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Sheltering and interference effects for multi-leg offshore substation platforms interacting with sea ice

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ABSTRACT

Offshore substation platforms connect the array cable system of an offshore wind farm to the export cables and are often designed based on the jacket support structure concept with almost vertical legs. The size of these platforms, and the number of cables arriving at the platform through j-tubes, make that these have many structural elements crossing the waterline. For design of such multi-leg structures to ice loading, it is important to account for sheltering and interference effects as well as potential jamming of ice between closely spaced members. Guidance on these topics can be found in design standards; however, it mostly concerns four-legged structures with equal leg diameters for which experience has been obtained in full-scale and model-scale. In this paper we present results from a pre-study for a recent offshore substation design. A preliminary method for defining the sheltering and interference factors for multi-member structures with more than four vertical members and members of different diameters crossing the waterline is presented. The method is based on the original work on this topic by Saeki. The sensitivity of the global ice load on the platform support structure to the placement of cable j-tubes is investigated with the proposed method. The results are discussed in relation to design of substation support structures with a focus on dynamic interaction between ice and the platform, the potential benefit of lay-out optimization and extending the approach to include jamming and ice ridges interaction. This study highlights the need for further model-scale or full-scale testing to validate key assumptions required to develop these kinds of approaches for dealing with sheltering and interference on multi-member structures.

KEY WORDS: level ice, crushing, jacket, secondary steel

INTRODUCTION

A multi-leg structure can be a preferred offshore support structure at locations with sea ice presence. Most experience and guidance on how to deal with the ice loads on a multi-leg structure has been gathered in the context of four-legged platforms. These are, for example, the concrete gravity base platforms deployed in Sakhalin (Bekker et al., 2010). In the Bohai Sea more complex geometries have been used in the form of jackets with multiple supporting legs and in addition conductors interacting directly with sea ice (Timco et al., 1992; Huang et al., 2017). In both these regions, multi-leg structures have also been observed to experience ice-induced vibrations (Kärnä et al., 2010; Yue & Bi, 2000).

As part of the development of offshore wind in the Baltic Sea, multi-leg structures are also considered for locations with limited sea ice development, and to deal with unfavorable soil conditions for using monopiles as a foundation. The offshore substation platforms (OSP), which accompany a wind farm, are typically constructed with a jacket support structure, many j-tubes crossing the waterline, and one or more boat landings. As a result, these structures can have more than 20 elements directly interacting with sea ice, despite being classified as a three, four or six-legged structure. An example layout which is used for the study in this paper is shown in Figure 1. Moreover, in the case of monopile foundations for substations or wind turbines, the attachment of secondary steel such as a boat landing turns the structure into a multi-member structure from the perspective of the ice.

