Evolution of ice load prediction tools for hydrotechnical construction

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Abstract. The article provides an overview of the historical and contemporary developments in estimating ice loads on marine structures. It first underscores the significance of accurate ice load calculations for the safety and reliability of structures, and subsequently traces the evolution of ice load estimation techniques from past standards to current international standards and guidelines. The article then delves into the limitations of traditional methods for ice load estimation, which rely heavily on empirical data, before discussing the innovative and more precise discrete element method (DEM) for ice load estimation. The article outlines the benefits of using DEM over traditional methods and explores the diverse software options available for modelling ice loads on marine structures, including commercial and open-source alternatives. The article emphasizes the importance of staying up-to-date with the latest advancements in technology and techniques for ice load estimation, highlighting the crucial role that precise and reliable ice load estimation plays in ensuring the safety and dependability of marine structures in extreme environments. Overall, the article provides a comprehensive summary of the evolution of ice load estimation techniques for marine structures, from past norms to the contemporary use of DEM and advanced software packages. It underlines the necessity of continuous research to ensure that marine structures are constructed with the highest safety levels.

1 Introduction

Marine infrastructure, is subjected to an array of environmental forces, comprising wind, ice, etc. One force that is frequently disregarded is ice. The estimation of ice loads on marine infrastructure can be tremendously unpredictable and intricate, and it is crucial to comprehend and calculate them accurately. Failing to do so can have devastating outcomes, such as structural harm, reduced dependability, increased maintenance expenditures, and even loss of the infrastructure.

Ice loads can arise from ice impact, ice drift, ice pressure, and ice ridging. Accurate forecasting of ice loads is vital for the secure and dependable design of marine infrastructure. Ice loads can result in significant structural damage, diminish structural reliability, raise maintenance costs, and lower operational efficacy. In severe cases, ice loads can culminate in the destruction of the infrastructure.

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Important obstacle of computing ice loads on marine infrastructure is the complex nature of ice formation. Ice formation mostly depends on temperature and salinity. The characteristics of ice formation can vary broadly, even within a single ice field, and can have a substantial impact on ice loads. This is the reason why predicting ice loads on marine infrastructure challenging and necessitates the utilization of specialized tools and techniques.

A lot of technics have been formulated for prognosticating ice loads on marine infrastructure. These methods can be broadly categorized into two classes: analytical methods and numerical methods. Analytical methods employ simplified mathematical models to estimate ice loads, while numerical methods use more intricate models that can simulate the behaviour of ice in greater detail. Numerical methods are generally more accurate but necessitate more calculation resources.

Calculation of marine infrastructure against ice loads requires to take into account of an assortment of factors, including properties of ice, structure, environment. Various standards have been established for marine infrastructure in the regions with ice cover. One internationally recognized is ISO 19906 [1]. Ice-resistant coatings, ice-breaking devices, ice management strategies should be considered together when design marine structures in the ice regions.

Accurate calculation of ice loads can help engineers construct infrastructure that can withstand the harsh circumstances of ice-covered marine regions. Ice-resistant marine infrastructure typically includes integrating measures such as ice-resistant coatings, ice-breaking devices, and ice management approaches. Sometimes marine infrastructure may need to be formulated to break up ice, while sometimes marine infrastructure may need to be devised to resist ice action.

Failing to compute infrastructures against ice loads can have grave consequences. Some well-known cases exist when structures were demolished when ice starts to interact with them.

The safety and dependability of marine structures heavily relies on calculating their ability to withstand ice loads. Though predicting these loads can be challenging, employing appropriate techniques and tools can help ensure the safety and reliability of these vital structures. Designing ice-resistant structures typically entails implementing various strategies like ice-resistant coatings, ice-breaking devices, and ice management tactics. Proper assessment of ice loads can help engineers create more dependable structures that can endure the ice harsh conditions.

In the past, the calculation of ice loads on marine structures was mainly based on experience and empirical data, as there were no standardized guidelines and regulations. Engineers and designers used their past experience and observations of ice behaviour to estimate the forces that ice could exert on structures. While this approach was somewhat effective, its accuracy was limited, often resulting in conservative estimates that could lead to more expenses.

