Ice-induced vibrations of offshore structures - Looking beyond ISO 19906

Kärnä, Tuomas; Andersen, H.; Gürtner, A.; Metrikine, A.; Sodhi, D.; van het Loo, M; Kuiper, G.; Gibson, R.; Fenz, D.; Muggeridge, K.

Publication date
2013

Document Version
Final published version

Published in
Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions, POAC

Citation (APA)
Kärnä, T., Andersen, H., Gürtner, A., Metrikine, A., Sodhi, D., van het Loo, M., Kuiper, G., Gibson, R., Fenz, D., Muggeridge, K., Wallenburg, C., Wu, J. F., & Jefferies, M. (2013). Ice-induced vibrations of offshore structures - Looking beyond ISO 19906. *Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions, POAC*.

POAC'13
Espoo, Finland

Proceedings of the 22nd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2013
Espoo, Finland

ICE-INDUCED VIBRATIONS OF OFFSHORE STRUCTURES – LOOKING BEYOND ISO 19906

Kärnä, T. [1], Andersen, H.[2], Gürtner, A.[3], Metrikine, A[4], Sodhi, D.[5], Loo, M.[6], Kuiper, G.[7],
Gibson, R.[8], Fenz, D.[9], Muggeridge, K.[10], Wallenburg, C.[11], Wu, J-F.[12], and Jefferies, M.[13]

[1]Karna Research & Consulting, Helsinki, FINLAND
[2] Dr.techn. Olav Olsen, Lysaker, NORWAY
[3]Statoil, Trondheim, NORWAY
[4]Delft University of Technology, Delft, NETHERLANDS
[5] Consultant, Hanover, USA
[6] Concrete Structures, Oslo, NORWAY
[7] Shell Global Solutions International B.V., NETHERLANDS
[8] BP, Sunbury, ENGLAND
[9] Exxon-Mobil, Houston, USA
[10] Conoco Phillips, Calgary, CANADA
[11] ABS, SINGAPORE
[12] GustoMSC, Schiedam, NETHERLANDS
[13] Consultant, Gt. Gonerby, ENGLAND

ABSTRACT

The paper deals with the classical ice engineering challenge of ice-induced vibrations (IIV) of offshore platforms. There is still a general industry concern with aspects of IIV and the load amplification that can arise in some situations resulting from ice interaction with a structure. It was thought important to re-visit current design methodology and practice, as well as the data that led to their formulation. A joint industry project (JIP) was organized, in which the main offshore oil companies joined together to sponsor development and validation of models for ice induced vibration.

Broadly, the JIP: i) identified interesting aspects of the mechanisms behind IIV; ii) sponsored further development of three numerical modeling approaches chosen for the range of physics they captured; iii) and, provided calibrated models to an independent engineering company who used them to assess the model's accuracy in simulating five full-scale events whose data had been withheld from the model developers - ensuring an independent validation rather than a further fitting of models to data.

This paper is a "briefing" and provides an overview of the background, progress, and some validation findings: a status report on the reliability of present procedures available to the offshore industry when designing platforms in moving ice where IIV can be expected. The "science" behind the models will be presented by the model developers themselves (e.g. Hendrikse & Metrikine, 2013) and in further publications once the JIP confidentiality conditions expire.

INTRODUCTION

Crushing of ice against vertical offshore structures (from the narrow legs of jacket-type platforms through to caisson-islands) may cause substantial ice-induced vibrations (IIV) of those structures and, in some circumstances, the vibrational response of the platform can lead to increase in the global ice load. For example: (i) vibration-related load on channel markers in the Baltic appears to have caused failure of those markers and (ii) vibration-related loads on caisson islands in the Beaufort Sea nearly caused loss of Molikpaq in 1986. Mass dampers are being considered on newly designed platforms in the Sea of Okhotsk to reduce the effects of IIV on oilfield operations.

Ice deformation by creep accommodates the slow movement of the ice past a structure, but as ice velocity increases the ice must crush and/or buckle as it moves past the structure. Under many situations, particularly with ice velocity > 0.1 m s^{-1} (for full scale structures), the periodic ice crushing is random both in location across the ice-structure interface and in time. IIV are ubiquitous on a 'compliant' structure, but they have the characteristic of background "noise" with a wide range of frequencies and low levels of associated structural response; this type of ice interaction is often called *continuous brittle crushing (CBR).*

As the ice velocity reduces below a critical velocity, a 'self-organization' can become established with ice failure becoming coherent across the ice-structure interface. This phenomenon of ice failing simultaneously over a complete interaction area is denoted as phase-locked loading. Phase-locked loading can occur for two situations; intermittent brittle crushing (ICR) and frequency lock-in (FLI). At intermittent crushing the ice failure frequency is below all natural frequencies of the structure, whereas at frequency lock-in the ice failure frequency is close to one of the natural frequencies. Instances of large vibration and structural failure are associated with this self-organization of ice crushing, whether by FLI or by ICR.

