The Rideau Canal Skateway: A Preliminary Assessment of Current Practice to Estimate Bearing Capacity

Perry Godse[1], Shawn Kenny[1], Samuel Vamplew[2], Bruce Devine[2]

[1] Department of Civil Engineering, Carleton University, Ottawa, Canada
[2] National Capital Commission, Ottawa, Canada

ABSTRACT

Since 1971, the National Capital Commission (NCC) has transformed the Rideau Canal Waterway into the world's largest skating rink, the Rideau Canal Skateway (RCS). The Rideau Canal Skateway (RCS) is a 7.8-km ice path winding through Ottawa, the capital of Canada. The canal itself is a National Historic Site of Canada and a UNESCO World Heritage Site managed by Parks Canada.

A key determinant of the operational limits for the RCS is the bearing capacity, which governs the allowable deflection and stress due to surface loads from maintenance vehicles and users. Current practice is primarily based on a semi-empirical approach relating the ice load capacity with ice thickness. While practical, this approach has inherent uncertainty that does not account for effects such as temperature variation with depth, ice quality, multiple surface loads, stationary or moving loads, and boundary conditions (e.g., shoreline, canal walls). This study evaluates current practice and explores other opportunities to improve confidence in bearing capacity estimates. Outcomes from this study can be used to further support the development of evidence-based decision making for maintenance and operational activities by the operator, NCC.

1.0 Introduction

The ability of an ice cover to support surface loads is a critical consideration for engineering applications ranging from winter roads and ice bridges to recreational ice surfaces. The Rideau Canal Skateway (RCS), the world's largest natural skating rink, relies on sufficient ice thickness and strength to support thousands of skaters and maintenance vehicles throughout the winter season. Since 1971, the National Capital Commission (NCC) has overseen the operation of the RCS and employs a semi-empirical approach to estimate bearing capacity based on ice thickness and environmental conditions.

The bearing capacity of floating ice covers has been extensively studied in the context of both static and dynamic loading conditions (e.g., Barrette, 2015; Gold, 1971; Kerr, 1996; Masterson, 2009). A semi-empirical approach is commonly used to provide practical working guidelines for on the bearing capacity of an ice cover to support surface loads. These methods only provide an estimate of the load bearing capacity, for instantaneous loading conditions, through knock down factors based on field experience and engineering knowledge (e.g., Gold, 1971; Kerr, 1996; Masterson, 2009) that may be integrated within a risk management framework (e.g., OISHA, 2014). However, this approach does not explicitly account for many factors that may reduce bearing capacity. These include the spatial and temporal variation in ice quality (e.g., density variation, intralaminar bonding), material and mechanical properties (e.g., temperature effects on elastic modulus, flexural strength), environmental conditions (e.g., rapid cooling, extended warming periods), load conditions (e.g., number, magnitude, intensity), boundary conditions (e.g., mudline support, canal walls), mechanical response (e.g., static deformation, time dependent deformation, fatigue cycle history) and presence of defects (e.g., wet or dry cracks).

Consequently, there is a need to advance engineering tools capable of reliably and predictably estimating ice cover bearing capacity. Calibrated and validated through laboratory and field testing, numerical and analytical models can help overcome the limitations associated with empirical and analytical methods. This study examines the limitations of current practice and highlights opportunities to improve them, reduce uncertainty, and support the development of robust and practical engineering solutions with increased confidence.

