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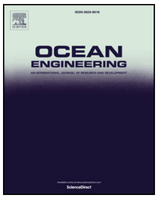

An assessment of sensitivity of the self-excited modelling approach for simulating dynamic ice-structure interactions to changes in temperature and scale effects

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ABSTRACT

Empirical relationships of compressive ice strength as a function of stress rate have been utilized in models of vibrations that arise during coupled ice-structure interactions. Central to current self-excited models (SEM) is a deterministic relationship of compressive ice strength as a function of stress rate based on uniaxial compressive strength data obtained from thin, first-year sea ice. However, full-scale observations, laboratory test data and fundamental knowledge of ice material behavior suggest that any such relationship would be influenced by factors such as temperature and the scale of the interaction. In this paper, the influence of temperature and scale effects is examined and first-order estimates of their effect on modifying the assumed strength vs. stress rate relationship are presented. This approach is used to assess the sensitivity of the SEM method to changes in environmental and interaction conditions. Results suggest that accounting for changes in ice temperature and the scale of interaction considerably affect ice-induced vibration responses predicted by the model. Additional large-scale experiments, full-scale data and the development of physics-based models of ice compressive failure are needed to better account for different ice conditions and different sized structures that may be considered in design.

1. Introduction

1.1. Background

When designing structures for ice environments, ice-induced vibrations (IIV), especially steady state vibrations, are an important engineering consideration. The international standard for petroleum and natural gas industries – Arctic offshore structures (ISO, 19906, 2010) provides design guidelines for dynamic ice actions (section A.8.2.6 of ISO 19906, 2010) and explicitly discusses the susceptibility of IIV through frequency lock-in (section A.8.2.14 of ISO 19906, 2010). Frequency lock-in refers to the condition when ice fails at a frequency close to the natural frequency of the structure (primarily due to crushing) and causes a dynamic amplification in structural response. Such behavior has been observed in the field especially when the natural frequency of the structure is within the range of 1–2 Hz (Peyton, 1968; Jefferies and Wright, 1988; Bjerkås et al., 2013a). The guideline provided in the ISO code recommends identifying the lowest structural mode susceptible to IIV and checking the stability criterion through modal damping. To calculate the modal amplitude at the ice action point, the method referred in the ISO code (Määttänen, 1978) uses the compressive strength - stress rate relationship proposed by Blenkarn (1970). This relationship (shown in Fig. 1) uses uniaxial compressive data collected by Peyton on thin, first-year ice on Cook inlet, Alaska (Peyton, 1968). The data shows ice strength increases as a function of loading rate up to a certain point and then start decreasing as loading rate is increased further until reaching to a point after which it is almost constant. Such behavior has also been observed and reported by other authors (Schwarz, 1970; Wu et al., 1976; Michel and Toussaint, 1977). It has been postulated that the negative slope in that relationship serves as a source of negative damping and if this is greater than the structural damping then the structural response will grow over time. Blenkarn termed this as self-excited vibration to explain IIV and a rigorous model was later proposed by Määttänen. Although the Peyton relationship was based on uniaxial compression test data, this relationship has been treated as universal and has been applied to full-scale lighthouse structures. However, fundamental material behavior of ice suggests that such relationship would be significantly influenced by ice properties and

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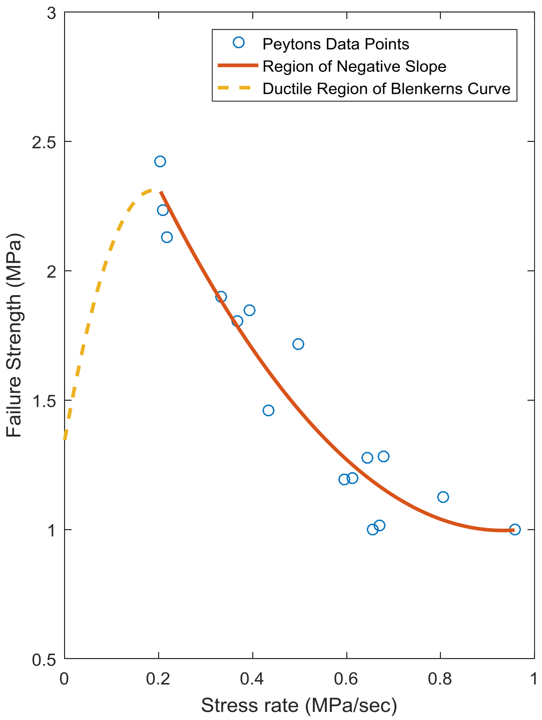

Fig. 1. Original Blenkarn's curve based on Peyton's compressive data (drawn after Blenkarn (1970)).

interaction conditions. In this paper, the variation in ice strength-stress rate relationship subjected to a variation in ice temperature and interaction scale is inferred based on the fundamental ice material behavior. The inference is then used to evaluate how such variation can propagate through the dynamic ice-structure interaction and affect IIV response.