Despite their importance to loads on offshore structures in ice covered areas, IIV are not sufficiently considered in the ISO standard 19906 on offshore structures (ISO19906, 2010); a particular concern is the conditions in which CBR transitions into FLI/ICR with the resulting load amplification and the role of the structure properties (e.g. waterline stiffness and vibration frequencies) in how that transition develops. A 'Joint Industry Project' (JIP) was organized to further investigate ice-induced vibrations; after discussions during 2009/10, the proposed project attracted sufficient participants (funding) to proceed in October/2010. The JIP was essentially completed in September/2012.

The JIP was developed around four activities: i) a 'workshop' involving invited contributors to identify the state of experience and divergence of understanding about IIV; ii) reviewing experience from laboratory to full scale, including aspects of data not in the public domain, to clarify the range of conditions and nature of IIV; iii) model development into working software that simulates IIV; and, iv) validation of the software against some of the identified experience. These activities were identified as 'work packages' WP1.1 to WP1.4 respectively, see Figure 1.

The intellectual lead of the JIP was jointly by Karna R&C and TU Delft, with Dr. techn. Olav Olsen (based in Lysaker, Norway) providing both project management and carrying out the independent validation. The JIP was supported by the following participating companies (Participants): Statoil, ExxonMobil, Shell, BP, Conoco Phillips, ABS, and SPM/GustoMSC.

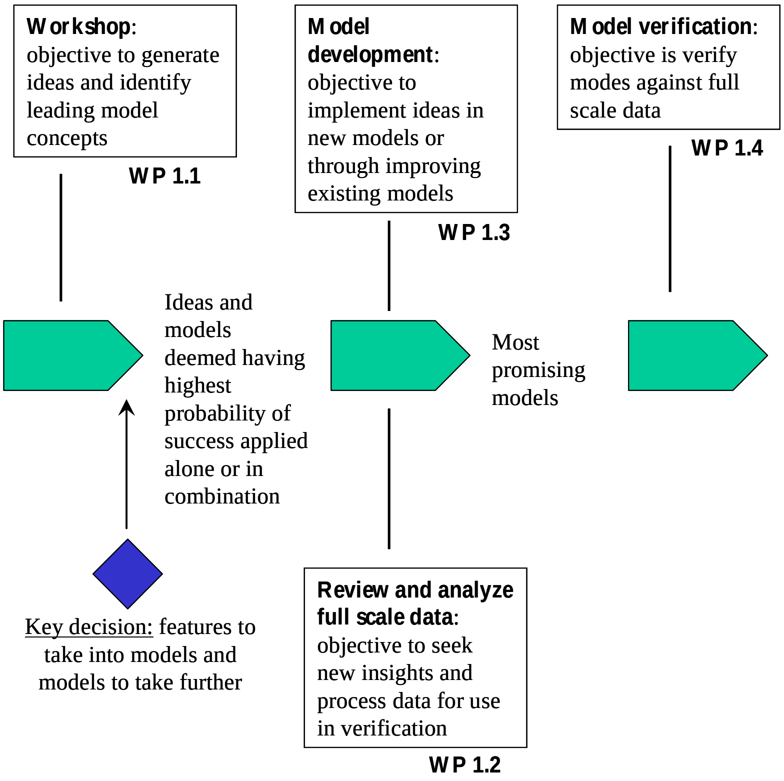


Figure 1: Intellectual framework relating the various tasks within the JIP

WP1.1: EXPERT WORKSHOP

Proceedings

Although there is now a substantial literature on IIV, the JIP was based on bringing identified contributors together to present and discuss their views in an invited 'workshop' setting. The workshop was held over two days, with the invited contributors being chosen to ensure a range of views was available to the JIP including: the phenomenological theory initiated by Blenkarn and developed by Määttänen; an ice failure mechanism described by Yue; the differing hypotheses about "hot spots" by Jordaan and Gagnon; the alternating ductile-brittle ice behaviour suggested by Sodhi; and, changes in the ice strength due to the reactive effects caused by the structure (Kärnä). For the purpose of the workshop, contributions were invited in the groups of *Theory*, *Experimental Evidence*, and *Models*. Each contributor to the workshop provided a written paper (Table 1), as well as their presentation; some aspects of the workshop have become public domain (e.g. Gagnon, 2012).

