MODELING ICE PROCESSES IN LABORATORIES AND DETERMINATION OF MODEL ICE PROPERTIES

Karl-Ulrich Evers
Hamburgische Schiffbau-Versuchsanstalt GmbH, Hamburg, Germany

Keywords: similarity laws, model ice, ice tank, mechanical model ice properties, sea ice, model test in ice, level ice, ice ridges, ice rubble, ice density, ice crystals, flexural ice strength, compressive ice strength

Contents

Summary

Strong effects of climate change are taking place in the Arctic. This climatic evolution is going to have significant impacts on both marine ecosystems and human activities in the Arctic. Due to the decline of sea ice in the Arctic, the maritime traffic in icy waters, in particular along the Northern Sea Route (NSR), the northern seaway connection between Europe and Far East, has increased significantly. Likewise, the activities related to the extraction of oil and gas has been increasing in the Arctic. Both the use of ice-going vessels and marine structures in ice-covered waters is a particular challenge in terms of environmental protection because it is associated with risks. To avoid interfering influences of the environment, ships and marine structures should be designed in such a way, so that the risk of an accident or damage due to ice and other prevailing environmental conditions (e.g. wind and waves) is minimized. In this context the ice forces acting on ships or offshore structures play a significant role.

In the past, the implementation of numerical and physical model testing has proven to help investigate the behavior of ships and marine structures in different ice scenarios. The insights gained from the experiments provide a basis for a sustainable and innovative technology of ice-breaking ships and marine structures in ice. In this chapter special emphasis is placed on description of similarity laws, model ice production process and presents various methods to determine the mechanical properties of model ice. This chapter gives a general overview only, thus the reader is advised to study the relevant literature.

1. Introduction

Physical models have been used for long time and are still currently used in the field of ice engineering to investigate natural processes because numerical models have not yet been able to simulate such complex processes. Physical modeling is used as a design tool for marine structures worldwide. The prevalence of hydraulics and hydrodynamics laboratories in research institutes across the world is testimony to the continued importance and influence of physical model testing in ice engineering today. This history and practice of hydraulic modeling has been reported in many books and papers.

Over the years technology has improved and the tools, techniques and procedures used in ice model tests have evolved. The rate of technological change has never been greater and new tools and techniques to improve the range of services offered by hydraulic and hydrodynamic laboratories are successively developed (Sutherland and Evers, 2013).

Qualitatively physical models are close simulations of the prototype and contribute to obtain a better understanding of the various processes and to see aspects in the model that are not obvious from prototype observations. Also trial and error changes that would be costly or impossible to make in the prototype are simple and inexpensive in the model, e.g. hull shape optimization of an icebreaking vessel.

The physical model simulates the prototype closely and therefore a physical model provides qualitative results, also for problems for which the processes are not well understood or well described by theory. Complex nonlinear physical processes, for example, can be reproduced in a well-designed physical model.

When designing a physical model the scales must be determined for the various model parameters. Model scales may be derived either from the governing equations or by dimensional analysis. Both methods have their strengths and limitations and hence both should be used. Neither method can completely describe a physical model since a model simulates the prototype better than either equations or dimensional analysis. That is why physical models are used (Kamphuis, W.J. 2000).

Icebreaking vessels, fixed and moored floating offshore structures (e.g. GBS, FPSO, FPU, buoys, SPAR , tension leg platforms and semi-submersibles) in cold regions may be subjected to different sea ice conditions. For design purpose it is essential to estimate the ice forces acting on the structure, the mooring system and its behavior in different ice conditions, like level ice, broken ice, ice ridges and ice rubble fields. Therefore ice model tests are carried out in ice facilities for various types of offshore structures to investigate the ice-structure interaction.

In general, the principles and similitude laws for model tests of structures in ice are based on commonly agreed theories and laws similar to model testing in open water. The primary purpose of this chapter is to give advice and background information on ice model testing of icebreaking ships, fixed and floating structures, to understand the important issues that should be taken into account when planning and conducting ice model tests.

In this chapter, the focus is placed on the physical modeling of sea ice. Modeling of river and lake ice is not subject to this chapter.

