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A decade of probing the depths of thick multi-year ice to measure its borehole strength ☆

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ABSTRACT

This paper offers the most comprehensive set of property measurements on multi-year ice to date, in the interest of addressing one of the most significant unknowns for Arctic engineering: multi-year ice strength. Borehole strength results are presented from 56 old ice floes in the gray literature and more than 600 tests conducted on 23 multi-year ice floes over the past decade, including the first-published results over the full thickness of a 12.7 m thick, cold multi-year hummock. The ice borehole strength is obtained by categorizing the pressure vs. time histories for each test into one of four main types of failure behavior. Vertical profiles of the temperature, salinity and borehole strength of multi-year floes in spring and summer demonstrate that the properties of multi-year ice are highly variable in space and time. The mean borehole strength and standard deviation of cold (−13 °C) multi-year ice is 34.2 ± 9.1 MPa, although strengths as high as 49.2 MPa do occur, making multi-year ice nearly twice as strong as cold first-year ice. The mean borehole strength and standard deviation of warm multi-year ice is 19.6 ± 7.2 MPa (at −5 °C) and 10.3 ± 5.3 MPa (at 0 °C). Ice temperature is shown to be the single largest factor influencing borehole strength: strength increases with decreasing ice temperature, however complex factors such as the ice failure mode and ice consolidation also bear upon the relation. For example, strengths measured in thick, level multi-year ice can be substantially higher than hummocked multi-year ice sampled at the same temperature, time of year and latitude. Similarly, a thoroughly weathered multi-year ice hummock in late summer can have considerably higher strength than a less weathered multi-year hummock in early spring. The study shows that multi-year ice does not deteriorate in the same manner as first-year ice, strength equations based solely on brine volume are not appropriate for multi-year ice and warm multi-year ice should not be assumed deteriorated. The viability of estimating the ice borehole strength from known ice temperatures is explored by fitting linear regressions to strength–temperature data for the two most common failure processes: well-defined yield failures (Type 2) and poorly-defined yield failures (Type 3). The Type 2 failure equation reproduces the measured strength profiles more closely than the Type 3 failure equation, but results are not ideal. A similar comparison was made for the effective borehole strength, i.e. the strength averaged over all test depths in a particular borehole. For the 64 boreholes examined, the Type 2 failure equation produced an upper bound for the effective borehole strength, but only when ice temperatures had been documented over at least half of the total ice thickness.

1. Introduction

Multi-year sea ice presents one of the most significant design and operational challenges for exploration, development and shipping systems in Arctic ice-covered waters. That was true in the past and it is still true today, despite the widely reported shrinkage in the extent of polar pack ice (Overland and Wang, 2013; Parkinson and Comiso, 2013; Serreze et al., 2007). A greater proportion of first-year ice and longer periods of open water may be advantageous from the engineering perspective, but it must be remembered that multi-year ice floes can encroach on near-shore areas at any time of year, and that multi-year ice is ever-present in the deeper waters offshore. Therefore, the thickness of multi-year floes likely to be encountered by Arctic offshore structures over their lifetime is key to designing well-engineered structures. Is the thickness of multi-year ice floes today different than it was 50 years ago? Recent measurements have shown that it is not uncommon to encounter multi-year floes with an average thickness of more than 8 m and embedded hummocks more than 20 m thick (Johnston et al., 2009; Johnston, 2011a), which is comparable to the multi-year ice thicknesses measured over the past 50 years (Johnston et al., 2009).

Design loads for future oil and gas structures are determined, in large part, by correlating key ice properties, such as ice thickness and ice strength, to full-scale ice forces —and that requires looking to past activities. Past oil and gas exploration has mostly taken place in relatively shallow waters of 45 m or less, which offers distinct advantages over the deeper-waters being explored today. In shallow water, bottom-

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founded structures can be used to resist the force of advancing sea ice. Also, landfast first-year ice is often present (from winter to spring) to buffer impacts with multi-year ice. That said, the three bottom-founded caisson structures that operated in various near-shore regions of the Beaufort Sea in the 1980s were all designed to withstand impacts with multi-year ice. Two of those structures, the Molikpaq Mobile Arctic Caisson (MAC) and the Single Steel Drilling Caisson (SSDC), did encounter multi-year ice floes, as discussed in Timco and Johnston (2004). The extensively instrumented Molikpaq still provides the only source of high quality data on the loads that thick multi-year ice can exert on wide offshore structures, including the most significant impact yet documented on a full-scale structure. That event occurred on 12 April 1986, as an 8 to 12 m thick multi-year ice hummock advanced towards the Molikpaq. The event produced high enough loads and structural vibrations to warrant a full-scale evacuation of the structure, essential personnel excepted. Our knowledge of multi-year ice has improved somewhat since then, but not enough to settle questions about the magnitude of ice forces generated by the 12 April event (Frederking and Sudom, 2006) and, more importantly, the forces that multi-year ice in excess of 12 m thick can exert on structures. Realizing that these questions are unlikely to be resolved by collecting more full-scale data – until another exploration or production structure is deployed in the Arctic, that is – this paper focuses on providing new information about the properties of thick multi-year ice for calculating ice forces from equations such as those in ISO 19906 (ISO, 2010).

