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Ice Considerations in the Design of Modern In-Stream Structures

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Modern river restoration and streambank stabilization designs are taking more natural approaches. Examples include vanes and weirs constructed of rocks or logs that encourage bank sedimentation and direct flow toward the channel center, also rock riffles and weirs to control grade. Successful projects help control bed and bank erosion, re-connect floodplains, increase flow diversity and improve habitat for fish and wildlife. To date, the design of these increasingly popular structures has been largely empirical and little is known about their performance on rivers with ice. In addition to the uncertainty of the structures' survival in ice, little is known about their effect on river ice processes. A critical question is whether these structures will cause ice jams, and ice jam floods where none occurred before. Due to their newness, design guidance for river restoration projects on ice-affected streams is lacking. This paper describes recent research at CRREL and Clarkson University to develop design guidance for in-stream structures on ice-affected rivers.

1. Introduction

Modern river restoration (RR) and streambank stabilization (SS) efforts are turning to more natural methods compared to traditional alternatives of riprap and concrete. Examples include vanes and weirs constructed of rocks or logs to direct flow away from the banks toward the channel center. These in-stream structures, often complemented by plantings to reinforce streambank soils, help control bed and bank erosion, improve flow diversity, re-connect floodplains, and improve habitat for fish and wildlife. To date, their design has been largely empirical and little is known about their performance on rivers with ice. In addition to the uncertainty of the structures' winter survival, little is known about their effect on the ice regime. A critical question is whether or not these new structure types will cause ice jams, and ice jam floods where none occurred before, and whether these changes are of consequence. Little design guidance exists for river restoration projects on ice-affected rivers.

Popular natural methods include rock and log vanes that extend out from one bank to direct flow toward the channel center, decrease bank erosion, and improve conveyance of water and sediment, particularly through bends. Fig. 1 shows a series of rock vanes that stabilize the bank along a bend of the Winooski River in Vermont. In-stream structures that extend across the entire channel include cross vanes, W-weirs, rock riffles, porous rock weirs, and U-drops. Cross vanes and W-weirs consist of connected systems of vanes that concentrate flow toward the channel center and erode pools downstream, while maintaining the pre-existing bed elevation at their low points. Rosgen (2001) and NRCS (2008) offer design guidance for these and other SS and RR structure types.

This paper summarizes recent research at CRREL and Clarkson University aimed at improving design tools for these structures on ice affected rivers. Initial results are described in Tuthill (2008) "Ice Considerations in the Design of River Restoration Structures and Tuthill (2009) "Monitoring of Streambank Stabilization and River Restoration Structures in Northern Vermont". Vuyovich et al., (2009) reports on a physical model study of ice transport in a straight channel with crossvanes and compares lab results to preliminary numerical simulations using the DynaRICE dynamic ice transport model (Shen and Lu, 2000). Recent improvements to DynaRICE allow modeling of ice forces on in-stream structures as well as transport of bed material. These new capabilities are currently being tested for different channel configurations and structure types (Knack and Shen, 2009).

2. Preliminary Ice Design Guidance for River Restoration Structures

Tuthill (2008a) offers basic design guidance for river restoration projects on ice-affected rivers, discussing potential effects on ice formation and ice breakup, as well as the structures' survivability in the river ice environment. A central design issue is ice passage past the structure, which is somewhat difficult to predict with existing theory and models. Considerable ice engineering research has identified the conditions for ice retention on rivers, and this guidance can also be used to predict conditions for ice passage past an in-stream structure (USACE 2006).

For the freezeup period, a major concern is frazil ice retention at the structures that might cause freezeup ice jams and flooding. An example is the 2005-2006 freezeup ice jam flood that occurred on the White River in Colorado following the heightening a rock diversion weir (Fig. 2) (Tuthill, 2008b). For breakup, the big concern is causing ice jams and flooding where none occurred before. Examples are river restoration projects proposed (but not built) for major ice the jam flood sites of Montpelier, VT and Oil City, PA.

