RESEARCH NEEDS ON RIVER ICE PROCESSES RELATED TO HYDRO-ELECTRIC INSTALLATIONS

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ABSTRACT

The Canadian Committee on River Ice Processes and the Environment (CGU - Hydrology) initiated the preparation of this report for two specific purposes:

The first purpose, given in Section 1 of this report, is to address the short term and long term academic research requirements by establishing centres of excellence in ice engineering.

The second purpose, given in Sections 2 to 8, is to present outlines of specific applied research projects which are recommended to achieve the following two objectives at the same time:

- to advance the state of the art of analysing ice conditions and evaluating the effects of river ice on the environment;
- to apply the research results for better planning, design and operation of hydro-electric installations.

The following sections describe eight top priority research needs. The research needs are presented in a format which can be used to develop unsolicited research projects or request for proposals. This format is designed to be helpful in formulating requests for proposals which may be issued by hydro-electric utilities, the Canadian Electrical Association, and other funding agencies which have an interest in supporting river ice research.

The results from each of the proposed research projects will lead to a substantial improvement in productivity of a large number of existing hydro-electric installations, and provide improved design criteria and procedures for future installations. Also, it is expected that the results of the proposed studies will be applicable to non-hydro-electric river projects such as evaluation of flooding due to breakup and ice jamming, and evaluation of fisheries resources in rivers.

It is expected that, in the future, the Committee and other researchers will identify additional top priority research needs, besides those described in this report.

1.0 ACADEMIC RESEARCH REQUIREMENTS IN ICE ENGINEERING

Ice has significant physical and economic impacts on the engineering works and the public at large. In spite of these impacts, our understanding of the many ice processes is limited.

In North America, research in ice engineering is performed at three complementary levels; government, private industry and academic. The governments sponsor centres of excellence such as the National Water Research Institute, the National Hydrology Research Institute and the U.S. Army Corps Engineers

Cold Regions Research and Engineering Laboratory. The focus of their efforts is evolving and becoming more tailored to support their national, international and global obligations. Private industries, including utilities such as Hydro Quebec, Ontario Hydro, Manitoba Hydro, B.C. Hydro, N.B. Power and New York Power Authority, fund practical research geared toward solving specific problems. Academic institutions perform fundamental research and develop technology that can be used in industry. They also educate engineers and scientists, and provide the engineering community with a continuous stream of expertise.

Presently, research at the government and private industry levels is well established, however a void has developed at the academic level. We must address this void to assure continued technological advancement in ice engineering. Institutes of learning can develop programs that have long term vision with an appropriate blend of fundamental and practical perspectives.

The University of Manitoba has expressed an interest in developing a centre of excellence in Ice Engineering. Manitoba Hydro is a strong advocate of this venture but additional support and participation is required from industry. Support, in principle, has already been obtained from a number of utilities.

Current plans for this venture involve establishing a long term program of research and education at the University of Manitoba, and acquiring frazil and anchor ice research apparatus and equipment from Canada Centre for Inland Waters. Initially, the focus of research would be on frazil and anchor ice projects but could expand to meet other needs of industry and the engineering community. The University's course curriculum would be expanded to include ice engineering.

In addition to a centre at the University of Manitoba, there is need for other centres across North America. These centres could have complementary focuses, perhaps on different ice processes, on predictive modelling or on operational aspects of ice engineering. The combined efforts of the centres would provide a broad research and education base that would complement and provide a foundation for the work being done by government and industrial entities. Administrators, researchers and practitioners must work together to establish these centres and develop the initial programs. The Committee on River Ice Processes and the Environment can make a valuable contribution by fostering and co-ordinating the overall effort.

2.0 EVALUATION OF STABILITY AND BREAKUP OF SOLID ICE COVERS

2.1 Scope of Research Need

The evaluation of the ice regime of a river includes the calculation of several complex and interdependent ice processes which are a function of meteorologic, hydraulic and bathymetric conditions. Because of the complexity of the ice processes, a numerical model is normally used in this evaluation. An important process, which is the most difficult to evaluate, is the breakup of solid ice covers. In this case, there are at least two important ice cover stability limits which must be defined:

a) the conditions which lead to the breakup of the first reach in the river (just before the formation of an ice jam).

b) the limiting breakup condition of a solid ice cover downstream of the toe of the ice jam. The breakup is principally caused by the forces of the upstream jam pushing on the solid ice cover.

Figure 1 illustrates these two breakup limits for which there are no computational criteria or methodology of evaluation.

The global objective of this proposed study is to develop a calculation methodology for the evaluation of breakup of solid ice covers.

2.2 Application and Significance of Expected Results

The results of this study would be used by a relatively large number of persons responsible for evaluating the ice regime in rivers, including the conditions for breakup of solid ice covers. The most important user group would be hydro-electric utilities. For example peaking power stations may produce large variations in discharge which can cause the breakup of solid ice covers. Another example is the unexpected failure of a power station which may force the operators to by-pass the water through another canal where a solid ice cover has formed. Typically these types of breakup and corresponding ice jamming evaluations must be carried out for the design and operating studies of the hydro-electric installation.

Another typical condition where breakup studies are carried out is for the prediction of expected breakup and ice jamming conditions for the relatively large number of flooding studies for towns situated along rivers such as the St. John's, Chaudière, North Saskatchewan, Peace, Yukon, etc.

2.3 Description of Possible Research Approach

The research approach is expected to include the following tasks:

1) Identify the parameters which govern the breakup of solid ice covers. These are expected to consist of, amongst others, the following:
   - the freeze-up conditions of the river;
   - the width of the river;
   - the solid ice cover thickness;
   - the variation in water level as a function of time;
   - the cracking of the cover:
     - along the river flow direction particularly along its banks;
     - across the river;
   - the bathymetry of the river;
   - the breakup resistance limits of the cover expressed as:
     - shear stress limit of the cover along the banks of the river;
     - the breakup limit by bending of the ice cover downstream of the toe of the ice jam;
     - the competence of the ice, expressed in terms of flexural strength or other mechanical properties;
   - the rapidly-varied transient conditions created by the breakup of the solid ice cover, formation of the ice jam, and release of the ice jam;
   - the Froude number which may affect the stability of the cover at the upstream end (Michel and Abdelnour (1976)).

