 1.5 m of consolidated ice thickness in the ridge and the 1.2 m level ice thickness in Scenario 1. Consequently, these results do not imply a confirmation of the ridge coefficient. Ridge loads derived from an application of formula (122) in SNiP are several times greater.

In summary, the reference to large scale field data given in the CSA commentary to estimate the crushing of the consolidated layer in the ridge has led to a substantially lower ice ridge load than that calculated with the use of the ice pressure-area relationship given in the API. The Russian codes have been developed for the Russian arctic and ridge loads are given by the product of a ridge coefficient and level ice loads. Consequently, the application of the Russian code to other arctic or subarctic area for the calculation of ridge loads should be cautioned.

The table below summarizes the areas in the various codes where there seems to be a lack of guidance and the assumptions needed beyond code guidance in order to calculate ice loads due to ridged ice.

Code	Comments on Code Guidance on Ridge Load Determination
CSA	• No equations are given for the calculation of ridge loads but references are given which contain methodology • Ice pressure given in the Commentary, rather than the main body of code • Calculated ice load assumes limit stress load (limit ridge failure at the structure)
API	• Comprehensive guidance given • Calculated ice load assumes limit stress load (limit ridge failure at the structure)
SNiP	• Only a ridge coefficient is given which does not explicitly account for the consolidated ice thickness, the width or length of the ridge and the presence of ice rubble in the sail and the keel
VSN	• Only a ridge coefficient is given which does not explicitly account for the consolidated ice thickness, the width or length of the ridge and the presence of ice rubble in the sail and the keel

4.3 Scenario 3 – pack ice of partial coverage

Figure 4.3 shows this scenario as given by *"Open pack ice of 1.2 m thickness interacting with a multi-legged structure of 100 m width. Determine the expected load for pack ice concentrations of 0.4 and 0.8 for floe sizes on the order of 10 to 50 m in diameter moving at a speed of 0.5 m/s. Assume the structure has four 20 m wide cylindrical supporting piers at the four corners*".

4.3.1 CSA

CSA does not deal specifically with loose pack interactions with monolithic or multi-legged structures. However it does address the probability of individual floes hitting a structure but, in a 4/10 to 8/10 pack, the probability of a hit is certain. In fact, the floes will jam between the legs of the structure and will cause the full pack force to be exerted across the 100 m width. The floes are large enough, and thick enough, to assure that there will be times when stability of the ice is not a governing criteria. This is partially verified by the stability calculation in Scenario 1. Again, it is assumed that driving force does not limit the force, nor does floe size since the floes described are assumed to pack together on the upstream side of the structure. Thus the CSA force is calculated as:

$$F_C = 0.92\,\{100/(1.2 \times 100)\}^{0.5} \times 100 \times 1.2$$
$$= 100 \text{ MN}$$

The expected force of 100 MN is the same as for the level ice of Scenario 1.

4.3.2 API

The API likewise code does not address specifically the present loose pack scenario but the same considerations as discussed above for the CSA code apply. Thus the expected force on the structure due to 4/10 to 8/10 ice cover is:

