DETERMINING DESIGN ICE ACTIONS FOR OFFSHORE STRUCTURES

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Outline

Guidance from ISO 19906 for ice actions

Background and changes

Applications

Reflections

History of ice load standards

Russia

- SNiP 2.06.04-82*, 2012, Loads and influences on marine structures (from waves, ice and vessels)
- VSN-41.88 Design of fixed ice strengthened platforms

Canada

- CSA S471-04, 2004, General requirements, design criteria, the environment, and loads,

United States

- API RP 2N, 1995, Recommended Practice for Planning, Designing and Constructing Structures and Pipelines for Arctic Conditions

ISO 19906 Arctic offshore structures

Normative Part

- Design methods
- Reliability and limit states design
  - Exposure levels
  - Representative action values
- General principles for calculating ice actions
- Ice events and design situations
  - Global and local actions

Informative Part

Clause 5.2 *Design methods*

For designs performed in accordance with the design process and limit states design verification procedure provided in this document, levels of safety and performance are established in Clause 7.

An alternative rational design method based on theory, analysis, and recognized engineering practice may be used in lieu of the design process and formulae provided in this document, provided that levels of safety and performance are at least equal to those established in Clause 7.

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Design methods (cont.)

Where possible, data from full-scale measurements of ice actions shall be used to verify new designs. Physical models and mathematical models may also be used to determine the response of structures to ice actions, in combination with ocean current, wind and wave actions. If ice model tests are used in the design process, the designer is advised to seek independent verification of the results obtained as well as seek expert guidance regarding the most appropriate physical ice modelling techniques.

All hazards that can be reasonably foreseen during all phases of the design service life shall be identified and evaluated.

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Clause 6 *Physical environmental conditions*

Outlines the physical environmental parameters necessary for arctic offshore structure design.

Experts in the field of metocean and ice technology shall be involved with the analysis of data and its interpretation in order to ensure that reliable and appropriate physical environmental parameters are obtained.

Information required to characterize site-specific ice criteria shall be determined for the location of the structure under consideration.

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Clause 7 *Reliability and limit states design*

Design shall be in accordance with the limit states approach specified in 7.2

7.1.4 Life-safety & Consequences → Exposure level

- L1 *Manned, non-evacuated structures and high environmental consequence*
- L2 Manned, evacuated structures and managed environmental consequence
- L3 *Unmanned or low environmental consequence*

7.2.2 Representative action values

- *EL ice action shall be determined for each ULS design situation based on an annual probability of exceedance not greater than 10^{-2}.*
- *AL ice action shall be determined for each ALS design situation based on the exposure level. For* L1 *structures an annual probability of exceedance not greater than 10^{-4}. For* L2 *structures not greater than 10^{-3}.*

Partial action factors and action combinations → design actions

Clause 8 *Events and actions*

Qualitative guidance for calculating global and local ice actions

Structures or components subjected to ice events shall be designed for ice actions with annual probabilities as specified in 7.2.2, appropriate to the limit state and exposure level.

Methods based on full-scale action and response data from measurements on instrumented structures shall be used for the determination of representative ice actions on offshore structures, with due account of their applicability, and of the uncertainties in the data and the methods used in their interpretation.

6 pages Normative, 90 pages Informative!

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8.2.2 *Representative values of ice actions*

The design shall be carried out for EL ice actions and AL ice actions, as specified in 7.2.2.3 and 7.2.2.4.

Representative values of ice actions shall be calculated using probabilistic methods or deterministic methods for the ice parameters relevant to the event.

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8.2.3 *Ice events and design situations*

***Ice events** shall reflect:*

- *the relevant ice scenario, limiting mechanisms and ice failure modes for the geographical location of the structure, with reference to the provisions of 8.2.4, 8.2.5, 8.2.6 and 8.2.8; and*
- *the structural configuration and the relevant operational scenarios, including seasonal operation, ice detection, physical IM, manoeuvring of the structure and disconnection, with reference to the provisions of 8.2.7.*

→ Global, local, dynamic actions

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→ Global, local, dynamic actions