2.0 Current State of Practice

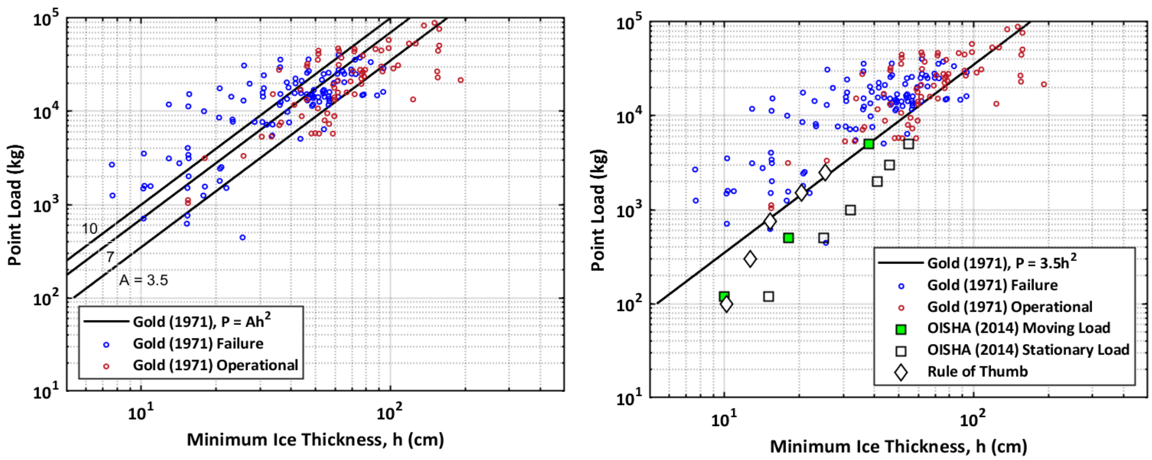
Knowledge on the bearing capacity of an ice cover has been advanced through empirical, analytical, and numerical modelling approaches (e.g., Beltaos, 2002; Gold, 1971; Kerr, 1976; Masterson, 2009; OIHSA, 2014; van Steenis, 2011; Wyman, 1950). A common semi-empirical relationship used to estimate ice load bearing capacity is the Gold (1971) equation:

$$P = Ah^2 \tag{1}$$

where P is the maximum load (kg), h is the ice thickness (cm), and A is an empirical coefficient that accounts for critical nominal stress and load distribution related to the ratio of the loading radius and ice cover characteristic length. This equation, originally derived from extensive field data, provides an operationally useful but simplified estimate of ice bearing capacity that assumes a homogeneous, crack-free ice sheet subject to an instantaneous, static load but does not account for time dependent deformations.

Gold (1971) concluded the empirical dataset could be bounded by coefficients (A) of 3.5 kg/cm^2 (50 lbf/in^2) and 70 kg/cm^2 (250 lbf/in^2). Industry guidelines (e.g., OISHA, 2014) recommend a narrower range (3.5 kg/cm^2 $\leq$ A $\leq$ 10 kg/cm^2) while providing reasonable approximation of the observed dataset and implicit safety (Figure 1a). OISHA (2014) also categorized risk levels and identified hazard management practices across this coefficient range.

As shown in Figure 1b, for lighter surface loads less than 5,000 kg, the semi-empirical approach, Equation (1), yields relative non-conservative estimates of the maximum allowable load in comparison with rules of thumb adopted by many Canadian provincial government authorities and recommended practices (e.g., OISHA, 2014). OISHA (2014) advises against the use of Equation (1) for lighter surface loads (< 5,000 kg) and provides explicit guidance on ice thickness requirements for slow moving, as well as short-term and long-term stationary (i.e., between 2 hours and 7 days) loads.



(a) (b)

Figure 1. Empirical observations on the relationship between the applied surface point load and ice cover thickness for (a) observed safe operational use and failures (after Gold, 1971), and (b) overlay of rules of thumb and recommended practices (after OISHA, 2014).

Analytical solutions (e.g., Gold, 1971; Masterson, 2009; Wyman, 1950) offer a robust framework to estimate ice cover deflection and flexural stress due to surface loading, based on the solution of partial differential equations. These models typically assume infinite or semi-infinite ice domains subjected to either concentrated point loads or distributed area loads. The engineering models, characterizing the mechanical response of an ice cover, can be extended to address other practical considerations such as the application of multiple simultaneous loads, ice cover deflection and loss of freeboard, or time dependent deformations.

As shown in Figure 2, both the empirical relationship, using Equation (1) with A equal to 3.5 kg/cm^2 and 7 kg/cm^2, and plate theory analysis, assuming a flexural strength of 800 kPa (see for example, Aly et al., 2018), show agreement across the range of ice thickness relevant to the RCS. The mathematical expressions provide a reasonable bound on the observational data (Gold, 1971) and highlight the role of load distribution, related to the loading radius and characteristic length, which was also recognized by Gold (1971). For lighter loads (< 5,000 kg), however, these approaches often produce non-conservative estimates when compared with industry guidelines (e.g., OISHA, 2014).

