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Editorial

Ice–Structure Interaction in Marine Engineering

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1. Introduction

The Arctic region is rapidly emerging as a strategic frontier due to its vast untapped oil and gas reserves—estimated to contain about 30% of the world's undiscovered natural gas and 13% of its undiscovered oil resources—as well as its potential to host future trans-Arctic shipping routes that could significantly reduce global maritime distances. However, the harsh ice-covered environment presents formidable technical and operational challenges for marine activities [1,2]. In this context, understanding the interaction between sea ice and marine structures has become essential for ensuring the safety, efficiency, and sustainability of engineering operations in polar waters. The interaction between sea ice and marine structures poses significant challenges to the safety, performance, and longevity of engineering systems in cold regions, including ships, offshore platforms, pipelines, and coastal infrastructure [3–7]. With the increasing strategic and commercial interest in polar regions, the demand for accurate understanding, modeling, and mitigation of ice-induced effects has become more urgent than ever.

Recent advances in experimental methods, numerical modeling techniques, and material science have enabled researchers to explore the complex and multi-scale nature of ice–structure interactions. However, challenges remain in terms of simulating realistic ice behavior, quantifying dynamic interactions under varying environmental conditions, and bridging the gap between model predictions and full-scale observations.

Major ice tank facilities such as the Hamburg Ship Model Basin (HSVA), the National Research Council of Canada (NRC), and the China Ship Scientific Research Center (CSSRC) have conducted extensive experimental campaigns involving ship–ice interaction, ramming behavior, and structural response under level and broken ice conditions [8–13]. These tests have advanced understanding of ice loads, fracture mechanisms, and energy dissipation processes, supporting the development and validation of computational models.

Numerical approaches are broadly categorized into mesh-based and mesh-free methods. Finite Element Method (FEM), along with Cohesive Zone Models (CZM) and Extended FEM (XFEM), are widely used in mesh-based simulations to predict ice failure and structural deformation [14–17]. While FEM is well-suited for continuum analysis, it can suffer from mesh dependency and complexity in handling crack initiation and growth. Mesh-free methods such as the Discrete Element Method (DEM) and Peridynamics (PD) are increasingly adopted for modeling large deformations and complex fracture behaviors [18–25]. These methods naturally handle discontinuities but often require high computational cost and careful parameter calibration. Hybrid modeling strategies that combine FEM with DEM or PD are emerging to leverage their respective advantages, though challenges remain in achieving accurate and efficient coupling across scales.

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To address these pressing research needs, this Special Issue on "Ice–Structure Interaction in Marine Engineering" brings together a collection of original research and review articles that contribute to the theoretical development, numerical simulation, experimental validation, and practical applications in this field. The topics span from ice modeling and ice-induced loads to fatigue damage, navigation in ice, ice-breaking mechanics, and the role of intelligent methods in performance prediction and decision-making. The goal of this Special Issue is to provide a platform for sharing the latest advances and to foster multidisciplinary dialog within the marine engineering and polar technology communities.

2. Published Papers

This Special Issue presents 13 peer-reviewed articles that showcase recent progress in ice–structure interaction studies, both in methodology and application. Key themes include:

Experimental methods in ice–structure interaction: Gutiérrez-Romero et al. conducted self-propulsion experiments in towing tanks using artificial ice blocks, offering insights into propeller–ice interactions (Contribution 13). Guo et al. explored the ramming behavior of an icebreaking research vessel through model-scale testing (Contribution 10). Sun and Huang investigated ice resistance of naval ships with non-icebreaking bows under various conditions (Contribution 7).

Numerical modeling and validation: Jang et al. validated multiple ice material models using FEA to predict impact loads (Contribution 12). Jia et al. employed peridynamic methods to simulate vertical ice sheet penetration (Contribution 11). Tian et al. developed a DEM-based numerical ice tank validated against physical tests for simulating structural responses (Contribution 6). Sun et al. proposed a CFD–DEM coupled model to predict resistance in brash ice channels (Contribution 5).

Fatigue and structural safety: Huang et al. presented field observations and a simplified method to evaluate ice-induced fatigue in aging offshore platforms in the Bohai Sea (Contribution 9). Wang et al. revealed a new failure mechanism in phase-locked ice crushing against structures using field data (Contribution 3).

Artificial intelligence and data-driven approaches: Zhou et al. proposed a machine-learning model for propulsion power prediction in ice, achieving high accuracy and generalization (Contribution 4).

Navigation and operational strategies in ice: Dong et al. developed a real-time ice channel recognition system based on deep learning (Contribution 8). Wu et al. constructed a coupled ice–wind–vehicle–bridge vibration model to assess traffic safety on sea-crossing bridges in ice-covered regions (Contribution 2). Gu et al. presented a dynamic positioning model for Arctic floating platforms under ice and wave loads (Contribution 1).

Together, these contributions reflect the depth and diversity of current research on ice–structure interactions and provide valuable references for both academia and industry stakeholders working in cold-region marine environments.

3. Perspectives

The articles in this Special Issue collectively demonstrate the growing maturity and diversity of research in the field of ice–structure interaction in marine engineering. They address key technical and scientific challenges, ranging from ice load modeling, structural safety, and ship navigation to experimental methods and intelligent prediction. This collection underscores that ice–structure interaction is not merely an engineering concern but a truly interdisciplinary field, involving mechanics, materials science, oceanography, data science, and environmental modeling. It is also a domain where field-based measurements, physical model testing, high-fidelity simulations, and machine-learning techniques can coexist and complement one another.

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The contributions of this Special Issue resolve several important technical uncertainties, yet at the same time raise further research questions that are fundamental to the advancement of ice mechanics and Arctic engineering. These include, but are not limited to, the following:

- Can unified multi-scale constitutive models be developed to capture the ductile-to-brittle transition and strain-rate sensitivity of ice under varied loading conditions?
- How can the scale effects in laboratory ice tests be effectively translated to full-scale structural design and operation strategies?
- What is the long-term fatigue behavior of complex structures under coupled ice–wave–wind environments, and how can this be accurately predicted?
- Can real-time ship navigation in ice-infested waters be made fully autonomous through intelligent ice recognition and path planning systems?
- What role will artificial intelligence and digital twin systems play in the integrated modeling of ice–structure–environment interactions?

These are specific yet critical questions that pave the way for specialized, forward-looking research. More broadly, two important perspectives emerge from this Special Issue. The first is the necessity for cross-disciplinary collaboration—uniting structural engineers, computational scientists, Arctic navigators, and marine ecologists—to address the complexity of ice environments holistically. The second is the urgency of connecting fundamental research with real-world applications, especially as Arctic shipping routes expand and offshore operations in cold regions become increasingly strategic. This Special Issue does not claim to capture the entirety of the research field, but it aims to reflect its momentum and the pressing scientific frontiers yet to be explored.

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