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River-Ice Problems: A State-of-the-Art Survey and Assessment of Research Needs

Report of the Task Committee on Hydromechanics of Ice
of the Committee on Hydromechanics
of the Hydraulics Division

Introduction

The annually recurring period of low temperature that much of Earth's surface experiences produces partial or total freezing of many natural bodies of water. The resulting ice can seriously impede the utilization of lakes and rivers for power generation, transportation, water supply, sanitary purposes, etc. River ice can cause especially serious problems through the damage it does to hydraulic structures and riverside facilities, by the flooding that often accompanies ice jams, and by impeding winter navigation. Engineering problems associated with the winter regime of rivers have been treated by field engineers and laboratory researchers for many years. However, their efforts have been largely directed toward development of ad hoc solutions for specific problems, and have tended to be sporadic and somewhat uncoordinated. The rapidly increasing demands placed upon Earth's water resources in recent years, and the attendant need fully to utilize these resources, have been responsible for an increased level of research into practically all aspects of the hydrologic cycle, including the winter behavior of rivers and lakes. It was against this background that the Task Committee on Hydromechanics of Ice of the ASCE Hydromechanics Committee was organized, to examine the state of development of river-ice mechanics, and to delineate the problem areas in which there exists an acute need for research leading to the development of improved engineering tools. The Committee's findings and recommendations are summarized herein.

After consideration of the full spectrum of engineering problems caused in

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part or whole by river ice, the Committee concluded that the highest research priorities should be assigned to the following topics: (1) Formation processes of river ice, (2) ice jams, (3) ice forces, and (4) heat exchange processes and the effects of thermal enrichment. Each of these problem areas is examined in the following sections. The report concludes with a discussion of other river ice problems which were also judged to warrant the attention of researchers and river engineers. This report emphasizes the hydraulic aspects of river-ice problems. This emphasis perhaps tends to obscure the complex interrelationships that exist between the hydraulics of ice-laden rivers and the hydrology of river systems subjected to freezing. River ice is an aspect of the hydrologic cycle, and hence is dependent on climatic and physiographic conditions, and sensitive to many highly variable factors. The particular nature of an ice occurrence is the result of the hydrologic input to a given watershed subjected to a certain succession of climatic events.

Formation Processes of River Ice

River ice forms after sufficient heat has been transferred, principally to the atmosphere, to reduce the water temperature to 0° C (or slightly below, in the case of supercooling). It is immediately evident that all three modes of heat transfer, i.e., convection, conduction, and radiation, can play a significant role in the process. However, the details of the several heat-transfer mechanisms involved, the physical and chemical processes that come into play in the evolution of ice covers during winter seasons, and the breakup or melting of the ice following the onset of higher air temperatures are only imperfectly understood and formulated. The major stumbling blocks encountered in analyzing the problem are formulation of the turbulent transfer of heat, between the river flow and both the ice cover and the river bottom, and from the ice to the atmosphere; the problem is compounded, of course, by the complexities of the dynamics of the water movement below and the air movement above the ice, and by the extreme temporal and spatial variabilities of the air velocity and temperature. During its life, ice undergoes important physical-chemical changes, due to enlargement of grain boundaries, which radically affect its strength and hence also the time and mode of breakup; the understanding of these evolutionary changes cannot be regarded as adequate.

The major problems associated with the initial formation of river ice are prediction of the date of freezeup; quantitative description of the formation, evolution, and disposition of frazil ice; and analytical formulation of the processes of formation and accumulation of surface ice.