Although these approaches provide estimates of ice cover bearing capacity, there is a need to better understand the inherent limitations of estimating allowable surface loads for lighter vehicles (i.e., < 5,000 kg) and thinner ice covers (i.e., < 50 cm), relevant to the RCS. Reducing uncertainty will support informed decision making on operational and maintenance activities (e.g., ice thickness requirements and load capacity) and improve confidence in the assessment of safety (risk) levels.

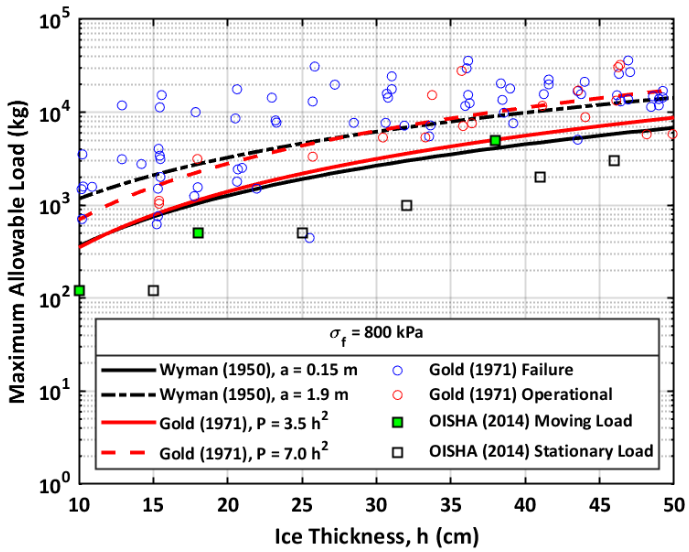


Figure 2. Estimated maximum allowable equivalent concentrated point load with ice thickness as a function of the load radius and empirical strength model. The field observations by Gold (1971) are also presented.

3.0 Uncertainties in Current State of Practice

The capacity for ice covers to sustain surface loads is governed by several factors including ice thickness, ice stratigraphy and quality, temperature, presence of defects (e.g., wet or dry cracks, air bubbles or pockets), stationary and moving loads, and boundary conditions. Current practice is used to address diverse industry applications across a range of geographic and environmental conditions.

3.1 Ice as a Building Material

Since the late 1800's, ice has been increasingly used as a natural material, present in ocean, lakes, rivers, and wetlands, for supporting transportation activities. At the beginning of the winter season ice is formed by an advancing freezing front from the water surface downward. This initial layer, known as congelation ice, develops a columnar grain structure that is influenced by the freezing rate and may include impurities (e.g., organic matter) and defects (e.g., air bubbles).

Once a stable base layer of clear, strong ice has formed, the RCS ice cover is thickened by control ed surface flooding, which may occur with or without overlying snow layer. The ice thickness must be sufficient to support the weight of personnel, equipment and ponded water without failure or the loss of freeboard. The flooding process brings relatively warm water from beneath the ice cover to the ice surface where it is exposed to the colder ambient air temperature, which promotes the rate of ice growth. Thicker ice allows for the deployment of heavier maintenance vehicles, which can range from small utility vehicles (1,000 kg) to larger tractors (5,000 kg). Snow maintenance practices, similar to ice road operations, can then be used during the season when a sufficient ice cover thickness has been achieved. Operational decisions related to flooding are based on an assessment of current and forecasted air temperature and precipitation (e.g., snow versus rain) conditions with the primary objective to optimize ice quality. The ice cover is assessed both qualitatively by evaluating the proportion of columnar (clear) ice, polycrystalline (opaque, snow-ice) ice, entrapped air, and bonding between layers, and quantitatively through density measurement of ice core sections. These factors may affect material properties (e.g., flexural strength) or mechanical behaviour (e.g., bearing capacity, deflection), which may also be influenced by the loading or thermal history.

