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Ice actions for hydraulic structures of primary flood defense Afsluitdijk - “Applying ISO 19906 at home”

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ABSTRACT

The Afsluitdijk is one of the Dutch Delta programme landmarks. Afsluitdijk is a 32 km long primary flood defense, separating lake IJsselmeer from the Wadden Sea and protecting large areas of the Netherlands against flooding. Over the period spanning 2018 - 2022 the levee will be upgraded by the consortium Levvel (BAM, Van Oord and Rebel). Ice resistance is one of the aspects that is part of the engineering scope of the project. A detailed study on ice actions that apply to the various exposed structural elements is performed, specifically for the hydraulic structures that are integrated in the levee. Dutch regulations with respect to ice actions do specify some levels for ice actions but are not very specific regarding their range of applicability. Ice engineering experience from projects abroad is integrated with Dutch temperate winter conditions, to derive fit-for-purpose ULS and ALS ice actions. The analysis procedure is scenario-based, following the ISO 19906 (2nd ed) limit-stress, limit-force, limit-momentum based approach. This paper describes the study approach and the main results that are obtained.

KEY WORDS: Ice actions; Temperate regions; Ice scenarios; Ice growth; Ice decay; Dams; Levees; ISO 19906; Arctic offshore structures

INTRODUCTION

Background

The Afsluitdijk has been protecting the Netherlands from the sea for almost ninety years, separating the former Zuiderzee from Wadden sea. The location of Afsluitdijk is illustrated by figure 1. An impressive photo of the construction (closure of Afsluitdijk in 1932) and a recent

photo are shown in this figure as well to visualize this impressive Dutch flood protection structure. Although appearing impressive, the dam no longer meets the current requirements for flood protection anno 2019. The Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat) therefore has initiated and is leading the Afsluitdijk upgrading project. Rijkswaterstaat is responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands, including Afsluitdijk. The contract for Afsluitdijk upgrading has been awarded to consortium Level.

The dam will be widened and raised by about two meters and the revetment on the outer side will be replaced. The sluices at Den Oever and Kornwerderzand will be reinforced and flood locks will be built in front of the navigation locks on the Wadden Sea side to act as storm surge barriers. To allow more water to be discharged from the IJsselmeer into the Wadden Sea extra sluices and pumping stations will be built at location Den Oever.



Figure 1. Illustrations of Afsluitdijk, top left: location, top right: closure during construction in 1932, bottom: recent photo of the dam at location Breezanddijk (courtesy: Rijkswaterstaat beeldenbank)

Scope and limitations

Witteveen+Bos is providing ice engineering related services to consortium Level. The scope comprises a review of ice conditions for location Afsluitdijk. Ice formation mainly occurs at

the lake IJsselmeer, but also at the Wadden sea (partial) ice cover is observed during cold winter periods. Selection of starting points for derivation of ice actions. Definition of ice interaction scenarios for structural components and a scenario-based calculation of ice actions for design.



Figure 2. Photos of ice pile up on Afsluitdijk slopes

The scope of the present paper is limited to the evaluation of design ice actions on vertical structures for Afsluitdijk. Separately, an assessment is made for sloping structures. This assessment focusses mainly on ice encroachment scenarios rather than ice actions and is not included in the current paper due to time limitations set to the submission date of POAC'19.

METHODOLOGY

Dutch standards and regulations

Whereas countries and regions with more severe and more frequent ice conditions tend to have well set regulations related to ice resistant design of offshore and waterfront structures, The Netherlands has some design regulations that refer to some extent to ice actions but no complete design standard for ice engineering. The Dutch national annexes to Eurocode are not considering ice actions at all.

In addition to Eurocode, the ROK 1.4, which is a normative Public Works design guideline for infrastructure in the Netherlands, gives some guidance on ice related effects that shall be considered in design. ROK1.4 specifies which conditions may affect ice actions on structures and sets minimum action levels to be applied. For calculation of ice actions for design one is referred to CUR 166 (NL), EAU 2012 (DE) and Stuvo report 59(NL). CUR 166 and EAU 2012 are design guidelines for retaining structures and waterfront structures respectively. Considering the text in ROK1.4 the specified minimum action levels may only be applied if substantiated by a detailed analysis. The minimum action levels provided by ROK1.4 are low, for reference: a minimum global line load of 50 kN/m is specified, where ice thicknesses in the Netherlands typically can reach about 30 cm.