Prediction of the Dates of Freezeup and Breakup.—There are two basic approaches to the prediction of the date of either the first appearance of ice or the date of first complete ice cover, and to prediction of the time of ice breakup. In the first approach the predictor is based on the results of statistical analysis of past records. The statistical tools are at hand, the historical records are usually readily available, at least for populated areas, and some work has been done in making regional interpretations of the data (8). This type of analysis is particularly useful in preparation of long-range plans where durations of ice cover play a role, as, for example, in planning cargo movements which can take place only under open water conditions. The second approach involves a heat-budget analysis, and is most relevant to short-range forecasts. The analysis combines theoretically and empirically determined heat transfer rates with meteorological forecasts of air temperature and humidity, cloud cover, wind speed and direction, and hydrological prediction of river stage and discharge. The results are short-range predictions (of the order of days, or at most, weeks) of the dates of critical changes in ice covers (6). The reliability of any prediction based on this method is, of course, no better than the accuracy of the meteorological and hydrological forecasts utilized. Therefore a major obstacle to the development of improved predictor methods is the lack of sufficiently accurate weather prediction, and current research directed toward improving weather forecasts is of central importance to development of refined predictors for ice occurrence and behavior. A continued effort is also required to improve heat-transfer calculations included in predictor methods, and to assemble an adequate data base on which to prepare regional long-range prediction curves. Finally, a fuller understanding of the evolution of the mechanical properties of ice is essential to accurate predictions of breakup.

Frazil Ice.—Frazil is ice which is suspended in the flow in the form of small crystals; supercooling of the water is essential to its formation (12). Frazil crystals will often agglomerate, float to the surface, and freeze together to initiate the formation of an ice cover. Under conditions favorable for its formation, it can be produced in a given reach of river in massive quantities, and can even block the entire flow cross section and cause extensive flood damage. Frazil may also block water intakes by agglomerating on submerged surfaces. Present methods for control of frazil ice rely primarily on introduction of heat into the flow to melt frazil that has already formed, or to prevent the liquid water from supercooling. While certain general principles concerning frazil formation are understood qualitatively (27,36), the processes of the initial formation, evolution, and subsequent disposition of frazil ice are only incompletely understood on a quantitative basis, and deficiencies in the present state of knowledge are severely hindering development of rational design methods for avoidance or alleviation of frazil-ice problems. A need exists for a comprehensive investigation of frazil ice, entailing analytical, laboratory, and field investigations.

Accumulation of Floating Ice.—The process of initial formation of ice on a river surface occurs more often by accumulation of ice fragments than by growth of anchored crystals into the flow. At low velocities the accumulation is generally only one fragment thick, and subsequent thickening is by growth into the melt. At intermediate velocities the orientation of the accumulated fragments is often random, giving a jumbled appearance to the cover, while at higher velocities the fragments are swept under the downstream ice, and the upstream end of the cover either does not propagate upstream or forms in a very irregular manner. Early attempts to establish criteria for the accumulation of ice were expressed in terms of a mean flow velocity, above which the fragments would be swept under the floating cover and the fragmented cover would not propagate upstream. More recently, criteria for the upstream progression of an ice cover by accumulation have been derived on the basis of vertical sinking (30) or underturning (2,35) as the modes of submergence of an arriving block, and have been expressed in terms of the approach flow Froude number. The submergence of individual floes beneath the leading edge of a stationary ice cover now is reasonably well understood; the mechanics of accumulation of the submerged blocks beneath the cover and the evolution of accumulations until they are several blocks thick have not been fully elucidated, but research efforts are underway to clarify this aspect of the problem, which is related directly to another important phenomenon, i.e., the formation of ice jams.

It should also be noted that understanding the mechanics of accumulation is directly relevant to another aspect of ice engineering. It is often desirable to accelerate the formation of a complete ice cover, either to stabilize the cover against later movement or to reduce the rate of heat loss from the water and consequent frazil formation. This is accomplished by reducing the velocity and increasing the depth of the flow by means of downstream control structures or by providing floating booms to initiate the accumulation.

A problem related to the general subject of river ice formation is the matter of terminology and classification of types of ice formations. A number of classification schemes have been proposed (20,25), but they are not in complete agreement. Efforts should continue to standardize terminology and to relate ice types to the various modes of formation and accumulation.