3.2 Empirical and Theoretical Methods

The semi-empirical approach developed by Gold (1971), represented by Equation (1), has been widely used in industry to estimate the minimum effective ice thickness required to support surface loads, based on observations of ice cover performance. Solutions for an infinite plate subject to a uniform distributed load (Kerr, 1975) can be related to the semi-empirical formula (Equation 1) through an expansion of the coefficient, A,

$$P = \frac{\sigma^2 h^2}{3(1+\nu)\mathrm{C}_1} \tag{2}$$

with the parameters

$$\alpha = \frac{a}{\mathrm{L}_c}, \quad L_c = \left(\frac{D}{k_w}\right)^{1/4}, and \quad D = \frac{Eh^3}{12(1-\nu^2)} \qquad \text{(2a), (2b), (2c)}$$

where σ is the ice nominal strength (Pa), h is the ice thickness (m), a is the load radius (m) L_c is the characteristic or flexural rigidity length, D is the flexural rigidity (N m), E is the elastic modulus (Pa), ν is the Poisson’s ratio, and k_w is the elastic foundation equivalent to the specific weight of water (N/m^3). The characteristic length is a scale defining the distance where load effects (i.e., deflection, rotation, forces) propagate from the point of load application.

Equation (2) can be rearranged to express a generalized form of a stress intensity factor, K_α,

$$K_\alpha = \frac{\sigma^2 h^2}{P} = 3(1+\nu)\mathrm{C}_1 \tag{3}$$

The ice cover thickness is a scale factor influencing the stress distribution profile with thickness and localization in response to surface load effects. The variation in the stress intensity factor (K_α) with the non-dimensional load distribution parameter (α) is shown in Figure 3, where the coefficient, C_1, is related to the Kelvin function in the Wyman (1950) solution (Kerr, 1976). As the loading radius decreases, for a load distribution parameter (e.g., $\alpha = 0.001 = 10^{-3}$), the stress concentration factors are 6.6, 4.7 and 2.7 for the Wyman (1950), Westergaard (Gold, 1971) and

Panfilov (Kerr, 1976) solutions, respectively. Only the Wyman (1950) solution properly accounts for the infinite stress condition due to an imposed theoretical concentrated point load (i.e., α = 0).

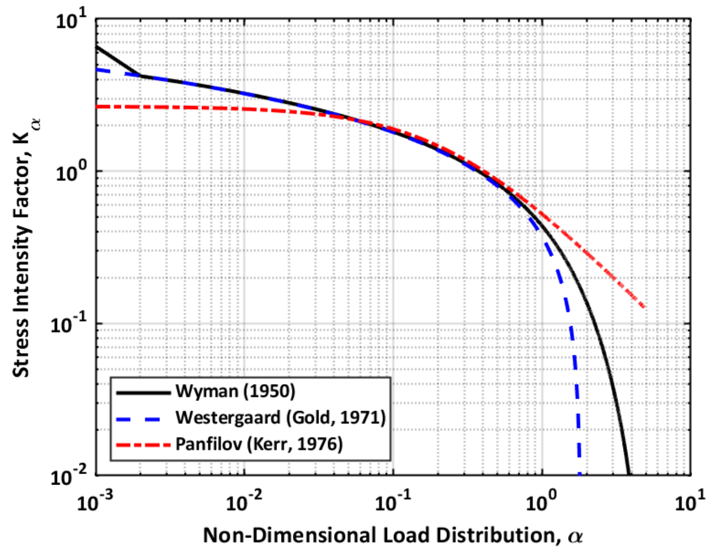


Figure 3. Stress intensity factor (K_α) as a function of the non-dimensional load distribution parameter (α).

For smaller load distribution values, α < 0.1, the ice cover mechanical response is influenced by the increased characteristic length (L_c) that will moderate the three-dimensional stress distribution and deformation response. Furthermore, thick plate theory indicates limiting stress intensity factors of 2.5, 3.0 and 3.4 for ice thickness to characteristic length (h/L_c) ratios of 0.1, 0.05, and 0.025, respectively. For ice thickness, ranging from 30 cm to 50 cm, this would correspond to load radii of approximately 0.7 m to 1.0 m, respectively, which are consistent with the gross area (i.e., global footprint) of typical vehicles operating on the RCS. Consequently, in reference to Figure 2, estimating maximum allowable surface loads has inherent uncertainty due to stress intensity effects, which is influenced by the ice thickness (h), loading radius (a) and characteristic length (L_c).