CUR 166 instead is specifying generally applicably ice action levels, which more or less fit to the typical design ice thickness observed in the Netherlands. Global ice actions are specified to be 400 kN/m¹ or 100 kN/m¹ for tidal conditions. Local ice actions are specified to be 1.5 MN. Furthermore, reference is made to EAU 2012 regulation for waterfront structures. Based on EAU 2012 similar action levels as specified by CUR 166 are obtained. Although specifying ice action levels, CUR 166 and EAU 2012 do not specify to which situations / structures / locations these action levels apply. In addition, the relations between ice thickness, ice action

and limit state definition are not clearly specified. These observations combined with the fact that ice engineering is not a major topic in the Netherlands result that engineers often either neglect ice actions for design or tend to base themselves on CUR 166, which is a guideline for waterfront retaining structures. The result is either that ice resistance of waterfront structures is either unknown or that it may become dominant in design if the high-end values of CUR 166 are applied. Both situations are undesirable for owners of infrastructure assets.

Project specific approach

The project setting of Afsluitdijk allowed for a project specific approach. The approach followed to derive ice actions for design is illustrated by figure 3.

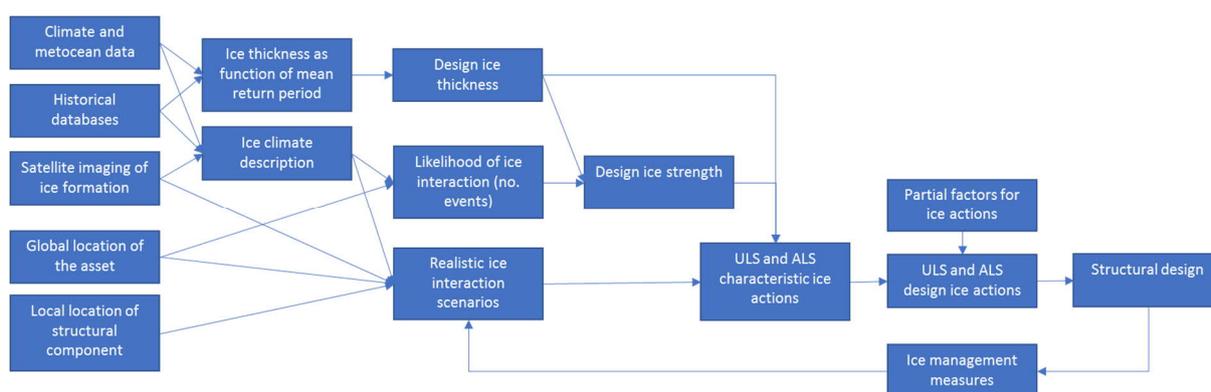


Figure 3. Project specific scenario-based approach

Key elements of the followed approach include:

- The combination of long-term temperature statistics with historical observations and datasets on ice features and ice thickness and satellite imaging on ice formation into ice climate identification and ice interaction scenario definition.
- Combination of long-term climate data with empirical expressions on ice growth and ice decay to obtain relations between ice thickness and mean return period.
- Correction of design ice strength in combination with design ice thickness given the limited number of ice interaction events per year according to ISO 19906 following the framework by Thijssen & Fuglem (2015).
- A limit stress, limit force, limit energy-based scenario approach following ISO 19906.
- Scenario-based calculation of global and local ice actions.
- Design optimization by integration of ice resistant design with ice management measures to cover specific scenarios.

REVIEW OF ICE CONDITIONS

Ice features

Project specific requirements set by Rijkswaterstaat state that the impact of a 20x20x0.3m ice floe shall be considered in design. No further details or requirements are provided. In order to better understand the ice climate at the project location, an analysis on satellite images over the period ranging from 1972 to 2018 is executed. Some examples are shown by figure 4.

The satellite images indicate that 100% ice cover for lake IJsselmeer is not a rare event. Ice floes sizes can range up to several kilometers. Ice ridges seem apparent from the satellite images and may have lengths up to a few tens of kilometers, indicating large scale ridge building to be realistic under the driving forces that may develop at lake IJsselmeer. This is an interesting observation because water currents are typically very low at IJsselmeer. Wind driving forces apparently exceed the ridge building limit stress action. Based on this observation the ridge building mode ice action is used as a lower bound global ice action for IJsselmeer side structural components of Afsluitdijk.