2) Carry out a literature review.

3) Identify possible case studies. Relatively good observations of breakup have been carried out on certain natural rivers, as well as on certain regulated rivers and channels controlled by hydroelectric installations.

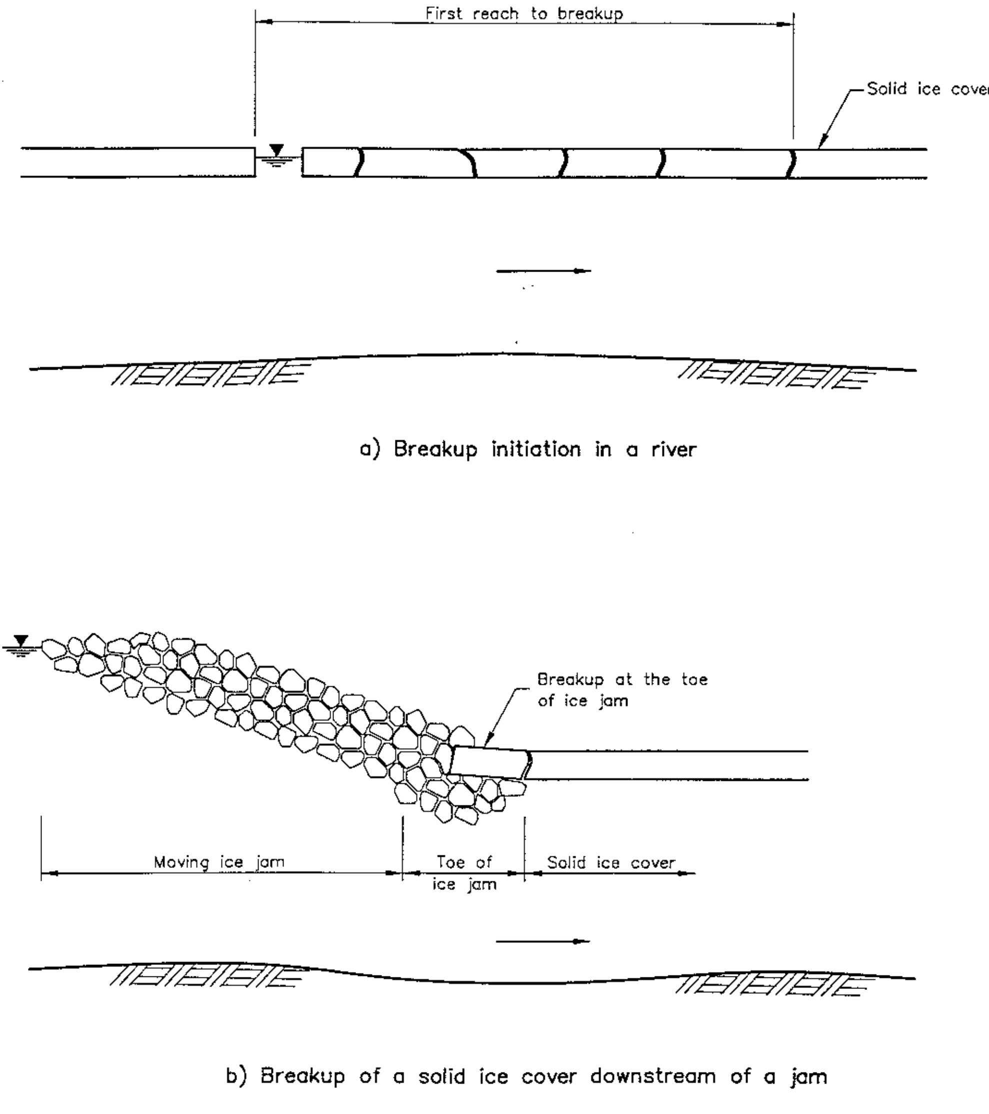


FIGURE 1 : BREAKUP LIMITS OF A SOLID ICE COVER

As the discharge rises in a given river, the breakup discharge varies as a function of the parameters mentioned in task 1 (amongst others). The objective of this task is to identify such rivers and the associated breakup related data, including:

- the existing observations of breakup;
- the additional observations of breakup, complemented by freeze-up and winter observations, which may be needed during this study, as mentioned in task 5 below;
- the discharge as a function time;
- the bathymetry of the river reach.

4) Elaborate the required theory of breakup based on the following:
   - identification of parameters (task 1);
   - literature review (task 2);
   - further development of ice mechanics theory for breakup;
   - contact with the known ice experts in this field;
   - laboratory tests of breakup, if a suitable theory of ice breakup can not be developed from the above steps.

5) Consider a new case study field program, specifically designed to carry out observations and measurements on one or more rivers and to provide calibration data for the modelling work described in task 7. (Future users of the results of this research should be contacted to support, or even carry out, this new field work).

6) Develop a complete calculation algorithm for the breakup of solid ice cover, the formation of ice jams, and the breakup of solid ice covers downstream of the toe of the jam.

7) Incorporate the algorithm in an existing global model like RIVICE (Tecsult et al. (1995)). If this model is not available at the time of study, then this algorithm can be programmed in another model, or in a separate model.

8) Analyze each of the possible case studies which were previously identified in task 3. This task includes:
   - review of the available data for each case;
   - selection of a limited number of cases for detailed analysis. It seems that between 5 and 10 cases would be appropriate;
   - quantitative analysis of breakup for each case with the help of the numerical breakup model (developed in task 6);
   - revision of the breakup theory and the calculation algorithm (if necessary);
   - revision of the quantitative analysis of the 5 to 10 case studies.

9) Preparation of a detailed report on the study.

3.0 USE OF RADARSAT SAR IMAGES TO EVALUATE RIVER ICE CONDITIONS

3.1 Scope of Research Need

The observation, interpretation, and analysis of ice regimes in rivers is important for the design of hydro-electric installations and for the evaluation of their impact on the environment. Following construction, the observation of ice conditions is again often required in order to better define the operation of power plants as a function of current and previously encountered meteorologic conditions.