2. History of Model Ice Development

Physical modeling of ice-structure interaction has become an important technique in determining the ice loads and optimizing the design of ice breaking vessels, arctic offshore structures, etc. The first use of a material to model natural ice behavior in scale physical models dated back to 1918 when blocks of paraffin wax were used to model ice movement on flowing water (USDI, 1980). Paraffin blocks were also used in 1949 for the first reported model of ice jamming on the St. Francis River near Bromptonville, Quebec (FENCO 1949). Since then, many alternative materials have been developed and adapted for use as model ice in physical models of diverse ice processes. (Zufelt and Ettema, 1996).

Sutherland and Evers (2013) gave a good history of model ice development. Today hydrodynamics facilities in Canada, U.S.A., Germany, Russia, Finland, Japan and Korea are operating ice tanks and refrigerated laboratories.

Model ice is an integral part of the physical modeling process of ice-structure interaction. The model ice must represent as accurately as possible the full scale mechanical sea ice properties (Sinha, 1987). Froude and Cauchy scaling laws are used for the majority of ice model tests so that the prototype structure is reduced in its linear dimensions by a constant scale factor λ .

The properties of the model ice must be adjusted such that its strength (compressive, flexural, shear and tensile), stiffness and thickness must be reduced from the full scale or prototype value by λ, however its density and frictional characteristics must be the same as the full scale values. It is important that the model ice is an accurate representation of the prototype ice -either freshwater ice or sea ice. (Timco, 1986).

In the first model tests with ice in St. Petersburg, Russia in 1957 (Shvayshteyn, 1957), the model ice was produced by freezing an aqueous solution containing a relatively high (~3%) concentration of sodium chloride salt. The salt was trapped within the ice and by internal melting, reduced the strength of the ice. This type of ice however, was not satisfactory because its stiffness (or strain modulus) was far too low and the ice exhibited unrealistic plastic deformation (Timco, 1986).

In Canada a synthetic model ice was developed by Michel in 1969, which was patented and used by a private company in Canada and the US. However the use of this type of model ice has not been pursued further.

Schwarz (1975) developed a tempering technique whereby sheets of ice were frozen from solutions containing a lower concentration of sodium chloride (0.6%) and by warming up the ice after freezing process. The improvement due to this technique is a more accurately scaled stiffness of the ice sheet compared to ice sheets containing higher concentrations of sodium chloride salt.

In 1979 Timco developed a refrigerated model ice grown from an aqueous solution containing urea as a chemical dopant, in order to achieve lower model ice strength compared to pure freshwater model ice. This type of ice has a thin upper granular congelation layer of which can be minimized by seeding and growing the ice sheet at the lowest temperature that can be achieved (Zufelt and Ettema, 1996).

Furthermore experiments with different chemical dopants were made and in 1986 Timco introduced a new type of model ice – termed EG/AD/S ice – containing ethylene glycol, aliphatic detergent and sugar. This type of model ice is single-layered without a congelation layer and has a fine grained and strictly columnar crystal structure. This EG/AD/S ice produces flexural strength σ_f, elastic modulus E, and E/σ_f ratio values that are very close to those of urea-doped ice, but it has more realistic fracture-toughness performance, and thus cracking replication, because it is nearly single-layered (Zufelt and Ettema, 1996; Timco, 1986).

A type of fine-grained model ice called WARC FG-ice was developed in Finland (Enkvist and Mäkinen, 1984) The ice sheet is grown by continuously spraying tank water (at 2% saline concentration) above an initially seeded sheet at room temperatures of –16 to –22°C. It is reported that similar results have been obtained using a 3% urea solution with the same growing technique, but that the urea provides no inherent advantage over the less costly NaCl (Zufelt and Ettema, 1996). The FG-ice is a fine-grained granular structured model ice which has several promising features. However, the granular structure limits the use of the ice since it does not accurately represent the structure of sea ice which is mostly columnar. The fine-grained model ice does not allow the ice to be scaled correctly in either uni-axial compressive strength or confined compressive strength (Timco, 1986). This may lead to a premature ice failure and a corresponding under-prediction of the loads on the full scale structure (Timco, 1984b; Wang, 1984). The WARC-FG has been modified by spraying a 2% saline solution, spraying is conducted with water of saline concentration varying between 0.1 and 1.6%. It is reported that WARC FGX-ice has better strength simulation characteristics than does WARC-FG ice (Nortala-Hoikkanen, 1990).