Commentary

It became clear that there was no consensus across a range of issues including: the cause of IIV; whether or not crushed ice existed in high pressure zones adjacent to a structure; whether the amount of ice crushing on a fracture event was a property of the ice, related to ice failure mode, or a consequence of structure motion; and, whether or not the energy required to clear crushed/fractured ice from the near-field was a significant energy dissipation mechanism in the ice-structure interaction. However, there was general acceptance that the spatial pattern of ice contact pressure (and thickness, if locally varying) should be represented in any modelling.

Table 1. Papers presented at November, 2010, Workshop

Author	Topic
	Contributions to Theory
John Dempsey	The relationship between the tensile fracture of sea ice and compressive failure mechanisms
Erland Schulson	The ductile-to-brittle transition in ice
Ibrahim Konuk	Computational methods for solving dynamic ice structure interaction problems
	Contributions to Experimental Evidence
Robert Frederking	Strain rate effects on compressive strength of ice and its relation to indentation processes
Takahiro Takeuchi	Randomness in strength of natural sea ice as well as in peak ice load
Lennart Fransson	Field tests on compressive ice failure in ice-indentation
Robert Gagnon	An inside look at lock-in (see Gagnon, 2012)
Mike Jefferies	Ice force and structure response measurements and data from Molikpaq experience at Amauligak I-65.
	Contributions to Models
Karl Shkhinek	Speed effects in compressive failure of an ice sheet against a vertical structure
Devinder Sodhi	Crushing failure during ice-structure interaction
Ian Jordaan	Indenter tests, analysis of crushed layer and ice-induced vibrations
Qianjin Yue	Analysis of dynamic ice force of narrow vertical structures based on full scale tests
Mauri Määttänen	Experiences in tackling ice-induced vibrations numerically and in design
Tuomo Kärnä	Physical mechanisms in different kinds of ice-induced vibrations.

WP 1.2: DATA REVIEW

Synthesis of Trends

The extensive data review and analysis was broken into two sub-tasks: *Laboratory & Medium Scale* and *Full Scale* data. In both cases the work involved compiling the published records, adding in proprietary or unpublished data, and then looking for trends between inputs (for example, ice velocity) and outputs (for example, dynamic load amplification). Review and analysis were focused on FLI, but ICR and CBR was also considered. From a fundamental perspective, the goal was to identify the processes (e.g. strain rate effect on ice strength) that should be included in a computational model of the ice-structure interaction. From a practical perspective, the goal was to identify the conditions that allow FLI crushing events to occur.

Data show that the onset of FLI can occur in several ways, but that most of the events of FLI appear to start in two phases. An initial phase of small or very small vibrations is followed by a rapid increase of the response. The feed-back effect in the ice force starts at the time of the rapid increase in the response. Test series with several events of FLI show that steady-state vibrations with almost constant amplitude can prevail while the indentation speed (v) is varied between two transitional values v_{cr1} and v_{cr2}. The response increases linearly with the indentation speed in this range. In the laboratory tests, this upper ice speed limit varied from $0.06\ \mathrm{ms}^{-1} < v_{cr1} < 0.25\ \mathrm{ms}^{-1}$ (depending on the experiment). Field data in the Bothnian Bay and in the Bohai Sea (lighthouse, channel marker and jacket platforms) suggest that FLI can be expected when the ice speed is less than $v < 0.05\ \mathrm{ms}^{-1}$. But, considering the uncertainties in the data, the upper limiting speed for onset of FLI may be as high as $v < 0.15\ \mathrm{ms}^{-1}$.

Full-scale data from the Beaufort Sea involved a rather different type of structure: a large bottom-founded barge, the 'Molikpaq'. And, a more subtle response to ice velocity was encountered. The Molikpaq had a fundamental frequency f_0 ~ 1.8 Hz. The 12th of May 1986 0300hrs event data (Jefferies et al., 2011) showed that the transition into time-coherent crushing developed at about 1.6 Hz, but that once established the same time synchronized crushing continued to as low as 0.2 Hz as the ice slowed. Thus, there was no lock-in to a structure defined frequency (which should have been about 1.6 – 1.7 Hz based on the observation that FLI often develops at a frequency slightly lower than f_0) although that frequency may have controlled the transition into self-organized ice crushing.

It appears that waterline displacements influence the interaction mechanisms that are responsible for FLI. Both laboratory data and full-scale data indicate that FLI is rare in very stiff structures, while FLI is a common phenomenon for compliant structures that exhibit waterline displacements in excess of about 2% of the ice thickness for jackets & channel markers or about 1% of ice thickness for wide structures (Molikpaq).

Commentary

There is consistency between the laboratory and full-scale experience, but simple inspection of the data is not providing fundamental insight. However, all the data reviewed support that ice induced vibration involves periodic, not continuous, ice crushing. This is certainly an important insight as it excludes some classes of model where ice is in a continuous state of failure. This does not conflict with the idealization of CBR as that actually comprises multiple, independent facture events with an overall frequency higher than f_0.