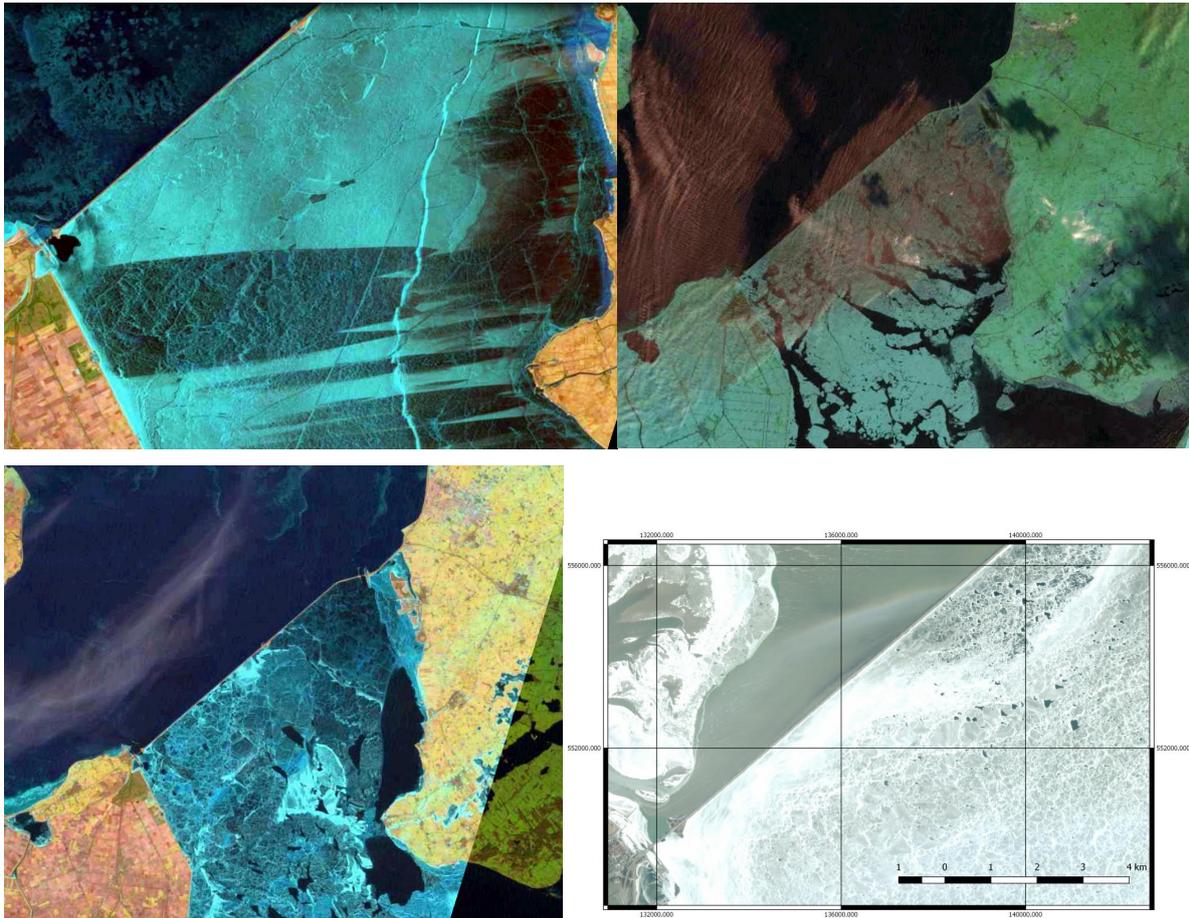


Figure 4. Satellite imaging of ice formation on lake IJsselmeer and the Wadden Sea (source: <https://landsatlook.usgs.gov/>)

Ice cover at the Wadden sea is clearly much less compared to lake IJsselmeer. Apart from the Wadden Sea saline water compared to the IJsselmeer fresh water its mainly the tidal effects that prevent a closed ice cover from being formed at the Wadden Sea. Interestingly it's the tidal currents at Wadden Sea that may cause higher velocities to be used in limit energy-based ice actions. The satellite images do substantiated floes larger than the 20x20 m specified. The combined likelihood of larger floe sizes with high interaction velocities however is low for most structural components. The orientation of a structural component relative to the tidal current direction is taken as a measure for scenario definition.

Ice thickness

Long term temperature data from the Dutch Royal Meteorological Institute (KNMI) data portal are used to derive the long-term temperature statistics. This temperature data is used to calculate ice thickness for design, in the absence of long-term ice thickness data. An approach based on long term ice thickness data would be more reliable but is not feasible given the limited number of ice thickness recordings near the project location. No ice charting reports are available and there is no information on specific features such as rafting. KNMI stations closest to Afsluitdijk are the stations in Stavoren and Vlieland, which provide daily temperature measurements back to 1990 and 1995 respectively. The station of KNMI in de Bilt provides data back to 1901. Therefore, a correction on daily average temperatures in cold periods for location Afsluitdijk compared to location de Bilt of +1.5 degree Celsius is established based on comparison of the shorter term data. Applying this correction allowed to use the longer term data from the Bilt for long term statistical analysis.