In the past, one of the most popular ways to calculate ice loads was through the use of empirical formulas. These formulas were created by studying ice behaviour in various environments and were used to relate ice loads to factors like ice thickness and velocity [2]. However, this approach had its limitations. For example, the formulas were often region-specific and could not be transferred to other areas. Additionally, they did not take into account the complex behaviour of ice in different conditions, such as the formation of ice ridges or the effects of temperature and salinity on ice properties [3]. The analytical method involved using mathematical models to predict ice behaviour and the forces it would exert on structures. However, these models often made idealized assumptions that did not match real-world conditions. Another approach involved using past experience and observations of ice behaviour to estimate ice loads, but this method was highly subjective and could lead to inconsistent design of structure [4].
As marine constructions can be exposed to harsh environment, the limitations of existing ice load calculation methods became apparent. It was necessary to develop more precise and dependable methods for ensuring the safety and reliability of marine structures. However, the absence of established regulations and standards made it challenging to achieve consistent and safe design practices. In response, organizations such as the International Association of Classification Societies (IACS) and the International Organization for Standardization (ISO) created regulations and guidelines. These were based on advanced numerical models that could accurately simulate the intricate behaviour of ice and provide precise predictions of ice loads under varying environmental conditions. Consequently, these guidelines have been instrumental in ensuring safe and consistent design practices for marine structures located in arctic regions [1].

2 Materials and methods

The methods used to calculate ice loads on marine structures have undergone significant changes over time. In the past, empirical data and experience were the primary sources for ice load calculation, and standards and guidelines were limited in scope. However, technological advancements and better scientific understanding have led to a shift towards numerical models for ice load calculation. The use of analytical methods, based on simple mathematical models, was prevalent in the past, but these methods had limited accuracy and did not account for complex ice behaviour in real-world conditions. With advancements in computing power and modelling software, numerical models can simulate ice behaviour with much greater accuracy, including ice formation, drift, pressure, and ridging. These models also allow for the analysis of complex structures and provide more accurate predictions of ice loads under different environmental conditions. Additionally, standardized guidelines and regulations have been developed to ensure consistent and safe design practices for marine structures in ice-covered waters. In the past, the design of these structures was based on experience and ad-hoc methods, which led to inconsistent practices and a lack of confidence in their safety and reliability.

The safety and reliability of marine structures in ice-covered waters have been improved through the development of standardized guidelines and regulations, such as the ISO 19906:2010 [1] standard for marine structure design. This standard provides guidance on how to design structures that can withstand ice loads and incorporates provisions for ice-resistant coatings, ice-breaking devices, and ice management strategies.

Advancements in technology have also led to improvements in the measurement and monitoring of ice loads on marine structures. In the past, accurate measurement and monitoring of ice loads were challenging, which made it difficult to validate ice load calculations. However, with the advancements in sensor technology and data acquisition systems, ice loads can now be measured and monitored in real-time, leading to better validation of ice load calculations. Remote sensing technology, such as satellite imagery and radar, has also enhanced the ability to monitor ice conditions and predict ice loads on structures by providing information on ice thickness, concentration, and movement. This information can be used to inform design decisions and validate ice load calculations.

Over time, significant changes in norms and standards have improved the accuracy and reliability of ice load calculations on marine structures. Numerical modelling has been a crucial step forward in this regard. Numerical models can be classified into two main categories: finite-element models (FEM) and discrete-element models (DEM) [5]. FEM models divide the structure and surrounding ice into smaller elements, allowing for accurate calculations of forces and stresses acting on each element. This approach is particularly useful for complex structures. On the other hand, DEM models represent ice as discrete particles with their own properties and behaviour, making it ideal for simulating complex ice features
such as the formation of ice ridges [6][7]. As the field continues to evolve, further advancements in numerical modelling are likely to lead to even more accurate and reliable estimates of ice loads on marine structures.

Improvements in measurement technology have complemented numerical modelling as a significant step forward in estimating ice loads on structures. Traditionally, sensors placed on the structure were used to record ice forces, but this method was limited by the complexity of ice-structure interactions and harsh environments. Recent advances in measurement technology, such as laser scanning and digital image correlation, allow for more accurate and detailed measurements of structural deformation and strain under ice loads [8-10]. This data can help validate numerical models and improve their precision.

Furthermore, the development of standardized guidelines and regulations has also significantly contributed to the estimation of ice loads on structures. The International Association of Classification Societies (IACS) and the International Organization for Standardization (ISO) have created guidelines for designing marine structures in ice-covered waters, based on advanced numerical models and rigorous testing [1,11-12]. These guidelines provide designers and engineers with a framework to ensure the safe and reliable operation of marine structures in harsh environments.

To summarize, the estimation of ice loads on marine structures has improved significantly over time due to the development of numerical modelling, measurement technology, and standardized guidelines and regulations. Numerical models provide a more accurate representation of ice behaviour and its interaction with structures, making them particularly useful for predicting ice loads on complex structures in harsh environments. Advances in measurement technology, such as laser scanning and digital image correlation, allow for more detailed and accurate measurements of structure deformation and strain under ice loads. Standardized guidelines and regulations, developed by organizations like the IACS and ISO, provide a framework for safe and reliable design practices. These advancements continue to improve the safety and reliability of marine structures in ice-covered waters.