Design situation → Ice event → Ice action

Ice action generated when an ice feature impinges on a structure

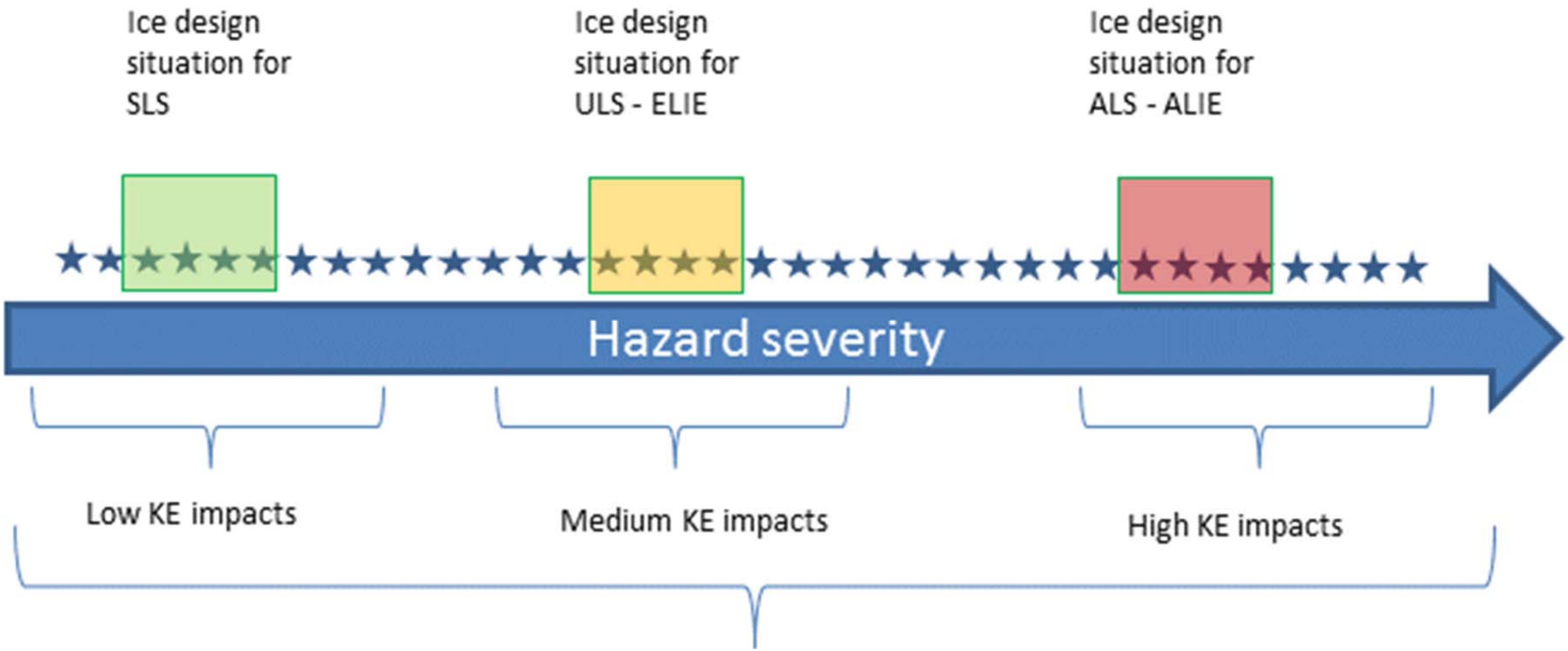
Environmental actions act on the ice feature, possibly limiting the magnitude of the ice action

Actions have units of force

Minimum of the two actions is the action experienced by the structure for that ice event

design situation

set of physical conditions representing real conditions during a certain time interval, for which the design demonstrates that relevant limit states are not exceeded (ISO 19900:2013)



Ice interaction scenario (e.g. iceberg impact)

★ **Ice event (e.g. impact of 100,000 ton tabular iceberg moving at 0.4 knots, ice strength 3 MPa)**

A.8.2 Ice events and actions (Informative)

Provides much more specific guidance (90 pages)

Representative values of ice actions

- Probabilistic approach
- Deterministic approach
- Monte Carlo simulation
- Ice action data