There are only two practical ways of observing ice conditions in rivers: by satellite images and by aerial photography. The existing conventional optical and infrared satellite images are limited by cloud cover, darkness and their resolution. Starting from the 1995-1996 winter, state of the art Synthetic Aperture Radar (SAR) images will be available from the RADARSAT program. These images will not be affected by cloud cover and darkness.

Therefore it is certain that hydro-electric utilities and other agencies will use SAR images from RADARSAT to observe and interpret ice conditions on rivers. The main problem, associated with the use of SAR images is that a manual, detailing the interpretation of ice conditions on rivers from these images does not exist. The main purpose of this proposed research project is to produce this manual which would be used by a large number of users concerned with river ice conditions.

3.2 Application and Significance of Expected Results

The use of SAR images from RADARSAT will be significantly more economic than observing river ice conditions by helicopters or light planes. As a result a large number of users would need the proposed manual. These include the following, amongst others:

- hydro-electric utilities;
- federal and provincial environmental and water resource agencies;
- project personnel concerned with public works projects such as bridges, flood control works, navigation projects, etc.;
- researchers requiring observation of ice conditions on one or more rivers.

Typically, the following observed ice regime characteristics are needed for ice regime analysis.

A) <u>Open water zones and different types of ice cover in movement</u>

1) Open water zones without frazil in suspension.
2) Open water zones with frazil in suspension.
3) Open water zones with different types of frazil slush on the surface.
4) Zones with anchor ice on the river bed.
5) Zones with detached floating anchor ice.
6) Open water zones with thin film ice on the surface.
7) Ice sheets in movement with the flow velocity.
8) Unstable ice covers (with irregular movement).

B) <u>Zones of stable ice cover of different types</u>

9) Border ice.
10) Static ice cover formed by thermal heat loss.
11) Frazil hanging dams. Different types of frazil ice deposits could be interpreted from ice cover fractures and metamorphosis of frazil ice deposits.
12) Hummocked thin ice covers formed by juxtaposition (thin ice jams).
13) Thick ice covers composed of ice blocks (thick ice jams).
14) Snow over an ice cover.

3.3 Description of Possible Research Approach

A possible approach to formulate the manual may include the following tasks:

1) Literature review of previous related studies (such as Leconte and Klassen, 1991).

2) Contacts with other river ice and SAR imagery experts in Canada, U.S. and Europe.

3) Choose about 5 rivers as case studies where ice observations by RADARSAT and other means will be available.

4) Numerically treat the RADARSAT images (with a chosen numerical image treatment software).

5) Compare the RADARSAT images with the observed river ice conditions for each river from:
   - aerial photos of good quality;
   - ice conditions observed directly from the banks of the river (or by helicopter);
   - ice conditions which are estimated by an ice expert based on:
     . river discharge as a function of time;
     . river bathymetry;
     . meteorologic conditions;
     . previous ice studies where detailed ice observations were carried out for other purposes (such as the Project Archipel data obtained on the St. Lawrence River (Desroches and Michel, 1986);
     . numerical model studies whereby a better interpretation of observed ice conditions is possible.

   These estimated ice conditions would only be useful if the observed surface ice conditions has some missing data details.

6) Evaluate the capability of defining the different types of ice conditions from RADARSAT images and the level of detail that can be obtained from the images.

7) Prepare manual on the interpretation of the different types of ice conditions and on the overall ice regime of a river from RADARSAT SAR images. The manual would include examples of detailed ice regime interpretation from RADARSAT SAR images for about 5 rivers.

4.0 TWO-DIMENSIONAL MODELLING OF SEVERE ICE JAMS UPSTREAM OF A CONSTRICTION

4.1 Scope of Research Need

The current theory on ice jams is mostly limited to one-dimensional analysis. That is, the changes in river cross-sections should be relatively gradual with distance (particularly with respect to the variation in the river width).

At relatively sharp natural or man-made river constrictions, such as at hydro-electric intakes and at bridge approaches, one-dimensional ice jam theory is inapplicable. The main objective of this research need is to develop a two-dimensional ice jam model which could be applied to the evaluation of relatively thick ice jams, composed of large ice blocks and producing high head-losses, at river constrictions.

4.2 Application and Significance of Expected Results

The results are expected to greatly improve the accuracy of ice jam evaluation at natural and man-made constrictions. This includes design of headrace canals, bridge approach and bridge pier spacing evaluation, designing of excavation (or fill) profiles in a natural river to reduce ice jamming effects; docks, marinas and other constricting structures in a river; and evaluation of ice jams at the entrance to channels around islands in a river. Moreover, the well known thickening of ice jams near the toe creates a natural constriction between the shear lines defined by the grounded portions of the jam at the sides.

4.3 Research Approaches

Figure 2 illustrates the river bank shape effects on ice jam stability. The finite-element method can be used to solve the evolution of ice jams as a function of the bathymetry of the river, water discharge, ice discharge, hydraulic, and meteorologic conditions (particularly wind) as a function of time. Existing two-dimensional dynamic hydraulic models could be used to evaluate the hydraulic conditions under the ice cover. For example, the existing TASE-SWAN Plus (Version 3.0) model, based on the description given by Zang et al. (1992), could be considered for this study; it is capable of handling highly transient conditions such as a surge resulting from an ice jam release.

The theory from the following related fields should be helpful in developing the two dimensional ice jam model.

1) Two-dimensional finite-element models from soil mechanics, especially related to land slides limits of rubble type material. The behaviour of rubble, particularly along the landslide failure boundaries, should be similar to the behaviour of ice blocks in an ice jam, particularly along the shear walls along the river bank;

2) Two-dimension models developed for modelling sea ice (Pritchard and Colony, 1976);

3) Two-dimensional model developed by Shen et al. (1994) which has been successful in modelling the ice transport and jamming on the upper Niagara River.