3.3 Boundary conditions

The boundary conditions used in Gold (1971) semi-empirical analysis and Wyman (1950) plate model assume an infinite plate supported by an elastic foundation. Apart from the larger areal expanse of Dows Lake, which may approximate the infinite plate assumption, the ice cover deformational response or stress state, along most of the RCS, may be influenced by local boundary conditions. In some sections of the RCS, the ice cover may be supported by the shoreline or mudline, and interact with the canal walls, which may impose translational or rotational constraints (e.g., pin, fixed boundary condition). These effects may be coupled with thermal stress due to temeprature changes. Since the basis for the current practice relies on an infinite plate analytical framework, the ommitance of different loading and boundary conditions creates uncertainty in the guiding stress range, as well as the chosen analytical framework. The impact of boundary conditions on bearing capacity has been broadly adddressed (e.g., Kerr, 1996; Masterson, 2009), with these studies indicating the bearing capacity may be reduced by up to 50% for these constraints.

3.4 Scale Effects in Ice

Ice is a complex material that can exhibit time, pressure and scale dependent deformation and failure mechanisms. Based on Equation (2), the maximum allowable load increases proportionally with ice thickness (*h*), flexural strength (σ_f) and load radius (*a*), as shown in Figure 4. The maximum allowable load associated with first crack (i.e., yield) and break through (i.e. failure), based on recommended values for C_1, predict comparatively higher load levels (Kerr, 1976). The semi-empirical approach (Equation (1) and Figure 1) normalizes these effects and suggests a scale relationship influenced by the loading and boundary conditions. However, the governing limits for applying linear elastic scaling laws are uncertain and the need to address other complexities, such as composite (laminated) material behavior or time-dependent behaviour, requires further assessment.

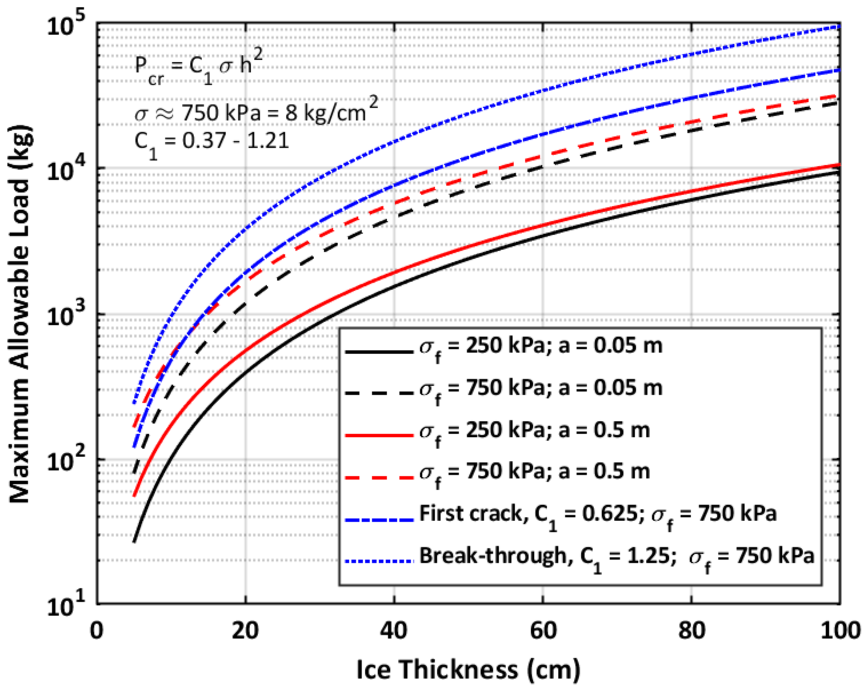


Figure 4. Estimated maximum load for first crack or breakthrough

As shown in Figure 4, the ice flexural strength has an influence on the maximum allowable load. Estimating ice flexural stress is typically conducted through small-scale field beam tests including cantilever, 3-point and 4-point beam bending tests. Each test imposes different conditions with respect to local shear loads and moments (in both different magnitude and distribution), constraints and stress concentration effects. Loading conditions must also be considered when calibrating field data to estimate the elastic modulus of ice. Both van Steenis (2001) and van der Vinne (2024) calibrated data from constant and ramp-loaded plate tests reported by Beltaos (1978) and Frankenstein (1963), finding that the elastic modulus (E) ranged from 0.1 GPa to 3.5 GPa for ice thicknesses between 6 cm and 75 cm.