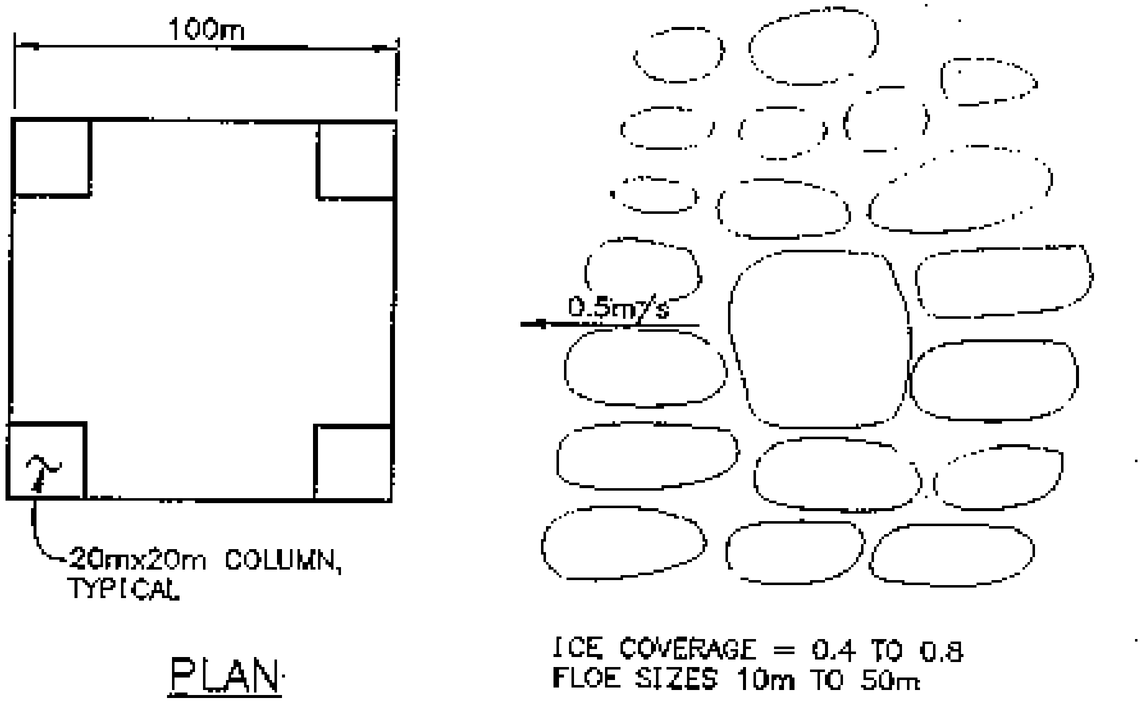
$$F = 1.2 \text{ m} \times 100 \text{ m} \times 1.5 \text{ MPa}$$
$$= 180 \text{ MN}$$

The expected force of 180 MN is the same as for the level ice of Scenario 1.

4.3.3 SNiP and VSN

There are no specific provisions in both SNiP and VSN for the determination of loads due to partial ice coverage.

Figure 4.3 – Partial Ice Coverage



By assuming that the ice will jam between the columns, and treating the resulting structure as a vertical sided structure, the ice loads on the multi-column structure will be similar in magnitude to those computed for Scenario 1. Thus, the ice loads using SNiP, with the application of formula (122) for wide structures, and using VSN, are respectively:

F^s = 159.4 MN
F^v = 171.6 MN

4.3.4 Comparison for Scenario 3

As none of the four codes addresses specifically ice loads due to partial ice coverage, a necessary assumption was made of ice jamming between the columns, thereby rendering the multi-column structure effectively a wide vertical structure. Consequently, the expected ice loads differ by the same amount as in Scenario 1. However, in a semi-continuous to loose pack such as this impacting a four legged structure, the following will influence and generally reduce the ice loads:

- ***The looser pack may flow around the structure as individual floes move relative to one another. The ice loading is then a result of friction between the floes and of momentum change associated with the floe movements. I wind tightens the pack, pack pressures will increase the force. At a thickness of 1.2 m, crushing will be much less frequent than for an infinite, level ice sheet.***

- ***Ice may not always jam between the legs of the structure, with the result that the force on 2 or 3 legs will be the contributors to the global force. For a relatively "tight" pack, the effective contact width could be 40 to 60 m instead of the full 100 m.***

- ***Smaller floes may be unstable and upend or roll when placed under pressure, thus limiting the pressure the pack is able to deliver to the structure.***

Thus for the situation of Scenario 3, it would be reasonable to regard the forces derived as extreme expected and not to factor them, as would generally be required for the level ice.

In summary, for all four codes, the designer is required to make assumptions on the behaviour of a moving loose ice pack on a multi-column structure in order to make use of code provisions for the purpose of calculating ice loads.

The following table summarizes our comments on code guidance for determining ice loads due to partial ice coverage.

