Cold Regions Science and Technology 138 (2017) 1–17

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

A critical review of Arctic pack ice driving forces: New sources of data

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ARTICLE INFO

Article history:
Received 18 November 2016
Received in revised form 6 February 2017
Accepted 26 February 2017
Available online 01 March 2017

Keywords:
Sea ice
Driving force
Pack ice
Limit force
Multi-year ice

ABSTRACT

This paper provides the details of ice loading events that can be used to further the understanding of pack ice driving forces in the Beaufort Sea. Several methods have been reviewed and employed including in situ stress measurements, loads on the Molikpaq offshore caisson, shoreline pile-up events, pile-ups and rubble fields on offshore shoals and relic berms, analysis of shear walls on offshore rubble fields, and analysis of deep ridge keels. Over 50 different events are identified with 33 suitable for a pack ice analysis. The data are considered in terms of both the ISO 19906 (2010) Arctic Structures Standard and pack ice pressures that can be exerted across various widths. A new approach is proposed, in which the calculated and measured values from past pack ice pressure events are used to predict limit force.

1. Introduction

What determines the force that an ice sheet or ice floe can exert on an offshore platform? Croasdale (1984) summarized this situation by viewing it as the minimum force value from three different limit situations. That is, the force on a structure placed in ice will be limited by one of three mechanisms:

- The strength of the ice sheet or floe acting on the total width of the structure (*limit stress*).
- The energy of the floe interacting with the structure (*limit energy* or *momentum*). This is usually associated with an isolated floe that impacts a structure and comes to a rest after its momentum is dissipated by the ice failure.
- The force available to drive an ice floe against a structure (*limit force*).

The highest ice forces generally result from ice-structure interactions that were controlled by *limit stress* (see e.g. Jefferies and Wright, 1988; Wright and Timco, 1994; Johnston et al., 1999; Timco and Johnston, 2003, 2004). In these cases there was sufficient force generated by the moving pack ice to cause the advancing ice sheet to fail across the total width of the offshore structure. This occurred even when the multi-year ice was several meters thick. But in a few recorded cases, the pack ice itself failed away from the platform (Wright et al., 1992; Wright and Timco, 2000). This is a *limit force* situation where the force that can be generated across the width of an ice floe or feature in pack ice was not sufficient to drive the feature to fail against the structure. But the important question is: What is this force level? Answering this question would help determine the maximum thickness and width of a multi-year ice floe or extreme ice feature that can be driven by the pack ice and fail across the full width of a given size and shape of offshore platform.

Unfortunately there is very little information on the situation of a first-year ice sheet failing and building a ridge against a thick multi-year floe. This is a complex situation where the dynamics of ridge-building are little known. One could speculate the important mechanisms based on observations of ridge building from the interaction of two first-year sea ice floes, or from rubbling and piling up of first-year sea ice against an offshore platform, grounded ice or a shoreline. In these situations, the first-year ice can fail by bending (flexure), buckling, crushing, splitting or a combination of these modes (i.e. mixed mode). With continued ice movement, the first-year ice begins to pile-up and this can cause changes in the mode of failure. Then the ice can ride-up the face of the pile-up, or fail against the front face of the pile-up with different failure modes, or can penetrate into the rubble pile. With floating first-year ice, the weight of the pile-up can cause a bending or flexural failure in one of the ice sheets and the broken ice can re-distribute itself before the process continues. The failure of first-year ice against a multi-year ice floe would likely be different due to the higher thickness and strength of the multi-year ice. The whole rubbling process has both spatial and temporal variations associated with it. Factors that one would expect to be important include the thickness of the first-year ice, the duration of the interaction process, the details of the mechanics of the rubbling process, the width of the interacting ice, the interaction geometry, and the failure or non-failure of the multi-year ice floe. Since

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http://dx.doi.org/10.1016/j.coldregions.2017.02.010

there is little known about these processes and forces due to the interaction of first-year ice with a multi-year ice floe, other approaches must be used to gain insight into this problem.

The concept of pack ice driving force has been described by Croasdale et al. (1992, 1996) and the state of knowledge in this area was recently summarized by Croasdale (2009, 2012a, 2012b). This approach has been adopted as part of the informative section in the 19906 ISO Arctic Offshore Structures Standard (ISO 19906, 2010). In the ISO 19906 (2010) standard it is referred to as the ridge-building action and is given by Equation A.8-53:

$$p_D = R\left(h^{1.25}\right)\left(D^{-0.54}\right) \tag{1}$$

where p_D is the ridge building action (line load) imposed by pack ice on a thicker ice feature per unit width [MN/m], h is the thickness of the pack ice [m], D is the width of the thicker ice feature [m], and R is a coefficient. Both h and D are geometric values related to the loading situation. Results from early in situ stress tests, discussed in detail later in this paper, indicated that the pack ice line load depends on the width D of the thicker ice feature. The exponent applied to D in Eq. 1 was chosen to fit this empirical data. The pack ice thickness h also has an exponent applied; this factor of 1.25 is used to 'normalize' the pack ice pressure to 1 m of ice (Croasdale, 2009; Sandwell and Canatec, 1994). The normalized line load is given by $p_D / h^{1.25}$. Finally, R and the exponent on D are coefficients derived by curve fitting to the data. R can be thought of as a 'material' property related to failure mode of the pack ice, and it incorporates some of the uncertainties in the values of h and D and the exponents applied to them. ISO 19906 (2010) also states that the frozen-in condition can be considered by application of a multiplicative factor of 1.5 to the ridge building action.