Ice thickness calculations are performed following Ashton (1983 and 1986). Ashton models for ice growth and ice decay including the adjustments for thin ice formation are combined into a total ice growth-decay model. The relations provided by ISO19906 are not useful for the typical Netherlands temperate conditions since direct FDD based expressions cannot deal with melting / ice decay periods in between periods of ice formation. Based on the daily mean temperature the rate of ice growth and ice decay is calculated following Ashton (1983) and Aston (1986). The result is illustrated by figure 5. Severe ice formation for lake IJsselmeer is concluded to range up to 35 cm. These results can be combined into a cumulative distribution function of ice thickness with a corresponding probability of exceedance per year, as shown by figure 6. Interesting to observe is the influence of the reference period considered. The effects of climate change and global warming can be seen in figure 5. This is however not taken into account for calculation of design values of ice thickness, since the data is insufficient to conclude about a direct dependence of (lower) extreme values of ice thickness as a result of climate change. The ULS (1/100 year) ice thickness for global ice actions is selected to be 0.3 m. Based on this level ice thickness a larger ice thickness of 0.5 m is proposed for local ULS ice interaction scenarios. Given the limited (100 year) measurement period the data does not provide a basis for the ALS (1/1000 year) ice thickness. Based on maximum reported values in codes and guidelines for North West Europe like EAU 2012 the ALS ice thickness is estimated to be around 0.5 m.

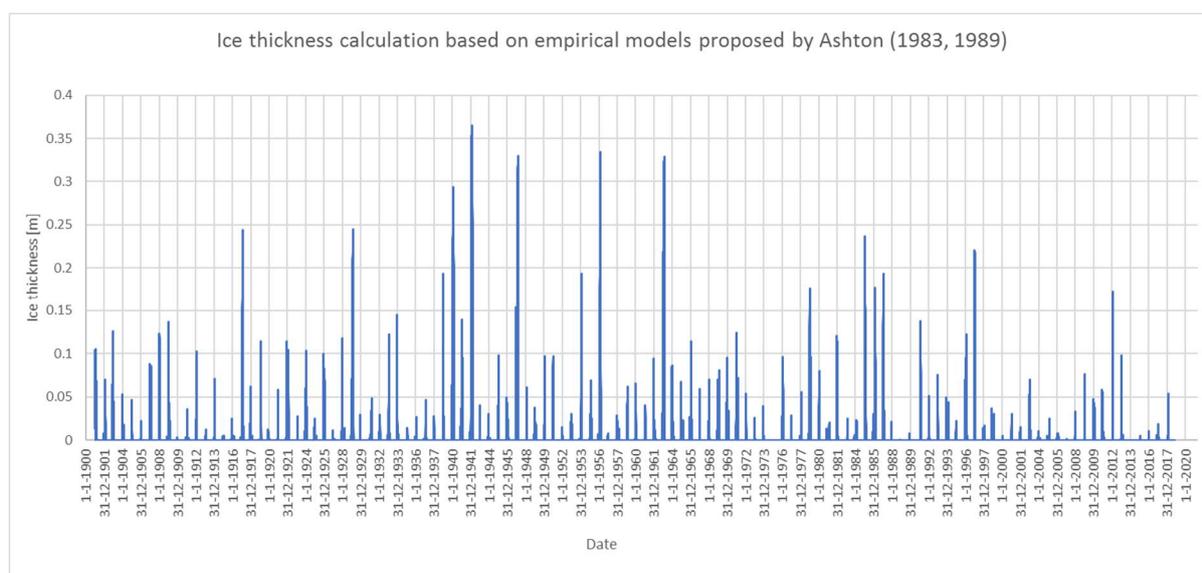


Figure 5. Calculated ice thickness based on KNMI temperature data and combined Ashton models for ice growth and ice decay

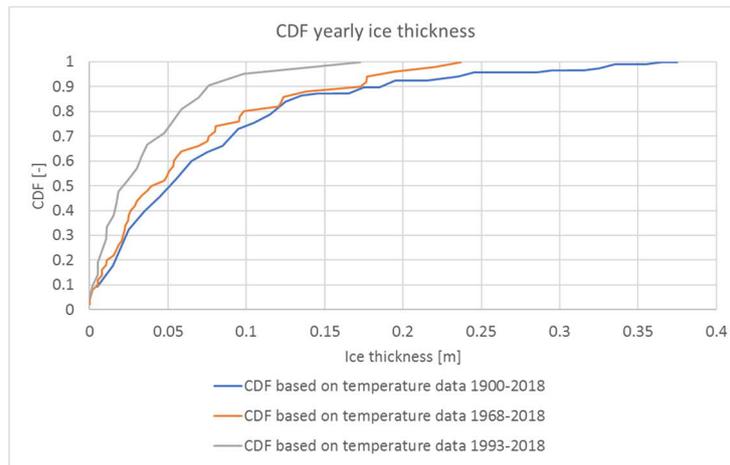


Figure 6. Cumulative distribution functions of ice thickness as function of reference period

Although the calculated ice thickness seems reasonable it needs validation in order to justify its use for design. Specifically for the calculation of corrected ice thicknesses for temporary structures needed for the rehabilitation the validity of the theoretical ice formation models is critical. Therefore, the model is validated based on photo's and ice reports indicating ice formation on lake IJsselmeer in the severe winters of 1934, 1940, 1979, 1985, 1987, 1997, 2012 and 2018. The overall performance of the theoretical model is concluded to be sufficient, with a typical error in the order of +/- 10%.