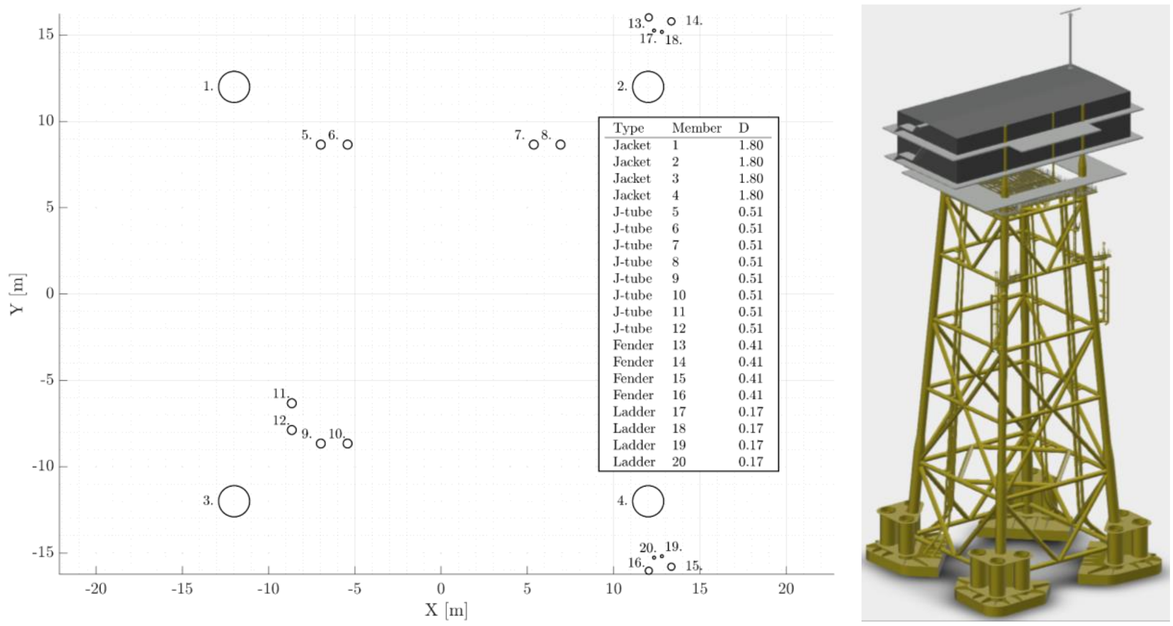

Figure 1 – Waterline geometry (left) of an OSP (right) including jacket legs, j-tubes, boat landing fenders and ladder stiles.

Numerous studies have examined the influence of multiple structural members on the magnitude and development of global ice loads. Most research has focused on the spacing of two or more adjacent members with identical diameters (Timco & Pratte, 1985; Shkhinek et al., 2004; Gurtner & Berger, 2006; Karulin & Karulina, 2009). Findings suggest that for identical diameters, the effect of the proximity of two members on ice load diminishes for a centre-to-centre over diameter ratio, L_{cc}/D, in the range of five to ten.

Zhang et al. (2024) investigated the effect of having two members with different diameters on global ice loads. Their numerical analysis examined a configuration consisting of a main pile leg and a smaller cable pipe in proximity. The results indicated that, for all orientations of the configuration, the total ice load was reduced compared to both the sum of the individual loads on the members and the load calculated for an equivalent diameter of the combined structure.

Other studies have investigated increasingly more complex geometries, incorporating ice cones at the waterline (Huang et al., 2013) or validating and predicting ice loads on multi-member structures, either planned or constructed (Timco et al., 1992; Li et al. 2017). These studies demonstrate that the ice loads on such multi-legged structures can be assessed through laboratory experiments.

The guidance provided by ISO 19906 for determining the global limit stress ice loads on multi-leg structures is primarily based on such laboratory tests. According to ISO 19906 (2019), A.8.2.4.9, the global limit stress action on such structures can be determined using the following equation,

$$F_s = k_s k_n k_j F_1 \quad \text{(Eq. 1)}$$

where F_1 is the ice action on one leg, k_s accounts for the interference and sheltering effects, k_n accounts for the effect of non-simultaneous failure, k_j accounts for ice jamming.

Some further guidance is available on the different factors involved, where k_n can typically be set to 1.0 if one assumes synchronized loading on all legs to be possible, and lower in case this is unlikely (a value of 0.9 is suggested in the standard). Guidance on accounting for ice jamming is limited, but for members with a spacing of $L_{\text{cd}}/D < 4$ jamming can be assumed to occur. For k_s, the following guidance is provided:

a) If the ratio between the clear distance L_{cd} (measured between two legs on a line perpendicular to the incoming ice) and the width D of the leg exceeds 5, the legs are assumed to act independently, although field evidence suggests some interaction still occurs for L_{cd}/D ratios around 10.
b) In typical multi-leg structures where the legs are not aligned in a single line, the legs become independent at higher values of L_{cd}/D.
c) For a typical four-leg structure, the maximum sheltering factor ranges from 3.0 to 3.5.
d) The angle of incidence of the ice drift influences the resulting ice action.

When applying this approach to structures with a different number of supporting legs interacting with ice — other than four — or with secondary elements crossing the waterline, potentially of varying diameters, determining the k-factors becomes more challenging. For legs or members with different diameters, the force F_1 and the criteria dependent on the L_{cd}/D ratio are no longer uniquely defined and sheltering and interference effects will depend more on direction of loading, as the symmetry of the problem is lost.

In this paper we present an approach to defining F_S for this type of multi-member structures which is based on the original work by Saeki (1986), adopted by Kato (1990). It is an approach used to provide insight into what accounting for interference and sheltering effects may yield for structures with more complex waterline cross-sections. Jamming is not considered, as the purpose of this exercise was to define a global sheltering factor to be used as input for loading calculations in a dynamic interaction scenario resulting in ice-induced vibrations. In the authors' opinion, such vibrations are unlikely to occur when the incoming ice interacts with a non-smooth jammed, interaction surface. The proposed method offers a way to account for these effects in spirit with the guidance in ISO 19906. It is important to note that the presented methodology is not intended to provide an accurate representation of the physical phenomena involved in ice interaction with a multi-member structure. Through this preliminary study, we identify where there exist gaps in design standards and literature and assess their potential impact on the overall global loads acting on the structure. A more fundamental development would require more field and lab experience for both understanding and validation.