Water velocity criteria and ice arching theory, can be used to gage the effect of in-stream structures on freezeup ice processes. As an approximate rule of thumb, to avoid thermal ice cover formation and arching of frazil pans, approach velocities upstream of an in-stream structure should be at least 1.5 ft/s, *and* the narrowest gap formed by the structure should be at least four times the expected diameter of the largest frazil ice floes (Perham, 1983, Calkins and Ashton, 1975). Lacking time or resources for more detailed analysis, bed slope profiles and water velocity measured from drogues provide a first-cut estimate of ice transport potential, ice formation mode, and ice type, with and without project.

The potential effects of a river restoration project on ice breakup, transport, and jamming are more difficult to predict. Critical issues are project location with respect to known jam sites and potential ice source reaches. The uncertainties on how in-stream structures affect breakup processes and the current lack of design tools are reasons against locating RR projects at sites known for ice jams and ice jam floods. Also, should a jam occur after construction, even if it had no effect, the RR project could be perceived as the cause.

Some ice-resistant designs currently exist for rock RR structures. Examples are the ramp-like vanes designed by the National Resource Conservation Service (NRCS), built of individually-placed quarried stones. Their mildly-sloped upstream faces allow large ice floes to ride over the tops without displacing the rocks (Fig. 3).

3. Physical and Numerical Modeling of In-stream Structures and Ice

Vuyovich et al., (2009) describe physical tests of ice conveyance with and without cross-vane structures in a straight channel. Three cross-vane structures were built in a moveable bed flume assuming a model-to-prototype (prot.) scale of 1:50. Bankfull width and depth were 200 and 6.9 ft prot. and bed slope was 0.0024 . Model plastic ice material was released at water flows 6200 and 1970 cfs prot. to gage whether the structures increased the potential for ice jam formation.

The flume experiments reasonably reproduced the hydraulic, scour, and ice transport processes one would expect on a normal flow, gravel-to-cobble bedded section of river of moderate steepness, and scour holes developed downstream of the structures, similar to those observed and measured in the field.

In the flume experiments, the cross-vane structures delayed but never completely stopped the ice run, even under conditions of low water flow and high ice discharge where one would expect jamming (Fig. 4). The moving ice did thicken to the channel bed, displacing some of the structure rocks. In preliminary DynaRICE simulations with similar ice and water discharge conditions, the ice grounded and stopped at the lowest weir, but numerical instabilities in areas of small water depths caused difficulties.

In spite of the differences between physical and numerical model predictions of ice jamming, the two models produced similar results in terms of hydraulic and ice passage processes. The surface flow patterns and velocity distributions in the vicinity of the vanes were alike, and the ice run thickened and slowed upstream of the vanes similarly in the flume and computer models.

The DynaRICE model has recently been modified to include sediment transport and calculation ice forces on in-stream structures (Knack and Shen, 2009). A method has also been developed for flow over dry bed areas, resolving the numerical instabilities near the structures. Initial simulations for the cross vane cases similar to Vuyovich et al. (2009) are encouraging. The model developed scour holes and sediment deposits qualitatively similar to those seen in the flume experiments and the field, and believably simulated ice transport and jamming with no stability problems (Fig. 6). Future tasks include simulations of ice dynamics in a curved channel with vanes, and validation of numerical model results against field observations and physical model study results.

4. Summary and Conclusions

River restoration and streambank stabilization projects are fast evolving to more aesthetic and environmentally-compatible methods that take advantage of natural materials rather than the traditional ones of riprap and concrete. To date, most designs methods have been empirical with little consideration of how the project might affect river ice processes or vice versa. This paper describes research by CRREL and Clarkson University to better understand the interaction of in-stream structures and ice, and develop more quantitative design tools.

CRREL's initial approach has combined field monitoring of existing structures with ice engineering theory and the use of physical models to develop basic design guidelines for river restoration projects on ice-affected rivers. Efforts are currently underway to adapt and utilize the DynaRICE model as a quantitative ice design tool for these fast emerging river restoration and streambank stabilization techniques.

5. Acknowledgments

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Fig. 1. Rock vanes deflecting flow and frazil ice away from a bank in the Winooski River near Willliston, VT.

Fig. 2. Freezeup ice jam on the White River in northwestern Colorado caused by the heightening a rock diversion weir.

Fig. 3. Ice resistant rock vane designed and built by the Vermont NRCS to stabilize an eroding bank along the Winooski River near Richmond, VT.

