Rock Diameter Effects on the Formation of Anchor Ice in Culverts

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Executive Summary

This project introduced readers to the issue of anchor ice. The work focused on the northern Minnesota Region. Researchers have made efforts to describe the formation of anchor ice. The formation process is a complex one. Anchor ice is the formation of ice at the bottom of the water column; the water freezes from the bottom upward to the top of the water surface. Formation of ice from the bottom up and freezing at the top is a rare occurrence. This project presented information on the background and proposed work to better understand this natural phenomenon. The report started with a broad literature review to help the reader comprehend the scope and depth of the issue. An analysis of culvert designs was done on two culvert design approaches, hydraulic and fish passage design procedures. These are explored to improve our understanding of how design decisions effect the formation of anchor ice. This work used a theoretic construct to explore the topic of anchor ice.
Description

History of Problem

Researchers have made efforts to describe the formation of anchor ice. The formation process is a complex one. Anchor ice is the formation of ice at the bottom of the water column; the water freezes from the bottom upward to the top of the water surface. Formation of ice from the bottom up and freezing at the top is a rare occurrence. Anecdotally, this has been a rare phenomenon in culverts, and it is not an issue that has been addressed in the design of culverts.

To help the reader understand the importance of the phenomenon, Figure 1 is an example of anchor ice in a concrete box culvert and Figure 2 is an example of anchor ice in a corrugated metal pipe (cmp) arch culvert where the bottom is open and the cmp is on top. The cmp arch is intended to simulate a riverbed and facilitate fish passage through the culvert. A culvert is the engineer’s attempt to control Mother Nature; it is a man-made structure. The primary function of culverts is explained as “Culverts are short conduits that are designed to pass peak flood discharges under roadways or other embankments” (Chin, 2013, p. 250). The main purpose of the hydraulic function is to protect property, both the road, and the upstream structures. They also have a secondary function related to fish and other wildlife passage through the culvert or under a busy road. However, when ice accumulates, the functionality of the culverts for either use is affected.

This particular research is focused on the northeast Region of Minnesota. Anchor ice is a naturally occurring phenomenon, in all frigid parts of the world. This phenomenon impacts habitats, fish populations, and local economics. The impact of this
naturally occurring event is an example of how humans and nature are still dependent upon each other.

Figure 1: Photos of anchor ice in a concrete box culvert located on Highway 35 in Minnesota. U.S. Forest Service. Reprinted with permission.

Figure 2: Corrugated metal arch pipe culvert and anchor ice. Located on a Minnesota Fire Road (FR). U.S. Forest Service. Reprinted with permission.

Problem Description

The purpose of this document was to present the theoretical background on culverts as a complex open channel flow structure, the impact of designing the culvert to accommodate aquatic organism passage, and recommendation for moving ahead in evaluation and control of anchor ice in relationship to culvert design in the northeast Region of Minnesota and other frigid regions. Figure 3 is a map of the culverts in northeast Minnesota Region.
The motivation behind the research was to develop a theoretical understanding of anchor ice and possibly gain funding for future research from the U.S. Forest Service (USFS) or the Minnesota Department of Transportation. Anchor ice impacts aquatic organism habitat in the northeast Region of Minnesota. The phenomenon of anchor ice formation in culverts has a far-reaching consequence for the habitat and the region. Fish populations are potentially impacted by anchor ice formation because the water column is eliminated in portions of the stream, and because the blocked culvert prevents upstream migration, which prevents spawning. Anchor ice causes erosion on the embankments of the river.

Figure 3: A map showing five of the USFS culverts that experience anchor ice in northeast Minnesota Region. U.S. Forest Service. Reprinted with permission.

Literature Review

Alfredsen and Stickler (2009) studied and collected data on the formation of anchor ice. A qualitative study of the anchor ice found it was considered a natural event.
Anchor ice formation effects water level and discharge, which in turn effects
hydroelectric production and fish population movement. These researchers have
described the process of the anchor ice formation process down river from hydroelectric
facilities. In order to understand the formation of anchor ice in the context of the river
downstream from a hydroelectric facility, the quantifying steep channel freeze up process
needs to be understood.

