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Ice ridge keel characteristics and distribution in the Northumberland Strait

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ABSTRACT

Ice ridges impacts are a major design consideration for offshore structures in the Arctic. Consequently, field programs on the frequency and characteristics of ridges can provide valuable empirical information for the design of future offshore structures. The Confederation Bridge ice force monitoring program monitors ice ridge keels through sonar instrumentation at the bridge. A total of 3199 keel cross-sections were identified during the 2007 and 2008 ice seasons using a new processing method. Of the 3199 keels identified, 137 keels caused loads over 1 MN. The shape of each keel was visually identified and classified as one of four shapes: triangular, trapezoidal, w-shaped, and multiple peak keels. Triangular and trapezoidal keels made up more than 60% of the keels that cause loads over 1 MN. Four of the five largest loads had keels that were trapezoidal. For the 3199 keel cross-sections, the depth, width, leading and trailing keel angles, bottom width and area were identified and distributions of these keel properties were developed. The distribution was then compared to the design keel depth distribution from the Confederation Bridge. The observed 2007 and 2008 keel depth distributions was slightly lower than the design distribution likely due to the significant number of multiple peak and w-shaped keels. Additionally, the maximum keel depth suggested by the observed distribution was shallower than the maximum predicted keel depth.

1. Introduction

Ice ridge impacts are often a principle consideration in the design of offshore structures in ice covered waters. When ice ridges interact with offshore structures, they cause load which must be accounted for in structural design. Empirical data regarding the ice ridge size and shape, as well as, load data resulting from ridge interactions with an offshore structure enable the development of more efficient design of safe structures in the Arctic.

Ice ridges have three main components: a keel, a sail, and a consolidated layer (Fig. 1). The largest part of the ice ridge is the keel, the underwater portion of rubble. The keel ice rubble is porous and consists of unconsolidated or lightly-consolidated blocks, broken off from the parent ice sheet. Little data is available on keel distributions in marginal ice zones as data is difficult to obtain and process. The development of methods to process the sonar data obtained at the Confederation Bridge and identify keels from that data, provides new information on keel depth distributions and keel shapes.

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2. Location

2.1. Confederation Bridge

The Confederation Bridge (Bridge hereafter) is the longest bridge to span ice-covered waters in the world, at 12.9 km long (Brown et al., 1996), and connects the Canadian province of Prince Edward Island (P.E.I) and the mainland of Canada (Fig. 2). The Bridge carries two lanes of traffic (one in each direction) across the Northumberland Strait (Strait hereafter) at its narrowest point.

The Bridge has 44 main span piers each founded on the seabed using gravity based foundations. Each pier has an ice shield designed to force level ice upward encouraging flexural failure of the ice (Brown et al., 1996). Each ice shield extends four meters below the water surface on average, depending on the tide and is 14.2 m in diameter at the waterline at Mean Sea Level (Fig. 3).

Ice interaction with deformed first-year ice features and level ice was one of the controlling lateral design load considerations for the Bridge. The maximum factored design lateral ice load for each bridge pier was 30 MN (Tadros, 1997). Due to the uncertainties associated with ice loading, an extensive ice force monitoring program was initiated to monitor the Bridge after its completion. The ice force monitoring program has operated for fourteen years (since 1997) with the objective to measure the ice loading on the Bridge and observe the associated ice and environmental conditions, to validate the ice design criteria, and to increase the amount of full-scale empirical data available from operating structures. The ice force

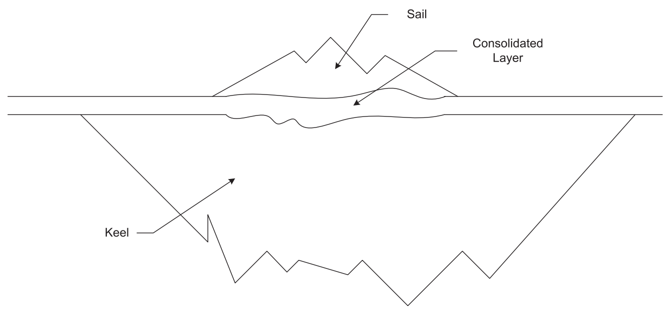

Fig. 1. Diagram of layers within the ice ridge.

monitoring program was also tasked with comparing the observed conditions to the ice, load, and weather conditions assumed during design.

2.2. Northumberland Strait

The active ice conditions, abundance of ridges, and the ice force monitoring program make the Strait and the Bridge in particular an excellent location for a study of ridge properties and their affect on structural loading. Ice forms in the Strait in late December and the last ice leaves the Strait in late April. The Strait experienced 633 freezing degree days (FDD) in 2008 and 580 freezing degree days in 2007 (IFN Engineering, 2007a,b,c, 2008a,b,c,d). The level ice thickness in the Strait between 2007 and 2008 was on average less than one meter (Brown, 2007).

