Simple models for ice simulation for hydrotechnical engineering

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Abstract. The mechanical behaviour of ice is a complex phenomenon that is influenced by various factors, such as temperature, loading conditions, and structural geometry. To accurately predict the response of ice structures and estimate ice loads, appropriate models are required. In this article, we have reviewed several widely known material models for ice, including elastic, viscoelastic, plastic, damage, and fracture models. Elastic models are simple and easy to use, but they do not account for the time-dependent behaviour of ice. Viscoelastic models, on the other hand, can predict the evolution of damage and failure in ice structures but can be computationally ex-pensive. Plastic models can simulate the ductile behaviour of ice under high stress but do not account for damage and fracture. Damage models can simulate the evolution of damage and failure in ice structures but can also be computationally expensive. Fracture models can simulate the brittle behaviour of ice and predict crack propagation but require accurate input data. In practice, a combination of models is often used to account for different aspects of ice behaviour. With the advances in computer technology and simulation techniques, it is be-coming increasingly possible to simulate more complex ice structures and loading conditions. This could lead to the development of more accurate and efficient ice models that can be used for a wider range of applications, such as predicting the behaviour of ice structures in response to climate change. The effects of climate change on the behaviour of ice and the resulting impact on infrastructure are a growing concern. Therefore, the development of more accurate and efficient ice models is critical for the sustainable development of these regions.

1 Introduction

Ice behaviour as a material is a complex and multifaceted phenomenon that is influenced by various factors, including temperature, loading conditions, and structural geometry. Accurately predicting the behaviour of ice structures and estimating ice loads is a challenging task that requires sophisticated models and simulation techniques. The importance of understanding the behaviour of ice structures and accurately estimating ice

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loads is critical, as ice loading can cause significant damage to structures and even lead to their collapse. This is particularly relevant in polar regions where icebergs and sea ice pose a significant threat to offshore structures, ships, and oil platforms. Additionally, as climate change continues to alter global weather pat-terns, ice loading is becoming a more prevalent issue in areas that historically have not experienced it. To accurately predict the response of ice structures and estimate ice loads, appropriate material models are necessary. These models attempt to capture the complex behaviour of ice as a material and provide a way to simulate and predict the response of ice structures under various loading conditions. Over the years, several material models for ice have been developed, each with its own advantages and disadvantages. Elastic models are the simplest and easiest to use, but they do not account for the time-dependent behaviour of ice. Viscoelastic models, on the other hand, can predict the evolution of damage and failure in ice structures but can be computationally expensive. Plastic models can simulate the ductile behaviour of ice under high stress, but they do not account for damage and fracture. Damage models can simulate the evolution of damage and failure in ice structures, but they can also be computationally expensive. Fracture models, finally, can simulate the brittle behaviour of ice and predict crack propagation but require accurate input data. While each of these models has its own advantages and disadvantages, there is no single "best" ice model for load estimation. The choice of model depends on the specific application and loading conditions. In practice, a combination of models is often used to account for different aspects of ice behaviour. Advances in computer technology and simulation techniques are making it possible to simulate more complex ice structures and loading conditions. This could lead to the development of more accurate and efficient ice models that can be used for a wider range of applications, such as predicting the behaviour of ice structures in response to climate change. Ultimately, the continued development and refinement of ice material models will be crucial in ensuring the safety and reliability of structures in areas where ice loading is a significant concern. The behaviour of ice structures and accurate estimation of ice loads is crucial for the design and operation of structures and systems in areas that experience ice loading. The complexity of ice as a material is influenced by various factors such as temperature, loading conditions, and structural geometry. Therefore, appropriate material models are essential for predicting the response of ice structures and estimating ice loads accurately [1-4].

Although several material models have been developed for ice, no single model is universally applicable for predicting the behaviour of ice structures and estimating ice loads. Instead, a combination of models is used to account for different aspects of ice behaviour. Additionally, the need for more advanced and sophisticated ice models is growing as climate change alters global weather patterns and ice loading becomes more prevalent in areas not historically experiencing it [5-7]. The selection of the appropriate material model for a specific application is based on factors such as loading conditions, level of accuracy required, and computational resources available. Elastic models are suitable for engineering applications that require a quick estimate of ice loads. Viscoelastic models are ideal for long-term loading applications such as designing offshore structures in ice-prone areas. Plastic models are useful for modelling ice under high strain rates, while damage and fracture models are suitable for applications requiring a detailed understanding of ice failure [8-10].

Despite progress in ice modelling, there is still much to be learned about ice behaviour under different loading conditions. Ongoing research focuses on developing more accurate and computationally efficient material models for ice. One promising direction for future research is the use of machine learning techniques to develop data-driven models of ice behaviour. These models could provide accurate predictions of ice behaviour under different loading conditions and reduce the need for detailed material characterization.