Ice events

Global actions

Local actions

Dynamic actions

Operational measures to reduce ice actions

Physical and mechanical properties of ice

Limiting mechanisms

Global ice action limited by environmental driving actions

- **A.8.2.4.6 Limit force actions due to the ridge-building process F_B**
  - Width of floe and pack ice driving force
- **A.8.2.4.7 Limit energy global ice actions F_E**
  - Mass and velocity of floe, also eccentricity

Global action minimum of ice action and lowest limiting environmental action

Ice action algorithms (global)

Global pressure from level ice; vertical structure

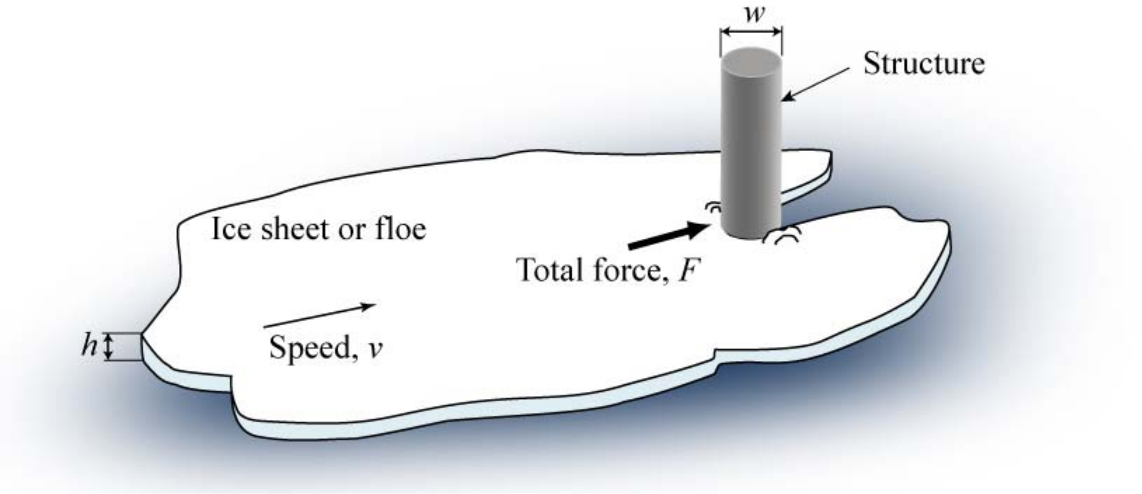
Global action from a first year ridge; vertical structure

Global action from level ice; sloping structure

Global action from MY ridges; vertical and sloping

Global pressure for sea ice

Level ice sheet interacting with a vertical structure



Global pressure for (level) sea ice (A.8-21)

$$p_G = C_R \left[\left(\frac{h}{h_1} \right)^n \left(\frac{w}{h} \right)^m + f_{AR} \right] \quad \text{(A.8-21)}$$

$w/h > 1$

$m = -0.16$

$n = -0.5 + h/5$ for $h < 1$ m (Norströmsgrund)

$n = -0.3$ for $h \geq 1$ m (Molikpaq)