At the NKK Ice Model Basin in Japan the ice sheet production is similar to that of the FG- or FGX-ice. The tank water urea concentration is held at 2.5% and the spray water concentration at 0.5 to 1.3%. This allows the tank water temperature to be brought down to –0.4°C (the approximate freezing point of the spray water yet still above the tank water freezing point) prior to seeding. The difference in concentrations of the tank and spray water prevent the growth of columnar ice at the bottom of the initial ice sheet during consolidation and tempering (Narita et al., 1988).

In 1989 the Helsinki University of Technology (HUT) rebuilt their ice model basin and sought an ice material that was fine-grained and brittle to properly model icebreaker testing. HUT uses only 0.5% ethanol as a dopant as a noncorrosive, nonhealth-hazardous material. The resulting GE (granular ethanol) ice is produced by continuous spraying over the basin at air temperatures of approximately –10°C (Jalonen and Ilves, 1990).

Until late 1980's The Hamburg Ship Model Basin (HSVA) produced a refrigerated model ice grown from an aqueous solution containing urea as a chemical dopant by application of a seeding technique. This type of model ice is strictly columnar structured but has a thin upper granular layer. The brine is entrapped along the boundaries of columnar ice crystals. Some time before the target ice thickness is achieved the ice growing process is stopped and the ice is warmed up at a constant air temperature to achieve the desired strength in the model regime.

Investigations with respect to the improvement of ice properties were made by using various dopants like EG/AD/S and glycerol instead of urea. However, on one hand these chemical dopants reduce the translucence in the water and glycerol is rather costly. The aspect of excellent water translucence is important, because the observation of ice failure processes, propeller-ice interaction and ice clearing by means of underwater video recording. On the other hand the content of sugar in the EG/AD/S dopant may cause bacterial pollution and the chemical stability of the dopant with sugar additive cannot be easily maintained.

Thus, today an aqueous solution containing sodium chloride (~0.7% concentration) is used as dopant at HSVA in combination with air bubble entrapment, in order to get a stable chemical condition in the tank water and to improve the mechanical properties.

By using a single dopant system the grown model ice sheet consists of a three-layer system:

- thin hard upper granular layer
- transition layer with higher dopant concentration
- weak columnar crystal layer

Figure 2-1 shows a thin section of first-year sea ice. The structure of this type of ice is columnar with a thin hard granular layer on top. Since the model ice is denser than in full scale, the criteria for buoyancy similitude may not be met. Thus methods were developed at NRC Canada for EG/AD/S CD-ice (Spencer and Timco, 1990) and HSVA, Germany, for NaCl doped model ice to incorporate air bubbles (see Figure 2-2) into a growing ice sheet in order to control its overall density (Evers and Jochmann, 1993).

For this purpose a new model ice production technique (Evers and Jochmann, 1993, Hellmann et al.,1992) was developed at HSVA and is applied by pressing air saturated water under high pressure through perforated tubes fixed at the bottom of the ice tank during ice growth process at about – 20°C air temperature. When the water leaves the tubes the pressure drops. Tiny air bubbles of 200-500 μm diameter which rise upwards and are embedded in the growing ice sheet. The content of micro bubbles affects also the E/σ_f ratio which increases significantly and the ice behaves more brittle when it fails. A secondary effect of air inclusions is the opaque color of the ice giving a better contrast between model and ice in images taken from underwater (Evers and Jochmann, 1993).