Ice Jams

There is a large body of literature on ice jams, much of which has been reviewed in the extensive annotated bibliography prepared by Bolsenga (7). However, most of the publications present only qualitative observations, and there is a paucity of quantitative data on the conditions leading to formation of ice jams. Nevertheless, the qualitative observations suggest certain lines of attack to be pursued in seeking an improved understanding of the processes of jamming. It is generally agreed that ice jams are initiated in rivers at obstructions such as constrictions (see Fig. 1 as an example), abrupt changes in channel slope or alinement, stationary ice covers, etc. Only recently, however, have attempts been made (17,27,30) to quantify the characteristics of obstructions which can cause jamming. Even these attempts have been confined primarily to one-dimensional situations, and the results are generally expressed in terms of the flow Froude number. While it is generally observed that the lower limit of Froude numbers associated with jamming is in the range 0.06 to 0.09, it is also known (19) that ice-transporting flows with higher Froude numbers do not always jam; i.e., some obstruction must be present to initiate and support the jam. Two approaches to the quantitative formulation of ice-jam phenomena seem logical in light of these observations. The first involves application to fragmented ice covers of the principles of continuum mechanics, including in the analyses the constitutive properties of fragmented ice, in order to develop predictors for the stress distribution in, and the geometric configuration of, ice jams. The analytical model would have to be two-dimensional in the case of straight channels and three-dimensional for curved or meandering streams. The second approach is based on the study of sites which historically have experienced recurring jams, to determine the hydrological and physiographic stream characteristics that are associated with a high jamming potential. In field investigations, particular attention should be focused on the formative stages of jamming, for which there are very few detailed observations, both because of the precipitous nature of the onset of jamming, and because of the difficulties of access during large movements of ice.

The two lines of investigation should be coordinated: the analysis providing a framework within which to organize and examine the pertinent variables, and the field studies providing the data necessary to validate the analysis.

A related problem inherent in the prediction of the time of occurrence of an ice jam, as opposed to site prediction which would be the goal of the aforementioned studies, is understanding of the breakup process that supplies the ice which forms downstream jams. There are two main types of breakup: mechanically-driven and thermally-driven; both types should be amenable to analysis. The ice sheet can be treated as a plate subjected to either hydraulic or thermal loading, or to both. The principal complications foreseen are the difficult boundary support conditions of the ice cover, the variable nature of the ice strength, and the buckling that can occur when an ice slab fails under the action of a load parallel to its plane. Determination of the effect on ice strength of the deterioration of the ice cover, through the processes of candling

FIG. 1.—Ice Jammed at Highway Bridge, Lancaster, N.H., 1967

and rotting, is of central importance to both types of breakup. While it is generally conceded that rotting involves enlargement of the grain boundaries by melting, there is presently no means for predicting the rate at which rotting progresses through an ice cover under given thermal and hydraulic conditions. It is believed that a comprehensive laboratory and field program to determine the rate and characteristics of the rotting process could yield reliable predictors for the occurrence of rotting, as well as for its rate and effect on the strength of the ice cover.

Once an ice jam has formed, it is often necessary or desirable artificially to induce its breakup. Various measures, including blasting, cutting of relief channels, and dusting to increase the heat uptake and thereby accelerate the melting process, have been used with varying degrees of success. While such measures are necessary in many cases, the greater research need at present is for an understanding of the formation processes so that measures may be taken to prevent jamming.

Jamming can also result from massive production of frazil ice. Jams of this type commonly form downstream from open-water areas at channel obstructions or at points where there is a decrease in channel slope (e.g., at the entrance to a reservoir). While generally associated with the early winter formation period, frazil jams do sometimes occur at other times during the winter season. Results of research efforts outlined previously in the section on frazil ice are required to understand and alleviate the conditions under which jams of frazil occur.

Ice Forces

It is well known that the forces which ice exerts on structures and shorelines can be enormous and often produce extensive damage. The general design

FIG. 2.—Ice Boom on St. Lawrence River Near Ogdensburg, N.Y.

technique used to insure that intake structures, piles, abutments, ship hulls, etc., will not fail under ice loadings is to provide them with sufficient strength that the ice fails first. Sometimes, however, resisting the full magnitude of the expected ice forces is not practical and alternate means are relied upon; e.g., ice booms (see Fig. 2) can be designed to retain ice until the force in the boom reaches a certain level, whereupon elements of the boom submerge to allow passage of some ice over the boom. A problem related to the boom problem is the analysis and prediction of the stress distributions in a fragmented ice cover. This latter area has importance also in the understanding of the forces exerted on vessels moving through brash-ice covers.

