Chapter 8

SUMMARY AND CONCLUSIONS

Keel load modelling is a complex and multifaceted problem which has not been fully understood, in spite of many investigations. This thesis documents the development of a new approach to first-year ridge keel load modelling. Insight into the keel load prediction problem was gained through a series of investigations which involved the organisation and analysis of prior work and new experimental investigations. The body of work in this thesis is partitioned into background research, exploratory experimentation and model development phases.

In the background chapter a detailed research effort is described in which many literature sources are interpreted, grouped and examined. The topics included parent ice properties and physical characteristics of ridges, a review of ice rubble shear strength, a study of laboratory and full-scale ridge load investigations and a review and sensitivity study of ridge keel force models in the literature. This background study laid the groundwork for subsequent investigations by demonstrating the scarcity of controlled experimental results, and by exposing parametric and force model uncertainties.

Following the background chapter exploratory experiments are described, the first of which was a multiphased pilot ridge study involving work with both ice blocks and sand. Subsequent larger scale ice ridge/structure interaction experiments provided detailed information into both cylinder and cone shaped structure interaction mechanics. A program in which an *in situ* technique for determining the shear strength of ridge keels was then developed and tested in the laboratory. All of these programs provided direction for future tests and new data sets, which were grouped with those from the literature for a composite regression study.

The regression study was concerned with developing best-fit empirical formulas which avoided the theoretical trappings of pre-existing models and dealt with variable multi-colinearities and some laboratory scale effects. Focus was primarily on ice rubble shear strength and structure interaction forces. Ridge keel shape was also briefly examined in this chapter insofar as it was demonstrated that a "sine" shaped keel approximation was more suitable than the traditional triangular shape in matching measured cross-sectional areas and for use in analytical modelling. In the study of ice rubble shear strength, state-dependencies and high variability were revealed and quantified. Best-fit empirical models for Mohr-Coulomb yield criteria were ascertained from the composite data set and a more fundamental study of shear data provided a non-linear interpretation of the behaviour of ice rubble strength.

The study of earlier and recent structure interaction experiments collectively, led to the conclusion that the most significant parametric grouping describing ridge forces was based on hydrostatics as used in earth pressure formulas. Though highly significant and effective, the raw form of the regression formulas did not provide guidance on the composition of the proportionality coefficients. This weakened confidence in predicting forces outside the range of the laboratory tests considered. Because of this, a new series of experiments which were sensitive to the unique boundary conditions and alignments of ridge/structure interactions were undertaken. They involved the substitution of sand for ice rubble in indentation tests which afforded a level of control and measurement that enabled the development and calibration of a highly effective force model.

The specific goals of the sand experiments were to investigate "sand keel" failure modes, structure shape effects, effective structure width, keel shape sensitivities, ridge indentation at peak load and the evolution of rupture surfaces and debris accumulations with penetration. A parallel series of tests was performed in which a cone-shaped model was used since there is considerable interest in industry in this structural shape. There was no attempt to scale sand indentation forces. Analysis of the sand tests collectively made it possible to adapt and calibrate the time-tested passive earth pressure formula as a load prediction model for sand ridge interactions. This highly successful model application provided a solid geotechnical base solution which was then exploited for the ice ridge problem.

The model developed for vertical structures using sand tests was tested against the laboratory ice ridge results. The absence of displaced rubble accumulation (surcharge) underwater in the ice ridge experiments supported the omission of this effect in the model. Uncertainty over the parametric values for ice rubble shear strength promoted the use of two different sets of yield criteria. Both yield criteria from literature sources and values derived empirically in this study were used in the model and the merits of both were discussed. Ultimately, the model developed in this thesis performed very well by consistently predicting loads within 20% of measured values. The measured versus predicted force comparisons showed a higher scatter for the cone tests than those for the vertical structure, even though average interaction forces were well predicted by both.

The analytical advantage of the first-year ridge keel modelling approach developed in this thesis is that the ridge shape is better approximated, ridge width is a factor, surcharge effects are considered, an effective structure width model was developed and implemented, and the model was effectively tested against a large body of new data. Also the model is closed form and singular, has been successfully applied to vertical and conical structures, and is based on fundamental earth pressure equilibrium mechanics as are other approaches already in the literature. A further advantage is that the input yield criteria have been critically examined so that parametric uncertainties are quantified and reduced.

The last chapter of this thesis considers fluid dynamics, inertia effects and the application of the new load model to full-scale force prediction. Though only a review, it was demonstrated that fluid dynamics can play a significant role in ice rubble behaviour underwater at larger scales. It is pointed out that there is no significant evidence of speed related fluid dynamic of fluid inertial effects on interaction forces in the laboratory. Thus these effects are not considered in the full-scale sensitivity study, though it is recommended that they be the focus of future research thrusts.

The full-scale load prediction performance of the model developed in this thesis was considered in light of other models from the literature, Dolgopolov *et al.* (1975) and Croasdale (1994). The load values from the new load model were consistently in the range of the loads expected when one considers the *cross-over* technique which employs both of the other models. A comparison of model sensitivity results with the average ridge factor and ridge keel line loads from field data sources shows excellent agreement for the new model. By way of comparison, for design conditions analogous to those for the Northumberland Strait, the thesis model predicted a force which was equivalent to the average of the forces predicted by 10 other models from the literature.

There are many opportunities to improve upon and advance the work thrusts described in this thesis. Of these opportunities two feature prominently; detailed investigations of ridge keel fluid dynamics/inertia effects, and, field work. Field experiments feature as the most significant and probable source of new information. Verification of failure modes, measurements of ridge geometries, *in situ* tests of rubble shear strength, and ultimately, full-scale force measurements should, and will, have the greatest influence over future model developments. Without question, field studies such as these should be the immediate focus of organized research efforts.