Before proceeding, a few words will be given about the nomenclature used in this paper. Often, the term 'old ice' is used to describe both multi-year and second-year ice, but it is important to distinguish between the two types of ice, as much as possible. Although second-year and multi-year ice can appear similar from the surface (Johnston and Timco, 2008), their material properties can be quite different. Second-year and multi-year ice floes were both sampled during this study, but multi-year ice is the focus of this paper. Here, multi-year ice is distinguished from second-year ice using the standard WMO age/thickness definitions (WMO, 1970), supplemented by the measured vertical profiles of ice salinity and ice strength. Multi-year ice floes can be level or extremely deformed (Johnston et al., 2009), particularly when the ice contains hummocks, i.e. hills of broken ice formed mechanically due to pressure. Since most multi-year ice floes have undergone some degree of mechanical deformation, what appears to be 'level' multi-year ice may in fact be deformed ice that has weathered over time. Both level and hummocked multi-year ice can contain soft ice, voids or cavities (Johnston, 2011a), so the term 'consolidation' applies to all forms of multi-year ice. That said, the three distinct layers commonly used to describe ridged first-year ice (sail, consolidated layer and keel) are not appropriate for multi-year ice, as property measurements will show.

2. Borehole indentor: the field-worthy means of measuring ice strength

Our knowledge of multi-year ice comes from the past 50 years of field programs, most of which took place in the 1980s when interest in the Beaufort Sea was at its height. Field programs play an essential role in advancing our understanding of multi-year ice, especially since, to date, the properties of natural multi-year ice have not been accurately reproduced from ice grown in the laboratory environment. Field programs offer the only means of harvesting natural multi-year sea ice for laboratory studies and measuring ice properties in the field. Most field programs are conducted in early spring, when the ice is coldest, strongest, and brine drainage is minimized. Measurements are usually restricted to the uppermost several meters of ice, with few exceptions (Cox et al., 1984, 1985; Jeffries et al., 1987, 1988), largely because the effort of extracting blocks (or cores) of ice increases exponentially with depth. It is a testament to the dedication of field personnel that gains have been made during these programs because, as Sinha (1992) aptly states, "the environmental conditions during tests, especially field tests, can be physically unbearable for both test equipment and personnel".

Traditional strength measurements involve cutting and carefully machining small specimens of ice, putting them in a test frame and then applying a known load until the ice fails prematurely or exhibits a clear yield point. Laboratory strength tests on multi-year ice include uniaxial unconfined compressive strength tests (Sinha, 1984, 1986; Cox et al., 1984, 1985 and others), confined compressive strength tests (Cox et al., 1984, 1985; Sinha, 1986) and triaxial confined compressive strength tests (Cox et al., 1984, 1985). These tests provide fundamental information about the basic properties of sea ice but they also have several inherent problems. The tests may seem deceptively simple but, for sea ice, they are labor-intensive and extremely difficult to perform correctly (Kovacs, 1985). Plus, obtaining meaningful test results is not trivial, due to artifacts introduced when extracting the core, preparing the specimen, setting up the test and conducting the tests themselves — and the list of complications increases in late spring or summer, when solar radiation and warm air temperatures conspire to alter the ice soon after it is removed from the ice sheet. Test results also strongly depend upon the ice microstructure, which is known to be highly variable for multi-year ice (Cox et al., 1984, 1985; Richter-Menge et al., 1987; Sinha, 1984). Furthermore, engineers struggle to understand how the properties of specimens extracted from the uppermost several meters of ice relate to ice floes in nature, particularly when the solution to many engineering problems requires having strengths through the full thickness of ice.

The borehole indentor system was developed to remedy some of the problems associated with conventional strength tests. As the name implies, borehole strength tests are conducted in a borehole, be it augured or cored, to obtain the in situ confined compressive strength of the ice. Since the tests are conducted in situ, specimens need not be prepared, which is beneficial because it allows the ice to remain as close as possible to its natural state. The ice borehole strength is less dependent upon crystallographic orientation than other types of compressive strengths (Sinha, 1986), but relating it to conventional strength measurements is complicated by factors including, but not limited to, the loading rate, ice temperature, degree of confinement and surface area. For example, the ratio of borehole strength to uniaxial, unconfined compressive strength can range from two to five (Masterson, 1996; Masterson and Graham, 1992; Shkhinek et al., 2010; Sinha, 1986), depending upon the ice properties and test parameters. The interpretation of borehole strength tests presented in Masterson (1996) shows that, during a borehole strength test, the properties of crushed ice forming in front of the indentors are key to relating the borehole strength to the uniaxial, unconfined compressive strength of the ice (Masterson and Graham, 1992).

The applicability and field-worthiness of the ice borehole indentor system has been proven over nearly four decades of use on old ice floes across the Arctic and sub-Arctic (Fig. 1), during the field programs listed in Table 1. From 1973 to 1986, the borehole indentor was used to obtain strengths needed to calculate ice forces on structures and to successfully verify the integrity of floating ice platforms and floating ice roads (Masterson and Graham, 1992). However, those studies are not publicly available since they are part of the so-called 'gray literature' (reports that are difficult to obtain and/or may be still confidential). At that time, the borehole strengths in the open literature consisted of just three multi-year floes in springtime, tested at a single depth (Sinha, 1986, 1991). Data from the gray literature were made available to the author for a preliminary study of borehole strengths in 2002 (Johnston et al., 2003b). An expanded set of data is presented here, including borehole strengths of old ice floes in the Beaufort Sea (Fenco, 1973, 1982a; Geotech, 1984; Gulf, 1978), Kennedy Channel (Danielewicz and Cornett, 1984; Danielewicz and Metge, 1982), central Canadian Arctic (Geotech, 1986a), the Labrador coast (Fenco, 1977) and multi-year ice drilling platforms in the Canadian Arctic Islands (Fenco,