The freeze-up processes in steep channels are dynamic and generate important
water factors that impact the environment (Anctil, Dube, Morse, & Turcotte, 2013a). The
research approach used the application of a mechanistic heat budget model. Steep
channels are found in most cold regions and can be characterized by gravel bed, fast-
flowing segments and a gradient above 0.05 %. This has a strong impact on the
development of ice features.

Ice process occurs in steep gravel bed channels are completely different from
mild gradient rivers. Steep bed channels have unique morphology and the anchor ice
formation is driven by heat fluxes in and out of the system that are related to the
morphology (Anctil, Dube, Morse, & Turcotte, 2013b). Using the model framework,
stream hydrographs can be used to make better estimates of discharge in steep channels
and improved understanding of anchor ice formation.

A study by Bergsma (2013) called for the expanding market for tunnels, such as
the Orlovsky Tunnel, in cold regions. The presence of anchor ice and high flow velocities
require a more robust tunnel protection. This research further explained the impact of
anchor ice on the tunnel building experience. The article discussed the possibility of the
immersed tunnel project being closed down because of the formation of anchor ice on different important structures.

The natural phenomena may affect structures, and there is evidence to suggest that environmental changes occur as well. A report by Castle, Snyder, and Wright (2008) illustrated the changes that rivers undergo in connection to anchor ice. Stream erosion of glacial deposits may affect the occurrences of certain fish populations. The impact of wildlife and gravel beds may be connected. The researchers contended that an understanding of stream morphology and associated dynamics of bed load transport is important for predicting the future response to land use and climate change, as well as for designing successful restoration projects for the natural environment.

This improved understanding may also lead to the need for certain types of river flow forecasting to predict areas of concern for anchor ice formation. Researchers explored the configurational entropy theory for the monthly stream flow forecasting (Cui & Vijay, 2014). Three main parts comprising this theory include the following: Determination of density, parameters by cestrum analysis, and extension of auto correctional. According to the Cui and Vijay, (2014), 19 river basins were tested using this method, and the method satisfactorily forecasts high and low water flows.

The evolution and hydraulic resistance of anchor ice on gravel bed is another important issue. A laboratory study on the evolution of anchor ice and the hydraulic effect within a gravel bed was conducted Daly, Kerr, and Shen (2009). Their results showed that anchor ice is initiated by frazil ice accumulation on bed gravel at a depth equal to half the bottom gravel diameter below the crown level of the gravel. No in-situ ice growth was found. Daly et al. also discussed the different stages of anchor ice growth.
It was found that in the final stage of growth that the gravel bed was covered by ice. While this is informative, it is expected that bottom gravel morphology and water velocity will have an impact on this result.

The Great Lakes, Canada, and parts of Sweden are regions that can get down to frigid temperatures in the wintertime. Qu’s (2006) research of anchor ice in super cooled water may have a huge impact on water infrastructures in many cold regions. This research modeled the formation of frazil ice and heat transfer mechanisms to understand the phenomenon of anchor ice (Qu, 2006). Frazil ice is a collection of loose ice crystals in water. Frazil formation looks like a slushy materialization of the ice on the surface of the water. This leads to the growth of anchor ice. Understanding the phenomenon of frazil ice on a global scale could help researchers on finding new ideas on how to manage anchor ice.

The global perspective on frazil ice may be important to many researchers. Daly and Ettema (2006) took a different look at the issue and addressed the problem of water intake becoming blocked by frazil ice. As a team they reviewed the current understanding of the processes of frazil formation and intake blockages in Lake Michigan. Methods of monitoring and mitigating the problem were included in their study. In northern Sweden, research is taking place on the impact of anchor ice. Lind, Nilsson, and Weber (2014) studied the effects of ice formation on riparian and in-stream vegetation in northern Sweden. They covered 25 reaches, spanning from ice-free to ice-rich perimeters. The researchers challenged that if ice induced winter floods are reduced in number, an important natural event for riparian and in stream vegetation control will be lost. This
possibly led to the immigration of more plant species from the south (Lind, Nilsson, & Weber, 2014).