One equation for both data sources + Baltic

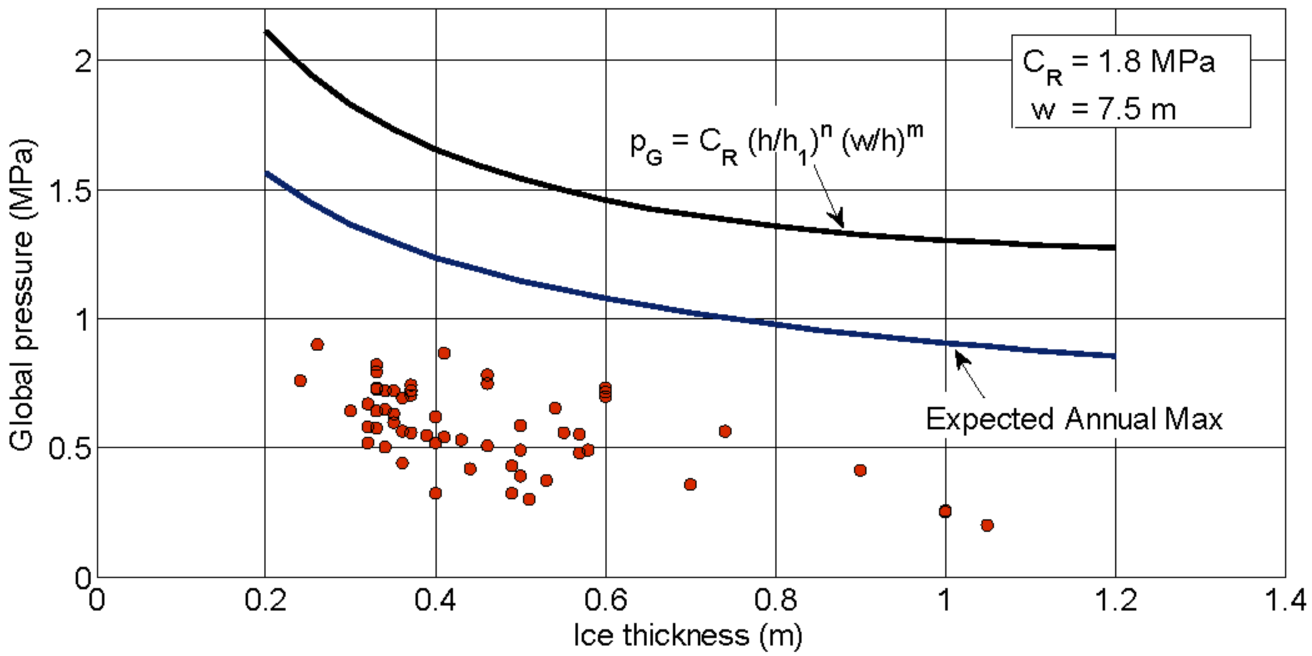
C_R ice strength coefficient

Deterministic analysis

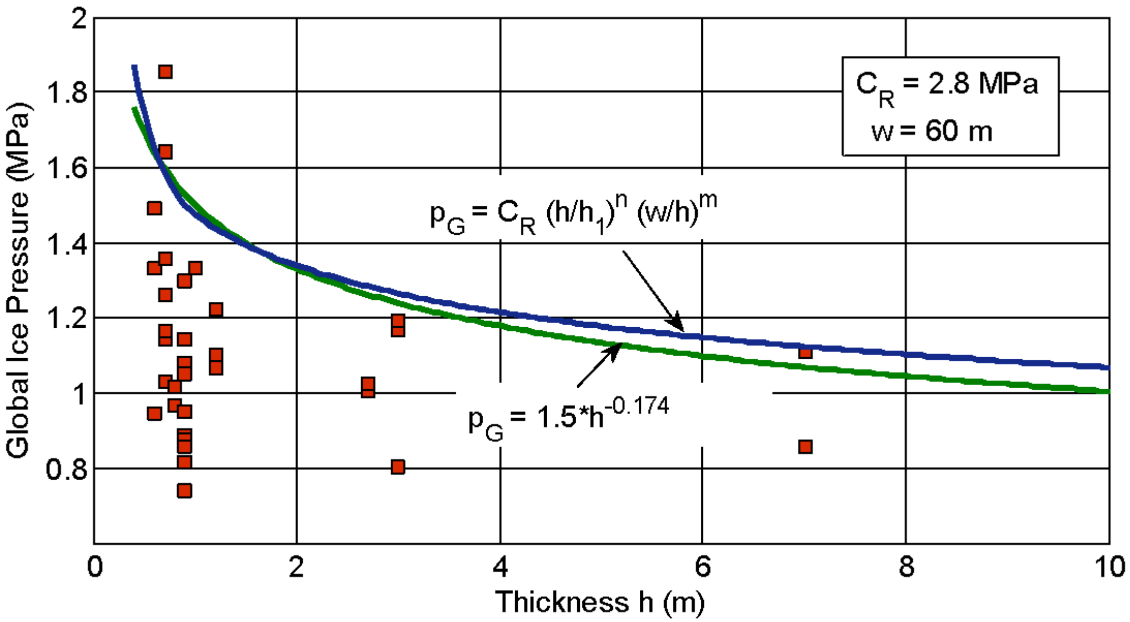
C_R (MPa)	Region
2.8	Arctic FY and MY ice
2.4	Subarctic - off NE Sakhalin
1.8	Temperate - Baltic