Scale effects have been quantified through experimental studies (e.g., Frederking and Sudom, 2013; Lau et al., 2001; Williams and Parsons, 1994) where decreasing flexural strength follows an inverse power relationship with increasing specimen size. This trend is also captured by empirical equations (Aly et al., 2018) that relate stress to beam volume through a power law function. This is supported by other field studies (Lavrov, 1971; Määttänen, 1975) that indicate lower measured flexural strength in comparison with ice tested in controlled laboratory environments.

Furthermore, beam tests do not consider the multi-axial stress state of a plate resting on an elastic foundation and do not address the characteristic length governing the ice cover response. For floating ice covers, the characteristic length (L_c), can be approximated as $20h^{0.75}$, meaning that for ice thicknesses between 20 cm and 50 cm, L_c varies between 13 m and 16 m. This approach may not be valid in narrow channels of the RCS, with the canal width less than 25 m, where the mudline support or interaction with the canal walls may influence the ice cover deformational or stress response. For these load cases, the assumption of an infinite plate on an elastic foundation are no longer valid. This issue requires correction when extrapolating flexural stress states from beam-scale experiments to the biaxial stress state of ice plates.

In these cases, the current analytical framework leads to the conclusion that elastic modulus estimates from static plate-loaded tests capture the instantaneous elastic response differently, which may also underestimate real-world behaviour compared to beam tests. Beam-scale bending tests often report a higher effective modulus nearly three times greater due to their shorter load durations and constrained boundary effects (van Steenis, 2001). However, the elastic modulus is not a fixed value since under time-dependent loading conditions (e.g., slow-moving or stationary loads), ice undergoes creep, exhibiting a lower effective modulus governed by load rate, temperature, and internal ice structure. The through thickness temperature gradient, observed in the field, further influences the static modulus estimates.

3.5 Scale Effects in Ice Material Properties

Strength data for ice specimens indicate ice quality, generally related to ice opacity, exhibit flexural strength related to temperature and ice density (Barette, 2009). There is a general increase in strength with temperature and a stronger correlation with ice density. Ice quality metrics, such as opacity and density, relate to the internal structure such as ice type (i.e., congelation, snow) and presence of defects (e.g., air bubbles, voids, fracture planes) that affect strength behaviour. Additionally, ice formation processes including freezing to ground, flooding, or snow accumulation can produce laminated or composite layers with non-uniform mechanical properties that introduce discontinuities in flexural behavior and alter how stress propagates, particularly under field conditions. These structural heterogeneities can shift the nature of boundary conditions from idealized free edges to complex, partially restrained or clamped scenarios.

Despite extensive research on the thermal properties of snow, ice, and sea ice, there is no universal acceptance to quantify thermal effects on ice bearing capacity across different conditions. Yen (1981), and Sinha (1996) provides insight into the influence of temperature on ice mechanics, yet their full integration into plate theory and analytical frameworks remain unresolved. Kerr (1976) presents empirical approaches, utilizing correction factors and coefficients to account for temperature effects and dimensional parameters, that modify the bearing capacity. However, these adjustments do not account for the transient heat energy balance or internal stratigraphy and ice quality, which introduces a parametric bias. As mean seasonal temperatures warm, approaching the melting point, diurnal variations in latent heat flux energy drive stratigraphic melting, recrystallization, and density redistribution processes. This introduces additional complexity influencing the mechanical behavior of ice. Timco and O'Brien (1993) highlight how exposure to fluctuating temperatures alters ice salinity and porosity, impacting load-bearing capacity. In freshwater ice, long-term effects include recrystallization and delayed creep, which influences ultimate failure conditions. While studies have established temperature-dependent relationships, the implication for bearing capacity remains a topic for consensus as it relates to all expected deformation mechanisms.

4.0 Discussion

Accurate predictions of ice bearing capacity are essential for engineering applications in cold regions, yet uncertainties persist due limitations of existing empirical and analytical models, and knowledge on the ice quality in terms of material and mechanical properties, which will be influenced by future climate variability. A key limitation is allowable load limit require an assumed flexural strength estimate to predict bearing capacity. Typically, ice flexural stress is estimated through small-scale field-bending tests (e.g., four-point, three-point and cantilever bending tests). These tests serve as proxies for in-situ strength but are limited by their scale, boundary conditions, and test setup, which may not represent full-scale loading scenarios like those encountered on the RCS. Studies (Aly et al., 2018; Frederking and Sudom, 2013; Williams and Parsons, 1994) indicate that flexural strength decreases as beam volume increases, suggesting that small-scale tests in controlled environments may overestimate real-world bearing capacity due to size effects. This has significant implications for engineering safety factors, operational decision-making, and the design of ice-bearing infrastructure.