In the following discussion, ice forces are classified as those exerted by floating ice sheets, those produced by fragmented ice accumulations, and finally ice forces experienced by moving vessels. Each of these has distinguishing features and involves different investigative approaches.

Forces Exerted by Floating Ice Sheets.—There is considerable question concerning the correct design values to be applied to a structure to insure that it can resist ice forces. For a number of years this uncertainty was due in large measure to inadequate knowledge about the way in which ice fails, but several modes (e.g., crushing, bending, splitting, and buckling) have now been identified (28). Since the force exerted by the ice on a structure depends to a great extent on the mode of breaking, an immediate research objective should be to determine, through laboratory and field tests, the conditions for occurrence of the different modes. Experiments should be guided and complemented by analytical work which will provide the framework for interpreting the many tests necessary to cover the important ranges of strength and thickness, shape and size of structure, etc. It should also be pointed out that the analytical work does not entail merely straightforward application of existing techniques developed in the theory of elasticity and plasticity and applicable to materials having simple rheological behaviors. To cite a single example of the complexities that arise, prediction of the length of breaking of a cantilever ice sheet subjected to a dynamic end loading involves not only a combined bending and axial-load analysis of a plate with complex rheological properties resting on a linearly elastic foundation, but also the dynamic interaction between the plate and the supporting fluid below. Since most ice loads are dynamic in nature, a full treatment requires consideration of rates of loading and the dynamic response of the ice sheet. There is also a pressing need for further research into the rheological properties of ice, with the goal of relating these properties to its crystal structure, conditions of formation, and thermal and stress history. Thus a comprehensive treatment entails sustained work over a period of time by both analysts and experimentalists.

Forces of Fragmented Ice Accumulations.—In contrast to the localized force analysis described previously, the forces produced by fragmented ice accumulations require a "field" approach. The general geometry of the ice accumulation, the spatial variation of the constituent force elements, and the local interaction of the fragments all are necessary ingredients in a complete analysis of the stress distribution in fragmented ice fields. The research thus necessarily entails consideration, both in analytical work and in laboratory and field experiments, of the stress-strain characteristics of fragmented covers as functions of fragment properties, accumulation thickness, loading rate, etc. The results that should be forthcoming from such a comprehensive attack would have applicability far beyond immediate problems such as the design of ice booms, and an improved understanding of the forces involved in ice jams, since the results would also have immediate bearing on problems related to the behavior of arctic pack ice, the mechanics of windrows of piled ice that occur at lake and ocean shorelines, etc.

Forces Exerted on Moving Vessels.—While related to the two preceding subjects, this area of research has particular importance, highlighted by the recent consideration of the use of large vessels for transport of bulk commodities in Arctic regions. On a less dramatic scale, the recent inquiries into the feasibility of navigation-season extension on the nation's inland waterways have also demonstrated the need for a better understanding of the forces involved in moving a vessel through either virgin or fragmented ice covers (see Fig. 3).

While results obtained in both of the areas of ice-force investigation discussed previously would have applicability in the present problem, the particular problems associated with moving vessels require separate investigation and study. The immediate objective of these studies should be development of the capability to predict the constituent elements of the total resistance exerted by the ice on the moving vessel, including the components resulting from frontal breaking, friction along the hull sides, displacement of the fragmented ice, and the hydrodynamic interaction between the ice cover, the vessel, and the surrounding fluid. Attempts have been initiated along these general lines of attack (3,15,18,23). Undoubtedly a successful attack on these problems will entail laboratory modeling, field testing, and analysis. While much of the research will consider only conventional hull shapes, effort should also be directed toward the merits of special types of vessels specifically designed to minimize the ice forces or to optimize clearance of channels through ice. In this latter area, model techniques