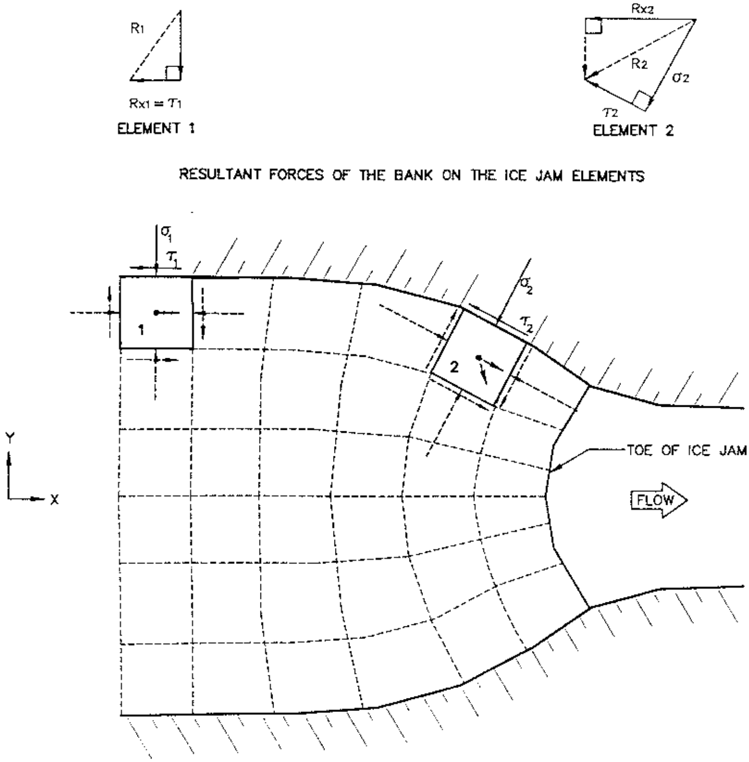
Figure 3 schematically illustrates the nature of expected ice forces of an ice jam on the South Nation River. The application of the one-dimensional SIMGLACE model did not yield satisfactory results without adjustment of the ice stability factor to field conditions (Rousseau et al. (1983)).

5.0 DEVELOPMENT OF A NEW FRAZIL, ANCHOR ICE, AND BORDER ICE MODEL WITH THE HELP OF PROJECT ARCHIPEL DATA

5.1 Scope of Research Need

Hydro-Quebec possesses excellent detailed observations of the ice regime on the St. Lawrence River between the Beauharnois power station and the Port of Montreal. These observations include (Desroches and Michel, 1986):

- Hourly discharge;
- Hourly climatic data;
- Hourly water level data;
- Longitudinal and vertical profiles of water temperature;



⟵ – FORCE OF THE RIVER BANK ON THE ICE JAM

- - -⟶ – OTHER INTERNAL FORCES (SHEAR AND COMPRESSIVE STRESSES AND WEIGHT COMPONENT) AND EXTERNAL FORCES (DRAG FORCES OF WIND AND WATER)

τ_1, τ_2 – BANK SHEAR FORCES ON ELEMENTS 1 AND 2 RESPECTIVELY

σ_1, σ_2 – BANK COMPRESSIVE FORCES ON ELEMENTS 1 AND 2 RESPECTIVELY

R_1, R_2 – RESULTANT FORCES OF THE BANK ON THE ICE JAM ELEMENT 1 AND 2 RESPECTIVELY

R_{x1}, R_{x2} – RESULTANT LONGITUDINAL FORCES OF THE BANK ON ELEMENTS 1 AND 2 RESPECTIVELY

FIGURE 2 : ILLUSTRATION OF RIVER BANK SHAPE EFFECTS ON ICE JAM STABILITY

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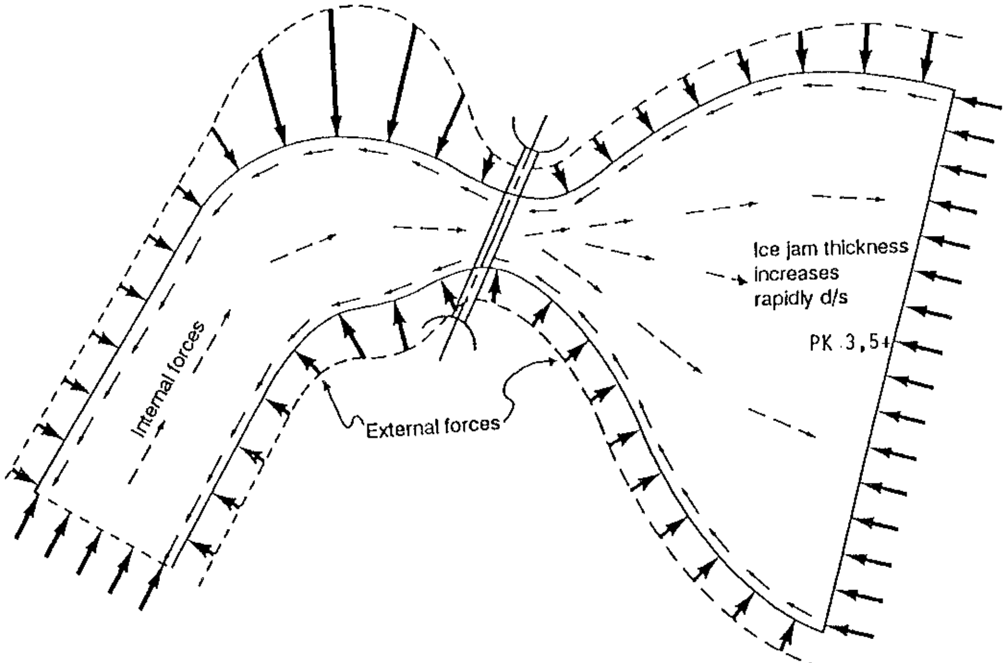

FIGURE 3 : SOUTH NATION RIVER - SKETCH OF EXPECTED INTERNAL AND EXTERNAL FORCES ON THE ICE JAM AROUND THE BRIDGE

- Continuous measurements of the vertical profile of the water temperature at two points in the zone where anchor ice typically forms;
- Frazil ice concentrations in the flow at different depths;
- Growth in frazil ice deposits on objects of different forms and composition;
- Maps on the almost daily evaluation of border ice;
- Almost daily maps on the flow pattern and the concentration of moving ice in the flow;
- Almost daily maps of the evolution of anchor ice deposits;
- Concentrations of different types of moving ice at several cross-sections;
- Classification of the surface dimensions of blocks of moving anchor ice at several cross-sections;
- Classification of the density of the ice samples of anchor ice;
- Aerial photos for different conditions of formation of skim ice and sheet ice in movement;
- Detailed photos of observed different ice characteristics;
- Detailed bathymetry;
- Streamlines and velocity distributions across the river under open water conditions.