The R value of 2 was chosen to fit to the data from five in situ stress tests. Subsequent measurements on the Molikpaq offshore platform resulted in an additional five data points that indicated higher R values, on the order of 10. The ISO standard states that an upper bound estimate at the 99% confidence level is given by $R = 10$, and that $R = 6$ can be used for a 50% confidence level. It also states that if a probabilistic approach is used, the parameter R should be uniformly distributed between 2 and 10. There is little basis for this assumption of a uniform distribution for the R value, largely because of the limited data. This large range of possible R values leads to an uncertainty of the pack ice force by a factor of five. Setting too low a value for R, or too high a probability of a low value of R, can lead to an under prediction of forces from the interaction of multi-year floes with a structure.

Both industry and regulators have indicated that pack ice driving forces remain a large unknown when it comes to design of offshore structures for ice-covered water. Methods for their determination are inconclusive, which complicates the reliability of load estimates for engineering design and may be an impediment to development in these regions. For example, in an Ice Experts Workshop (Timco, 2012), leading ice engineering experts were asked to predict the loads due to a multi-year ice floe embedded in pack ice interacting with a vertical structure in the shear zone of the Beaufort Sea. All used the pack ice driving force as the determination of the force, yet there were still very large discrepancies (a factor of over 3.5) for predicting loads. This large uncertainty is unacceptable to operators and regulators. Many past determinations of pack ice forces were based on a limited, field measured data set and rather crude analysis techniques.

What can be done to try to narrow this uncertainty in the pack ice driving force? Barker and Timco (2012) took a critical look at various methods that could be used to reduce the uncertainty in pack ice driving forces in the Beaufort Sea, in an effort to better understand the R value and how it impacts engineering design. They identified and ranked a number of approaches that had not yet been evaluated in the context of pack ice driving forces. They showed that data mining of well-documented extreme ice features and ice pile-ups could be useful as input into analytical and numerical models of ice forces. This marriage of large-scale data and force calculation methods may produce new information to refine pack ice forces. The present paper continues this effort to narrow the uncertainty in pack ice driving forces, by re-examining the approach given in ISO 19906 (2010) and the data (from the in situ field measurements and the force measurements on offshore platforms) that were used to derive the ISO approach. The paper then explores the forces that can be derived from observations of extreme ice pile-up features and events to try to obtain additional data on the forces that Arctic pack ice can generate.

2. The simple approach

At first glance it would seem that determining the pack ice driving force should be quite straightforward. In its simplest form, the external driving forces are comprised of wind and current shear on the ice. For a large area of pack ice, the total stress (S_t) is the sum of the wind (air) shear stress (S_a) and the water (current) shear stress (S_w) and is given by.

$$S_t = S_a + S_w = \rho_a{}^* \, C_a * v_a{}^2 + \rho_w * C_w * v_w{}^2 \tag{2}$$

where ρ is the density ($\rho_a = 1.2$ kg/m^3; $\rho_w = 1020$ kg/m^3), C is the drag coefficient ($C_a \sim 0.002$, $C_w \sim 0.005$; see e.g. Kubat et al., 2010) and v is the speed. For the Beaufort Sea region, a typical current speed is on the order of 0.15 m/s. A wind speed of 20 m/s is a reasonable value for a sustained wind speed in this region. The question is: What fetch length should be used to calculate the force from this shear stress? If a fetch length of 100 km is assumed for a continuous pack ice cover (with 10/10ths concentration), this gives a force per unit width of 107 kN/m. If a fetch length of 200 km is assumed for these conditions, a force per unit width of 214 kN/m is calculated. Thus estimates can be made if there is a fetch-limited situation. But for the Arctic, the fetch length is effectively unlimited. Thus, this simple calculation can only give an estimate of the range of pack ice driving force values for the Arctic by assuming a range of nominal fetch lengths, but is not helpful in providing a unique value for the driving force there.

It is useful to examine the implications of Eq. 2 with respect to pack ice driving forces. The equation shows that the shear stress and the resulting forces are a function largely of the wind speed and to a lesser extent the current speed. Thus it would be expected that if the wind speed is low, the pack ice forces would also be low. This is not a concern for an offshore platform but it could be for vessels operating in these conditions. Even at lower wind speeds, in-plane pressure in the pack ice can impede vessel movement. Kubat et al. (2016) have developed models to predict pressured ice conditions for the Beaufort Sea which appear to work well (see also Kubat et al., 2015). For an offshore platform, the influence of the pack ice pressure becomes relevant during high wind and storm conditions. To gain a better understanding of the pack ice forces during these conditions, it is necessary to examine the more "extreme" ice features in the Arctic since they were very likely created during high wind or storm events. It is important for the reader to understand that the features described in this paper should not be taken as being representative of the range of ice pile-up features in the Arctic since only the larger features were chosen to obtain information on pack ice forces during high loading events.

3. Approaches to refining pack ice driving forces

To date, there have been only a few methods employed for determining the pack ice driving force. These methods require a number of assumptions, both explicit and implicit, to calculate the pack ice driving force. In this paper, past methods for determining pack ice forces are re-examined to help to identify these assumptions and provide guidance on the reliability of each method. Also, as noted above, a number of new approaches are discussed that may provide additional data on