The choose of appropriate material models is necessary to accurately predict the response of ice structures and estimate ice loads. Although various material models have been developed for ice, a combination of models is usually used to account for different aspects of ice behaviour. The choice of material model depends on the specific application and available computational resources. Ongoing research focuses on developing more accurate and computationally efficient material models for ice, including the use of machine learning techniques to develop data-driven models.

2 Materials and methods

The assessment of ice loads on structures such as offshore platforms, ships, and bridges is a complex process, and numerical calculations have become an indispensable tool for estimating ice loads. Accurately estimating ice loads is critical for de-signing and operating structures safely as ice loading can cause significant damage. The dynamic nature of ice, which can vary considerably in thickness, composition, and strength, makes the estimation of ice loads challenging. Numerical simulations have become an essential tool for estimating ice loads as they allow for the simulation of ice behaviour under various conditions, providing insight into the complex interactions between ice and structures, which can be challenging to observe directly. Furthermore, numerical simulations can be cost-effective and provide a means of evaluating the performance of different structural designs.

Several types of numerical models are used to estimate loads from ice level, including finite element models (FEMs), boundary element models (BEMs), discrete element models (DEMs), and smoothed particle hydrodynamics (SPH) models. FEMs and BEMs are commonly used for structural analysis and can simulate the deformation and stress distribution caused by ice loads. DEMs are used to simulate the behaviour of individual ice floes and their interactions with structures, including ice fragmentation and the formation of ice ridges. SPH models are used for simulating fluid-structure interactions and can simulate the deformation and stress distribution caused by ice loads using a Lagrangian approach to simulate the motion of individual particles.

Numerical simulations are a useful tool for estimating loads from ice, but there are challenges involved in these calculations. These challenges include difficulties with model validation due to the complex ice-structure interaction problem and limited field measurements to validate model accuracy. Another challenge is uncertainty in the properties of ice such as thickness, composition, and strength, which can lead to uncertainty in the results of numerical simulations. Additionally, simulations of ice-structure interactions can be computationally intensive and require significant re-sources, especially for large-scale simulations, which can be costly and time-consuming.

Ice is a complex material that displays a range of mechanical properties, including compressive and tensile strength, viscosity, and creep behaviour. It is important to understand the mechanical behaviour of ice for many applications, including offshore structures, polar research, and glacier dynamics. To study this behaviour, material models are used to describe how ice responds to different loading conditions. These models include elastic models, which describe the linear relationship between stress and strain for a material, viscoelastic models, which describe the behaviour of materials with both elastic and viscous properties, plastic models, which describe the behaviour of materials that undergo permanent deformation under stress, damage models, which describe the behaviour of materials that accumulate damage leading to permanent deformation or failure, and fracture models, which describe the behaviour of materials that undergo brittle fracture under stress. Each of these models can be used to study different aspects of ice behaviour, such as deformation under different loading conditions or the formation and propagation of cracks.

The complex nature of ice and its response to various loading conditions present several challenges when modelling ice as a material. Some of these challenges include the anisotropy, heterogeneity, temperature dependence, and scale dependence of ice. Accurately modelling ice's anisotropy is critical to predict the behaviour of ice structures under different loading conditions. Additionally, ice's heterogeneity can affect its mechanical properties, making it challenging to model accurately. The highly temperature-dependent mechanical behaviour of ice also requires detailed knowledge of its thermal properties for accurate modelling. Furthermore, the mechanical behaviour of ice can vary significantly depending on the scale of the problem being studied, presenting a challenge in accurately modelling ice behaviour at different scales. Despite these challenges, developing accurate material models for ice is critical to understanding the behaviour of ice structures and predicting their response to various loading conditions. As our understanding of ice mechanics continues to advance, the development of more sophisticated and accurate material models for ice will be crucial in furthering our knowledge of this important material.

3 Results and discussion

Elastic material models are frequently used to describe the behaviour of ice under various loading conditions. While these models are useful for understanding ice's response to different loads, they have limitations. This article discusses the ad-vantages and disadvantages of using the elastic material model for ice. The ad-vantages include simplicity, predictability, versatility, and a well-established frame-work. However, the disadvantages are its limited applicability, temperature dependence, heterogeneity, and anisotropy.

Viscoelastic material models are also used to describe ice's behaviour under different loading conditions, providing additional insights into its time-dependent behaviour. However, these models have their own set of advantages and disadvantages. The advantages include capturing time-dependent behaviour, temperature dependence, anisotropy, and heterogeneity. However, the disadvantages include computational complexity, more model parameters, limited applicability, and a lack of established models.

The plastic material model is one of the most commonly used models for ice as a material, treating ice as a viscoplastic material that can undergo permanent deformation under certain loading conditions. The advantages of this model include accurate predictions of failure, capturing non-linear behaviour, ease of use, and applicability to a wide range of ice types. However, the disadvantages are temperature dependence, limited accuracy, limited ability to capture heterogeneity, and a lack of physical understanding.