This data was collected for Project Archipel which was stopped before this data was analyzed in detail. The objective of the proposed study is to analyze this data, and improve our capability of evaluating the following conditions:

1) Heat balance in a river under the various types of possible ice conditions.
2) Generation of skim ice, moving sheet ice, and frazil.
3) Accumulation and release of anchor ice.
4) Progression and release of border ice.

5.2 Application and Significance of Expected Results

The evaluation of heat balance, skim ice and moving sheet ice, anchor ice, and border ice are important on rivers, particularly on regulated rivers with hydro-electric installations. Typically on these rivers the discharge is highest during winter when the electric demand is also the highest. Therefore, long reaches of open water and unstable ice conditions may exist.

Under these conditions the evaluation of the above four conditions is very important for the design of hydro-electric installations and for their operation after construction.

5.3 Description of Possible Research Approach

With the enormous amount of data available from the observations of the Archipel Project, the following list of tasks is currently foreseen:

1) Review the available data in order to select those which will be used in this study.

2) Organize the data according to the above four required conditions to be evaluated (heat balance and three different types of ice conditions).

3) Define the formulations to be considered to evaluate the above four required conditions. The formulations by Tsang (1988), Marcotte (1984, 1986) and Robert (1986), Shen et al (1994), Matousek (1984) and Svensson, et al. (1989) should be particularly considered.

4) Evaluate approximately the four conditions, based on the available data. The objective of this task is to understand completely the heat balance and the observed ice regime between the Beauharnois power station and Lachine Rapids.

5) Consider different two-dimensional hydraulic models and choose the best model for this study. The model should be capable of calculating hydraulic transient conditions for a river that is partially covered with an ice cover. Consideration of the two-dimensional ice-hydrodynamics model of Shen et al. (1994) may be a good starting point.

6) Develop or select existing theoretical formulations which are most appropriate for evaluating the four conditions, and develop a new two-dimensional calculation algorithm.

7) Program this algorithm in the two-dimensional hydraulic model. This task includes testing of the modified two-dimensional model to verify that the calculated results correspond to the theory developed in task 6. (The existing 1-D model by Marcotte, and the 2-D model by Shen were developed and tested for large rivers. The new model should also be applicable to small and medium sized rivers.)

8) Use the selected data from Project Archipel to:

   - calibrate the theoretical formulations chosen for the two-dimensional model;
   - modify the theoretical formulations, the computation algorithm, and the corresponding programming instructions (if necessary).

9) Prepare two reports for the users of this study consisting of:

   - theory, calculation procedure and results of comparing the theory to the observed Project Archipel conditions;
   - users' manual for the two-dimensional model designed to compute the hydraulic conditions, heat balance and the previously mentioned three ice conditions.

10) Outline additional field programs needed to complete model verification and calibration, if necessary.

6.0 EFFICIENT METHODS OF FORMING AND MAINTAINING STABLE AND SMOOTH ICE COVERS

6.1 Scope of Research Need

Energy generation at several hydro-power stations is restricted in early winter. The progression of the ice cover may be relatively slow which may cause production of large volumes of frazil ice and moving sheet ice upstream of the cover. Large volumes of ice may in turn produce thick and rough ice covers which typically reduce head for hydro-electric energy generation during formation as well as during the entire winter. In early winter, at peaking power stations, the strength of the new ice covers, formed at low discharges, may be insufficient to maintain stability at the peak discharge. These factors cause a reduction in peak power production capability during the period of peak seasonal demand, and limit the variation in power production to satisfy the varying hourly demand.

The objective of the proposed research project is to document empirical solutions developed at certain stations and further analyze actions that will favour the rapid formation of a stable smooth ice cover, thus reducing the periods when peaking cannot be used.

6.2 Application and Significance of Expected Results

One major example is the Beauharnois power station where 400 MW is unavailable during the period of ice cover formation.

Similarly, several other hydro power stations cannot use peaking or vary the discharge at the period of ice cover formation. Otherwise, the cover can break, move with the flow and cause jamming further downstream.

The cost of these losses in available capacity is important since they occur during the period of annual peak power demand.

Empirical methods have been developed at several hydro power stations to favour ice cover formation. For example, at Beauharnois, a detailed sequence of actions has been determined from practical experience over a period of several decades. In addition, the phenomenon is well documented.

An analytical evaluation of each case study should be carried out. This can be subdivided into these steps: formal description of the operating rules and sequence of actions currently undertaken to control the ice cover conditions, theoretical analysis, identification of major parameters, limiting values, roughness of ice cover, optimal sequence of actions, sensitivity analysis, alternative solutions, analysis of measured ice conditions of previous winters, and costs of constraints to power production.

The expected end result is a more efficient and more rapid method of building a stable and smooth ice cover, thus reducing capacity losses due to ice cover formation.

6.3 Possible Research Approach

Formulation of the procedure adopted at a few selected hydro power stations where detailed information is available:

- Document all the steps in the procedure used to ensure the rapid stabilization of the ice cover.

- Identify factors involved in the ice processes, for instance: thermal growth, incoming flow of ice, ice types, meteorological conditions, ice cover progression, ice cover movement; after formation, determine the variation in ice covert stability as a function of time and position along the river, changes in ice cover thickness and roughness, variation in discharge, etc.

- Examine limiting cases for various conditions when the observations are well documented. Study the variations for different years with associated different hydraulic and meteorologic conditions. (The hydro-electric operating conditions at a number of sites is summarized by Wigle et al. (1988)).

Modelling the ice evolution during the process of ice cover stabilization:

- Use available river ice models. Add modules when required; develop basic formulations and carry out theoretical analysis of additional information.

- Compare computed and observed values over several years. Modify the equations and computation procedures in the models.