C_R =1.8 represents ELIE (10^{-2}) value for Baltic

Global pressures at Norströmsgrund lighthouse



Global pressures from Beaufort Sea



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determine values of

h ice thickness

C_R ice strength coefficient (MPa)

C_R Ice Strength Coefficient

Function of σ / σ_o

- Ice type
- Temperature
- Salinity
- Grain structure

How adjusted

- Small scale specimens
- Borehole jack
- Calculation

Exposure;

- **we are adding another dimension to C_R**

C_R ice strength coefficient

Previous C_R related to region and properties

Exposure has been added, Table A.8-4 Baltic

n	Total distance (km)	Return period (years)	$F_P(p)$	C_R (MPa)
1	6	1	0.5	0.99
1	6	100	0.99	1.45
24	135	1	0.5	1.34
24	135	100	0.99	1.8
24	135	10,000	0.9999	2.3
100	563	1	0.5	1.49
100	563	100	0.99	1.96

Test case – Global Ice Action

Norströmsgrund type structure; vertical, cylindrical - 10 m dia. in Northumberland Strait environment

Ice conditions

- **Thickness, floe size**
- **Morphology, ridges, rubble, rafting**
- **Ice charts, satellite imagery**

Metocean conditions

- **Reversing tidal currents, wind, storms, temperature, ice drift speed and direction**

Ice actions; level ice and ridge

Northumberland Strait ice conditions

The Guardian

Deterministic method

- ***deterministic methods, in which extreme (e.g. thickness, for sea ice) or abnormal (e.g. mass or kinetic energy, for icebergs) and nominal values (e.g. pressure) of ice parameters are combined to construct ELIE and ALIE for which corresponding actions are calculated***

ELIE (10^{-2}) ice thickness and nominal values ice pressure (0.5) give EL ice action

Northumberland Strait

C_R for Temperate region

- FDD; 700 mean of annual max, 950 max over 60 years

Norströmsgrund; C_R = 1.8 MPa for 10^{-2} (ELIE)

- C_R = 1.35 MPa for $F_p(p) = 0.5$ (annual max)

Norströmsgrund exposure 135 km/year

Northumberland Strait 3000 km/year

Adjust C_R for greater exposure; C_R = 2.14 MPa for 10^{-2} (ELIE)

- C_R = 1.67 MPa for $F_p(p) = 0.5$ (annual max)

Comparison of cases

Northumberland Strait vs Baltic

C_R for ELIE (10^{-2}) and annual max

Return Period	$F_p(p)$	C_R (MPa) Baltic	C_R (MPa) Northum.	h_i (m)
1	0.5	1.34	1.67	0.6
100	0.99	1.8	2.14	0.73

Ice thickness from measurements and FDD

Ice actions - level ice

Deterministic; 10 m diameter structure in Northumberland Strait

a. 10^{-2} ice thickness with annual max C_R

b. 10^{-2} C_R with annual max ice thickness

Case	C_R (MPa)	h_i (m)	p_G (MPa)	F_G (MN)
a	1.67	0.73	1.23	9
b	2.14	0.6	1.66	10

Limiting conditions

Are there environmental driving actions that produce full envelopment of the structure?