METHOD TO ACCOUNT FOR INTERFERENCE AND SHELTERING

To deal with more complex geometries in a general way Equation (1) needs some modification. One way of modifying is the following,

$$F_S = \sum_{i=1}^{N} k_{s,i,\theta} \, F_{1,i} \tag{Eq. 2}$$

where i refers to the leg (or member) number and $k_{s,i,\theta}$ is the smallest sheltering and interference factor for leg i and incoming ice angle θ. This assumes failure to be simultaneous on all members (the worst-case scenario) either in the context of peak loads used in crushing equations or when the sheltering factor is applied as a factor in time-dependent load calculations.

To define the interference and sheltering factor $k_{s,i,\theta}$ we base ourselves on the work of Saeki (1986), which was later adopted and rewritten by Kato (1990). Saeki assumed that each leg experienced the maximum ice force during an interaction simultaneously, which is in correspondence with the definition of $k_{s,i,\theta}$. We consider only the Type B interaction identified in their work, as indicated by Figure 2, as it is most relevant and occurs most often. Type A interaction, consistent with the ISO 19906 guidance under point a) above, only occurs for specific angles for a couple members typically. As suggested by Saeki, type C interaction can be treated as a Type B interaction taking only the shortest distance to a free channel into account. The latter overestimates the loads in the case the distance between the two free ends is small, as in that case the possibility of buckling failure should be considered. Consideration of buckling failure is not done here to avoid complexity.

Due to variations in diameters, as well as differences in literature and guidelines, distances between members may be defined differently. To avoid confusion, we distinguish three definitions, illustrated in Figure 2. Firstly, L_{cd}, or L in ISO 19906, refers to the clear distance between two members measured perpendicular to the incoming ice. Secondly, L_{fe}, denoted as L_2 by Kato's adaptation of Saeki's equations, is defined as the distance from the centre of the leg to the nearest free edge. Lastly, we define L_{cc} as the centre-to-centre distance between two members, perpendicular to the incoming ice drift direction.

The sheltering and interference factor $k_{s,i,\theta}$ is defined by Kato for Type B failure as,

$$\begin{array}{ll} k_{s,i,\theta} = 0.083\,(L_{\text{fe}}/D - 1) + 0.58 & 1 \le L_{\text{fe}}/D \le 6 \\ k_{s,i,\theta} = 1 & L_{\text{fe}}/D \ge 6 \\ k_{s,i,\theta} = 0.58\,L_{\text{fe}}/D & 0 \le L_{\text{fe}}/d < 1 \end{array} \tag{Eq. 3}$$

Where D is the diameter of the sheltered leg (in the wake of the leg first in contact with ice). By adopting these equations, the legs become independent for $L_{\text{cd}}/D > 5.5$, and will always be independent when perpendicular on a line. The last equation implies that a leg experiences zero load when its centre aligns with the free end. This is considered a somewhat excessive reduction in load, especially for larger structural members.

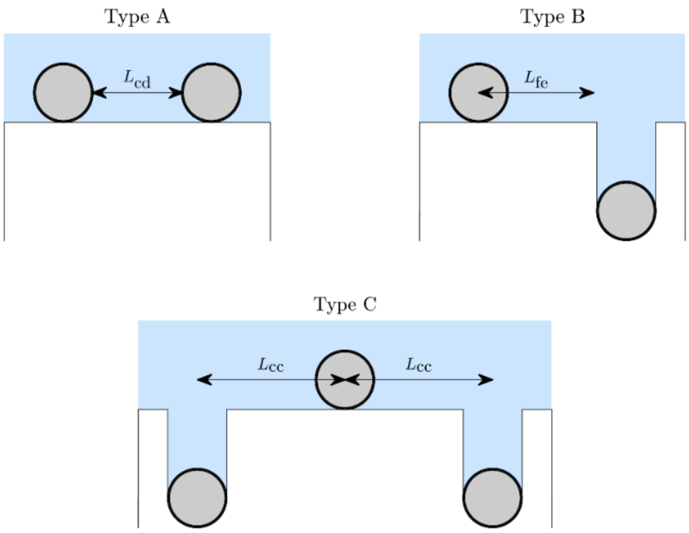

Figure 2 – Types of interference and sheltering situations according to Kato (1990) and different definitions for spacing. Figure adopted from Kato (1990). Note, Saeki (1986) originally introduced the interaction types as Type I-b, Type II and Type III, respectively.