The winds in the Strait are primarily from the west between January and March (Brown et al., 2009), moving ice approximately perpendicular to the long axis of the bridge. The Strait is also tidal and flood tides flow in the same direction as the prevailing winds. Ice in the Strait comes from three sources: first-year ice forming in the Strait, land fast ice that breaks off of land surrounding the Strait, and ice that moves into the Strait from the Gulf of Saint Lawrence (Williams, 1996). The combination of winds and tides create dynamic ice conditions that generate many deformed ice features in the Strait each year. It has been estimated that 6000 ridges interact with each pier of the Bridge annually (Lemée and Brown, 2005).

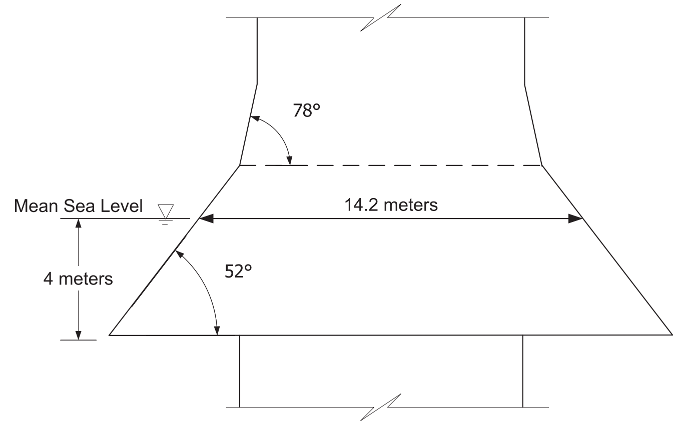

Fig. 3. Diagram of the ice shield geometry of the Confederation Bridge.

3. Instrumentation

The Bridge is instrumented in and along the rigid frame made by Piers 31 and 32, west of the navigation span. The Bridge frame that includes Pier 31 and 32 was originally instrumented with hundreds of sensors including displacement gauges, tilt meters, strain gauges, and over 200 thermocouples to research loading and behaviour from a variety of sources (Cheung et al., 1997). The ice force monitoring program at University of Calgary monitors the data from ice pressure panels, tilt meters, accelerometers, CCTV cameras, sonar and weather monitoring equipment (Cheung et al., 1997).

The data from the sensors on the Bridge are recorded by two types of data loggers located within the Bridge's hollow box girder. The data

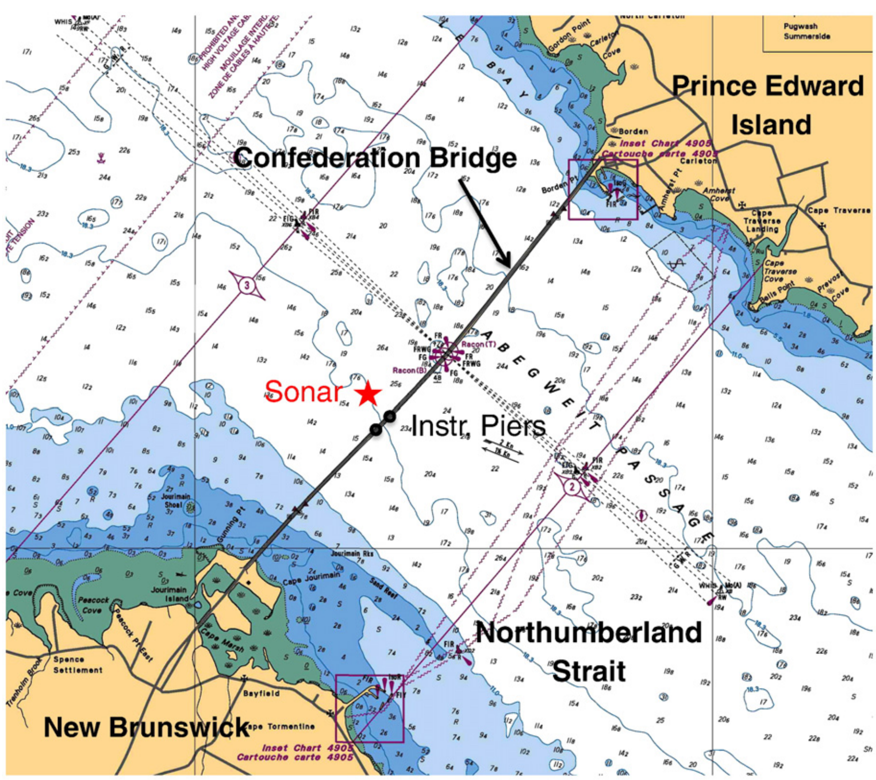

Fig. 2. Map of the location of the Confederation Bridge in Eastern Canada.