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A field study of grounded ice features and associated seabed gouging in the Canadian Beaufort Sea

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ABSTRACT

During the late summer of 1983, the southern Canadian Beaufort Sea was invaded by vast areas of thick sea ice features called hummock fields. Thousands of these features drifted into shallow water (10–27 m water depth), became grounded and remained in place throughout the following winter. During the grounding event, it was assumed that the deeper ice ridge keels would have gouged the seabed. In April 1984, eight features with gouging potential were visited and investigated from the ice surface. Conditions allowed for measurement by sonar of the geometry of seabed gouges at two locations, named M1 and M2, as well as the geometry of the ice keels that caused the gouges. Volume and mass of the ice features were estimated from stereo air photography gathered earlier in the winter, from which elevation profiles were obtained. On-site elevation profiles confirmed elevations. The hummock field at site M1, estimated at 277,000 tonnes, produced a gouge 2 m in depth and a front mound about 3 m high ahead of its keel. This feature had also been uplifted 2 m at its leading edge. The deepest gouge was 3.5 m, caused by hummock field M2, with an estimated mass of 1.16 million tonnes, which fragmented during the grounding process. A seabed gouging survey conducted in August 1984, in open water conditions, confirmed gouge depth at M2. Data on seabed soils were obtained at the M2 site one year later, in September 1985, as part of a geotechnical field survey. These cases of seabed gouging by massive sea ice features are unique in that they were found and documented with the ice features that made them still in place. All gouge, ice and soils data relevant to these two events are summarized herein, as a full-scale data set intended to increase understanding of seabed gouging and allow validation of models.

1. Introduction

Subsea pipelines are considered a means of bringing Beaufort Sea oil and gas resources to shore. One of the most significant challenges facing these structures is gouging of the seabed by ice keels (Fig. 1). To protect the pipelines against this ice, the method of choice is to bury them to a safe but cost effective depth below the seabed (Barrette, 2011; King, 2011; Liferov et al., 2014; Paulin et al., 2014). For a discussion of a real case design scenario in that area, see Leidersdorf et al. (2001).

Proper guidance to pipeline design, including adequate burial depth, would benefit from information on real scale events. However, full scale gouging scenarios are eminently difficult to observe or to document. To the authors' knowledge, there currently are very little data in the open literature on full scale ice features and their associated seabed gouges. On the other hand, over the last five decades, a large number of physical tests have been conducted to simulate full scale events (Barrette and Sudom, 2012, 2014). These were generally conducted in a laboratory or similar facility. Over the last 20 years, there have also been a significant number of numerical simulations reported in the literature (Babaei and Sudom, 2014).

Since before this work was initiated, and to this day, there has been a consensus among experts and design engineers that what is needed is full-scale information to validate physical models and numerical methods. That is the rationale for the present paper.

In September 1983, the Canadian Beaufort Sea was subjected to an unusual incursion of thick, heavily ridged ice floes called hummock fields. After October 6th, these became, by definition, second-year ice. The incursion appears to have originated from the break-up of the rough, seaward portions of the land fast ice offshore Alaska, near Barter Island in particular. As the features drifted into shallower areas, driven by a storm with strong winds from the NW, some of the ridges and hummock features became grounded after gouging the seabed over several kilometres. In April 1984, a field study was conducted to locate and measure some of these features and their associated gouges. The main motive was to obtain information on gouge characteristics (e.g. depth, width, side slopes, soil properties) and ice feature properties (e.g. volume, mass, keel geometry).

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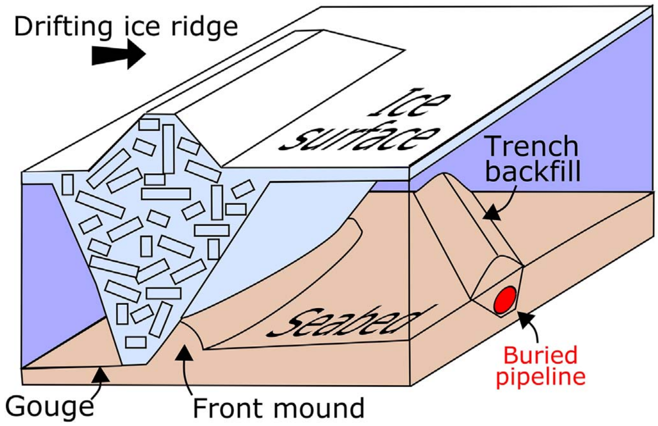

Fig. 1. Simplified seabed gouging scenario involving an ice ridge and a subsea pipeline.

A total of eight features were visited. Seabed gouging was detected at four of the features, but only at two of the sites was it certain that the ice feature encountered had caused the gouge.

The purpose of this paper is to describe the outcome of the 1984 field study. Firstly, the logistics and methodology of this operation are summarized. Secondly, information is provided on both the keel and the resulting gouging pattern, obtained from two specific grounded ice features. Validation and further data on one of the gouges was obtained the following summer. Soil data from a subsequent geotechnical site survey are also included. More information is provided in the original field and analysis reports (Offshore Systems Ltd., 1984, McGonigal, 1985b, respectively). These data should of interest for future analytical and numerical modeling.