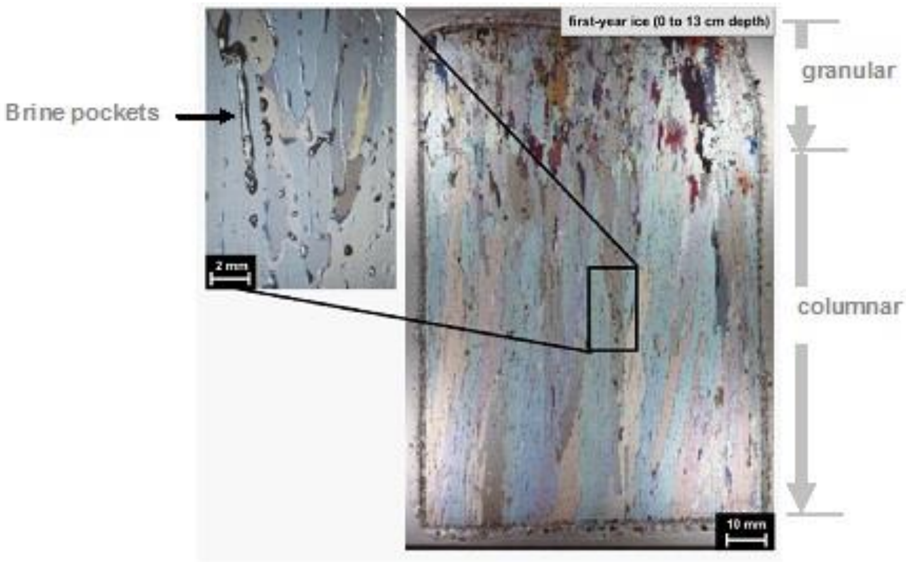

Figure 2-1. Thin section of first-year ice showing the ice platelets and the brine pockets along the grain boundaries (photo courtesy of M. Johnston; Timco & Weeks 2010b).

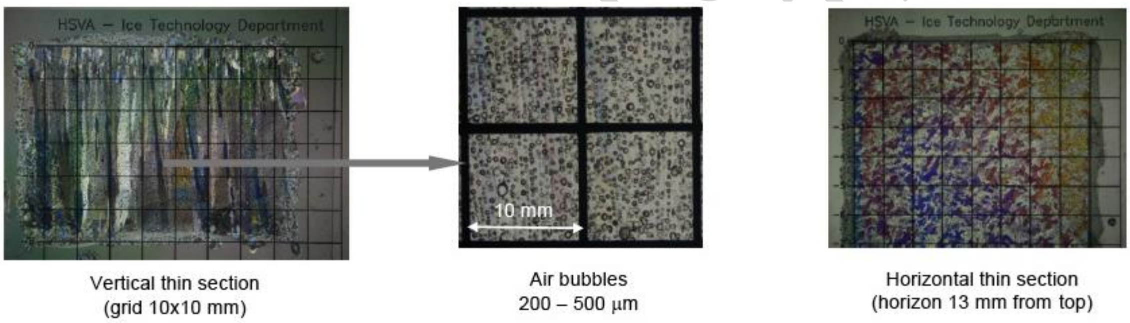

Figure 2-2. Vertical and horizontal thin sections with micro bubble inclusions in model ice.

3. Similitude Considerations and Scaling

The application of physical models is a well established engineering practice, especially in hydraulics and the design of ships and offshore structures (Hughes 1993; Chakrabarti 1994). William Froude (1810-1879) studied the resistance of ships in a towing tank in 1870, which involved inertial and gravitational forces. Osbourne Reynolds (1842-1912) developed the *Reynold*s number in his study of flow in parallel pipes to distinguish between laminar and turbulent flow conditions. (Briggs, 2013).

The Cauchy number $\nu_{\mathrm{p}} = \lambda^{3/2} \nu_{\mathrm{m}}$ is one of the dimensionless numbers of physics. It is named after Augustin Louis Cauchy (1789-1857) and gives the ratio of inertial forces to the elastic forces in solids. Furthermore, it is used in the similarity theory. Two processes which take place mainly under inertial and elastic forces are mechanically similar if their Cauchy numbers match.

The Froude, Reynolds and Cauchy numbers are the most important non-dimensional similarity parameters used in physical ice modeling. To insure total similitude in model tests, the Froude-, Reynolds- and Cauchy numbers must match those of the proptotype. This is virtually not possible unless a fluid used in tanks can be found where $\nu_p = \lambda^{3/2}\nu_m$ (ν = viscosity, λ = scale factor, m index for model and p index for prototype). Because doped water in the tank is the working fluid, its viscosity is very close to that of pure water, hence the condition is not accomplished and therefore the viscous effects cannot be modeled correctly. At low speeds this is in general not a problem but has to be kept in mind for high speed tests or if tests are conducted at high scale factor (Timco, 1984a). The effects of such non-similarity are called "*scale effect*". The model boundaries should simulate the prototype conditions as closely as possible, but a perfect simulation can never be achieved. For example due to the limited width of the ice tank the tank walls cause a confinement of the ice sheet. This phenomenon must be taken into account when tests in managed ice (ice floes) are conducted. The difference in response between the model and the prototype resulting from such simplified boundary conditions is called "*laboratory effect*".

When conducting ice model tests the behavior of the vessel or structure must be similar as in full scale. If this requirement is fulfilled the results for the model can be transferred to full scale by a proportionality factor λ.