The equations are therefore altered to the following,

$$
\begin{aligned}
k_{s,i,\theta} &= 0.083(L_{\mathrm{fe}}/D-1)+0.58 && 1 \le L_{\mathrm{fe}}/D \le 6 \\
k_{s,i,\theta} &= 1 && L_{\mathrm{fe}}/D \ge 6 \\
k_{s,i,\theta} &= 0.58\, L_{\mathrm{fe}}/D && 0.5 \le L_{\mathrm{fe}}/D < 1 \\
k_{s,i,\theta} &= min(0.29, f_{\mathrm{s}}) && 0 \le L_{\mathrm{fe}}/D < 0.5
\end{aligned}
\qquad \text{(Eq. 4)}
$$

where the last term introduces the direct sheltering fraction f_{s}, which defines the proportion of the projected width of a structural member not in the wake of another member. Adding this term implies that the factor $k_{s,i,\theta}$ is kept at 0.29 until the fraction f_{s} becomes smaller than 0.29 (there is less than 29% of the projected width of a member in contact with ice). This value is based on the original equations evaluated at a free edge distance of $0.5D$. An illustration of the dependence of $k_{s,i,\theta}$ based on the definition of type B failure by Saeki and the adjusted definition on the position of the leg in the wake of another leg is shown in Figure 3.

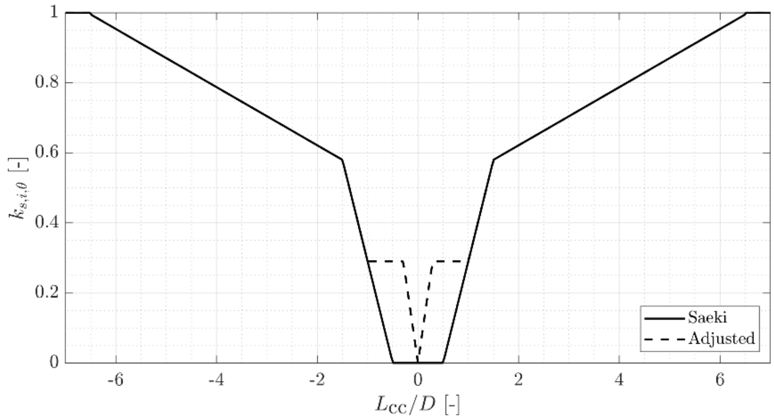

Figure 3 – Sheltering and interference effects on a member in the wake of another equal sized member as a function of the centre-to-centre distance, normalized with the wake member's diameter. Note that this normalization applies only to similar-sized diameters, as the profile is diameter ratio dependent.

In the case of structural members with different diameters, two additional scenarios must be considered beyond those covered by Saeki. These conditions are illustrated in Figure 4. When direct sheltering occurs, as in Figure 4 (left), the load is here, in the absence of data, just assumed to reduce to 29% of the maximum load, treating it as similar 'loss of confinement and direct contact' as for the Type B Saeki sheltering. In case of partial nearby open water, the load reduction is determined based on the fraction of the radius exposed. These conditions are expressed with the following equations,

$$F_G = min\ (0.29, f_s)\ F_{G,unsheltered} \quad \text{(Eq. 5)}$$

$$F_G = \left(\left(1 - \frac{a}{r}\right) + \frac{a}{r} k_{s,i,\theta}\right) F_{G,unsheltered} \quad \text{(Eq. 6)}$$

where Equation 5 and Equation 6 yield the global ice load on the large structural member in the left and right cases, respectively, in Figure 4. This approach assumes a linear dependence of the load reduction on the degree of exposure to open water.

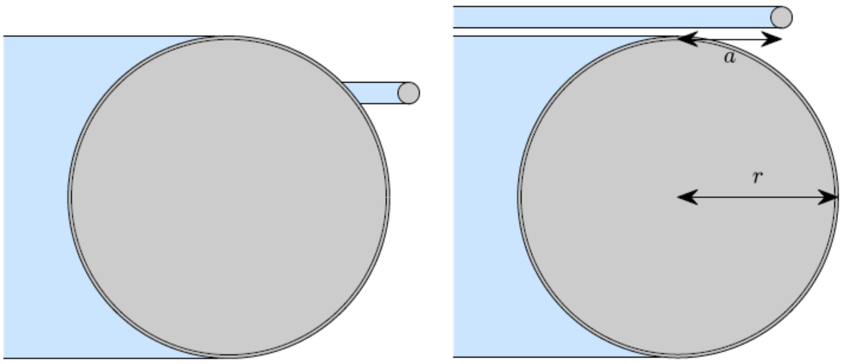

Figure 4 – Additional cases to be considered for structures with members with different diameters.