Limit energy or momentum; size and velocity of the floe

Limit driving force on floe; wind, current & ridge building

Deterministic application for EL (10^{-2}) ice action is problematic

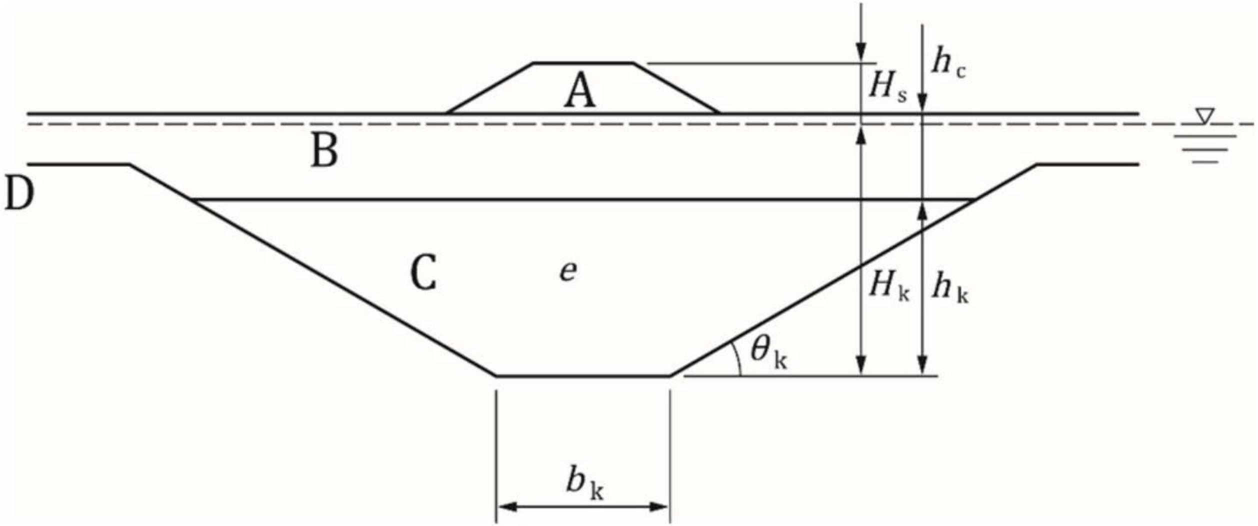
Do checks

Design condition - first year ridge

Norströmsgrund and Northumberland Strait

F.M. Williams

First-year ridge - idealized



h_c consolidated layer thickness

e keel porosity

h_k keel thickness

First-year ridge action

Comprised of a consolidated layer and keel

$F_r = F_c + F_k$

Ridge characteristics depend on its history

- Consolidated layer; thicker but weaker than level ice
- Keel; keel depth depends on ice thickness, time

Probabilistic approach desirable

Consolidated layer action F_c

Consolidated layer;

use formula (A.8-21) making allowance for history, temperature, spatial variability of layer

1. thickness, h_c generally 1.5 to 2 x adjacent level ice
2. strength, C_R weaker because it is warmer (sail insulation), higher salinity because seawater tapped between the broken ice pieces in the ice
3. what C_R value to use? Exposure; km. vs # of ridges

Northumberland Strait ridge

Consolidated layer, 10 m dia. structure

Early season ridge

- Consolidated layer thicker
  - h_c = 1 m, C_R = 1.2 MPa, p_G = 0.83 MPa, F_c = 8.3 MN
- Keel depth a function of ice thickness (h_k = 7 m)

Late season ridge

- Consolidated layer thinner
  - h_c = 0.5 m, C_R = 1 MPa, p_G = 0.82 MPa, F_c = 4 MN
- Keel deeper because of thicker ice (h_k = 15 m)

First-year ridge keel ice action (A.8-50)

$$F_{\mathrm{k}} = \mu_{\phi} h_{\mathrm{k}} w \left(\frac{h_{\mathrm{k}} \mu_{\phi} \gamma_{\mathrm{e}}}{2} + 2c \right) \left(1 + \frac{h_{\mathrm{k}}}{6w} \right) \qquad \text{(A.8-50)}$$

where

w	width of the structure
h_k	keel depth
ϕ	angle of internal friction
μ_ϕ	$= \tan(45 + \phi/2)$
c	apparent keel cohesion (kPa)
γ_e	$= (1-e)(\rho_w - \rho_i)g$ effective buoyancy, in units consistent with c
e	keel porosity,