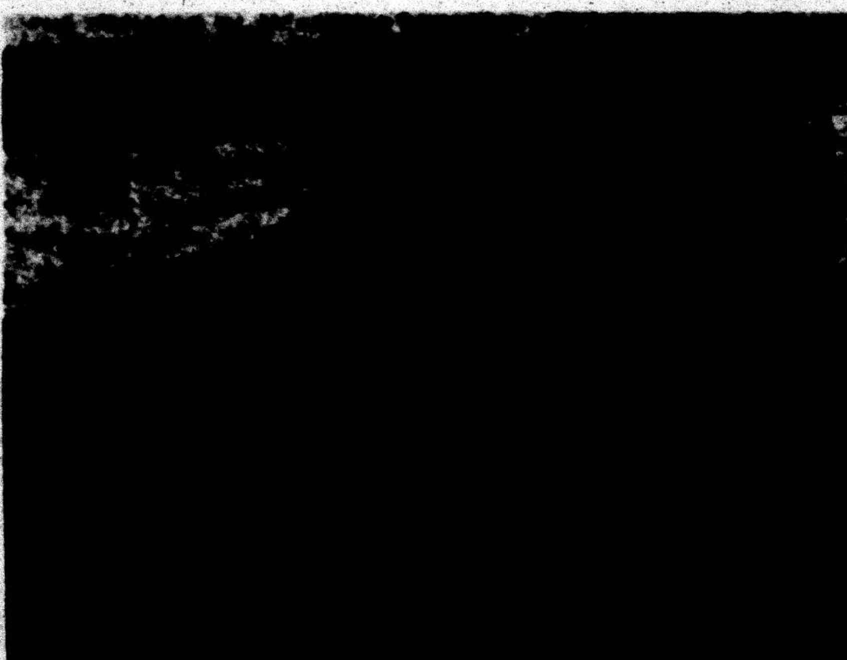

FIG. 3.—Towboat Navigating in Ice on Mississippi River, February, 1972

should prove to be particularly advantageous, since a wide range of geometries may be tested at a cost relatively low compared to that of prototype testing.

Degradation of River Training Works.—River training works, including bank revetments, spur dikes, levees, and other works, often experience degradation resulting from scour and erosion by moving ice. The greatest severity is generally associated with thick ice and sudden breakup, but damage often occurs well downstream from reaches which attain a complete ice cover. The techniques to combat the problem, other than simple replacement of damaged portions, include use of larger riprap sizes than otherwise required, increase in mass of the control structures, and regulation of flows by upstream reservoirs. All these measures are regarded as only partially successful; consequently, a need exists for studies which would result in design of more resistant structures.

Thermal Effects

There are two central questions related to the thermal behavior of rivers. What is the undisturbed thermal regime of the river? What are the effects on this thermal regime of man's utilization of the river? At present neither question can be answered in quantitative terms with confidence. The first problem, documentation of existing thermal regimes, is not as simple as one might first suppose. Even small above-freezing water temperatures (of the order of a few hundredths of a degree) can result in significant changes in the formation, evolution, and breakup of a river ice cover.

Documentation of Natural Thermal Regimes.—There exists considerable misunderstanding concerning the nature of the thermal regime of natural rivers. For example, bubbler systems are sometimes installed on the premise that a significant thermal gradient exists which may be utilized for local suppression of surface ice. On the other hand, the water flowing in ice-covered rivers is widely considered to have an isothermal temperature of about 0° C, and hence to be inert in terms of convective and conductive heat transfer to the ice-liquid interface. Neither concept is wholly correct. Bubbler systems can be effective for local ice suppression even if only very slight temperature variations exist, provided a sufficient volume of water is moved by the system. Indeed, a continuous supply of water at 0° C to the free surface will maintain an open area of some extent, since the heat of fusion must be transferred from the water to the air before freezing will occur. It has also been observed that temperature differences as small as 0.02° C, which generally are undetected by the commonly used hand-held glass thermometers, may effect a change in the underside of the ice cover from an essentially smooth, flat surface to a surface with rugged wave forms (5), or produce extensive open areas in the ice cover. Considering the seemingly disproportionate effects produced by small temperature differences, it is essential to the adequate documentation of winter thermal regimes that inexpensive but highly accurate thermometer systems be developed, and that the thermal regimes of natural rivers be extensively documented at representative sites on rivers with sizes ranging from small tributary streams to large navigable waterways. Intensive examination of a few sites would undoubtedly yield greater benefits than incomplete data obtained at many stations, since the complexity of the thermal regime and history preclude proper interpretation on the basis of a few scattered measurements. What should be measured in such a program? Undoubtedly the principal quantities are those which govern the thermal processes of conduction, convection, and radiation, i.e., water temperatures and velocities, ice thickness and extent, surface temperatures, wind velocities and air temperatures, net surface radiation, and ground water and other thermal effluents introduced into the river.