VERIFICATION FOR A 'STANDARD' FOUR-LEG STRUCTURE

The approach defined in the previous section is verified by applying it to a four-legged structure with equal diameter legs and the leg spacing L_{cd}/D varying from 2 to 18. Note that in this case the approach yields diameter independent sheltering factors as the geometry scales with D. Results for $k_{s,\theta}$, the global sheltering and interference factor calculated as the sum of the individual member factor, are shown in Figure 5 for an angle of attack of the ice (measured clockwise from the positive x-direction) between 0 and 45 degrees. The global sheltering factor can be used in this case for comparison to the guidance in ISO 19906 as the legs have equal diameters. Due to symmetry the pattern repeats itself for every quadrant of 45 degrees.

The method yields a maximum factor $k_{s,\theta}$ between 3.0 and 3.5 for ratios of L_{cd}/d between roughly 4 and 8 approximately. This is the range for the ratio ISO 19906 (2019) suggests using for a four-legged structure. As it overlaps with the range where jamming effects may start to occur this result seems reasonable. From L_{cd}/d about 14 there is a direction where all four legs are loaded and become independent, in line with the guidance in ISO 19906. For very small leg-spacing a direct sheltering effect applies for almost all directions.

A further comparison can be made to some numerical results, though this is challenging as results do not always separate the effect of sheltering and interference and non-simultaneous failure. An example can be seen in the results reported by Skhinek et al. (2009). A similar trend to that in Figure 6 is observed in Figure 5 of their paper. However, the values are generally lower than what we obtain from our method even when a non-simultaneous factor of 0.9 is applied.

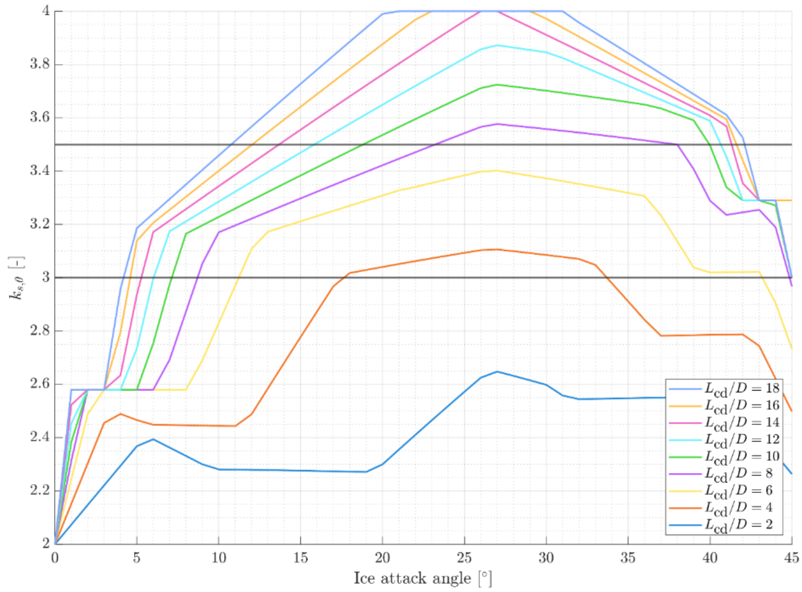

Figure 5 – Global sheltering and interference factor $k_{s,\theta}$ as a function of angle of attack of the ice and leg spacing for a four-legged structure with equal diameter legs.

RESULTS FOR A SUBSTATION JACKET WITH J-TUBES AND BOAT LANDINGS

Next, we apply the method to complex water-line cross-section of the OSP, depicted in Figure 1. The total global ice load as a function of ice incident angle is shown in Figure 6.