Code	Comments on Code Guidance on Partial Ice Coverage Loads
CSA, API, SNiP and VSN	• No specific provisions for loads due to partial ice coverage • No specific provisions for evaluating ice jamming potential • Calculated ice load assumes limit stress load across an ice-jammed width •

4.4 Summary comparison of ice load calculations

The level ice loads have been determined by applying the limit stress condition. The loads determined from applying the CSA provisions are considerably lower than those from the API, SNiP and VSN codes. This results primarily from a difference in the determination of the ice crushing pressure. In the CSA code, large scale field information is referenced and this has been applied directly in the global ice load estimation. The ice pressure-area relationship cited in the API code gave larger global loads. The API ice pressure-area relationship is also referenced in the CSA but is indicated in the CSA as only applicable to local ice pressures. The SNiP and the VSN codes, using an indentation formulation without apparently considering the effect of size (or scale), also produced larger ice loads.

The crushing of the consolidated thickness dominates the ridge loads calculated in accordance to CSA and API. Again, with the use of large scale field information given in the CSA commentary, the CSA load is considerably lower. The SNiP and VSN code do not provide guidance on calculating ridge loads on the basis of ridge characteristics. Rather, the ridge load is given by the product of a ‘ridge coefficient’ and the level ice load.

None of the four codes addresses specifically ice loads due to a partial ice cover. An assumption was made of ice jamming between the columns in the multi-leg structure in order to rationalize an ice load.

Table 4.1 presents a summary comparison of the ice loads calculated by following the four codes.

Table 4.1 Comparison of Ice Load Calculations

Item	CSA	API LRFD	SNiP	VSN
Scenario 1 – Level Ice	• 100 MN • limit stress • upper bound of empirical large scale data	• 180 MN • limit stress • mean + 2 std dev of ice pressure – contact area relationship	• 597.6 MN (formula 121, applicable to a monopod structure) • 159.4MN (formula 122, applicable to a wide structure) • limit stress • indentation formulation without size (or scale) effect	• 171.6 MN • limit stress • indentation formulation without size (or scale) effect
Scenario 2 – FY Ridge	• 127 MN • limit stress • crushing of consolidated thickness, upper bound of empirical large scale data • clearing of sail and keel rubble	• 239 MN • limit stress • crushing of consolidated thickness, mean + 2 std dev of ice pressure-contact area relationship • clearing of sail and keel rubble	• 896.4 to 1195.2 MN (formula 121, applicable to a monopod structure) • 239.1 to 318.8 MN (formula 122, applicable to a wide structure) • application of a 'ridge coefficient' to the load calculated for level ice; no explicit consideration for consolidated thickness in ridge and rubble in sail and keel of ridge	• 257.4 MN • application of a 'ridge coefficient' to the load calculated for level ice; no explicit consideration for consolidated thickness in ridge and rubble in sail and keel of ridge
Scenario 3 – Partial Ice Coverage	• no provisions for determining ice loads due to partial ice coverage and for evaluating ice jamming potential • calculated ice load assumes limit stress load across an ice-jammed width • load same as that for Scenario1 • rationalized by limit stress of ice crushing across the full width of structure due to ice jamming	• no provisions for determining ice loads due to partial ice coverage and for evaluating ice jamming potential • calculated ice load assumes limit stress load across an ice-jammed width • load same as that for Scenario1 • rationalized by limit stress of ice crushing across the full width of structure due to ice jamming	• no provisions for determining ice loads due to partial ice coverage and for evaluating ice jamming potential • calculated ice load assumes limit stress load across an ice-jammed width • load same as that for Scenario1 • rationalized by limit stress of ice crushing across the full width of structure due to ice jamming	• no provisions for determining ice loads due to partial ice coverage and for evaluating ice jamming potential • calculated ice load assumes limit stress load across an ice-jammed width • load same as that for Scenario1 • rationalized by limit stress of ice crushing across the full width of structure due to ice jamming

4.5 Commentary on Code Use and the Differences in the Codes

As mentioned at the outset, the ice loads in the previous sections have been determined by interpreting and applying the provisions in the various codes as an offshore structure designer might if he were requested to estimate ice loads without any other reference point. It was demonstrated that, in the case of the SNiP code, using the codes in such a manner could lead to a situation where the designer will not be able to select the appropriate equations to calculate ice loads unless he is knowledgeable in ice mechanics. It was also demonstrated that there could be a considerable difference between the ice loads determined from applying the CSA and the API codes, even though the development of these two codes shared a number of experts in ice mechanics and much of the background ice data. This reflects the situation in which the codes are used as strict "recipes" rather than, as intended, as guiding documents for experienced ice engineers.