1.2. Literature review

The first scientific interest in understanding the dynamic nature of ice-structure interactions associated with IIV arose in the late 1960s when this phenomenon was first observed on fixed vertical-pile offshore platforms in Cook Inlet, Alaska (Peyton, 1968; Blenkarn, 1970). Through the use of full-scale measurements, both authors concluded that a moving ice field can induce severe vibrations to slender offshore structures; however, the explanation offered by each author regarding the cause of these IIVs differed significantly. In these earliest analyses, the ice failure processes was described as a stick-slip type phenomenon that followed a sawtooth loading pattern. Comparing his observations to his laboratory test series, Peyton (1968) concluded that ice has a "characteristic failure frequency". The notion that these vibrations were of a self-excited nature was first proposed by Blenkarn (1970), who correctly identified that both the properties of the ice and the structure play an important role in governing the interaction dynamics. Blenkarn also highlighted the need to consider the natural vibration modes of the structure to assess its susceptibility to damped or steady-state resonant vibrations, a condition commonly referred to as "lock-in". The physical ice conditions observed to be of most significance by Blenkarn were ice speed and thickness.

Less than a decade later, similar problems were encountered with navigational aids and lighthouse structures built in the Gulf of Bothnia, Finland, ultimately resulting in damage and in some instances failure of these structures (Engelbrektson, 1977; Määttänen, 1978). Research undertaken by Määttänen further explored the self-excited nature of ice–structure interactions associated with IIV on full-scale lighthouses (Määttänen, 1977, 1978). Similarly, channel markers in Gulf of Bothnia were also found to be prone to ice-induced vibrations. One of these markers was instrumented in Winter 1987–1988 and severe stresses were recorded due to steady-state vibrations or "lock-in" phenomenon (Nordlund et al., 1988). Very few cycles were required for the structure to reach peak amplitude from rest which led the authors to believe that the excitation mechanism has a significant force component that is dependent on the displacement and/or velocity of the structure. Due to the observed shift between high-level and low-level amplitude, the excitation mechanism was thought to be comprised of a random force superimposed by an interaction force that is dependent on the structural displacement or velocity.

Similar dynamic effects, which ultimately led to cases of structural failure, were later reported on jacket platforms in the Bohai Sea, China (Xu and Bernt, 1981). Two jacket platforms (one of which was a small flare jacket) were reported to collapse within a period of 10 years. Based on field measurements on a full-scale six-legged jacket platform in combination with numerical analysis, it was concluded that an amplified resonant response can be expected under a certain combination of ice floe velocity, spatial ice load distribution and damping properties of the structure. To help mitigate these vibrations ice breaking cones were installed at the water level. While this did reduce the extent of ice crushing, a different cyclic failure process leading to vibrations was observed due to repeated flexural cusp failures. Also, during high tidal currents, the failure frequency of the thin ice could potentially reach of the natural frequencies of the structure (Yue and Bi, 2000; Yue et al., 2007).

In Canada, observations of dynamic ice forces acting on bridge piers (Neill, 1976; Montgomery et al., 1980) highlighted that in some structures the dynamic response of the pier may exceed the static response during a peak ice force event. As offshore technology continued improve and evolve in the 1980s, operations moved further north into increasingly challenging ice conditions. During this time it was believed that IIV issues were most relevant for narrow structures and this issue was less of a concern for wide structures. This belief was challenged during the winter of 1986, when thick multi-year ice caused severe ice-induced vibrations leading to partial liquefaction of the foundation of the 90 m wide Molikpaq Mobile Arctic Caisson structure, which was operating in the Beaufort Sea (Jefferies and Wright, 1988; Frederking and Sudom, 2006). Cyclic behavior with a frequency of approximately 1.4 Hz was recorded with peak vibration amplitudes up to 10 mm which lasted for four minutes (Timco and Wright, 2005). These IIVs and associated foundation issues created significant concerns about the stability of the structure, which ultimately resulted in an evacuation of the platform. A comprehensive review of these early observations was provided by Sodhi (1988), and these incidents, along with uncertainties associated with full-scale measurements from the Molikpaq have been broadly discussed in the ice mechanics community (Taylor and Jordaan, 2011; Jordaan et al., 2011).

To help address uncertainties around full-scale loads for first-year ice interactions with fixed structures, the European Union funded two major full-scale ice force measurement projects in the northern Gulf of Bothnia in a span of five years. The first of these was entitled "LOw LEvel Ice Forces" (LOLEIF), and the second was entitled "STRuctures in ICE" (STRICE). Ice force was directly measured against Norströmsgrund lighthouse using nine ice force measuring panels; ice thickness and air temperature were also recorded. While the full datasets and reports for the LOLEIF and STRICE projects are not readily accessible, brief descriptions of the test setup can be found in the literature (Schwarz and Jochmann, 2001; Bjerkås et al., 2013a). Results from the LOLEIF project show that effective pressure decreases with nominal interaction area and also with increasing ice thickness (Schwarz and Jochmann, 2001). The STRICE data have been extensively analyzed by Bjerkås to study the dynamics of ice structure interactions and associated ice-induced vibrations (Bjerkås and Skiple, 2005; Bjerkås et al., 2013a, 2013b). From these analyses, three different interaction modes, namely intermittent crushing, frequency lock-in and continuous crushing were