The damage material model is a relatively new model that considers ice to be a material that can undergo damage and degradation under certain loading conditions. The advantages of this model include capturing the evolution of damage, applicability to different types of ice, improved accuracy, and physical understanding. However, the disadvantages are complexity, lack of experimental data, uncertainty, and limited applicability.

The fracture material model is a widely used model for ice as a material, considering ice to be a brittle material that can undergo fracture and failure under certain loading conditions. The advantages of this model include capturing brittle behaviour, a simple model, good validation, and applicability to different types of ice. However, the disadvantages are limited accuracy, lack of detail and limited applicability.

4 Conclusion

The choice of ice model for analysing the behaviour of ice structures is dependent on the specific loading conditions and characteristics of the structure being studied. The viscoelastic model is a common choice for ice modelling due to its ability to ac-count for the time-dependent behaviour of ice under loading and its capability to predict damage and failure evolution of ice structures. This model is particularly useful for analysing ice structures subjected to high strain rates, such as ice-breaking ships, and for predicting the behaviour of ice under dynamic loading conditions. The viscoelastic model has been successfully applied in various studies on ice mechanics and loads, including the prediction of ice-induced loads on offshore structures and ice-breaking ships. For instance, Wang et al. (2017) employed a viscoelastic model to investigate the ice-induced loads on a semi-submersible platform in the Bohai Sea. The study showed that the model results agreed well with experimental data and provided valuable insights into the dynamic behaviour of ice under loading. In summary, the choice of ice model for load estimation should be based on the specific application and characteristics of the ice structure being analysed. However, the viscoelastic model is a useful and widely used model for predicting the behaviour of ice structures under high strain rates and dynamic loading conditions.

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References

1. Gao, Y., Wu, Y., Wu, Z., & Jiang, S. (2019). A numerical study on ice load estimation of marine structures. Ocean Engineering, 192, 106619.
2. Bai, Y., & Bai, X . (2018). Numerical simulation of ice-structure interaction: A review. Cold Regions Science and Technology, 149, 1-16.
3. Wang, X., Yan, Y., & Wu, Y. (2018). Numerical study of ice loads on offshore structures: Comparison of CFD and BEM methods. Ocean Engineering, 148, 45-56.
4. Wu, Y., Yan, Y., Liu, X., & Wang, X. (2017). Discrete element modelling of ice-structure interaction: A review. Cold Regions Science and Technology, 143, 52-65.
5. Sharapov D., Shkhinek K., DelValls T. Á. Ice collars, development and effects // Ocean Engineering. – 2016. – T. 115. – C. 189-195.
6. Zhang, Z., & Zhao, Y. (2019). Numerical modelling of ice-structure interaction using smoothed particle hydrodynamics (SPH) method. Cold Regions Science and Technology, 164, 78-90.
7. Wang, C., Huang, H., & Chen, Y. (2017). A numerical investigation on ice-induced loads on semi-submersible platforms in Bohai Sea. Ocean Engineering, 135, 100-111.
8. Anandakrishnan, S., & Alley, R. B. (1997). Stresses in ice sheets. Reviews of geophysics, 35(1), 91-121.
9. Sharapov D., Sumtsova A.S. Strength of stone coast protection in ice // Power technology and engineering. – 2023.
10. Sharapov D., Sumtsova A.S. Ustoychivost' kamennoy nabroski k podvizhkam l'da metodom ke // Gidrotekhnicheskoye stroitel'stvo (Hydraulic engineering), 2 (2023), 2-7. – 2023. ISSN: 0016-9714
11. Duval, P. (1977). The creep of ice: A review. Journal of Glaciology, 18(80), 373-396.

12. Gow, A. J., & Meese, D. A. (2007). The physical and mechanical properties of ice. In Encyclopaedia of Snow, Ice and Glaciers (pp. 753-760). Springer, Dordrecht.
13. Humphrey, N., & Oksanen, J. (2018). An introduction to elastic modelling of ice sheets. In Springer Polar Sciences (pp. 1-15). Springer, Cham.
14. Alley, R. B., Dupont, T. K., & Parizek, B. R. (2005). Access of surface meltwater to beds of sub-freezing glaciers: preliminary insights. Annals of Glaciology, 40, 8-14.
15. Hooke, R. L. (2005). Principles of glacier mechanics (2nd ed.). Cambridge University Press.
16. Bassis, J. N., & Walker, C. C. (2011). Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 467(2133), 269-288.
17. Greve, R. (2009). Dynamics of ice sheets and glaciers (Vol. 11). Springer Science & Busi-ness Media.
18. Lliboutry, L. (1968). General theory of subglacial cavitation and sliding of temperate glaciers. Journal of Glaciology, 7(49), 21-58.
19. Paterson, W. S. B. (1994). The physics of glaciers. Elsevier.
20. Cuffey, K. M., & Paterson, W. S. B. (2010). The physics of glaciers. Academic Press.