The CSA code anticipates, and industry demands, that experts in ice mechanics would be retained for establishing ice loads for the design of offshore platforms. The code is also quite specific that information from ice load databases beyond the code, which may be more relevant to the design case at hand, should be used. An expert with appropriate resources would thus be able to determine design ice loads in accordance with the design objectives of the code. However, for a person who does not have a background in ice mechanics, the CSA code, which has very few equations and suggested values for ice parameters, is somewhat difficult to use for estimating ice loads. Inevitably, an expert would be able to exercise judgment and select the most appropriate method and ice characteristics to derive appropriate ice loads.

As an example, a key issue is the ice pressure to be used for different widths of structures. This is area dependent, and will depend on the type of ice, whether first year or multi-year, or whether it is in arctic or sub-arctic areas. This is an issue, which is subject to continuing debate even between experts.

For a wide structure (100 M) in 1.2 m of level ice, the API code would give a reference pressure (from the P/A curve) of approximately 1.5 MPa. In contrast, the Sanderson curve referenced in CSA would give a pressure of 0.95 MPa in similar circumstances (both for Beaufort Sea ice). An experienced ice mechanics engineer, however, will know that the API curve is truncated at approximately 25 m5 of loaded area and, therefore, would question the applicability of the API data for large contact areas.

While narrow structures were not the subject of this report, the pressures, and hence the loads, would show much less disagreement than for the wide structures.

The expert, therefore, would examine available large scale ice data in addition to those given in the codes, assess the applicability of these data and come up with one pressure, and hence one ice load for a given ice scenario, regardless of which code he is using. Therefore, the only real difference between the CSA and the API codes is in the target structural reliability which in turn leads to different specified return periods for the design ice load. In other words, the design ice events for these codes will be different.

With the SNiP code, different equations are provided for calculating ice loads on narrow and wide structures, but no precise definition, is given to differentiate between the alternatives. Therefore, a code user unfamiliar with ice/structure interaction will have difficulty in selecting the more appropriate equation. An ice mechanics expert, on the other hand, would be able to assess the applicability of the different equations given in the code, select the correct equation and derive a reasonable ice load. As a further example, both the SNiP and VSN codes give numerical values for ridge coefficients for load determination, but there is virtually there is no discussion on the basic assumptions supporting these coefficients. Again, only an ice expert would be able to assess the justification of applying these ridge coefficients.

In summary, therefore when the backgrounds to the codes are fully understood and the input parameters assessed the ice experts, it is anticipated that the loads derived, particularly from the CSA and API codes, will be much closer than may be otherwise concluded from this report.

5.0 Summary and Conclusions

5.1 Structure Design approach

All four codes, the CSA, API, SNiP and VSN codes, follow a limit state design method which calls for the proportioning of the structural components such that the factored component resistance is greater than the effects of the sum of the factored loads.

In the CSA code, the load and component resistance factors have been calibrated to an explicitly stated reliability level. For Safety Class 1, structural components with great risk to life and environmental damage, the specified annual probability of failure is 10^{-5}. For Safety Class 2, structural components with small risk to life and environmental damage, the specified annual probability of failure is 10^{-3}. Within this framework, the return periods for the design loads are clearly stated in the code. The code also indicates that, should the designer choose to adopt an alternative design method, these intended level of safety must be achieved.

The API code has been calibrated against historical experience and practice in the Gulf of Mexico. The probability of failure is 10^{-3} in 20 years, which this translates to an annual probability of failure of 5×10^{-5}. The return period for the design loads is specified.