Analysing the modifications that could be made to improve the ice stabilisation process:

- Study of light structures used to accelerate ice cover stabilisation. Carry out sensitivity analysis, evaluate the effects of flow variations, and investigate alterative solutions.

- Study of the influence of particular aspects like the geometry of the river, meteorological data or external influences.

- Examination of potential improvement to present techniques.

Preparation of a report containing all the results of the study, including the practical application of the results of the new findings.

6.4 Nature of Required Data and References

1) Detailed observations at a few power stations.

2) Recent publications on ice cover stability, ice cover roughness and other pertinent aspects for the problem studies.

3) A mathematical model stimulating the generation and the evolution of river ice.

7.0 COHESION EFFECTS ON THE STABILITY OF ICE JAMS SUBJECT TO FREEZING

7.1 Scope of Research Need

Currently, the stability and evolution of ice jams is determined under one of the following two hypotheses:

1) The ice accumulation is cohesionless, or;

2) The ice accumulation has cohesion where the cohesion term is considered in the following form:

$$F_c = 2ctL$$

Where

F_c = Force of cohesion of ice to two river banks
c = Cohesion per unit area of ice/bank interface
t = Average thickness of ice cover between cross sections
L = Distance between cross sections

The main problem is that there are no guidelines to evaluate "c". Also it is recognized that "c" may vary due to solid ice freezing from the surface, compaction and inter-particle freezing in ice accumulations because of supercooled water. Guidelines are required to evaluate "c" for different field conditions associated with release of ice jams and frazil generated hanging ice dams.

There is also a need to clarify the definition of cohesion. For example, is it important to determine what is the effect of a formation of a solid crust on top of an ice jam (accumulation cover). The formation of this type of solid ice cover may be considered explicitly as illustrated by Lal and Shen (1990). However, the additional strength, or limiting stability, of the solid ice cover formed over an ice jam is expected to be quite different from the limiting stability of a solid ice cover without an accumulation cover under it.

7.2 Application and Significance of Expected Results

The results would be applied for the evaluation of the release of ice jams and hanging ice dams under the following difficult conditions:

1) Release of an ice jam in the spring which originally had formed in winter, following breakup from a winter freshet. In this case, cohesion develops in the jam during the winter because of the following ice processes, amongst others:

   - Freezing of the water between the ice blocks from the water surface downward. Michel (1984) illustrated the increase in stability due to this effect for large rivers such as the St. Lawrence River; Lal and Shen (1990) considered the surface ice crust explicitly in their stability analysis.

   - Freezing at the contact points between the blocks if the internal temperature of the blocks was less then 0°C when breakup suddenly occurred in winter.

   - Freezing around the blocks, particularly at the contact points between the blocks if the ice jam was subject to supercooled water flow. This may be the origin of "compact frazil" hanging dams which tend to solidify during winter in locations downstream of rapids.

   - Development of cohesion between blocks as a function of time because of the internal compressive stress in the ice jam.

2) Release of ice jams, including hanging dams in winter, which were subject to the ice processes mentioned above. This can occur during a temporary warm spell where there is an increase in discharge, a reduction in ice supply from upstream and thermal effect that reduces particle size and may weaken the cohesion strength of the ice cover.

3) Release of ice jams formed in the spring which have stayed in place relatively long. Here the initial focus of the research could be the development of cohesion strength as a function of time during winter, followed by a reduction of cohesion strength during spring.

The release of the ice jams/hanging dams has to be understood in order to carry out flood level calculations with numerical models. Currently only "good judgement" is used in estimating "c". Underestimating cohesion can result in premature calculated release of ice jams/hanging dams and significant under estimation of design flood levels.

Also, if unacceptable flood levels can occur due to important winter accumulations of ice, then mitigation measures can be considered, such as cutting of ice cover along the shore. This may lower the discharge at which the ice jam/hanging ice dam will release. After release, the ice accumulation is expected to loose its cohesion effects between ice blocks/ice particles. This hypothesis should be verified by research.

7.3 Possible Research Approach

1) Evaluate ice processes contributing to cohesion. A preliminary list is mentioned above.

2) Identify river sites where potential winter ice jams occur as a result of winter freshet such as on the Chaudière River, and sites where frazil hanging dams occur downstream of rapids such as on the Smoky River upstream of the town of Peace River.

3) Monitor the above identified ice processes with field measurement of water temperature, ice accumulation thicknesses, surface freezing, which may be complemented by laboratory measurements of the rigidity of the ice accumulations until breakup.

4) Plan a field observation program during spring breakup to monitor the conditions under which each ice jam/hanging dam release occurs. Measurements of discharge, water temperature, and water profile as a function of time are required as a minimum (complemented with photographs of the release conditions).

5) Numerically model the release of the observed ice jams/hanging dams in order to better interpret the observed ice conditions, and to evaluate the ice cohesion "c" of the ice accumulation. (Note that cohesion may substantially increase the erosion limit of the ice accumulation in addition to increasing its stability against crushing and release).

   In order to correctly model the hydraulic and ice conditions, a dynamic model is required. This model should be capable of evaluating local changes as a function of time as well as the effects of transient conditions resulting from breakup and evolutional ice jams upstream and downstream of the particular case study site.

8.0 EVALUATION OF MAXIMUM ICE IMPACT LOADS ON CONTROL STRUCTURE GATES

8.1 Scope of Research Need

The maximum design force on a control gate is normally equal to the dynamic ice impact load. Currently the evaluation of this load is very approximate because there have been no direct or indirect measurements of ice forces on gates reported in the literature.

However, Hydro-Quebec and other hydro-electric utilities possess data on the deformation of gates caused by ice impact forces. It is proposed that a study be carried out whereby this data is used to calculate the corresponding ice impact loads which caused the deformation. The study will include the corresponding hydraulic conditions and estimated ice block conditions which caused the ice impact load.

8.2 Application and Significance of Expected Results

Currently, simple "rule of thumb" design procedures are used to compute ice forces on gates. These procedures are not well documented and, as a result, these design procedures vary between different organizations in the hydro-electric field. Because of the uncertainty in design procedure and associated design parameters, it is likely that the current gate designs include excessively high safety factors. This results in a significant increase in cost of the gates over the required cost if design ice impact loads could be evaluated more accurately.