The discussion is separated into:
- geometrical similitude
- kinematical similitude
- dynamical similitude

3.1. Geometrical Similitude

The ratio of full-scale prototype "length" (e.g. length, width, draught etc.) L_p to a model-scale "length" L_m is constant:

$$L_p = \lambda L_m \tag{3-1}$$

For areas A and volumes $\forall$ one gets correspondingly:

$$A_p = \lambda^2 A_m \tag{3-2}$$

$$\forall_p = \lambda^3 \forall_m \tag{3-3}$$

where $\forall$ is the displaced volume.

3.2. Kinematical Similitude

The ratio of full-scale prototype "time" T_p to a model-scale "time" T_m is constant and named kinematic model scale factor τ:

$$T_{\mathrm{p}} = \tau T_{\mathrm{m}} \tag{3-4}$$

Geometrical and kinematic similitude result in the following scaling factors for "velocities" V and accelerations a:

$$V_{\mathrm{p}} = (\lambda / \tau) V_{\mathrm{m}} \tag{3-5}$$

$$a_{\mathrm{p}} = (\lambda / \tau^2) a_{\mathrm{m}} \tag{3-6}$$

-

-

-

Bibliography

Ashton, G. (Editor), (1986). *River and Lake Ice Engineering.* Water Resources Publications LLC, Littleton, Colorado, USA [A collection of key studies made in river and lake ice processes and engineering developments.]

Assur, A., (1958). Composition of sea ice and its tensile strength. In: *Arctic sea ice. U.S. National Academy of Sciences* – National Research Council, Washington, D.C., Publication 598, pp. 106-138. [Comprehensive description of the tensile strength of sea ice.]

Azarnejad A., and Brown T.G., (1998). Observations of ice rubble behaviour in punch tests, Proceedings of 14th IAHR Symposium on Ice – Ice in surface waters, July 27-31,1998, Postdam, NY,USA, pp. 589-596. [Description of the behavior of ice rubble and the geometry of the failure planes during punch tests.]

Bazant, Z., (1995). Scaling of Quasi-Brittle Fracture and the Fractal Question, *Journal of Engineering Materials and Technology*, October 1995, Vol. 117 [A review on scaling of failure of structures made from quasi-brittle materials.]

Bertram,V., (2000). *Practical Ship Hydrodynamics,* Butterworth-Heinemann, ISBN075064851, [Comprehensive textbook about ship hydrodynamics, seakeeping, maneuvering and CFD.]

Briggs, M. J. (2013). Basics of Physical Modeling in Coastal and Hydraulic Engineering, U.S. Army Corps of Engineers, Report ERDC/CHL CHETN-XIII-3, September 2013. [Technical note presenting a brief overview of the basics of physical modeling. The scope is limited to physical modeling topics that are used in free-surface fluid flow problems.]

Chakrabarti, S.K., (1994). *Offshore structure modelling. Advances Series on Ocean Engineering* – Volume 9. World Scientific, pp 470. [Comprehensive textbook on modeling of marine offshore structures].

Chakrabarti, S. K., (2002). *The Theory and Practice of Hydrodynamics and Vibration., Advanced Series on Ocean Engineering* – Volume 20, World Scientific, reprinted 2008. [Textbook on hydrodynamics and vibration phenomena.]

Enkvist, E. and Mäkinen, S., (1984). A fine grain model ice. Proc. IAHR Symposium on Ice, Hamburg, Germany, Vol. II, pp. 217-227. [Introduction of a new model ice type to be used for model tests in ice tanks]

Evers, K.-U. and Jochmann, P., (1993) .An Advanced Technique to Improve the Mechanical Properties of Model Ice Developed at the HSVA Ice Tank, Proceedings of the 12th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), 17- 20 Aug. 1993, Hamburg, Vol. 2, pp. 877 – 888 [Description of model ice production methods and techniques in ice tanks]

FENCO, (1949). Model Study of the Bromptonville Ice Jam. Foundation Engineering Company of Canada, Internal Report.

Frederking, R. and Häusler, F.U., (1978). The flexural behaviour of ice from *in situ* cantilever beam tests, Proc. IAHR Symp. on Ice Problems, Part I, Lulea, Sweden, pp. 197-215. [Discussion of the elastic theory of a beam on an elastic foundation and presentation of results from *in situ* cantilever beam tests in Spitsbergen.]

Frederking, R. and Gold, L.W., (1975). Experimental Study of Edge Loading of Ice Plates, *Canadian Geotechnical Journal*, 1975, 12(4): 456-463, 10.1139/t75-053. [Description of model test performance and analysis of edge loading large plates of granular ice.]