The limit state design format in the SNiP code is different from those in the CSA and the API codes by incorporating additional load and component resistance coefficients such as the coefficient of load reliability, coefficient of working condition and coefficient of structural reliability. The return period for the design loads is not specified. The targeted level of structural reliability is not apparent, nor is the uniformity in component reliability.

5.2 Ice Design Approach

A full range of modern ice load models for the calculation of ice loads resulting from all types of ice features are referenced in both the CSA and API codes. Probabilistic methods are recommended by both codes. API allows the use of deterministic methods although little guidance is provided in this respect.

In contrast, the SNiP and the VSN codes appear to be limited in their ice design provisions. Only two types of ice features, namely level ice and ice ridge, are considered. Topics such as ice induced vibrations are not covered. Semi-probabilistic methods for establishing ice characteristics for ice load calculations do not appear to lead to ice loads with consistent levels of annual probability of exceedance.

5.3 Ice Load Calculations

The level ice loads determined by applying the CSA provisions are considerably lower than those from the API, SNiP and VSN codes. This results primarily from a difference in the determination of the ice crushing pressure. The large scale field information referenced in the CSA code is used.

The ice pressure-contact area relationship in the API gives higher global loads. The same pressure-area relationship is referenced in the CSA but is

indicated in the CSA as only applicable to local ice pressures. The SNiP and the VSN codes, using an indentation formulation without accounting for size or scale effect, produces higher loads.

The crushing of the consolidated thickness dominates the ridge loads calculated in accordance to CSA and API. Again, with the use of large scale field information, the CSA load is considerably lower. The SNiP and VSN code do not provide guidance on calculating ridge loads on the basis of ridge characteristics. Rather, the ridge load is given by the product a ‘ridge coefficient’ and the level ice load.

None of the four codes addresses specifically ice loads due to a partial ice cover. An assumption was made of ice jamming between the columns in the multi-leg structure in order to rationalize an ice load.

The ice loads in this study have been determined by interpreting and applying the code provisions in the various codes as an offshore engineer might if he were requested to estimate ice loads using only the information given in the codes. Much of the difference in the so determined ice loads can be attributed to this manner of code usage. In actual design practice, the codes will be exercised by ice experts such that the backgrounds to the codes are fully understood. It is anticipated that the ice loads so derived, particularly from the CSA and API codes, will be much closer than may be otherwise concluded from this report.

5.4 Closure

A comparison of the CSA, API, SNiP and VSN codes has been made by examining the structure design approaches and the ice design methods presented in the code provisions. Some of the clauses relating to ice load calculations in these codes have also been exercised to determine ice loads for selected ice scenarios. Since these scenarios are specified, the clauses relating to the probabilistic determination of ice parameters have not been compared. For the scenarios examined, the ice loads following the SNiP, VSN and API codes are comparable in magnitude and are considerably greater than those derived from the application of the CSA provisions.

Although there are similarities in the development of the CSA and the API codes (both are reliability based and use a limit states design method), interpretation and application of the provisions in these two codes by a person not familiar with ice mechanics can still lead to considerably different ice loads, which, in turn, would result in considerable differences in the proportioning of the structure. An ice expert, in contrast, will be able to take advantage of available large scale ice data in addition to those given in the codes, assess the applicability of these data and derive one ice load for one ice scenario. The only real difference between the CSA and the API codes is in the target reliability, which leads to different return periods specified for the design ice load.

The SNiP and the VSN codes differ from the CSA and the API code primarily in that the return period of design extreme environmental loads is not specified and that multiple coefficients are applied to loads and component resistances. Consequently, it is not apparent if there is a target level of structural reliability. The ice design provisions in the SNiP and the VSN codes are limited in comparison to those in the CSA and the API codes.

6.0 References

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Abstract

This report compares four different codes that have been developed for ice loads on offshore structures: Canadian CSA code, American Petroleum API-RP-2N code, the Russian SniP code and the Russian VSN code. Each of these codes is described, and ice loads are calculated with each code for different ice loading scenarios.

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