Since anchor ice is a phenomenon that occurs in frigid periods of time actual visual evidence is critical to understand it in the real world. Daly, Gagnon, Weyrick, Vuyovick, and Zaitsoff (2009) used web cameras to monitor real time ice conditions at hydropower plants, navigations reaches, or other locations that have ice related flooding. The cameras winter seasons are the 2000-2003 winter seasons. They provided an effective way of monitoring and analyzing river ice conditions (Daly et al., 2009). Other researchers have done research on the phenomenon using less visual evidence.

Using less visual evidence may be effective in studying anchor ice (Shen & Wang, 1995). Their research explored the transport of frazil granules and its relation to frazil jam evolution. Experiments are conducted by using low-density chips to determine the transport rate over a range of flow conditions (Shen & Wang, 1995). Doreing and Qu (2005) discussed a series of laboratory studies that were carried out on the evolution of anchor ice around rocks and on gravel beds. According to Doreing and Qu (2005) the formation of anchor ice can be recorded in different flow patterns and frazil ice attachment. Frazil ice occurs when water is cooled below the freezing point. Doreing, Shen, and Shi (2004) documented and explored a series of experiments that were carried out by using a counter-rotating flume located in a computer-controlled cold room. Researchers found that water velocity strongly influenced frazil ice evolution (Doreing, Shen, & Shi, 2004). Dube, Turcotte, and Morse (2014), the researchers main focus was the formation of anchor ice during winter in culverts. They also explored the formation of
anchor ice in steep channels during the winter. They found that ice formation regulates water flow, levels, resistance, bathymetry, and water quality and fish habitat.

Crystal types and sizes, growth mechanisms, patterns, orientation, and their porosity are factors that impact the development process on formation of anchor ice and ice dams. Two main types of ice crystals were observed; they were columnar ice crystals and fixed frazil ice crystals (Dube & Turcotte, et al., 2014). The bedrock and underlying sediment may be influenced by different factors. Lacey, Leconte, and Leconte (2013) suggested that sediment transport caused by anchor ice might have an influence on the annual sediment transport budget of a river. These authors argued that anchor ice is river ice forming on the riverbed, which forms on cold and clear nights in turbulent streams that have a rough riverbed that consists of boulders, stones, and gravels and very coarse sand. It forms through the accumulation of frazil ice, which becomes anchor ice (Lacey et al., 2013). The process may be complex in nature researchers are studying the issue with great interest.

Researchers have tried to bring the issue of anchor ice to front of the scientific community. Lacey, Leconte, Leconte, and Tremblay (2014) called for increased study of the importance of cycles of river dynamics and formation of anchor ice. Sediment transfer is also measured by using riverbed particles. This is measured after each multi day cycle event. In this study, anchor ice release and run off events happened to be coincidental and no specific mechanisms of the cycle event was found.

**Analysis**

Early U.S. Forest Service road and water crossings designs were simple bridges that did not alter the natural channel. These did not appear to have anchor ice problems.
The next generation of road crossings were culverts designed based on optimizing hydraulic performance.

*Figure 4:* (A) Historic bridge over river. (B) Minimum culvert design flow based on hydraulic design. (C) Culvert design based on hydraulic design and aquatic organism passage.

The modern design is based on a combination of hydraulic optimization and aquatic organism friendly performance, which is closer to the historic culvert. However, this design approach has large (4”-6” diameter) rocks to ease the aquatic organisms passage. It appeared that these combined with a reduction in depth and velocity might create conditions that favor anchor ice formation.

In culvert design, the engineer considers the potential flow control conditions and sizes the culvert. The assumed conditions and design calculations that yield an internally consistent solution are considered the correct design solution. The potential flow conditions are shown in Table 1.
Table 1
Culvert Flow Control

<table>
<thead>
<tr>
<th>Entrance/Inlet</th>
<th>Exit/Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submerged</td>
<td>Submerged</td>
</tr>
<tr>
<td>Partially Exposed</td>
<td>Free Outfall</td>
</tr>
</tbody>
</table>

For each flow control situation, there are a number of hydraulic conditions that result in inlet and outlet control with different resulting hydraulic conditions. These potential combinations are shown in Table 2.