Haase, A., van der Werff, S. and Jochmann, P., (2012). DYPIC - Dynamic Positioning in Ice: First Phase of Model Testing, Proceedings of the 31st International Conference on Ocean, Offshore and Arctic Engineering OMAE 2012, July 1-6, 2012, Rio de Janeiro, Brazil, Paper No. OMAE2012-83455. [Paper addressing model tests in ice with respect to dynamic positioning of an icebreaking vessel]

Hellmann, J.-H., Rupp, K.-H., Evers, K.-U. and Häusler, F.U., (1992). Method and devices for forming a sheet of ice for, in particular, tests with ship models or models of marine structures, Patent No. PCT/EP1992/000305; DE 4106930 A1. [Patent specification about ice sheet production for model tests with ship models and marine structures.]

Hughes S.A., (1993). *Physical models and laboratory techniques in coastal engineering, Advanced Series on Ocean Engineering*, Vol. 7, World Scientific Publishing, Singapore. [Textbook covering topics of physical models, systems of units, dimensional analysis, types of similitude and various hydraulic similitude criteria applicable to coastal engineering models.]

Hutter, K. and Jöhnk,K., (2004). *Continuum Methods of Physical Modeling - continuum mechanics, dimensional analysis, turbulence*. Springer Verlag Berlin-Heidelberg-New York, 2004, ISBN 3-540-20 619-1. [Textbook giving an introduction to continuum thermomechanics, the methods of dimensional analysis and turbulence modeling.]

ISO 19906 (2010). ISO/TC 67/ SC7. Petroleum and natural gas industries – Arctic offshore structures, 2010. [ISO 19906 is one of a series of International Standards for offshore structures.]

Jalonen, R. and Ilves, L., (1990). Experience with a chemically-doped fine-grained model ice. Proceedings of the 10th IAHR International Symposium on Ice, Espoo, Finland. International Association for Hydraulic Research, vol. 2, p. 639–651. [Article on chemically-doped model ice].

Jensen, A., Hoyland, K. V. and Evers, K.-U., (2000). Scaling and measurement of ice rubble properties in laboratory tests. Proceedings of the 15th International Symposium on Ice (IAHR), August 28 - September 1, 2000, Gdansk, Poland, Vol. 1, pp. 105- 112, ISBN 83-85708-39-1. [Presentation on ice rubble shear tests in an ice laboratory.]

Johnston, M., Masterson, D. & Wright, B. (2009). Multi-year ice thickness: knowns and unknowns. Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Luleå, Sweden. [Paper on studies of multi-year ice in the Canadian Arctic. Compilation of about 5000 thickness measurements of multi-year sea ice from about 30 studies, spanning more than 50 years].

Kamphuis, W. J., (2000). *Introduction to Coastal Engineering and Management - Advanced Series on Ocean Engineering* Volume 16, Published by World Scientific Publishing Co. Pte. Ltd., ISBN 981-02-3830-4. [Textbook on coastal Engineering]

Leppäranta, M. (2005). *The Drift of Sea Ice*. Springer-Verlag, New York, 266 p. [Comprehensive textbook on drifting sea ice].

Leppäranta, M. and Hakala, R., (1992). The structure and strength of first-year ridges in the Baltic Sea. *Cold Regions Science and Technology*, 20 (1992), pp. 295-311. [Journal paper focusing on morphology and properties of first-year ridges in the Baltic Sea]

Narita, S., Inoue, M., Kishi, S. and Yamauchi, Y , (1988). The model ice of the NKK ice model basin. In Proceedings of the 9th International Symposium on Ice, August, Sapporo, Japan. International Association for Hydraulic Research, vol. 1, p. 782–792. [Paper on the production of model ice at the NKK ice model basin]

Nortala-Hoikkanen, A., (1990). FGX Model Ice at the Masa-Yards Arctic Research Centre. In Proceedings of the IAHR 10th International Symposium on Ice, Espoo, Finland. International Association for Hydraulic Research, vol. 3, p. 247–259. [Paper on the production of model ice at the MARC ice model basin]

Riska, K., Leiviskä, T., Nyman, T., Fransson, L., Lehtonen, J., Eronen, H. and Backman, A., (2001). Ice Performance of the Swedish Multi-Purpose Icebreaker Tor Viking II. Proceedings of the POAC01, Ottawa, Canada. [Article on results achieved during ice trial with Swedish icebreaker Tor Viking II.]