What is consistent across all the reviewed data in the current JIP is that ice induced vibrations seems to be influenced by the structure. It should also be noted that although it is easy to produce a feedback in the laboratory to induce vibrations by choosing models with low damping (< 5%) the situation at full scale may arise with considerably more damping (> 25%). Structural displacement is certainly plausible as a feedback mechanism for causing the onset of vibration in an FLI mode (time synchronization), but there remains an open question of whether that is sufficient feedback for ICR with its spatial coherence across a wide range of frequencies. Logically, an additional feedback mechanism is the shear stiffness within the ice sheet ("far field") but this potential mechanism could not be examined from the available data.

WP 1.3: MODEL DEVELOPMENT

Model Selection

The lack of simple trends emerging from 'data analysis' had been anticipated with the JIP being focussed around numerical ice-structure interaction models that compute detailed force/displacement/acceleration time histories for an interaction described by various environmental variables (ice thickness, ice speed etc.) and by structural properties (waterline stiffness, modal frequencies). The original JIP proposal was based on updating the PSSII (Procedure for dynamic Soil-Structure-Ice Interaction) model developed by Tuomo Kärnä and with provision for a 'second' model to investigate identified aspects from WP1.1 and/or WP1.2 that were insufficiently represented in PSSII.

In choosing additional models, a desire across the JIP was to include a wide range of alternative views into the underlying causes of IIV that had emerged during the workshop and subsequent data analysis. It was recognized that the PSSII model represented a 'structural feed-back with rate-dependent strength' view and that the project did not want to duplicate model idealizations. Based on these considerations, two additional models were selected:

- Metrikine's inclusion of a spatial dimension in the idealization of ice behaviour, providing multiple feedback mechanisms for initiating the CBR/FLI transition
- Sodhi's focus on near-field stiffness as the feedback mechanism, again an interesting concept and consistent with reported fracture damage prior to crushing failure.

The Participants felt that the Metrikine and Sodhi models offered aspects of the physics of ice-structure interaction that were both plausible and not included in PSSII. It was therefore decided to proceed with development and calibration of the PSSII, Hendrikse & Metrikine (HM), and Sodhi models and that all three would be subjected to independent validation.

Common Framework

The Participants were concerned that "ice mechanics" might get lost in the details of the structural idealization. Accordingly, all model developers were required to adopt single degree of freedom (SDOF) idealizations of the structure to allow the easiest comparison between models. Practically, this is consistent with the initial approach used in engineering analysis of structures during an earthquake.

All three models had a similar idealized form with a SDOF structure acted on by independent near-field elements which in turn were loaded by an elastic far-field (whose outer boundary moves with constant velocity). Where the models differ is in the details of the near-field physics, the size and number of the near-field elements acting on the common structure, and the degree of shear coupling in the far-field that acts on the near-field elements.

Some parameters are common to all models: (i) the structures width at waterline (and thus the width exposed to ice action); (ii) the structures horizontal stiffness at the waterline in direction of ice movement; (iii) damping of structure (as viscous equivalent of hydrodynamic drag, aerodynamic drag, radiation damping into foundation, and hysteric loss within the foundation soils); (iv) thickness of ice sheet moving towards the structure (generally taken as uniform); and, (v) the "far field" ice drift velocity towards the structure (a constant in any simulation).

However, the different idealization of the near-field results in each model having its own additional parameter set for the near-field.

Model Features

The PSSII model idealizes a random and rate dependent ice strength, and with the near-field stiffness related to the near-field strength. Clearing of the crushed/spalled ice is not explicitly simulated, but is implicit with a specified decrease rate for post-crushing pressure. Commonly, forty near-field elements are used. The far-field ice consists of independent strips with no shear coupling. There is a specific rule for how much ice that crushes on each fracture event, which is perceived as a model idealization and not a user input. This model is largely as described in Kärnä et al. (1999).

The HM model (Hendrikse & Metrikine, 2013) model is based on the idealization that ice strength is variable within an ice sheet (although in reality it could be ice thickness as well), but that the crushing of individual areas of ice is coupled back to other crushing zones because of the elastic shear stiffness within the ice sheet. This spatial coupling of ice failure zones is the kernel of the model. When a strong ice element comes into contact with the structure, the ice behind it deflects and this allows adjacent ice elements to come into contact and develop load; the interplay between the far-field stiffness and the near-field elastic coupling allows the overall ice failure to either be random local failures or to transition into a synchronized failure where the crushing of one element dumps load onto adjacent elements causing their failure in turn and thus synchronization.