Table 2
Culvert Flow Conditions

<table>
<thead>
<tr>
<th>Case #</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Submerged Entrance Submerged Exit</td>
</tr>
<tr>
<td>2</td>
<td>Entrance controlled; Submerged Entrance, Free Outfall</td>
</tr>
<tr>
<td>3</td>
<td>Entrance controlled; partially exposed; entrance free outfall</td>
</tr>
<tr>
<td>4</td>
<td>Entrance Control; Partially Exposed Entrance; Submerged Exit</td>
</tr>
<tr>
<td>5</td>
<td>Exit Control; Partially Exposed Entrance; Submerged Exit</td>
</tr>
<tr>
<td>6</td>
<td>Exit Control; Long Culvert; Partially Submerged Entrance, Free Outfall</td>
</tr>
<tr>
<td>7</td>
<td>Exit Controlled; Partially Submerged Entrance; Submerged Exit</td>
</tr>
</tbody>
</table>

There is no direct solution for most of the cases 1-7. Initial assumptions are made, calculations are performed based on the assumptions, and then internal consistency checks are performed to see if the solution is reasonable in the real world. Controlling design case is frequently related to culvert barrel flow being either subcritical or supercritical.
Figure 5 shows a diagram of specific energy is related to the depth of the water. For any given flow rate, and channel geometry, there is a specific energy for the flow. This specific energy will result in a flow depth that is either subcritical or super critical.

Figure 5: Specific energy diagram

For a given specific energy, a subcritical depth occurs when the water depth is greater than the critical depth, which results in a slow, steady flow. Supercritical depth occurs when the water depth is less than the critical depth. In the supercritical depth flow regime, inertia forces, resulting in shallow depth and rapid velocity, dominate the flow.

The one additional complication is the impact of friction on the design calculations. If a culvert is short, usually assumed to be a culvert of less then 25 feet, no friction is usually assumed. If the culvert is long, Manning’s equation is used to estimate friction associated with the flow. In either flow regime, the flow can be described using
the Manning equation, given below, to relate flow rate or flow velocity to a number of variables including channel roughness.

\[ Q = \frac{1.49}{n} AR_n^{5/3} S_o^{1/2} \]

Equation 1: Manning’s equation

Where:

- \( Q \) = Flow Rate, (ft\(^3\)/s)
- \( A \) = Flow Area, (ft\(^2\))
- \( n \) = Manning’s Roughness Coefficient
- \( R_n \) = Hydraulic Radius, (ft)
- \( S_o \) = Channel Slope, (ft/ft)

The first step in understanding the system is comparing a standard hydraulic design to a rough surface (High Manning’s “n”) hydraulic aquatic organism friendly design. The Manning’s equation can be used to consider the impact of roughness on culvert design and culvert behavior. For this project, the Manning’s equation variables are all held constant except the roughness coefficient \( n \). A culvert design is performed for the selected flow rate. The Manning’s “n” is adjusted to maximum roughness for the software being used, and a new flow rate, flow regime, and culvert control is determined for the new conditions. The increased roughness is to simulate the impact of adding, “resting” rocks to the culvert barrel.
Table 3  
*Impact of Roughness on Hydraulic Design*

<table>
<thead>
<tr>
<th></th>
<th>1.5’ (18” Diameter) pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 0.013 (Smooth)</td>
</tr>
<tr>
<td>Q</td>
<td>15 cfs</td>
</tr>
<tr>
<td>$y_c$</td>
<td>1.405 ft</td>
</tr>
<tr>
<td>$y_n$</td>
<td>-1.80 ft</td>
</tr>
<tr>
<td>Super/Subcritical</td>
<td>Supercritical</td>
</tr>
<tr>
<td>Inlet/Outlet Controlled</td>
<td>Outlet Controlled</td>
</tr>
</tbody>
</table>

The resting rocks reduce the hydraulic capacity. Thus for the same hydraulic requirements, the aquatic organism friendly culvert will have an increased culvert diameter. The increased culvert diameter decreases the water depth at lower flow rates. These conditions expose the resting rocks to the air. During extreme cold, the air super cools the exposed rocks and freezing begins at the rocks and expands to cover the bottom, as noted in the literature review. This is the formation of anchor ice.

**Conclusion**

The assumption indicates that the hypothesis increased channel roughness due to performing an aquatic organism friendly culvert design initiates anchor ice formation is not unreasonable. The topic warrants detailed theoretical development, including heat transfer and head budget calculation, and experimental verification.
References