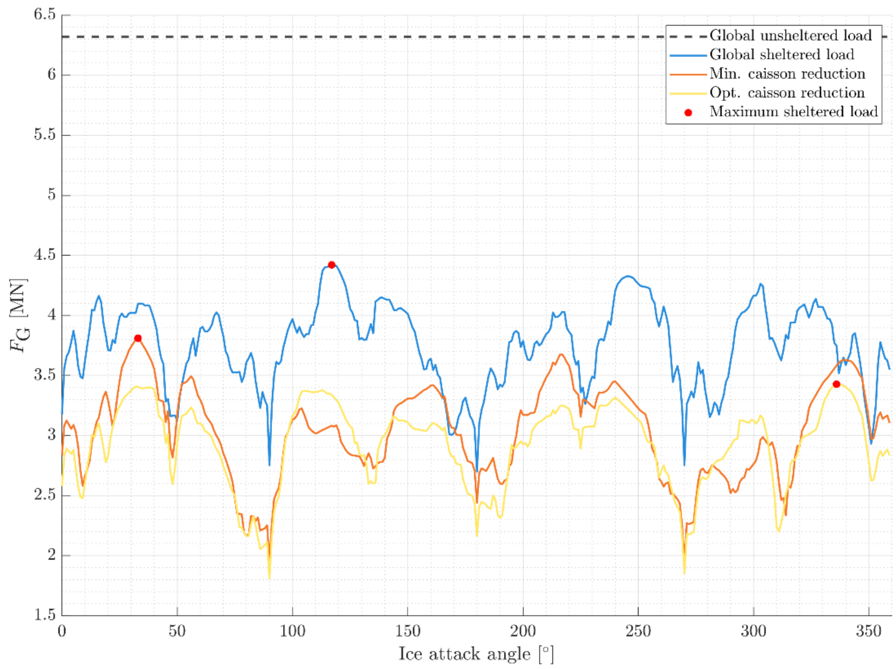

Figure 6 – The total global ice load as a function of ice incident angle for the initial design as shown in Figure 1 and for two updated designs featuring two caissons bundling all the J-tubes discussed below.

We find a global sheltered load of 4.42 MN out of a total unsheltered load sum of 6.32 MN. Or a sheltering and interference percentage of 69.9%. The unsheltered load sum assumes all legs are independently and simultaneously loaded with the ice failing in crushing regardless of the possibility for this happening. The sheltering and interference effect is relatively more than typical for a four-legged structure (75%). This is to be expected though as there are many angles of attack with more structural members sheltered than typically is the case for a four-legged structure with equal diameters. This effect is expected to be more pronounced for larger OSPs with more complex geometries. As the number of structural members increases the sheltering and interference percentage can be expected to drop, although the total global ice load on the support structure may of course increase. The figure also clearly illustrates the angle dependence of the global load. The direction of 117 degrees coincides with full (or close to full) loading of many structural members as can be seen in Figure 7.

The approach presented here allows to get a quick indication of the direction dependent global ice action for complex geometries of multi-member structures. It can be used to identify possible directions of interest for a dynamic analysis and straightforwardly defines a sheltering and interference factor for the members and total structure. Additionally, the approach used here allows for a degree of optimization in the layout of the structure, and to explore the potential impact on global ice loading.