To enhance confidence in addressing scale effects using predictive tools, bearing capacity tests should be conducted across a range of load, scales and contact areas (e.g., 100 kg – 2,500 kg). Measuring ice deflection and breakthrough loads under controlled conditions, particularly paying attention to mimicking the same field conditions, allows for validation of theoretical models and refinement of failure criteria. These tests are particularly valuable in assessing non-uniform loading conditions and interactions with boundaries (e.g., shoreline edges, canal walls). A significant opportunity for improving ice engineering predictions, particularly along the RCS involves comparative and sensitivity assessments of flexural failure with improved analytical models.

Aligning field data with controlled laboratory testing can help refine the mechanical behavior assumptions used in the RCS context. This includes monitoring environmental and ice cover conditions such as meteorological variables, ice temperature, deflection profiles, localized boundary conditions, and spatially distributed effective ice thickness. Laboratory tests that investigate the influence of different load types and distributions, boundary conditions, controlled temperature variations, and stratigraphic layering of the ice (including grain structure and bonding characteristics) would improve the reliability of model parameters. Additionally, elastic properties derived from dynamic loading and temperature-dependent tests offer further insights.

One of the most effective ways to reduce uncertainty is through field testing programs, and comprehensive meteorological and physical surveys. Ice core sampling and ground-penetrating radar (GPR) can provide crucial data on the thickness distribution of an ice cover, its stratigraphy, strength parameters, and internal defects. This will correlate environmental conditions with ice behavior and expand the RCS dataset for more robust engineering applications.

Advancements in real-time temperature sensing enable continuous assessment of ice conditions in response to thermal fluctuations and load-induced stresses, proving crucial for evaluating climate variability impacts on RCS operations. Seismic methods, commonly used in geological surveys, can assess ice integrity by measuring wave propagation through ice layers, improving load-bearing predictions when correlated with ice stratigraphy and strength data. Monitoring ice sheet deflection and freeboard provides insight into structural response under applied loads, with studies like Masterson (2009), emphasizing deflection trends in predicting failure mechanisms. Ground-penetrating radar enhances accuracy by distinguishing actual ice thickness from assumed values, supporting comparisons between punching and flexural failure in warming conditions. Lighter-weight support vehicles and alternative mobility platforms, such as tracked or low-ground-pressure vehicles, can reduce surface stress. Adaptation strategies, including geogrids and composite ice strengthening in areas with poor localized ice quality can also offer ways to increase load capacity.

5.0 Concluding Remarks

Enhancing confidence in ice bearing capacity predictions requires a comprehensive approach that integrates field data collection, real-time monitoring, laboratory calibration, and refined modeling techniques. There are many factors (e.g., boundary conditions, scale effects, material composition, and thermal variability) influencing ice bearing capacity that require further investigation to improve operational safety and optimize engineering decisions. While empirical models provide practical guidelines, their reliance on historical data limits their applicability under evolving climatic conditions. Conversely, the reliance on analytical models such as the Wyman (1950) plate theory introduces parametric uncertainties that are often addressed through conservative risk factors. The introduction of correction factors, such as those proposed by Kerr (1976), further addressed by the OIHSA (2014) and USACE (2002) attempts to address temperature dependencies, but are limited to specific conditions or risk acceptance which do not capture the full range of ice behavior. Temperature fluctuations influence ice porosity, stratigraphy, and mechanical strength, necessitating a more robust framework that integrates thermal and mechanical effects into bearing capacity assessments.

Future research should refine build on the current risk philosophy while relating experimental and analytical approaches best practices, outlined by OIHSA (2014) and USACE (2002) to achieve a better consensus on ice bearing capacity. Continuing to integrate the constitutive framework presented by Sinha (1996) with adjusted analytical approaches in a scaled and coupled thermal-mechanical model remains a challenge requiring further validation and refinement. As the RCS adapts to climate variability, incorporating real-time monitoring, material reinforcement, and improved analytical methods will be essential for maintaining safe ice operations.

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