Keel properties

only keel depth h_k, no shape

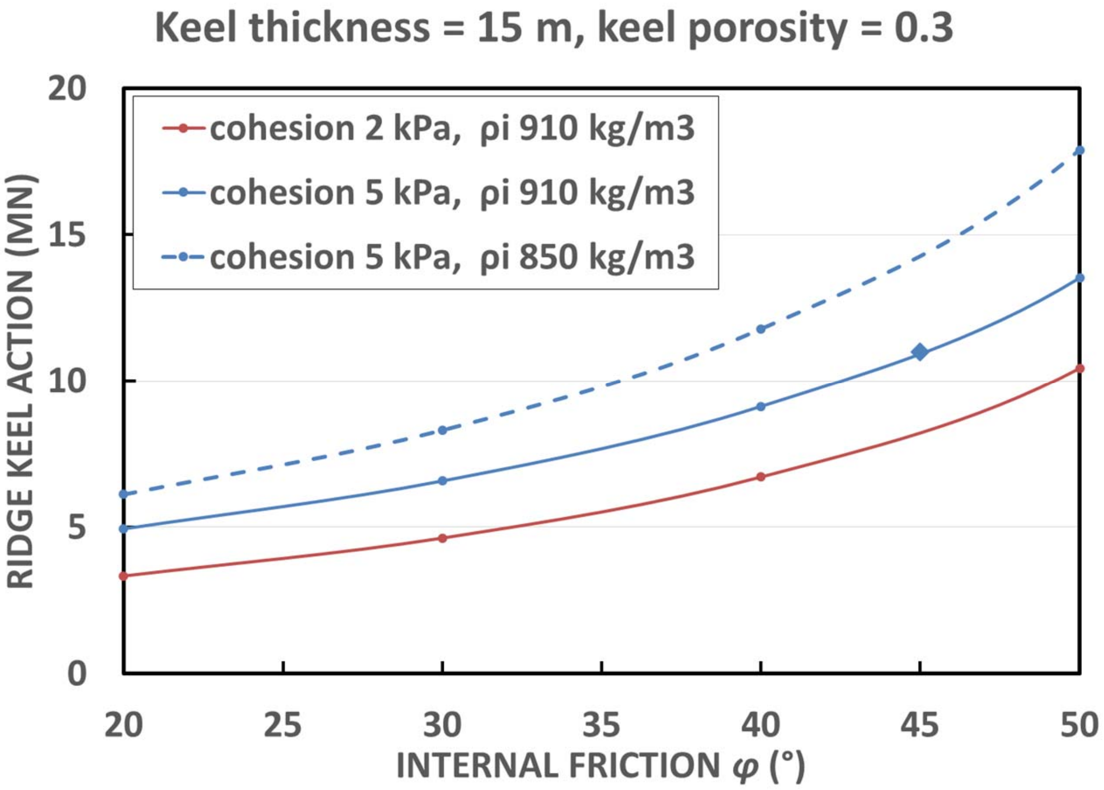
friction angle, ϕ = 20° to 50°

apparent cohesion, c = 0 to 6 kPa

effective buoyancy, $\gamma_e = (1-e)(\rho_w - \rho_i)$

Norströmsgrund and Confederation Bridge action data analysed to infer keel properties

Ridge keel action, 10 m dia. structure



Northumberland Strait ridge ice action

Early season ridge late in season

- Keel depth a function of ice thickness (h_k = 7 m)
- Cohesion = 5 kPa, keel porosity = 0.3, ρ_i = 910 kg/m^3 , φ = 45°
- F_k = 3 MN

Late season ridge keel

- Keel deeper because of thicker ice (h_k = 15 m)
- Cohesion = 5 kPa, keel porosity = 0.3, ρ_i = 910 kg/m^3 , φ = 45°
- F_k = 11 MN

Ridge actions; early/late $F_R \approx$ 3+8.3 = 11 MN **late** $F_R \approx$ 11+4 = 15 MN

Probabilistic approach

Probabilistic methodology; characterize the ice, metocean and climatic conditions of the Strait

Global ice action F_G from p_G (A.8-21)

- **Random inputs**
  - Floe diameter, thickness, concentration, ridge keel depth
  - Properties; consolidated layer, C_R keel, e, c, ϕ

Environmental driving forces F_E

- **Random inputs**
  - Floe speed, diameter and thickness
  - Wind and current speed, pack ice pressure

Minimum of F_G and F_E for each event

Reflections

Physics of our ice action algorithms

- Level ice crushing, are we overloading C_R?
- Ridge disintegrating under action, is it a c-ϕ material?
- Standard allows alternative algorithms

Reflections (2)

Probabilistic Methodology, random parameters;

- **Nature of distributions, supporting data**
- **Limits on distributions, physical**
- **101 cases for EL and AL actions to explain ELIE and ALIE**
- **Meaningful simplification**

Reflections (3)

Look to the literature to do a check on any calculated ice actions

Can we provide more definitive guidance on ice encroachment / pile-up?

- discrete element / particle models

Collect new data where possible

Continue to reanalyze existing data

ISO 19906 provides our best guidance for determining design ice actions

THANK YOU