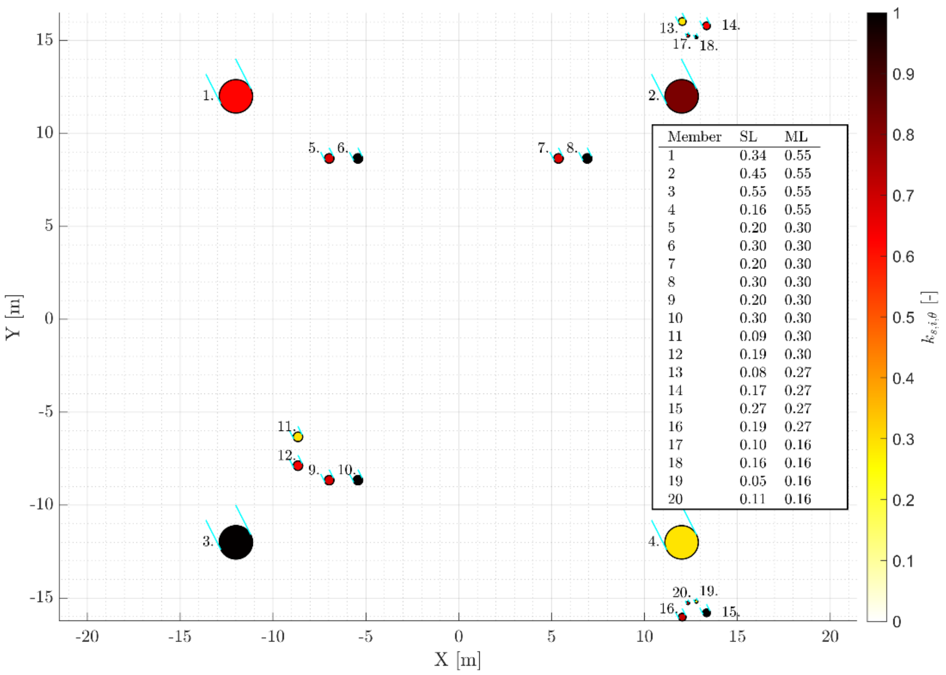

Figure 7 – Ice sheltering factors, interference factors, sheltered load (SL) and maximum load (ML) in MN for each waterline-crossing member at the worst angle of attack, 117 degrees.

It is important to note that lay-out optimization is never done solely with respect to (global) ice loads. Often at locations where structures of the type considered here are a viable option the hydrodynamic loading, direction of interarray cables and site layout is of at least equal importance. Additionally, there is limited validation data for the magnitude of the sheltering effect obtained with the approach presented in this paper. And optimization for ice floes or level ice interaction alone should never be done given that, for example, effects of jamming and ridge interaction may yield higher loads. Nevertheless, we briefly explore the potential for load reduction by optimization of placement and bundling of structural members.

From a global load perspective, there is limited potential for significantly reducing the load in specific quadrants by changing the position of individual members. While removing an entire boat landing can have some effect in a particular direction and may slightly reduce the global load, its location is often governed by prevailing wave conditions our other operational constraints. However, a more impactful optimization on both global load and sheltering & interference is to bundle J-tubes within caissons. This strategy can be considered both for protection of the j-tubes to ice loading as well as reducing the global load on the support structure.

For example, grouping of the eight j-tubes included in the OSP analyzed here into two equivalent surface-area caissons, with the j-tubes housed inside, reduces the global load by a minimum of 13.8%, illustrated in Figure 6 by ‘min. caisson reduction’. Further reduction can be achieved by optimizing the j-tubes’ placement through careful selection of their position. Figure 8 illustrates the optimal positioning of the two caissons along the dashed line in terms of global ice load on the substation. This line was chosen to align with the existing guide positions on the original substation foundation. This optimization reduces the load by 22.5% compared to the loads on the initial design, illustrated in Figure 6 by ‘opt. caisson reduction’. It should be noted that the resulting lay-out may be more susceptible to jamming highlighting the importance of not merely optimizing for level ice loads.

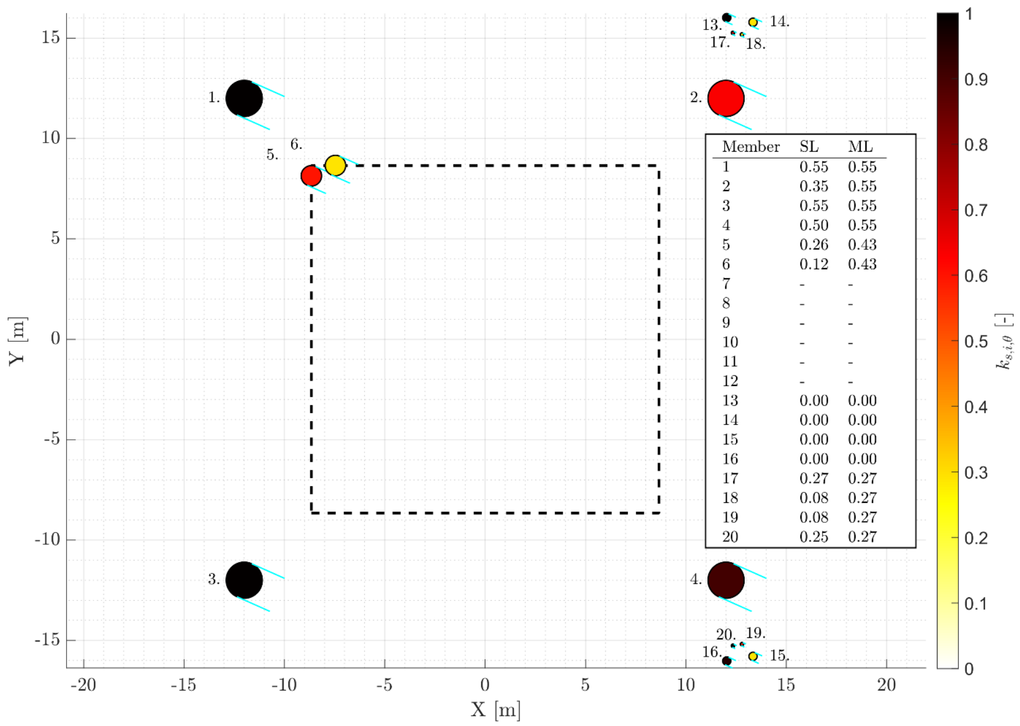

Figure 8 – Ice sheltering and interference factors given for the worst angle of attack, 336 degrees, for the optimal position for two caissons in terms of global ice load reduction.