Effects of Thermal Effluents on River Ice.—There is at present only one detailed method (1,13) available for predicting the extent of ice suppression downstream from the section where a thermal load is imposed on a river. For some purposes, such as overall planning, it is adequate; for others it is not. The limitations stem from the simplifying assumptions (one-dimensional flow, complete mixing, unrefined formulation of surface-heat-transfer processes) made necessary by inadequacies in the present understanding and formulation of the constituent phenomena. An indication of the limitation of the method is given by the fact that among 34 sites considered for validation of the computational procedure, only two were considered satisfactory for a rigorous validation (14). An effort should be made to extend the method, or devise other methods, to account for unsteady effects, for lateral and longitudinal dispersion of the effluent and for the nonuniform geometrical characteristics of natural rivers. The extension of the method will involve both field and analytical investigations and could profitably be carried out in conjunction with a study of the natural thermal regime upstream from a source of thermal effluent.

For local suppression of ice, recourse is often made to the use of air-bubbler systems (see Fig. 4), or to so-called velocity systems. The effectiveness of both systems is generally predicated on the existence of a thermal reserve in the stream, and the function of both systems is to advect the warmer or ice-free water to the location of desired melting or ice suppression. These systems are also sometimes used for ice flushing. There are at present only crude means

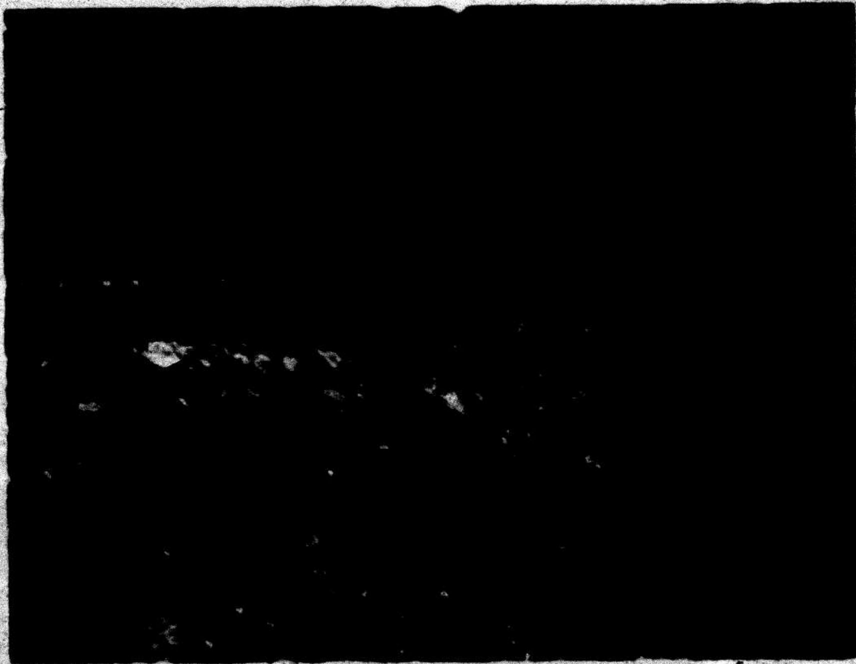

FIG. 4.—Aerial View of Ice Cover Suppressed by Bubbler Action, Duluth, Minn., 1972

available to guide the design and selection of the systems available (32), and all too often the approach taken is one of "try it and see how well it works." There clearly exists a need for a rational design procedure.