The Sodhi model (Sodhi 1991, 1995, 2001) idealizes the near-field ice as numerous ‘asperities’ (“bumps” in the ice sheet that comes in contact with the structure); the model was extended to consider spatial and temporal synchronization of these asperity compressions. A particular feature of the asperity concept is that there is an implied effect of distance along the ice-structure interface. During loading at low relative speed between ice and structure, the forces acting on many asperities increase together until fracture takes place (either progressively or simultaneously), whereas the forces on different asperities develop non-simultaneously and incoherently during the short contact duration at high relative speeds. The issue is the correlation between the forces that develop on adjacent asperities at different relative speeds. Based on a statistical approach, an engineering approximation for the correlation is inbuilt into the model using extensive calibration at laboratory scale.

WP1.4 VALIDATION

Methodology

Each model developer calibrated their model; the data for this calibration was a free choice for the model developers. Each developer was required to report their calibrations and to provide guidance on how the models should be used for different ice conditions.

The calibrated models were then passed to Olav Olsen (OO) for an independent validation (“blind test") of the model for some selected full-scale events, with OO basing the validation only on the developers ‘user manual’ and their recommended rules for ice properties. Some relevant values were also calculated based on ISO19906 (ISO19906,2010) when more detailed data was unavailable. The properties of the structure (f_0, stiffness and damping) were determined from other studies and using standard methods. Comparison between simulated and measured signals is deemed to demonstrate the capabilities and potential limitations for each of the models.

Following the independent validation, model developers were given the opportunity to improve their model’s fit to the data and to comment on the parameter/property changes needed to obtain better fits than achieved in validation.

Selected Events

At the start of the JIP it was anticipated that a reasonably wide range of full-scale data would become available for calibration and validation of IIV models, these data sets include dynamic response due to ice actions on several different kinds of structures (wide caisson, massive and slender multi-leg structures as well as monopods). However, difficulties were encountered with confidentiality limitations for both Bohai and Sakhalin data. Of the remaining data, these were screened using the following criteria: (i) covering all three vibration modes (preferable with the same structure) and with different ice environmental conditions; (ii) include different structures (i.e. aspect ratios); (iii) ice environmental data available; and, (iv) the structural properties are reasonably well-known.

Although these criteria are reasonable, “perfect” validation events are rather difficult to find. In addition, available funding limited the number of cases that could be fully considered. Five validation cases were selected; two from the Molikpaq experience (12th of May 1986 0300hrs events) in the Beaufort Sea (Jefferies et al., 2011) and three from Norströmsgrund lighthouse measurement at the Baltic Sea collected during the STRICE project. Table 2 summarizes the validation events with some key information; none of these events represent pure CBR response.

Table 2 Selected validation cases

Interaction event		**Mode of interaction**	**Ice enviromental**			**Structural Properties**					
Event	Event No.		Velocity	Ice thickness (h)	Ice Temp.	Contact width (w)	Aspect ratio (w/h)	Frequency	Damping ratio of critical (ξ)	SDOF Stiffness	SDOF Mass
			[m/s]	[m]	[°C]	[m]		[Hz]	[%]	[GN/m]	[ton]
Molikpaq											
12 May 1986	**5**	ICR/CBR	0.085	2.1	-3.2	80	38	1.26	20	10	160000
12 May 1986	**6**	ICR	0.01	2.4	-3.2	80	33	1.26	20	10	160000
Norstromsgrund Lighthouse											
04-Apr-2002	**8**	ICR	0.03	0.55	-0.4	7.5	14	2.64	2	3.22	11700
25-Mar-2003	**9**	FLI	0.05	1.2	-0.4	7.5	6	2.64	2	3.22	11700
09-Apr-2001	**10**	FLI	0.1	0.68	0	7.5	11	2.64	2	3.22	11700

Measured data - accuracy and assumptions

Molikpaq

Acceleration at waterline: A single-degree of freedom (SDOF) representation of the response at waterline is needed. The waterline response was calculated based on a time-coherent weighted average of measured signals using the top “tiltmeter” (EL+5.8) and bottom accelerometer (EL-17.5m). The weight factor is 2/3 and 1/3 for the top and bottom signal, respectively, in accordance with recommendations given by experts on this structure and thus deemed as “not unreasonable”. For high-load events such as the 12th of May 1986 the motion at the top and bottom are more or less synchronized so the assumption above is reasonable.

Estimated global force: IIV was not expected with the Molikpaq and it was only equipped with slow-response ice load panels. Extraction of the > 0.1 Hz load data requires use of the strain gauges on the bulkheads within the structure. The forward modeling approach to do this, while maintaining traceability to dead-load calibration, was presented in POAC’11 (Jefferies et al., 2011) and this JIP adopted the load-time series data reported.