The results of the proposed study are expected to significantly improve the precision of design ice impact force evaluation and reduce the fabrication costs of future gates at existing installations (replacement gates) and at future new hydro-electric sites.

8.3 Possible Research Approach

In summary, the study is expected to consist of the following tasks:

1) Review the available data on gate deformation at Hydro-Quebec, Ontario Hydro, Manitoba Hydro, Newfoundland Light and Power, CRREL, and other organizations; and select the case studies where the deformations of the gates are significant enough so that the corresponding ice load can be estimated.

2) Evaluate the maximum ice forces for each case as a function of the nature and degree of its deformation (or deformations). Normally there are two different types of forces which are of interest:

   a) the local puncture type of force which produces a local deformation on the plaque of the gate;

   b) the global maximum force in the gate which caused permanent deformation of the main structural elements of the gate.

3) Carry out an ice block impact analysis. Following the evaluation of the above impact forces, dynamic ice mechanics theory should be used to estimate the corresponding hydraulic conditions, and ice block characteristics which causes the estimated ice forces. The following conditions can be estimated:

   a) characteristics of the ice block (minimum size, ice strength, thickness, its failure mode on impact, etc.);

   b) gate characteristics (rigidity, strength of the gate as a function of impact position, etc.);

   c) control structure characteristics (width of the gate and the piers, distance from the tip of the pier to the gate, etc.);

   d) hydraulic conditions upstream of the gate and upstream of the control structure, as well as the ice block dynamics upstream of the structure. The application of a numerical model, which simulates the hydraulic and ice block dynamic conditions, should be considered in order to correctly evaluate the field conditions. The discrete-element method may be useful for ice block impact analysis.

It is expected that a total 5 to 10 cases should be analyzed in detail.

4) Develop a new methodology for estimating ice forces on gates. A user's design guide should be developed and included in the final report.

5) Prepare a final report giving the detailed results of the analysis of the 5 to 10 case studies, as well as a recommended revised methodology for computing ice forces on gates.

9.0 SUMMARY

The Canadian Committee on River Ice Processes and the Environment has identified eight top priority research needs, particularly those related to the hydro-electric industry. This report describes the following needs and the associated possible research approaches to satisfy each need:

1) Academic research requirements in ice engineering, including the establishment of one or more centres of excellence in ice engineering.
2) Evaluation of stability and breakup of solid ice covers.
3) Use of RADARSAT images to evaluate river ice conditions.
4) Two-dimensional modelling of severe ice jams upstream of a river construction.
5) Development of a new frazil, anchor ice and border ice model with the help of Project Archipel data.
6) Efficient methods of forming and maintaining stable and smooth ice covers.
7) Cohesion effects on the stability of ice jams subject to freezing.
8) Evaluation of maximum ice impact loads on control structure gates.

The duration of completing each of these projects has not been estimated. This would be estimated during the preparation of a detailed proposal for each research need; some of the projects could take several years, depending on the scope of the planned work.

The objectives of formulating the above mentioned research needs is to help engineers, scientists and agencies dealing with river ice to focus their effort and support to top priority research work. Considering the importance of river ice to Canada and other nordic countries, this research work is expected to produce benefits which will be worth several times the cost of each of the proposed projects.

It is understood that other top priority research needs have been and will be identified, besides those mentioned in this report.

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11.0 REFERENCES

BELTAOS, S. (1995) - editor, River Ice Jams, Water Resources Publications, LLC, Highlands Ranch, Colorado, USA.

DESROCHES, P. and MICHEL, B. (1986), Observations du regime des glaces du Fleuve Saint-Laurent et des Rapides de Lachine, Proceeding of 4th Workshop on the Hydraulics of River Ice, Montreal, June 19-20, 1986.

LAL, A.M.W. and SHEN, H.T. (1990), Mathematical model for river ice processes, Journal of Hydraulic Engineering, ASCE, Vol. 117 (7), 851-867.

LECONTE, R., and KLASSEN, P.D. (1991), Lake and river ice investigation in northern Manitoba using airborne SAR imagery, Arctic, Vol. 44, Supp. 1, pp. 153-163.

MARCOTTE, N. (1984), Projet Archipel, Modélisation et analyse des glaces, International report N° 08743-RA-84/30, Hydro-Québec, service Hydraulique, division Études spéciales et recherches, 1984, 106 pages.

MARCOTTE, N. (1986), A simple mathematical model of moving sheet ice, Proceedings IAHR Symposium on Ice, Iowa City, August 18-22, 1986, pp. 89-100.

MARCOTTE, N. and ROBERT, S. (1986), Elementary mathematical modelling of anchor ice, Proceedings IAHR Symposium on Ice, Iowa City, August 18-22, 1986, pp. 493-506.

MATOUSEK, V. (1984), Types of ice runs and conditions for their formation, Vol. 1, 1984 IAHR Ice Symposium, Hamburg, 316-327.

MICHEL, B. (1984), Comparison of field data with theories on ice progression in large rivers, Canadian Journal of Civil Engineering, Vol. 22 (5), 789-814.

MICHEL, B. and ABDELNOUR, R. (1976), Stabilité hydromécanique d'un couvert de glace encore solide, Canadian Journal of Civil Engineering, Vol. 12, N° 4, Pages 1-10.

PRITCHARD, R.S. and COLONY, R. (1976), A Difference Scheme for the AIDJEX Sea Ice Model published in Numerical Methods in Geomechanics by C.S. Desai (editor), ASCE, pages 1194-1209.

ROUSSEAU SAUVÉ WARREN INC. et HYDRO-QUEBEC (1983), SIMGLACE - Documentation du programme, Hydro-Quebec report.

SHEN, H.T., SU, J.-S., LU, S.-A. and WAKE, A. (1994), A two-dimensional model for dynamic ice transport and jamming in the upper Niagara River, Vol. 2, 12th IAHR Ice Symposium, Trondheim.

SHEN, H.T. and WANG, D.-S. (1995), Undercover transport and accumulation of frazil granules, Journal of Hydraulic Engineering, ASCE, Vol. 121 (2), 184-195.