Ice crushing strength

Ice crushing strength is included in the analysis to be function of the size of the area over which ice fails in compression against structures, in line with ISO 19906. Different crushing strengths are derived for the IJsselmeer and the Wadden sea fresh and saline water conditions respectively. Severe winter conditions in the Netherlands are relatively mild compared to arctic or sub-arctic conditions. Air temperatures drop typically not far below $-10\text{ }^{\circ}\text{C}$, implying that the mean ice temperature will be minimum around $-5\text{ }^{\circ}\text{C}$. The effect of ice temperature on compression strength according to a number of applicable references are compared as is illustrated by figure 7. Based on this comparison, upper bound compression strengths for fresh and saline water for location Afsluitdijk equal to 3.0 and 1.5 MPa are derived for design. Please note that we already combine severe ice temperature conditions (which determine compression strength) with end of freezing period since the maximum ice thickness at the end of a cold period is calculated.

Ice cover with significant thickness at lake IJsselmeer and de Wadden Sea can be very mobile, as is proven by the ice pile up along the coasts as illustrated by figure 2. However, the number of ice - structure interaction events for a structure in or along the coast of these waters is definitely very low compared to offshore structures that have to survive mobile ice exposure due to continuous ice movement during a long winter period. The reference ice crushing strength values may be corrected for this factor according to the new ISO 19906:2018, following the approach suggested by Thijssen & Fuglem (2015). This is done for Afsluitdijk as well, for which a maximum interaction length equal to 10 km per year is conservatively used in order to not end up outside the range of applicability of the formulas. This results that reference ice strength coefficients C_R equal to 2.4 and 1.8 for fresh and saline water respectively is adjusted to 1.5 and 1.04 respectively. This correction is justified because the likelihood of

combined occurrence of extreme thickness, extreme crushing strength and ice movement towards the structure under consideration are very low for the Afsluitdijk hydraulic structures. Making this correction results effective ice crushing actions against a vertical structure that are in the same range as ice crushing actions following EAU 2012 or Korzhavin (1971) which are proposed by BS EN 61400-2:2009 (UK, Windmills) as shown in figure 8. The CUR 166 actions which are shown in this figure as well are derived based on the 0.5 m ice thickness 400 kN/m value mentioned in this guideline but corrected to 0.3 m ice thickness for fair comparison. It is concluded that the CUR 166 value does not represent well a 0.3 m ice thickness ice action for the exposure width which is typically of interest for structural engineers.

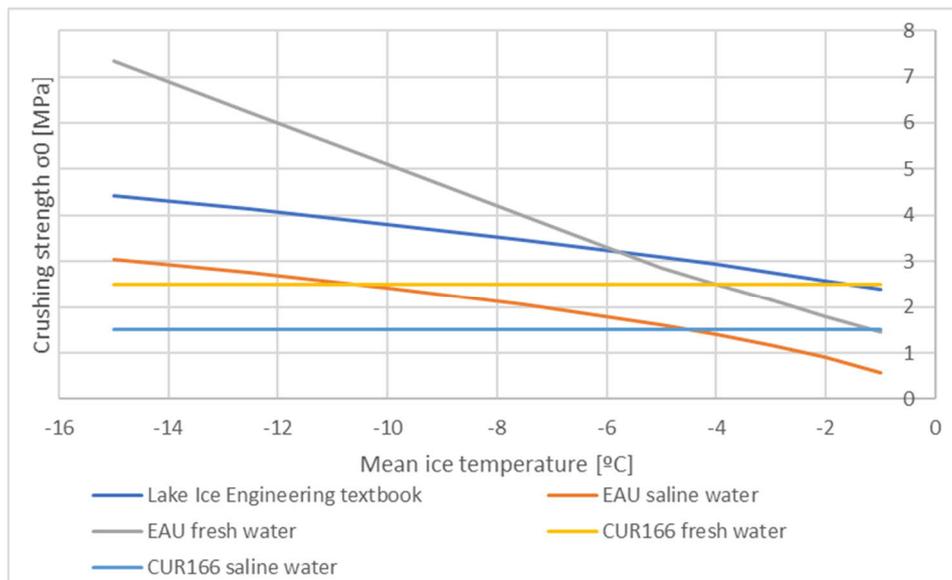


Figure 7. Ice crushing strength dependency on mean ice temperature for fresh and saline water