Sand, B., (2008). Nonlinear finite element simulations of ice forces on offshore structures, Doctoral Thesis, Luleå University of Technology, Department of Civil, Mining and Environmental Engineering Division of Structural Engineering

Sanderson, T. J., (1988). *Ice mechanics - Risks to offshore structures*, Graham &Trotman, London, 1988. [Textbook on ice mechanics and the risks to offshore structures in ice-covered regions.]

Schulson, E., (1999). The Structure and Mechanical Behavior of Ice, JOM - *The Member Journal of The Minerals, Metals and Materials Society* JOM 51 (2) (1999), pp. 21-27. [Publication on crystal structure and mechanical behavior of ice].

Schwarz, J., (1975). On the flexural strength and elasticity of saline ice. Proc. 3rd IAHR Int. Symp. on Ice Problems, Hanover, N.H., U.S.A., pp. 373-386. [Article on flexural strength and elasticity of saline ice.]

Schwarz, J., Frederking, R., Gavrilo, V., Petrov, I.G., Hirayama, K.I., Mellor, M., Tryde, P. and Vaudry, K.D., (1981). Standardized testing methods for measuring mechanical properties of ice, *Cold Regions Science and Technology*, 4 (1981) 245-253, Elsevier, Amsterdam - Printed in The Netherlands. [Working group report on standardized testing methods to investigate mechanical ice properties.]

Shvayshteyn, Z., (1957). Laboratory for Studying Ice and Testing Models of Icebreakers, Problem Arktiki 2, 1957, pp.171-178 (in Russian). [Report on a Russian ice laboratory for testing ship models in ice at the beginning of the ice engineering era].

Sinha, N., Timco, G.W. and Frederking, R., (1987). Recent advances in ice mechanics in Canada Reprinted from Applied Mechanics Reviews Vol. 40, No. 9, September 1987, p. 1214-1231 (IRC Paper No. 1488). [This publication is a review and summary of important advances made in ice engineering.]

Sodhi, D.S., Kato, K., Haynes, F.D. and Hirayama, K. (1982). Determining the Characteristic Length of Model Ice Sheets, *Cold Regions Science and Technology*, 6, 1982, pp.99-104. [Comprehensive study with respect to the characteristic length of model ice sheets].

Spencer, D.S. and Timco, G.W., (1990). CD Model ice: A process to produce correct density (CD) model ice. In Proceedings of the IAHR 10th International Symposium on Ice, August, Espoo, Finland. International Association for Hydraulic Research, vol. 2, p. 745–755. [Description of methodology to produce the correct density of model ice.]

Strub-Klein, L. and Sudom, D. (2012). *A comprehensive analysis of the morphology of first-year sea ice ridges.* Cold Regions Science and Technology, 82, pp. 94-109. [Comprehensive study of first-year ridges in natural sea ice.]

Sutherland, J. and Evers, K.-U. (editors), (2013). Foresight study on laboratory modelling of wave and ice loads on coastal and marine structures, Deliverable D2.3 , EC contract no. 261520, HYDRALAB-IV. [Comprehensive study of model testing techniques in hydraulic and hydrodynamic facilities.]

Svec, O.J. and Frederking, R.M.W., (1981). Cantilever beam tests in an ice cover: Influence of plate effects at the root, *Cold Regions Science and Technology* 4(2): 93-101.[Study of the plate effects at the root of cantilever beams in an ice cover].

Tatinclaux, J.C. and Hirayama, K. (1982). Determination of the Flexural Strength and Elastic Modulus of Ice from *In Situ* Cantilever Beam tests, *Cold Regions Science and Technology*, 6, 1982, pp.37-47. [Journal article on flexural ice strength and elastic modulus achieved from *in situ* cantilever beam tests].

Timco, G.W., (1981). Invited commentary: on the test methods for model ice. *Cold Regions Science and Technology*., 4: 269-274.

Timco, G.W.,(1986). EG/AD/S: A new type of model ice for refrigerated towing tanks. *Cold Regions Science and Technology*, 12: 175–195. [Journal paper on the new type of model ice (EGADS) developed by G. Timco (NRC Canada)]

Timco, G.W. (1984a). Ice forces on structures: physical modeling techniques. In: M. Määttänen (Ed.), 2nd IAHR State-of-the-Art Report on Ice Forces on Structures. Proc. IAHR Symposium on Ice, Hamburg, Germany, 1984, Vol. IV, pp. 117-150.[Working Group Report on Ice Forces on Structures.]

