3. PREVIOUS STUDIES

3.1 Objectives

As indicated in the introduction the objectives of the ice force studies, although basically the same, viz. to understand and quantify ice forces on offshore structures, were somewhat changed during the course of investigations. Before the 1970's the studies were mainly aiming at evaluation of "static" maximum ice force for various ice and structural conditions, based largely on experiences of cases of damages by ice "overloading" of lighthouse structures in the Gulf of Bothnia. At the start of the Phase 1 studies in 1985 the importance of dynamic ice action was focused at as well. In the initial declaration of the objectives, a static and a dynamic part of the ice load were defined, the latter with a "saw-tooth"-like time function, the amplitude of which was to be determined as well as the static ice load part. The intention was to study the "static" as well as the "dynamic" ice forces under a variety of structural and ice condition, since it was anticipated, that the ice-structure interaction would appear to be very sensitive to such variations.

Another important objective of Phase 1 one was the development and follow-up of various systems for data acquisition, such as instruments for measurement of structural "static" and "dynamic" responses with an extremely good resolution, video systems for automatic recording of ice drift situations and the ice force sensing panels.

Based on experience during the course of the investigations, the objectives were somewhat changed.

In particular, improved understanding of the mechanism of ice-induced vibrations (i.e. that the vibrations are "self-induced" as much as they are ice-induced and that the frequencies of the ice-load components are governed by the eigenfrequencies of the structures) made it clear, that it was better to concentrate on one single well-equipped structure located where ice drift is most frequent, than to spread out the resources. Data from FARSTUGRUND lighthouse was thus of the same character as data from NORSTRÖMSGRUND, but scarcer. Furthermore, the need of comparison between global and local ice forces as well as the need of a denser instrumentation for the refinement of the calculation model were good reasons for moving all he equipment to NORSTRÖMSGRUND, which was implemented before the observation period 1992.

It can be concluded, that the modifications of the initial objectives reflect a transition in the direction from a probabilistic to a more deterministic treatment of the ice-structure interaction problem. Initially, the phenomenon was assumed to be more complex and depending on "statistical" parameters to a greater extent than it now appears to be. At the present stage a deterministic formulation of ice-force expressions, such as Eq(2:4), appears to be a good basis for further research and for design purposes also, with conservative safety factors applied, particularly to the ice parameters. These parameters (strength, thickness) are likely to be the predominant contributors to the uncertainty of ice force predictions.

3.2 Scope and methodology

Since the scope of the previous studies is rather similar to that of the extended investigations and since the methodology for data acquisition and analysis is the same to a large extent, the presentation of the present report starts out from a recapitulation of the scope and methodology of Phase 1. In this section only a brief summary is presented, but more comprehensive descriptions are included in **Appendices 1 and 2**, where procedures for data acquisition and analysis are described quite in detail. These appendices are referred to also in the descriptions of the Phase 2 studies in Chapter 3 and the following chapters, where mainly novel features and thus not the procedures established during previous studies are addressed.

The structural responses due to ice action were measured and recorded by means of a system of accelerometers and inclinometers, including computer and filter units as well as tape recorders.

By means of the accelerometer systems the horizontal acceleration of the structures when vibrating were measured and recorded with a very good accuracy ever since the instruments were installed. A few outages occurred, but they were of minor importance.

The low-frequency or "static" deflection of the ice-affected structures were measured by inclinometers.

The accelerometers, as well as the inclinometers, are inertia sensing instruments of, in principle, similar basic design. The latter are, however, designed for measurement of extremely small inertia forces, primarily due to gravity in case of small changes of the tilt angles.

Great efforts were devoted to the development of such a system for measurement of the low-frequency components of the structural responses that constitute the basis for assessing the corresponding low-frequency ice force components. Realizing that the very small structural deflections had to be related to gravity, a pendulum system was tested parallel to the installation of inclinometers. After some trial operations and laboratory testing the preference was given to the latter instruments. Methods had then been developed for Fourier-processing of the signals in order to separate low-frequency from higher-frequency wave components and to distinguish between horizontal (inertia) and vertical (gravity) components. After one winter season of tentative operation the resolution of the inclinometer system was increased and during the winter season 1987-88 the performance of the inclinometers as well as other parts of the response measurement system was satisfactory.

Data regarding ice conditions have been acquired by means of video cameras, field sampling and study of reports regarding the large scale ice and weather conditions in the Bothnian Bay.

Video cameras mounted on the lighthouses were triggered automatically, when structural movements exceeded a certain acceleration limit. The ice drift velocity and the mode of ice failure could generally be determined by studying the video records and sometimes the thickness of broken ice could be estimated.

The field investigations were focused on measurement of ice thickness and ice temperature, and on sampling of cores for laboratory investigation of strength and other physical and mechanical properties.

A large collection of structural response data was acquired in the form of acceleration records, from accelerometers as well as from inclinometers. In order to avoid signal disturbances as much as possible, the signals were digitized before being recorded on magnetic tapes and, later, on diskettes. The data sequences were labelled so that they could be synchronized with the video records.