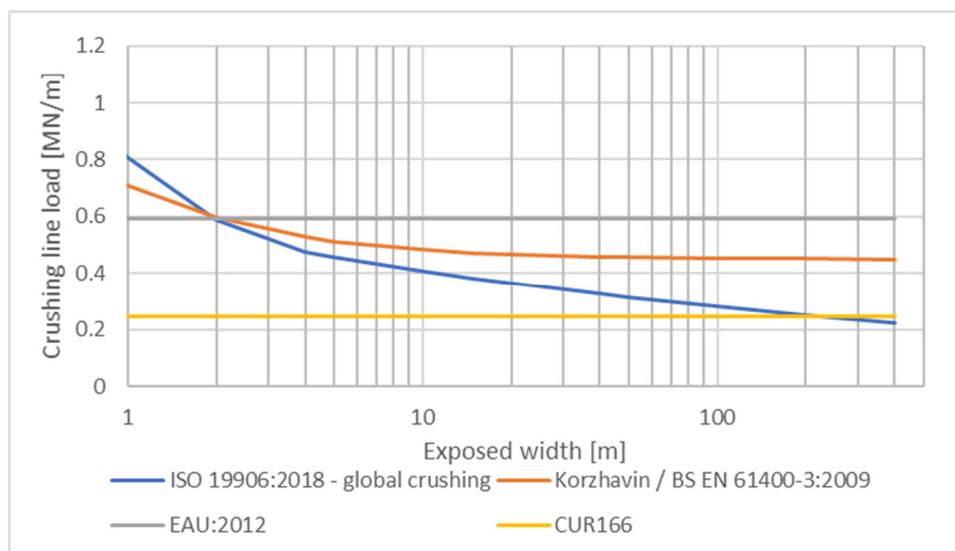


Figure 8. Comparison of effective global ice crushing actions following ISO 19906:2018 with exposure correction to Korzhavin (BS EN 61400-2), EAU:2012 and CUR 166 based action levels.

SCENARIO-BASED ASSESSMENT OF ICE ACTIONS FOR DESIGN

Introduction of the structure under consideration

This chapter shows a few examples of the implementation of the scenario-based assessment of ice actions for design. Although many more hydraulic structures that are part of Afsluitdijk project are considered, in this paper we focus on the Den Oever existing sluice complex and the ice actions from IJsselmeer side. Ice action scenarios for three structural components are discussed in this paper, the pillars, the lock gates and the walls of the dewatering channels.

