Spencer Dam Failure Investigation Report

In the early morning hours of March 14, 2019, Spencer Dam on the Niobrara River in northern Nebraska failed during a major flood and ice run on the river. An independent investigative panel was formed to examine the failure.

April 2020

Association of State Dam Safety Officials

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FOREWORD

The Association of State Dam Safety Officials (ASDSO), a national non-profit organization serving state dam safety programs and the broader dam safety community, presents the findings of the Spencer Dam Failure Investigation Panel regarding the failure of Spencer Dam in March 2019. The mission of ASDSO is to improve the condition and safety of dams through education, support for state dam safety programs and fostering a unified dam safety community. ASDSO undertook this project at the request of the Nebraska Department of Natural Resources, the state regulator, and the Nebraska Public Power District (NPPD), the dam owner, with this mission in mind and understanding the need for the dam safety community to learn from this failure.

ASDSO developed a Dam Failure Investigation Guideline in 2012 and, in partnership with the U.S. Society on Dams, established the forensic team for the Oroville Dam spillway failure investigation. Now, for the first time, ASDSO was asked to lead all aspects of a failure investigation. ASDSO established impartiality as a guiding principle for the investigation and, to that end, set up an oversight group of key ASDSO leaders to guide the investigation. The oversight group developed the investigation scope of work and budget and established criteria for needed Panel expertise. ASDSO sent a request for Statements of Interest to all members and the oversight group developed selection criteria and reviewed the statements of interest to select the Panel members. The oversight group guided other ASDSO decisions, such as schedule and budget modifications, throughout the course of the investigation and provided a review of the report for the Panel.

The Panel completed the investigation independently and in accordance with the scope of work. The report represents the Panel's opinion on the most likely failure scenario, organizational and human causes, and lessons to be learned for the dam safety engineering community. The dam owner and the state regulator cooperated completely in the investigation, and NPPD provided funding. However, neither entity was involved in the development of the scope of work, panel selection, or panel discussions, calculations, deliberations or decisions. Both had an opportunity to provide a review of the draft report for factual errors but not to change the conclusions or recommendations.

ASDSO would like to thank NPPD for providing funding for the investigation and appreciates the work of all involved in the investigation and presentation of the report. This effort will hopefully prove valuable to advancing best practices in dam safety engineering in the future.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

In the early morning of March 14, 2019, Spencer Dam on the Niobrara River in northern Nebraska suddenly failed during a major flood and ice run on the river. An independent investigative Panel was formed to examine the causes of the dam's failure and provide lessons learned for the benefit of the dam engineering profession and society. This report presents the findings of the Panel's investigation.

Following the failure of Spencer Dam, the Chief Engineer of the Nebraska Dam Safety Program (NebDSP) contacted the dam owner, Nebraska Public Power District (NPPD), who agreed that the failure should be investigated by the Association of State Dam Safety Officials (ASDSO) using ASDSO's previously developed guidelines. ASDSO convened an oversight group and selected four members for an investigation panel. To ensure independence, neither the NebDSP nor the NPPD had any input on the selection of the Panel's leader or members.

Spencer Dam consisted of a powerhouse, a 400-foot-long concrete spillway, and a long earth embankment (herein termed dike). The failure investigation focused on identifying what happened (the physical causes of the dam's failure), why it happened (the human and organizational causes) and the lessons learned from the failure (to keep such failures from happening again).

The Spencer Dam Investigation Panel (the Panel) reviewed a large amount of data provided by both NebDSP and NPPD and gathered and reviewed data from local, state, and federal agencies. Also, the Panel conducted in-person and telephone interviews with many of these agencies and with individuals who had insights to contribute. From the documentation provided, it appeared to the panel that the dam was well maintained.

The Panel's effort to reconstruct the events of March 13 and 14 were hampered by a lack of first-hand accounts due to the remoteness of the site, the evening and early morning timing of the failure, and severe weather conditions during the failure. The dam's operators were able to provide descriptions of what they saw during the event, but only at specific locations and times, and they were limited by visibility. Given the lack of first-hand accounts, this report describes the range of what might have happened and details the Panel's opinion of the most likely scenario for the dam's failure.