Filtering: Load and acceleration data measured for Molikpaq was passed through an anti-aliasing filter during the measurements. Unfortunately, it filtered out lower frequency more than first expected thus attenuating both the load and acceleration signals. In order to account for this during the validation work, the model simulation results for the Molikpaq cases were passed through a digital implementation of the physical filters (Spencer et al., 2011) using a 50Hz sampling rate. Thus ‘filtered model’ was compared with ‘filtered data’.

Nordströmsgrund Lighthouse

Drift direction: The direction of the ice drift is an important input parameter when transforming acceleration and force measurements into a SDOF system. The direction of the ice flow is estimated based on log data from the STRICE project in combination with detailed study of plane plots of acceleration and panel load distribution. The direction estimates are quite coarse and represents an uncertainty with respect to the results.

Estimated global force: The forces in the Nordströmsgrund data (STRICE-project) was measured by 9 load panels located on the eastern half of the lighthouse. The selected verification cases have ice drift from S and NNE. A limited number of relevant load panels are exposed for drift from certain directions, e.g. from S. Therefore, an approximate procedure based on mirroring technique has been used to estimate the global load. Based on this procedure, the resulting estimate will comprise the "true" order of magnitude and approximate period of the global load on the lighthouse. Several of the Nordströmsgrund cases also suffer from missing or defective load panel data and this is simply taken into account using the mirroring technique to estimate the global force.

Elevation for acceleration data: The accelerometer located at 16.5 meters above the lighthouse base, approximately 2.5 meters above mean sea level, is used when estimating the SDOF acceleration of the lighthouse.

Results

Space limitations prevent presentation of the load and acceleration time series comparisons for all five chosen validation events and all three IIV models. Table 3 summarizes the results of the validations for the three models together with a judgment on how well the model validated; Figure 2 provides plots illustrating the judgments of what was viewed as a 'reasonable' match to data and a 'poor' match.

Broadly, as will be evident from Figure 2 and Table 3, none of the models validate to a level that would be accepted for practical engineering across all five selected validation cases. But, each of the models has aspects that do capture what is seen in the measured data at least some of the time. There remains a particular weakness in dealing with the CBR to ICR transitions of validation Case 5, but the fact that the structure moved between these two modes three times within a two minute period suggests that the conditions within this event were marginal for sustained IIV in either mode so it is unsurprising that the numerical models preferred one mode or the other (depending on their idealizations). Figure 2 show that the PSSII model predicts a short transition from ICR to CBR and back to ICR.