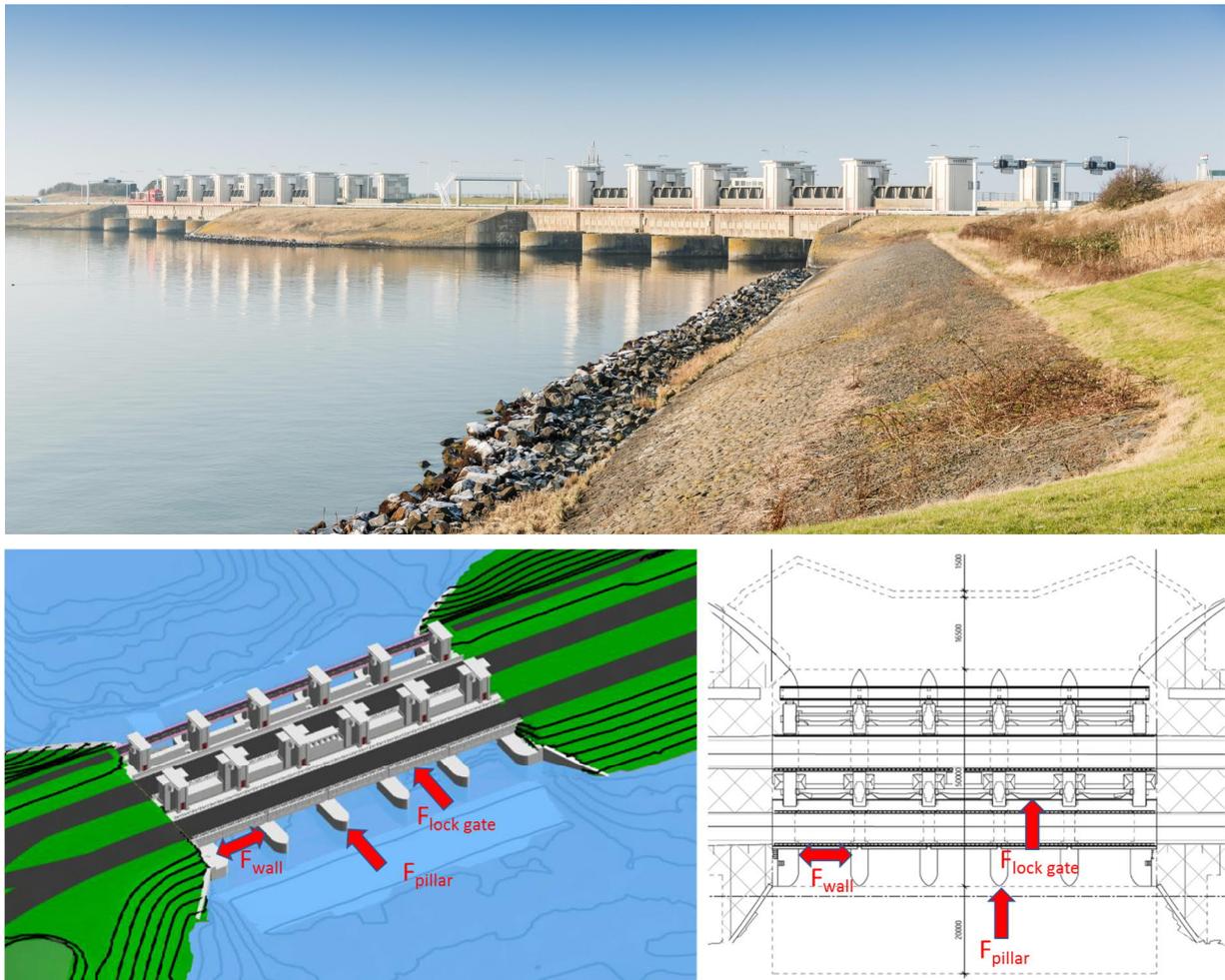


Figure 8. Illustration of the Den Oever sluice complex and the structural components for which ice actions are discussed in this paper.

Ice actions on pillars

The pillars are fully exposed to ice action impact. Given the location embedded in the dam the likelihood of the structure taking all the load from a large ice field however is low. Therefore, ice crushing over the full width of the structure (so evenly high actions on pillars, gates, etc.) is not a realistic scenario. Ridge building forces in an ice field however are sufficiently high to generate local ice crushing over smaller widths. This is therefore the decisive global ice action mechanism for the pillars, resulting an effective line load of 550 kN/m for ULS 0.3 m ice

thickness. Besides locally higher loads may develop if ice pressures concentrate at specific locations. For such a local scenario the ULS ice thickness should also be increased since rafting may very well cause higher local thickness. Local ice action for 0.4 m local ULS ice thickness is calculated to be 1.5 MN given the defined ice local compressive strength, the ice thickness and reasonable loaded area aspect ratios following ISO 19906.

Ice actions on lock gates

Ten lock gates are positioned in the five dewatering channels per sluice complex, five on the side of IJsselmeer and five at the Wadden Sea side. The gates are steel structures that can be lifted upwards to allow water to flow from IJsselmeer to the Wadden sea. The gates are positioned around 14 m behind the front sides of the pillars. It is therefore unrealistic that ice actions caused by a large intact ice field concentrate specifically on the gates. An ice field approaching the structure would be broken up by the pillars. When the structure is surrounded by thick landfast ice the global total ULS action is conservatively limited at the rubbing line load being equal to 110 kN/m. This is a conservative assumption since the location and stiffness of the gates relative to the pillars will result that global actions do typically concentrate more on the concrete structure. The decisive load scenario for the gates is formed by the impact of an ice floe that is approaches the structure with a certain velocity and is blocked by a gate. The ice drift velocity for this scenario is identified to be 0.2 m/s based on extreme current velocities in IJsselmeer and the ice drift speed as function of wind speed following Ashton's book River and lake ice engineering. The impact scenario calculation is based on a circular shaped ice floe with diameter equal to the dewatering channel width for which the contact area increases with the length over which the sheets fails in a crushing mode. ISO 19906 crushing formula with the narrow width adjustment as included in the 2018 update and ice strength coefficients as previously discussed are applied. Based on this calculation an ULS local ice load equal to 332 kN is derived for the lock gates. In addition to the consideration of horizontal ice actions, for the lock gates also vertical ice actions associated with add freeze, ice accumulation and actions from ice sheets frozen to the gates and the concrete structure are evaluated. Based on the outcome of this evaluation it was decided to apply ice management protocols to guarantee that the lock gates can be opened with sufficient reliability.