The most complete collection of response and video records was acquired during the winter season 1987-88. This collection contains a large number of records from ice drift events associated with more or less pulsating ice forces, many of which of pronounced resonance character. Some records from the 28th of March are particularly valuable, since resonance ice-structure interaction is represented as well as more "static" indentation and since field samples were taken shortly before the ice started to move.

The transformation of response data to ice force was performed by mathematical modelling of the structures and their constitutive properties etc. Finite element models were employed for determining the modes of deflection.

The dynamic ice-structure interaction was assessed by determining the dynamic equilibrium of simplified one-degree-of-freedom systems, the spring stiffness and internal damping of which could be determined within a narrow uncertainty range, since the fundamental structural frequency and the damping could be unambiguously identified in several records of free vibrations.

Whereas the transfer function, coupling the dynamic mode of deflection to the ice force, could thus be determined without further calibration measures, the corresponding static transfer function, i.e. the spring stiffness coupling static load and deflection, could only be roughly estimated without calibration tests. Pull tests were therefore performed in 1987 by means of a large tugboat. The time-histories of the applied forces were measured by means of load cells and the corresponding deflection time-histories were registered by means of the inclinometer system.

Several procedures for transformation of the response signals to ice force functions were developed and tested. Problems that had to be solved were associated with, for instance, the identification of small-amplitude, low-frequency signals in the strongly pulsating inclinometer output and then to dissolve those signals into horizontal and vertical components. Other problems were associated with base-line errors and difficulties to identify the true zero base-line in the response signals. It appeared, that integration could not be carried out over any longer time intervals without causing problems such as amplification of small base-line errors.

However, the problems were essentially solved by introducing Fourier-processing of the signals. By dissolving them into sinusoidal components the various filtering processes and base-line corrections were greatly facilitated. Moreover, the spectral characterization of the signals appeared to be beneficial to the understanding of the interaction mechanism and the generalization of the ice force, as will be further demonstrated.

The analysis procedures are described step by step in **Appendix 2.**

3.3 Survey of sampled data

Data sampled during the period 1979-85 (before the start of Phase 1) was presented and analysed in Report No. 2 of Phase 1. Data sampled during the course of Phase 1 was dealt with in Report No. 5.

The quality of the data has been improved continuously. Therefore, although early data were very useful as a basis for improving the understanding of the ice-structure interaction phenomenon and for further development of data acquisition systems and analysis methods, data from the end of the second period is preferred for deterministic analysis, due to its completeness and comparatively high resolution. Actually, as pointed out in Report No. 5, there was good reasons for concentrating the analysis on selected data from the winter season 1987-88, which records are unique, since both low-frequency and high-frequency responses were recorded with a very good accuracy and since the ice parameters could be assessed reasonably well, particularly during some sequences of strong resonance vibrations.

Some data from this period has been selected for reexamination, employing the improved analysis methods developed during Phase 2.

An overview of data from the winter season 1987-88 was presented in Report No. 5. Table 3-1 is reproduced from that report.

3.4 Proposed model of ice-structure interaction

As a result of the Phase 1 studies a model for assessment of forces exerted by drifting ice on offshore structures was proposed. Basically, this model consisted of one quantitative and one qualitative part.

The quantification was expressed in the form of a generalized time-history of the global ice force or the effective ice pressure (to be multiplied by the gross contact area to obtain the global ice force).

$$p_{eff}(t) = p_0 + \Sigma p_n \cdot \sin(n\omega_1 + \theta_n) \qquad (3:1)$$

Ice drift period	Max. acc.	Remarks
880113	0.35g	A few sequences of strong vibration
880117-20	0.40g	A few sequences of medium to strong vibrations
880205	0.10g	Field sampling 880210. 14 hours' intermittent vibration
(880110, 14)		Ice pressure (stationary)
880216	0.10g	Short vibration sequence
880211-26	0.25g	Many short and some long sequences
880301	0.20g	Several short and some long sequences
880303	0.25g	Several long and some short sequences
880307	0.20g	Many long and short sequences (mainly small amplitudes)
880310-11	0.20g	Many long and short sequences (mainly small amplitudes)
880320-26	0.10g	Many long and short sequences (mainly small amplitudes)
880328	0.35g	Field sampling 880328. Strong vibrations

Table 3-1: Observed ice drift periods in 1988 at Norströmsgrund

The loading function was thus represented by a constant p_0 and a series of sine waves with n = 1, 2, 3, 4 etc., the angular frequencies $n\omega_1$ of which are multiples of the fundamental structural frequency ω_1. The coefficients p_0, p_1 .. p_4 were tentatively quantified in relation to the peak pressure p_{max}. Typical relations between the effective pressure and the uniaxial ice strength were also indicated.

The qualitative part of the model was an attempt to explain the mechanism of ice-structure interaction, primarily the "dynamic" phenomena, although coupled to "static" indentation. Of course, these explanations were partly hypothetical, but were suggested as a basis for the planning of continued studies, particularly investigation of the distribution of the ice pressure not only in time but also in space.

The model thus proposed was described briefly in a report to the POAC 89 conference, which report is enclosed as **Appendix 3.**