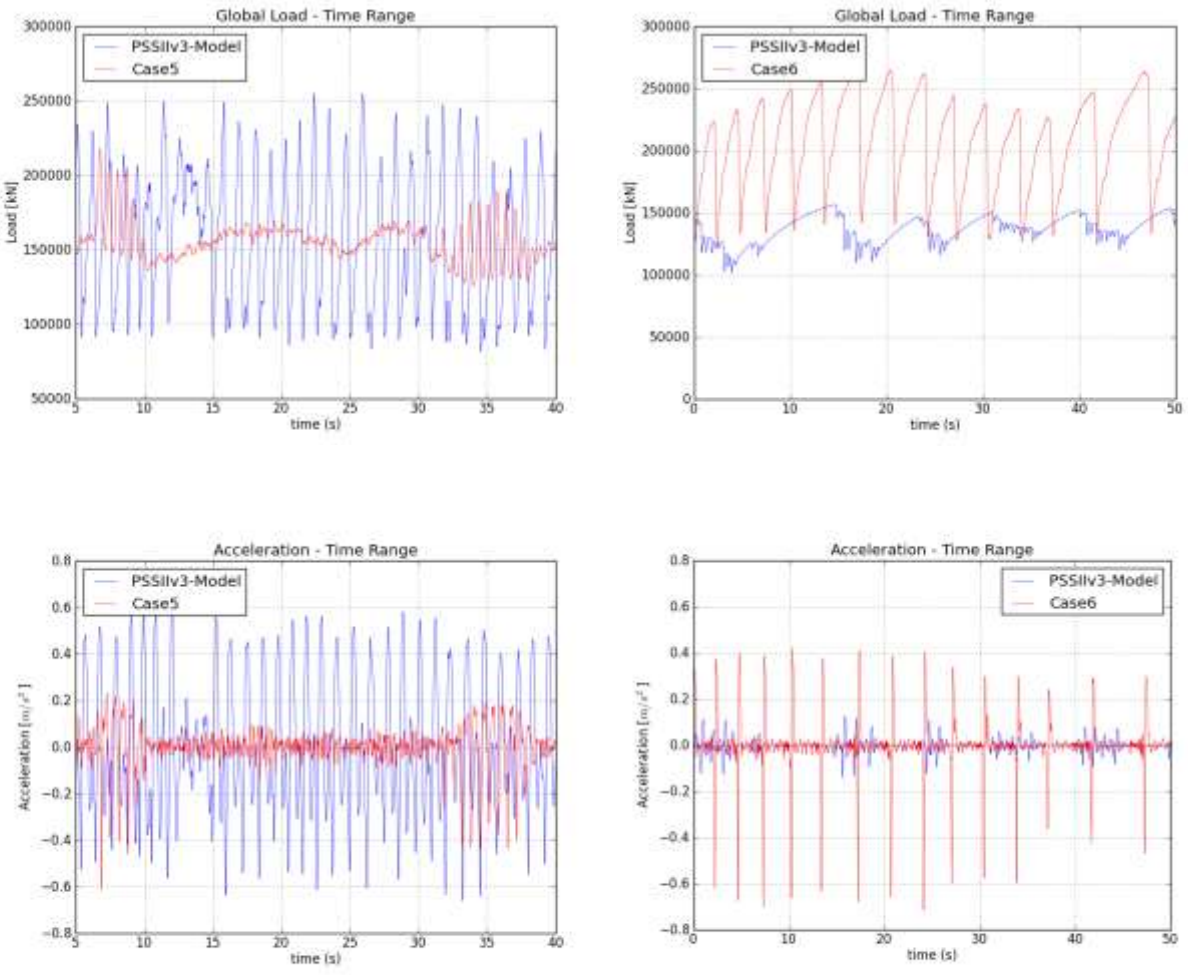
Further Calibration

Following the validation, model developers was given the chance to comment on the achieved fits and to discuss how to improve the match of their model to the data. Generally, modellers were able to do much better when "fitting" as compared to "predicting". The Sodhi model was, for instance, developed based on the results of small‒scale indentation tests with freshwater ice and the calibrated values of its parameters do not appear to directly upscale to thick ice sheets. When the full-scale data was made available to the developer several changes to the values of key parameters produced a rather impressive match to data as shown in Figure 3 for the Sodhi model.

Although Figure 3 is impressive, it needs to be remembered that the JIP was directed at independent validation. Perhaps the developers may need to better guide the model users, but there is also the possibility that aspects of relevant physics/mechanics are missing in each model – further work is needed before the offshore industry will have a reliable design tool.

Table 3: Independent validation results for all models

Case	Event	Mode	PSSII	HM	Sodhi
5	*Molikpaq,* *12th May 1986*	*ICR/* *CBR*	*Reasonable match (ICR and CBR)*	*Reasonable match (Mostly CBR)*	*Poor match (CBR)*
6	*Molikpaq,* *12th May 1986*	*ICR*	*Poor match (ICR)*	*Reasonable match (ICR)*	*Poor match (ICR)*
8	*Norströmsgrund,* *04th April 2002*	*ICR*	*Reasonable match (ICR)*	*Poor match (FLI)*	*Poor match (CBR)*
9	*Norströmsgrund,* *25th March 2003*	*FLI*	*Poor match (FLI)*	*Reasonable match (FLI)*	*Poor match (CBR)*
10	*Norströmsgrund* *9thApril 2001*	*FLI*	*Reasonable match (FLI)*	*Poor match (CBR)*	*Poor match (CBR)*



Reasonable match: PSSII Case 5 ***Poor match: PSSII Case 6***

Figure 2 Validation criteria: illustration of ‘reasonable’ and ‘poor’ matches of model to data (*data shown in red, model simulation in blue*)

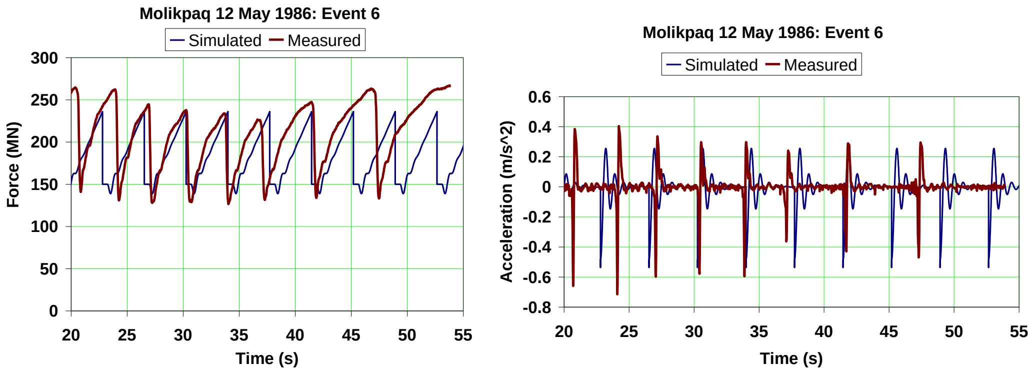


Figure 3 Improved fit of the Sodhi model after re-calibration following validation