Timco, G.W., (1984b). Discussion of a fine grain model ice. Proc. IAHR Symposium on Ice, Hamburg, Germany, 1984, Vol. III, pp. 553-554. [Timco's contribution to the discussion about fine grained model ice].

Timco, G.W., (2010a). Sea Ice, *Cold Regions Science and Technology* 60 (2010) 105–106. [Article of the editor of the journal Cold Regions Science and Technology.]

Timco, G.W. and Weeks, W.F. (2010b). A review of the engineering properties of sea ice, *Cold Regions Science and Technology* 60 (2010) 107–129. [Article discussing the mechanical properties of sea ice.]

USDI, (1980). Hydraulic Laboratory Techniques, United States Department of the Interior, Water and Power Resources Service (Bureau of Reclamation), Denver, Colorado. [Report on modeling techniques in hydraulic laboratories.]

van der Werff, S. and Haase, A., (2012). Influence of the Ice Concentration on the Ice Loads on the Hull of a Ship in a Managed Ice Field, Proceedings of 31st International Conference on Ocean, Offshore and Arctic Engineering OMAE 2012, July 1-6, 2012, Rio de Janeiro, Brazil, Paper No. OMAE2012-83927. [Investigation of ice loads on a ship hull in managed ice conditions].

van der Werff, S., (2012). Dynamic positioning in Ice – Assessment of hull forces induced by managed ice fields, TU Delft, Master thesis, June 2012.[Master thesis on model tests of dynamic positioning in ice – model test performance and analysis.]

Wang, Y.S., (1984). Discussion of a fine grain model ice. Proc. IAHR Symposium on Ice, Hamburg, Germany, 1984, Vol. III, p. 552. [Wang's contribution to the discussion about fine grained model ice].

Weeks, W. F. (2010) *On sea ice*. University of Alaska Press, Fairbanks, 664 p. [Comprehensive text book on sea ice.]

White, K. D., (1999). Hydraulic and Physical Properties Affecting Ice Jams, CRREL Report 99-11, US Army Corps of Engineers Cold Regions Research & Engineering Laboratory, Hanover NH, USA, December 1999. [Report on physical ice properties affecting ice accumulation processes].

WMO SEA-ICE NOMENCLATURE TERMINOLOGY – Volume I, WMO/OMM/BMO - No.259, Edition 1970 – 2014. [Nomenclature summary of specific sea ice terminology].

Wyman, M., (1950). Deflections of an infinite plate, *Canadian Journal of Research*, 1950, Vol. 28a, No. 3: pp. 293-302 [Study of deflection of an ice plate].

Zhang, Q. and van der Werff, S., (2012). Image Processing for the Analysis of an Evolving Broken-Ice Field in Model Testing, Proceedings of the 31st International Conference on Ocean, Offshore and Arctic Engineering OMAE 2012, July 1-6, 2012, Rio de Janeiro, Brazil, Paper No. OMAE2012-84117. [Article on image processing method for analyzing broken ice field in model tests].

Zufelt, J. E. and Ettema, R., (1996). Model Ice Properties, CRREL Report 96-1, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, February 1996. [Comprehensive report on modeling techniques in hydraulic engineering.]

Biographical Sketch

Karl-Ulrich Evers graduated as Dipl.-Ing. in civil engineering from the Technical University Hannover in Germany. After finishing his studies he started his career as a research engineer and project manager at the Hamburg Ship Model Basin (HSVA) in the Arctic Technology Department.

During his tenure, he is responsible for the execution of numerous ice model tests with offshore structures, investigations in ice mechanics and the preparation of expert reports. He participated in several expeditions to the Arctic where geodetic surveying of ice ridges and ice properties measurements were carried out under his leadership.

In addition to the daily business he coordinates projects at HSVA under the Program Transnational Access to Large Research Infrastructures of the European Union since 1996. In this program international user groups from Europe and associated states is given the opportunity to carry out projects in a unique research institution. In the period 1997-2014 he was Ice Committee Member of the International Association for Hydro-Environment Engineering and Research (IAHR). Presently he is member of the International Committee of POAC – Port and Ocean Engineering under Arctic Conditions.