Other Problems

While the subjects discussed previously were judged by the Committee to be the four priority areas in which research is urgently needed, there are a number of other specific problem areas that merit attention. A short, and by no means complete, listing of some of these is presented in the following, together with a commentary on the needed research efforts. Undoubtedly, new problems will arise as greater demands are placed on rivers during winter seasons.

Ice Formation on Submerged Surfaces.—The accumulation of ice on submerged surfaces is generally related to the formation of frazil (26), although anchor ice may be produced directly on the body by radiative heat transfer. Regardless of its origin, icing of submerged surfaces is a recurring and serious problem, for which the usual solution in the past has been the addition of heat by one means or another. Possible use of special ice-phobic surface coatings would provide an alternate means of alleviating the problem.

Properties of Ice.—The thermal properties of ice are fairly well documented, but the mechanical properties are not sufficiently well established (26). It is difficult to correlate the different sets of laboratory data because of the many different test procedures and specimen configurations that have been used, and because of inadequate reporting of the thermal (and other) conditions during the tests. Hence there is a need for additional testing of ice strength, with the tests covering the important ranges of crystal size and orientation, ice temperature, sample size and shape, loading configuration, etc. and for reporting of the test conditions and results. There is presently also a need for a generally acceptable means of accurately measuring the crushing strength under field conditions.

Friction Factors.—There are limited data available on the friction factors associated with the undersurface of river ice covers. The presence of frazil greatly complicates the problem, as does the formation of ice ripples (4,9,21,22) on the underside of the cover. According to Nezhikovskiy (29), the extensive Russian experience on the effect of frazil indicates a general decrease in the friction factor through the winter season; the decrease is generally attributed to a reduction in the amount of frazil present. Exceptions to this general picture do exist, and deserve study. The problem is further complicated by a lack of documentation on the change in the hydraulic roughness of the river bed due to the presence of ice. An improved understanding of friction factors associated with ice covers would enable more accurate prediction and evaluation of stage-discharge records.

Sediment Transport in Rivers with Ice.—There is almost no documentation on the effects of an ice cover on the sediment transport characteristics of a river. When it is recalled that water temperature is known to have a major effect on the sediment transport rate (16,34), and since the velocity distribution is radically altered by the presence of the ice cover, it is reasonable to speculate that the sediment transport regimes might be significantly different between winter and summer. Both laboratory and field studies are needed to establish the characteristics of sediment transport beneath ice. The studies should benefit from the extensive knowledge already available on sediment transport in rivers under ice-free conditions.

Design of Water Intakes for Ice Conditions.—The problems involved in designing nonsilting water intakes from rivers are well known. Similar problems arise in the design of intakes which will function when rivers are ice laden. At present the problem is generally solved by *ad hoc* techniques applicable to specific situations (26), and even these are generally adopted only after the problem occurs. It is expected that many of these techniques could be placed on a rational basis by examining the conditions causing the problem and the effectiveness of the solution adopted. This should lead to rational design methods based on extensive field experience. At present there is available no comprehensive summary of these techniques, or description of their relative success in overcoming the problem.

Formation of Icings (Naleds) and River Glaciations.—An icing (the corresponding Russian term is "naled") is the successive accumulation of ice in layers which results from a continual supply of water to the surface. These accumulations can cause extensive damage or expense through their action in blocking drainage structures, interfering with road usage, inundating structures or other facilities, and by causing local flooding. Remedial measures are generally taken in reaction to the occurrence of an icing, and generally are treated as a recurring maintenance function. The causes of icing are reasonably clear. However, a definite need exists to consider the causes of icings during the design and site-selection phases of a project so as to minimize the control efforts which will be required later. As in other problem areas involving ice, the need exists to quantify and disseminate the rather extensive experience with icings which at present exists in only a qualitative form and resides largely with engineers who have been confronted with problems arising from icings. Valuable engineering guidance can be obtained from the extensive literature on the subject, much of which has been summarized (10,11).

