International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 32, No. 1, March 2022, pp. 16–23; https://doi.org/10.17736/ijope.2022.jc849

http://www.isope.org/publications

A Smoothed Particle Hydrodynamics Framework for Interaction Between Ice and Flexible Pile

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In this paper, smoothed particle hydrodynamics (SPH) is extended to simulate the ice–structure interaction by coupling an ice model with a structural model through a simple but effective interfacial contact model. The ice model embeds the softening elastoplastic model with the Drucker–Prager yield criterion to simulate the failure progress of the ice, and a linear elasticity model is adopted for predicting the structural deformation. The developed SPH model is employed to simulate the interaction between the level ice and a moving vertical compliant pile. The ice loading on and the response of the pile are evaluated. The results are compared with the experimental data and the corresponding numerical result with a rigid pile without considering the structural elasticity. The results explore the significance of the structural vibration and its effects on ice loading during the ice-breaking process, as well as the necessity of including structural dynamics in ice–structure modeling.

INTRODUCTION

With the increasing exploration and exploitation of hydrocarbon and ship transportation in the Arctic region, the ice–structure interaction has received increasing attention recently. In Arctic engineering, the fixed vertical structure (e.g., pile) is a typical structural form of offshore platform. When an ice sheet interacts with such a structure, a significant ice-induced load imposes on the structure, yielding a structural vibration and ultimately threatening the operation, reliability, and safety of the structure. Therefore, a better understanding of the dynamic process of the ice–structure interaction and a reliable modeling tool are sought in the design of Arctic offshore structures for both fatigue and ultimate limits.

Because of the complexity of the ice–structure interaction, most of the existing modeling tools are empirical formulas (Palmer et al., 2010) or phenomenological models (Hendrikse and Metrikine, 2016; Ji and Oterkus, 2016). These theories and models are constrained by their narrow ranges of application and are suitable for limited types of structures and ice conditions (Hendrikse et al., 2018). In addition, numerical approaches for modeling the interaction between the ice and the vertical offshore structure exist in the public domain (e.g., Liu et al., 2017; Sharapov and Shkhinek, 2018; Van den Berg et al., 2019). However, these attempts assume that the structures are rigid, and thus the ice-induced structural deformation and vibration, which are of importance for design and operations of offshore structures, cannot be considered. Although the ice-breaking process and the ice-induced loads on the structure can be predicted to a certain extent by using these models, their accuracies are questionable in cases of significant structural vibrations, which mutually affect the ice-breaking and the ice load. Thus, it is highly important to develop efficient numerical tools, which fully couple the ice model with an appropriate structural model, to tackle the challenges in predicting the complex dynamic process of ice–structure interaction.

In the past decades, smoothed particle hydrodynamics (SPH) has been widely applied to computational fluid simulations (Shao and Lo, 2003; Khayyer and Gotoh, 2013; Zheng et al., 2014), fluid–structure interaction problems (e.g., Antoci et al., 2007; Khayyer et al., 2018, 2019, 2021; Zhang et al., 2019) and structural dynamics (e.g., Libersky et al., 1991; Bui et al., 2008; Deb and Pramanik, 2013; Zhang et al., 2017; Ren et al., 2019). Attributable to its Lagrangian nature and mesh-free discretization of the spatial domain, SPH has demonstrated its advantages for dealing with problems involving large deformations (e.g., violent free surface flow and large structural deformation and failure). In our previous work, SPH was developed to model the bending and compression failure progress of ice (Zhang et al., 2017), ice breaking induced by a rigid moving ship (Zhang et al., 2018), and the kinematic responses and flexures of an ice floe under the action of waves (Zhang et al., 2019).

As indicated above, the structural deformation and vibration may be significant in the ice–structure interaction problems. These can be modeled by coupling an appropriate structural dynamics solver with the existing SPH framework for the ice–water–structure interactions. The key part of the coupling is to develop approaches for ice–structure and water–structure coupling. In this paper, an ice–structure coupling approach through a simple and effective contact condition imposing on the ice–structure interfaces is developed. By using this approach, one can couple the ice model with different structural dynamics models depending on the material properties. The ice model is built on our existing work (Zhang et al., 2017), where an elastoplastic constitutive model, integrated with the Drucker–Prager yield criterion and cohesion

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Received August 8, 2021; updated and further revised manuscript received by the editors October 18, 2021. The original version (prior to the final updated and revised manuscript) was presented at the Thirty-first International Ocean and Polar Engineering Conference (ISOPE-2021), Rhodes, Greece (virtual), June 20–25, 2021.

KEY WORDS: Ice–structure interaction, ice loads, structural vibrations, SPH.