SVENSSON, U., BILLFALK, L. and HAMMAR, L. (1989), A mathematical model for border-ice formation in rivers, Cold Regions Science and Technology, Vol. 16 (2), 179-189.

TECSULT, ACRES, LASALLE CONSULTING GROUP and SNC-SHAWINIGAN (1995), RIVICE Model Documentation, Final report prepared for the River Ice Model Project Steering Committee, Environment Canada (Volumes I, II and III).

TSANG, G. (1988), Development of Mathematical Modelling for Prediction of River Cooling and Frazil and Anchor Ice Formation, Proceeding of the 5th Workshop on the Hydraulics of River Ice, June 1988, Winnipeg, Man., Pages 393-416.

WIGLE, T. and FOULDS, D., editors (1988). Optimum Operation of Hydro-electric Plants During the Ice Regime of Rivers. NRCC Publication 31107.

ZHANG, H., KAHAWITA, R., SHEN, M. and LI, Z. (1992). A PC-based Numerical Package for the Simulation of Two-dimensional Free Surface Slows. Proceeding of Second Canadian Conference on Computing in Civil Engineering, Ottawa, Canada, pp. 794-803.

DISCUSSION

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The authors have assembled a valuable list of research topics and needs in the field of ice hydraulics. I appreciate the time and effort directed towards this process. However, I would like to make a few comments about the content of some parts of the report. First, I have a concern that simply by issuing a document of this type, the reader will assume that the only research issues are those identified in the report. There is no way that we can collectively identify in one document all the needs related to the science of river ice, or even for hydropower operations, for that matter. I think it is important to establish a processes that allows for a continuous assembly of research needs and objectives. Perhaps the committee could operate as a clearing house for research ideas, whereby problems would be identified by practitioners, the committee would assess the scope of the research required to develop the appropriate technology to solve the problem, define some reasonable research objectives, and promote the research ideas with the appropriate institutions or agencies in Canada.

With respect to the way the research has been outlined, I think there is some confusion between problems and/or technology development (subject matter) and process (how one should go about solving the problem and which data one should use to develop or calibrate the technology). Certainly, the research needs are the most important to identify. It is gratifying to see discussion that identifies the use of the research and how it might pay off in the long term. However, I first would prefer to see a rigorous summary of research needs identified, and then perhaps a summary of opportunities to undertake the research, given our collective knowledge of field sites, existing modelling tools, and data availability (ie. identifying the location of applicable test data and how to access this data).

In addition to the issues that you identified, I would have the following fundamental topics (in no particular order) to offer:

1. Frazil production and floe development in turbulent streams. This is a process that is fundamental to freeze-up in many rivers and virtually nothing is known about the process.

2. The stability of skim ice formed by primary nucleation on the surface of a turbulent stream. That is, how thick is it, what does it take to entrain the ice particle, and will it melt before it is carried to the surface? This is a little esoteric but it is important in determining when and if skim ice will form. It would be worthwhile to validate Matousek's approach to quantifying this particular processes.

3. The development of algorithms to calculate the rate of progression of ice covers over falls and rapids. This would involve calculating the transport of frazil under the ice cover downstream, the increase in the backwater condition downstream, the submergence of the falls, and the staging of ice over the falls. The transport and deposition of ice along the underside of the ice cover is of fundamental importance in this problem.

4. The development of a lodgment model. I think there are as many theories on how lodgement develops as there are ice hydraulicians. Personally, I have learned a lot about lodgement on the Niagara River project but we have to develop methods to generalize the procedures so they can be applied to other rivers. This can be done without using two dimensional models.

5. You talk about identifying ice forces on dams. This is of major importance, but of even more significance is the issue of ice forces on bridge piers. We still do not have a rational way of identifying ice forces on bridge piers that will account for the size of the river without having to rely on specific field observations. We need to develop ways to identify which reaches of rivers (on a global scale) produce ice runs and what would be the intensity of the run and the size of the floes. Some of this simply involves a systematic review of historical WSC records within a selected data framework and a judicious regional analyses of the resulting data.

6. One of the big issues related to predicting breakup is the melting of the snow pack, both in terms of the flow increases and the reduction in the strength of the ice. Any work I have done results in calculations of snow melt at rates that are much larger than typically observed, even if one takes the maximum optimum melt rates . Why the discrepancy?

7. Modelling the collapse of freeze-up ice covers is of particular interest to me because it is very important in determining the stability of ice covers during fluctuating river flows. You identified it as one of your research topics. I would support this. Hung Tao Shen and Jon Zufelt have made substantial progress in developing models to simulate this phenomenon but more work is required. However, because the process is highly non-linear it is not so much of an ice problem, but more a dynamic modelling problem.

8. There is still substantial disagreement about the roughness of the underside of ice jams, be they composed of frazil or large ice floes. Far too much reliance is being placed on the old questionable Russian data There are so many ice covers formed from frazil each year, why not rigorously measure a half a dozen or so and get good design roughness values?

9. The modelling of freeze-up on **non-regulated** rivers is still not well understood from a spatial perspective. The water temperatures, ice formation, role of border ice, multiple lodgements, etc. have not been quantified, nor have we developed any conceptual or mathematical models to simulate the freeze-up process. As a start, we need some good systematic measurements on a few selected rivers.

These are just a few of my ideas on what issues are of importance in our business. They are not terribly complicated for the most part and I do not know why we still do not have acceptable answers for some of these problems. I suspect that there is no **national will** to find out about these things. The federal government **has failed us on most fronts**, by not providing leadership or the infrastructure to do this kind of work, and I think that the Provinces do not see this as their concern.

It also appears that hydropower companies are too parochial to pool their resources and leverage money out of governments to set up an institute with sufficient mass to achieve anything. With respect to Randy Raban's ideas, I think they are very noble, except I do not see any gains being made by having one or two people working at four or five locations across Canada. We need one Institute or Centre that is dedicated to this type of work and that has sufficient staff and capabilities to integrate the theoretical development, numerical and physical modelling, and the field expertise to make some progress on these initiatives. What would it cost, $1.6 to 2 million a year? This is very small compared to the money that is spent and/or lost on hydraulic/ice engineering activities in Canada.