Glacier Outbursts.—The discharges of streams originating from temperate glaciers often have imposed upon the normal runoff a sudden large discharge or burst, which results when a large amount of water is suddenly released from a glacier; several occurrences and the resulting extensive damage have been described (31, 33) in considerable detail. In some cases they are a frequent, almost regular occurrence, while in others they seem to be unpredictable (24). The primary need in this area is for a method of assessing for specific sites the probability of occurrence of bursts, the likely magnitude of the resulting surges, and their potential for damage. Techniques presently used to assess the damage potential include examination of historical records, evaluation of physical evidence of past events, and, to a limited degree, assessment of the potential of a current hazard where no precedent exists. This latter is rendered most difficult, since the impounded water is often not visible at or near the surface.

Ice at Navigation Locks.—Over the past decade there have been increasing efforts to navigate waterways during periods of ice. As a result, the difficulties associated with ice at navigation locks have become of increased importance. The problems are many and varied, and much of the needed research suggested previously will aid in the solution of these problems. The difficulties include icing of gates, formation on lock walls of ice which must be removed periodically to maintain adequate clearances, the necessity of separately locking through ice pushed into the lock chamber by approaching vessels, interference with mitre-gate operation, blockage of intakes and valves, and icing on walkways, access platforms, and other minor structures which compromise safe operations. Besides research into the particular phenomena causing the problems, a need exists for early recognition of the problems associated with ice in the design phase of project planning.

Computer Simulations.—Many areas of engineering have made significant forward strides in recent years by means of numerical simulation made possible by the capabilities of modern, large-storage, high-speed computers. As the underlying physics of ice problems are placed on a progressively firmer founda-

tion, ice-engineering problems will no doubt also become more amenable to solution through numerical simulation of the complex processes involved. For example, the development of ice covers during winter seasons, the formation and evolution of ice jams, ice suppression by thermal enrichment, and unsteady ice forces acting on complex structures appear to be logical problems for analysis by numerical simulation. A continuing effort should be made to simulate such phenomena via numerical means using computers, and to identify those parts of the simulations which are least reliable or most sensitive to the input data.

Conclusions

The examination of river-ice problems presented herein has, by necessity, avoided the details of many of the problems, and the recommendations for future research thus have been more in the sense of giving direction rather than prescribing specific research tasks. Four areas of priority (formation processes of river ice, ice jams, ice forces, and thermal effects) are identified, together with a category of problems which defy simple classification into any one of the four areas. Where possible, the present state of knowledge has been indicated. In general this knowledge lags behind the current state of knowledge in comparable areas of river hydraulics associated with nonice periods. In view of the persistence of the problems, it is hoped that research will be initiated to reduce this gap and ultimately provide the practicing engineer with methods and techniques which may be used with confidence to alleviate the problems.

This report is respectfully submitted by the Task Committee on Hydromechanics of Ice of the Hydromechanics Committee of the Hydraulics Division.

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Appendix—References

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tion, ice-engineering problems will no doubt also become more amenable to solution through numerical simulation of the complex processes involved. For example, the development of ice covers during winter seasons, the formation and evolution of ice jams, ice suppression by thermal enrichment, and unsteady ice forces acting on complex structures appear to be logical problems for analysis by numerical simulation. A continuing effort should be made to simulate such phenomena via numerical means using computers, and to identify those parts of the simulations which are least reliable or most sensitive to the input data.

Conclusions

The examination of river-ice problems presented herein has, by necessity, avoided the details of many of the problems, and the recommendations for future research thus have been more in the sense of giving direction rather than prescribing specific research tasks. Four areas of priority (formation processes of river ice, ice jams, ice forces, and thermal effects), are identified, together with a category of problems which defy simple classification into any one of the four areas. Where possible, the present state of knowledge has been indicated. In general this knowledge lags behind the current state of knowledge in comparable areas of river hydraulics associated with nonice periods. In view of the persistence of the problems, it is hoped that research will be initiated to reduce this gap and ultimately provide the practicing engineer with methods and techniques which may be used with confidence to alleviate the problems.

This report is respectfully submitted by the Task Committee on Hydromechanics of Ice of the Hydromechanics Committee of the Hydraulics Division.

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