Fig. 4. Near ice stoppage at cross-vanes during physical model testing in CRREL Flume.

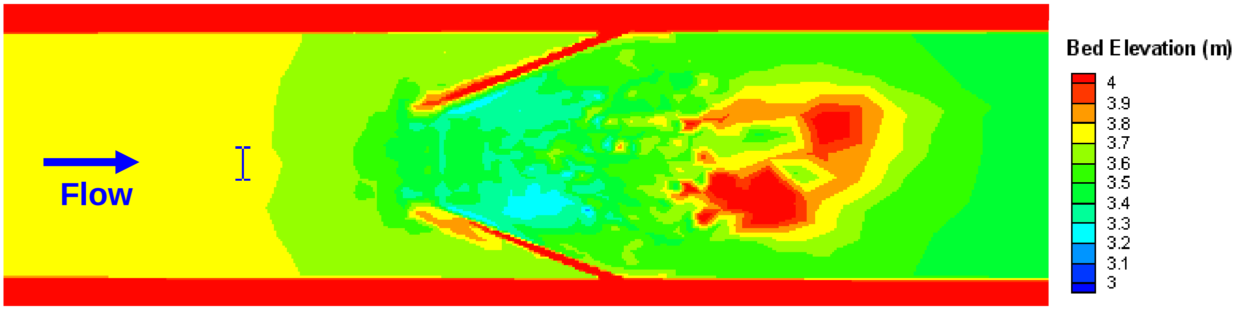

Fig. 5a. DynaRICE simulation of bed scour and deposition downstream of a cross vane

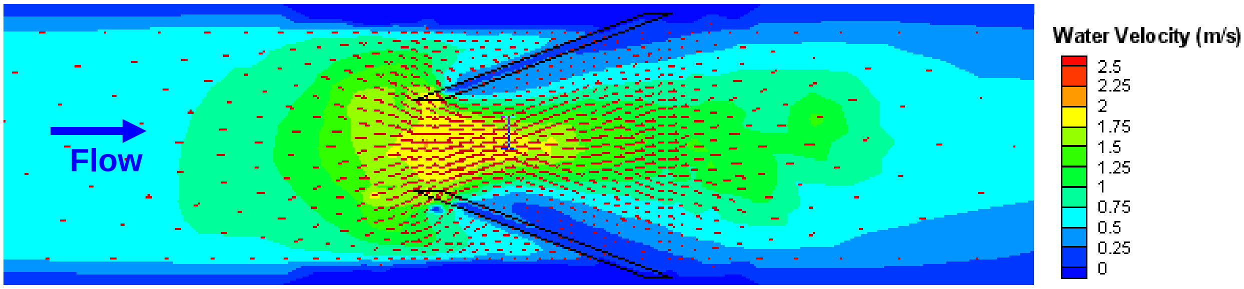

Fig. 5b. DynaRICE simulation of water velocity distribution for ice jam at cross vane.

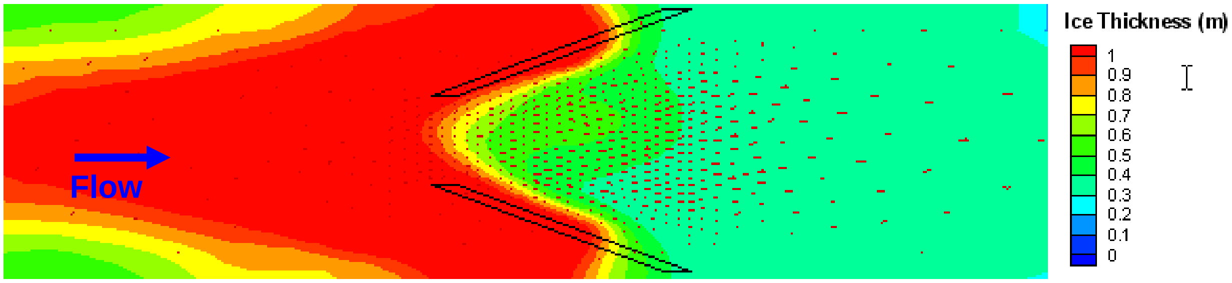

Fig. 5c. DynaRICE simulation of ice jam thickness ice jam at cross vane.