2. Previous field investigations

The interaction between a drifting sea ice feature and the seabed is complex and involves many factors, among them: geometry and mass of the feature, shape and internal strength of the keel, driving forces applied to the feature, its speed and direction during impact, strength of the seabed soil and deformations in the soil ahead of and below the ice keel. Documenting full-scale seabed gouging events was the purpose of the Dynamics of Iceberg Grounding and Scouring (DIGS) program on the Labrador continental shelf, conducted in 1985 (Hodgson et al., 1988; Lever et al., 1991; Woodworth-Lynas et al., 1991). Keel and sail dimensioning and iceberg motion were obtained. Seabed interactions, calving and rolling events were captured. Gouges in water depths exceeding 100 m were characterized visually and seabed mapping and profiling were performed with seismic systems and echo sounders. While of great importance, the iceberg scenario offshore Labrador is quite different to gouging by sea ice in the Arctic.

Large-scale field simulations have also been performed. In Shapiro and Metzner (1987), two large slabs of sea ice were hauled along short stretches of beach with a bulldozer, while the load was recorded with a dynamometer. In Liferov and Høyland (2004), an artificial ice ridge was built and pulled across a soft silty clay seabed with a heavy loader (or a pneumatic winch), while pulling force, vertical and horizontal displacement were monitored.

On-land gouge relicts (from gouging activity dating back thousands of years) have also been studied (Woodworth-Lynas and Guigné, 1990; Eden and Eyles, 2002). Although information on the gouging keel was impossible to obtain, the study did generate useful information on sub-gouge deformation, a critical element in estimating burial depth (e.g. Woodworth-Lynas, 1998; Been et al., 2013).

Seabed mapping allows an appreciation of the extent and severity of gouging activity over a large geographic area. In the Beaufort Sea, this has historically been done by conducting geophysical surveys at given geographical locations, using ship-borne instruments such as echo sounders, side-scan sonars and sub-bottom profilers. The collected information includes gouge depth, width, length, orientation, density and frequency. Large area repetitive surveys of the seabed were conducted by government and industry every few years from 1978 to 1991, and from 2001 to 2008 (Blasco et al., 2011). Some results of these are contained in industry studies such as MacLaren Atlantic Ltd (1977) and Shearer (1979), as described in Hnatiuk and Brown (1977), Hnatiuk and Wright (1983) and Lewis (1977).

In addition to regional surveys, some site-specific studies of particular grounded ice features have been conducted. Kovaks and Mellor (1971) documented the gouging and soil displacement caused by an ice island that grounded near Babbage Bight off the Yukon Coast in the winter of 1971. Reimnitz et al. (1972) documented ice islands and decaying first year features which remained after breakup, and recorded local gouge tracks and soil disturbances near the ice keel. In one case, a front mound 1 m high was measured ahead of an ice island fragment. These early surveys of ice island gouging lacked information on the actual grounding event.

3. Sea ice incursion – September 1983

In early September 1983, a vast plume of thick ice fragments that originated from the break-up of land fast ice offshore Alaska drifted into the southern Canadian Beaufort Sea. By October 10th, the mass of pack ice had progressed eastward across the Beaufort Sea to the northernmost tip of the Tuktoyaktuk Peninsula. The ice was now classified as second-year ice because it had not melted during the summer. Most of the floes contained large pressure ridges with deep keels and many contained multiple ridges and deformed ice grouped closely together, which are called hummock fields. The plume was driven towards the shore by the storm and the deep keels grounded in water depths from 10 to 25 m, producing many new gouges. The grounded ice features would become the nuclei for the land fast ice that winter. The edge of the land fast ice followed the 20 m water depth contour (with considerable local variation) as is normally the case. The bathymetry chart in Fig. 2 shows the land fast ice boundary and the extent of the second-year ice floes that remained within the land fast ice on January 26th, 1984.

4. Field programs undertaken following the sea ice incursion

4.1. Survey of second-year ice floes and hummock fields October 1983

A sea ice field survey was conducted in late October 1983 to document the nature, composition and thickness distribution of ice floes that formed the incursion. By early October, these fragments had coalesced into very large floes up to 15 km across, consisting of large ridge and hummock field fragments bonded together by a matrix of new ice and rubble consolidated (i.e. refrozen between blocks) 35 cm to 1 m deep. The ridge fragments typically accounted for 10% to 80% of a floe. The rubble matrix varied from 20% to 80% of the area of the floes that were investigated, and ranged from 1 m to 3 m deep. The ridge keels were consolidated to a depth of 4 to 8 m below sea level. Very few voids were encountered when drilling through the keels. Ridge sails were not well consolidated but the spaces between blocks were well packed with crushed ice and some refrozen meltwater, giving a visual impression of very low porosity. Results are reported in McGonigal (1985a).

4.2. Ice gouge field program April 1984

In April 1984, a 10-day field program was mounted to identify and