FURTHER DEVELOPMENT

All three models considered in this JIP had two components: (i) tracking the relative motion of the structure to the ice at the near-field level, including aspects like the opening up of gaps and the difference between loading and unloading phases; and, (ii) the ice behaviour model including a strain-rate dependent strength, the amount of ice crushing on each fracture event, and the stiffness reduction from damage by fracture nucleation before failure. The JIP identified PSSII as offering the most sophisticated representation of (i) and further PSSII allowed encapsulation of (ii) as 'functions'. The PSSII model is also sutiable for simulating the response of a multi-degree of freedom systems. It was decided to support further development of PSSII towards a standard ice-structure interaction computational simulator and with the facility to allow other researchers to simply modify the idealization of ice behaviour, thus allowing future work to focus on "ice mechanics" rather than the numerical implementation of structural dynamics in moving boundary situation.

The original form of PSSII was 1960's era FORTRAN66, a style that is difficult to understand and quite distant from modern object-oriented coding. A modern object-orientated style is needed if the 'numerical' aspects are to be isolated and allow PSSII to become accessible to other researchers in ice mechanics. The JIP was therefore extended to include a re-coding of PSSII into FORTRAN90, with increased internal documentation. The revised code was verified against the original.

The updated PSSII code is now available to other researchers as 'open source' code. The JIP confidentiality restrictions limit such further work with PSSII to researchers under contract to one or more Participants until 2015, but the intention and hope is that the open-source PSSII will become a useful starting point for further work in modelling IIV. Particular aspects that are amenable to straightforward further development include: the rule for the amount of ice fracturing on each event; stochastic assignment of ice strength within the ice sheet; the stiffness reduction in the near-field from parent ice because of pre-failure cracking; the shear coupling within the far-field; and, energy dissipation in clearing the spalled/fractured ice during unloading.

CLOSURE

The 2010-12 JIP was a significant investment by companies interested in developing platforms for ice-infested areas. The JIP has provided significant insight into the reliability of the available methodologies regarding IIV. It is suggested that the revealed situation is unsatisfactory because, although some models provided reasonably good simulations for some cases, no model was able to predict correspondence with measurements for all circumstances. The effects of ice velocity on IIV frequency and a general inability to predict cyclic loading amplitude and period were key shortcomings in the models.

Participants came to the opinion that further work required more academic investigation. It is hoped that the initiative taken to move PSSII into an open-source computation environment will assist in this. The open-source code has been developed to the point where researchers can investigate differing idealizations by working with alternative 'user defined' functions for various aspects of ice behaviour.

REFERENCES

Gagnon, R. (2012). An explanation for the Molikpaq May 12, 1986 event. *Cold Regions Science and Technology*, Volume 82, October 2012, Pages 75-93

ISO19906 (2010). International Standard ISO 19906, Petroleum and natural gas industries - Arctic offshore structures. First Edition, ISO 19906:2010(E). December 15.

Jefferies, M., Rogers, B., Hardy, M., Wright, B. (2011). Ice Load Measurement on Molikpaq: Methodology and Accuracy. *Proceedings of the 21th international Conference on Port and Ocean Engineering under Arctic Conditions (POAC*), Montréal, Canada.

Hendrikse, H., Metrikine, A.V. (2013). The influence of friction at the ice-structure interface on ice induced vibrations. *Proceedings of the 22th international Conference on Port and Ocean Engineering under Arctic Conditions (POAC),* Espoo, Finland.

Sodhi, D.S. (1991). Ice-structure interaction during indentation tests. *In Ice-Structure Interaction: Proceedings of IUTAM-IAHR Symposium*, edited by S. Jones et al., Springer Verlag, Berlin, p. 619–640.

Sodhi, D.S. (1995). An ice–structure interaction model. *In Mechanics of Geomaterial Interfaces,* edited by A.P.S. Selvadurai and M.J. Boulon, Elsevier Science B.V., Amsterdam, p 57–75.

Sodhi, D. S. (2001). Crushing failure during ice-structure interaction. *Journal of Engineering Fracture Mechanics*, 68:1889–1921.

Spencer, P., Morrison, T., Jefferies, M. (2011) The effect of low pass filters in the Molikpaq data acquisition system on "phase lock" interaction signals. *Proceedings of the 21th international Conference on Port and Ocean Engineering under Arctic Conditions (POAC*), Montréal, Canada.

Kärnä, T., Kamesaki, K. & Tsukuda, H. (1999). A numerical model for dynamic ice-structure interaction. *Computers and Structures* 72(1999) 645 - 658.