Ice actions on the walls of dewatering channels

Due to their orientation ice actions from ice impact or drifting ice on the walls of the dewatering channels cannot become high. The decisive ice load scenario for the walls is formed by thermal expansion. CUR 166 specifies ice actions due to thermal expansion solely as function of ice thickness and temperature increase rate. EAU2012 refers to Jessberger (1980), who has proposed thermal expansion ice actions as function of both rate of temperature increase and initial (lowest) temperature. A comparison is shown in figure 9. It is concluded that for the mild winter conditions of the Netherlands the CUR 166 action levels for 8 °C temperature increase per hour are most likely conservative upper bound values and the sensitivity to a lower temperature increase rate is very high. Jessberger expressions appear to be better applicable for mild conditions and show a more gradual dependency on the rate. The Jessberger values therefore are proposed for design, resulting 150 kN/m ULS ice action. Upper bound values are derived according to the maximum ice sheet buckling force as function of ice sheet length and are applied to cap the calculated action levels. This upper bound is not decisive for the dewatering channels, but for other hydraulic structures of Afsluitdijk it is. Moreover, we have distinguished between part of the walls between which the ice sheet is exposed to sun light and parts for which this is not the case. In absence of sun light, the temperature increase rate can never be very high and lower values in this case are proposed for design.

Ice loads by thermal expansion

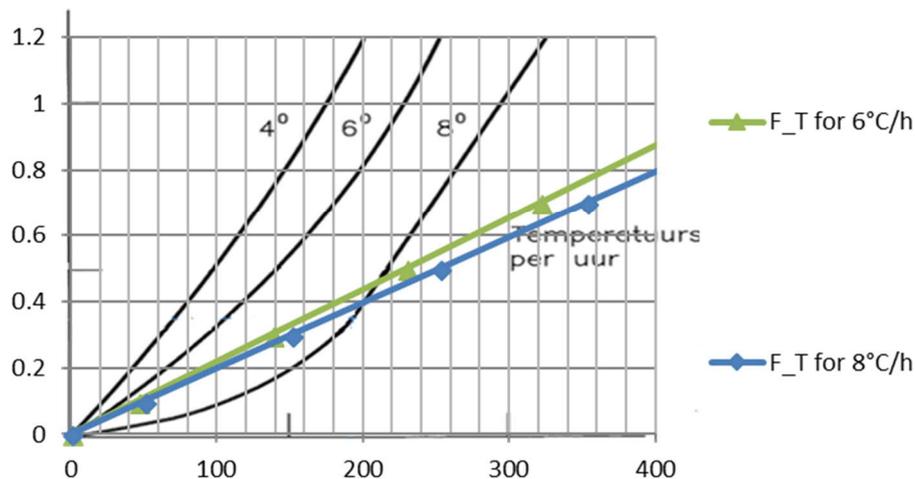


Figure 8. Thermal expansion ice actions according to CUR 166 and Jesberger

CONCLUSIONS

This paper discusses important aspects of the study on appropriate design ice actions for the Afsluitdijk upgrading project using the ISO 19906. Well substantiated optimization compared to standardized CUR 166 upper bound action levels formed the main objective of the study. The detailed scenario-based study following a combination of applicable international design standards, guidelines and literature that are performed allowed the team to significantly optimize ice actions for design.

Important ice engineering aspects that have been incorporated:

- A combination of various data sources are used for ice climate identification and ice interaction scenario definition.
- Combinations of long-term climate data with empirical expressions on ice growth and ice decay allowed the team to obtain relations between ice thickness and mean return period.
- Correction of design ice strength in combination with design ice thickness turned out to be possible given the limited number of ice interaction events per year according to ISO 19906 following the framework by Thijssen & Fuglem (2015).
- A limit stress, limit force, limit energy-based scenario approach following ISO 19906 is used as a solid basis for appropriate ice action calculation for individual structural components.
- The scenario-based calculation resulted global and local ice actions for design for ULS and ALS limit states.
- Last but not least design optimization by integration of ice resistant design with ice management measures is proposed to cover specific scenarios.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Consortium Level for the ability to execute the study presented in this paper. Dutch regulations with respect to ice actions do specify some levels for ice actions, but are not very specific regarding their range of applicability. The importance of Afsluitdijk and the momentum of the project allowed us to perform an in depth study. We truly believe that the results of this study could be further processed into a generally applicable document for ice resistant but economically optimized design of waterfront structures in the Netherlands. After doing challenging ice engineering projects for many years in cold regions abroad, the Witteveen+Bos expert team was very happy to be able to our knowledge and experience for the design of one of the Dutch major Delta programme landmarks. Within the team we have often said: “Finally we are able to apply the ISO 19906 at home!”

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