DISCUSSION

The method presented in this paper contains some assumptions for which no full-scale or model-scale data for validation exists to the knowledge of the authors. These are for example the assumption of the direct sheltering factor of 0.29 in Equation 4, and the assumptions on how to account for the situations presented in Figure 4. It highlights some directions for relevant laboratory scale testing which could allow to expand upon the work by Kato for structures with members of different diameters. Aside from these assumptions, several relevant effects which may develop when a multi-member structure interacts with the ice have not been accounted for yet.

For multi-legged structures, ice jamming may need to be accounted for due to the potential accumulation of ice rubble between elements. This rubble can be challenging to clear and given sufficient strength, may behave as a single structural unit (Palmer et al., 2015). As a result, Palmer et al. recommends minimizing the number of members in the waterline especially in close vicinity to each other, contrasting with a typical substation design, and in direct contrast with the proposed caisson solution of Figure 8. The occurrence of jamming may be strongly configuration specific, and not easily reproduced in laboratory conditions, as for example Li et al. (2017) reported that ice jamming effects did not occur for their specific setup, which was well within the generally accepted L_{cd}/D for jamming to occur.

Nonetheless, ice jamming can be incorporated into the model through an extension, where a jam is assumed between each two members with a spacing less than L_{cd}/D of four, for example. The global load can then be determined as a function of the attack angle, assuming the jammed members behave as a single geometric unit, as proposed by Palmer et al. (2015).

A further extension is possible for ice ridges, where the keel must be considered, making the interaction more complex, especially when accounting for the underwater geometry of a multi-member structure. Developing such a model could be valuable for quickly identifying the position where an ice ridge is likely to generate the highest global load on a structure.

Li et al. (2017) conducted an experimental study on ice loads acting on a complex multi-legged oil pier, consisting of a 3×6 array of non-vertical piles, for ice incident angles of 0, 15, and 30 degrees. The study observed significant interference, sheltering, and non-simultaneous failure effects, though distinguishing these effects was challenging due to the complexity of the configuration. Sheltering factors were found to range from 2.8–3.4, 3.2–4.0, and 3.3–4.2 for angles of 0, 15, and 30 degrees, respectively. In comparison, this study found factors of 3.0, 6.1, and 5.3 for when subjecting the same 3x6 array of non-vertical piles to ice loads in the same directions.

A closer examination of Li et al.'s results show that the piles were rarely subjected to significant loads when partial sheltering occurred, even when a substantial portion of the structure's width could be exposed to ice loads. This may be due to the presence of mixed failure modes, such as bending and crushing failure, observed in their study. In particular, the bending failure on the front piles would lead to ice break-up, significantly reducing the loads on the piles in the wake. As a result, a direct comparison is somewhat challenging and less insightful than initially anticipated.

However, Li et al. (2017) did report instances of crushing failure, and one particularly notable finding was the clear presence of the interference effect associated with Saeki’s (1990) Type A interaction, along with strong non-simultaneous failure effects. These observations indicate that extending our presented model is necessary to account for these additional effects.

CONCLUSIONS

A preliminary sheltering and interference method is presented which aims to define angle dependent reductions on the individual members of a multi-member structure based on the original work on the topic by Saeki. The method yields results based on similar principles to, and consistent with ISO 19906 guidance for four-legged structures and limited numerical data. It can be straightforwardly applied to structures with more than four structural members crossing the waterline and interacting with sea ice. An example application to an 18-member jacket for an offshore substation platform shows how the sheltering and interference effect is strongly angle dependent and the degree of additional sheltering that can be expected for such structures, when compared to four-legged structures. The method relies on several key assumptions on the sheltering and interference effects for members of different diameters which could not be validated based on experimental or full-scale data. Obtaining such data is key to establishing relevant guidance on the topic of sheltering and interference for multi-member structures of more complex geometries such as the substation platforms currently designed for the Baltic Sea offshore wind development.

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