3 Results and discussion

The Discrete Element Method (DEM) is a numerical technique utilized to simulate the behavior of granular materials, which includes ice particles. DEM models are employed to estimate ice loads on marine structures and for other engineering applications. A range of software packages is available for DEM simulation, comprising both commercial and open-source programs (Fig. 1).

![Fig. 1. Example of ice beam by DEM](https://www.mdpi.com/2077-1312/10/10/1359)

EDEM is a prevalent commercial software package used for DEM modelling. It is a multi-physics simulation software that enables users to simulate the behaviour of granular materials, including ice particles. EDEM offers advanced features for modelling complex shapes and interactions between particles and structures. Various engineering applications, such as mining, pharmaceuticals, and construction, have used EDEM for simulation purposes.
Another commercial software package that can be utilized for DEM simulation is Rocky DEM. It is a potent tool for simulating the behaviour of granular materials and can be used for various engineering applications, including mining, food processing, and pharmaceuticals. Rocky DEM provides a user-friendly interface and advanced features for modelling complex shapes and interactions between particles and structures.

Open-source software programs, such as LIGGGHTS and YADE, are also available for DEM modelling. LIGGGHTS is a powerful open-source DEM simulation software that enables users to model particle-particle interactions, particle-fluid interactions, and particle-structure interactions. YADE, another open-source DEM simulation software, offers advanced features for modelling granular materials, including ice particles, in large systems with complex shapes and interactions between particles and structures. These software packages provide users with flexible and customizable solutions for discrete element modelling of ice loads on marine structures, complementing the widely-used commercial software packages such as EDEM and Rocky DEM.

4 Conclusion

To ensure the safety and reliability of marine structures, it is essential to accurately calculate ice loads. Over the years, ice load estimation has advanced from simplistic empirical models to sophisticated numerical models based on physics and mechanics principles. International standards and guidelines have played a significant role in standardizing ice load calculations, ensuring consistency and accuracy in the design of marine structures.

The discrete element method (DEM) has been a significant advancement in ice load estimation. DEM simulates the behaviour of granular materials, including ice particles, providing a more precise and dependable estimate of ice loads on marine structures. DEM offers several advantages over traditional methods, including the ability to model complex shapes and interactions between particles and structures.

Modern software packages, both commercial and open-source, have made it easier to implement DEM simulations for ice load estimation. Commercial software packages such as EDEM and Rocky DEM offer advanced features for modelling complex shapes and interactions. Meanwhile, open-source software provides researchers and developers with a more flexible and customizable solution.

The development of advanced models and software for ice load estimation has significantly improved the safety and reliability of marine structures in extreme environments. However, as technology continues to evolve, there is a need to remain up-to-date with the latest advancements to ensure that structures are designed and built to the highest safety standards.

Future advancements in ice load estimation may include the application of machine learning and artificial intelligence algorithms to enhance the accuracy and efficiency of ice load simulations. These methods can allow for more comprehensive modelling of ice behaviour and its interaction with structures. Additionally, remote sensing technologies, such as LiDAR and satellite imagery, may provide more accurate measurements of ice properties, leading to improved ice load numerical calculations.

Due to increasing of building of marine structures, safety and reliability should remain a top priority. Properly calculating ice loads is a crucial aspect of ensuring the integrity of these structures in extreme environments. The advancements in ice load estimation discussed in this text provide a solid foundation for the future development of marine structures and the ongoing efforts to ensure their safety.

The task of calculating ice loads on marine structures is critical and complex, requiring advanced modelling techniques and software. Over time, the evolution of ice load estimation has transformed the design and construction of marine structures, from simplistic empirical
models to advanced DEM simulations. Standardization efforts, through international guidelines and standards, have also contributed significantly to the accuracy and consistency of ice load calculations.

DEM simulations have been a significant advancement in ice load estimation, offering several advantages over traditional methods. The use of modern software packages, including EDEM, Rocky DEM, LIGGGHTS, and YADE, has made it easier to implement DEM simulations and provided a more flexible and customizable solution for researchers and designers.

To continue improving the accuracy and efficiency of ice load estimation, exploring new technologies and techniques is necessary. The integration of machine learning and artificial intelligence algorithms, along with remote sensing technologies, may offer opportunities for more comprehensive modelling of ice behaviour and its interaction with marine structures.

Ultimately, the safety and reliability of marine structures in extreme environments depend on accurate and reliable ice load estimation. Thus, staying with the most modern calculation approaches is vital to ensure that marine structures are designed with the best possible way to reach the desired levels of safety.

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