Based on the operators' accounts, the evidence left after the failure, and other observations and data, the Panel found that the most likely failure scenario is as follows:

1. A wet autumn and colder than normal winter produced frozen ground, substantial thicknesses of river ice cover and snowpack. A winter storm, characterized as a bomb cyclone, affecting the entire Great Plains began around March 12 and initially produced temperatures above freezing resulting in rainfall or mixed rain and sleet on the snowpack and frozen ground. This storm produced flooding and dynamic breakup of the river's ice cover. As time progressed, weather conditions became colder and windier.
2. During the evening of March 13, dam operators opened all four of the dam's Tainter (radial) gates to their maximum six-foot opening on the spillway crest. They later released stoplogs from some of the other bays to increase outflow but were not able to open most of the stoplog bays due to ice
3. Around midnight on March 13, a major ice run came down the Niobrara River, failing the Stuart-Naper Bridge and damaging the Highway 11 (Butte) Bridge. Both bridges are upstream from Spencer Dam.
4. One or more ice jams occurred upstream from the dam, backed up flood waters and burst sending a great amount of ice rubble and flood water toward the dam.
5. Ice rubble likely clogged the opened gates and stoplogs of the dam's spillway and the reservoir rose to the dike crest.

6. Continued inflow of ice and water into the reservoir pushed some ice rubble onto and over the crest and downstream slope of the dike. Ice pushed through the upstream brick wall of the powerhouse.
7. Flow overtopped the dike, causing the downstream side of the dike to erode. The erosion led to headcuts, which grew in several locations along the dike's downstream slope. The dam's embankment dike breached in two locations, the first breach occurring around 5:15AM. The breaches widened and discharged water and ice rubble downstream.
8. The flow of water and ice failed the dam and swept through a house and other buildings located immediately downstream from the dam, causing their destruction and the disappearance of the lone resident (who was later declared dead by drowning). The flow spread over the channel and its floodplain downstream of the dam and was impeded by the approach embankment of Highway 281, located a short distance downstream of the dam. When the flow breached the highway embankment, it formed a major new channel through the breach.
9. The ice run carrying ice and debris continued downstream, where several other bridges were damaged or destroyed. The Panel completed hydraulic modeling of the river downstream. The Panel concluded that the failure of the dam did not exacerbate flooding more than a few miles downstream and certainly not in the village of Niobrara 39 miles downstream. The factors that led to this conclusion were: the small size of the Spencer Dam reservoir, the several bridges and other restrictions that potentially caused ice jams, the massive size of the flood and ice run, and the decrease in peak flow (attenuation) of flood water as it traveled downstream in the wide river floodplain.

The flood of water and ice greatly exceeded the capacity of the dam and its spillways. In the panel's opinion, there was nothing the operators at the dam could have done the morning of the flood that would have kept the dam from failing given the magnitude of the flood and ice run.

If the dam had not been present, the Panel believes that the structures immediately downstream would have not been safe during this flood of water and ice; and the highway bridge and the local structures including the house would likely have been washed downstream by the initial surge of water and ice. If the dam had been modified prior to the event to pass the flood and ice run, the downstream highway embankment would likely still have backed up water and ice, flooding and damaging the house, before failing the highway embankment.

The Panel identified two key, human factors contributing to the dam failure and consequences (Chapter 6):

1. There is a notable lack of knowledge about ice-run-related potential failure modes generally in the dam safety industry. Specifically, NebDSP did not know that Spencer Dam had previously failed and was damaged in ice run events. NPPD had limited knowledge of past ice run events at the dam.

   ASDSO maintains a database of 380 dam failures. Although the database is weighted toward more recent failures (post 2010), no dam in that database was reported to have failed during an ice run. The National Performance of Dams Program lists one dam failure due to an ice flow in 1976. The Dam Safety Industry generally lacks knowledge of how ice runs can impact the safety of dams in cold weather regions. Current dam safety best practices do not include evaluating run-of-the river dams for stability during ice runs.

   Ice was involved with the 1935 failure of Spencer Dam. In 1960 and again in 1966, the dam’s gates and powerhouse were damaged by ice. These incidents do not appear in ASDSO’s database as ice-related failures. There was no consolidated history of the dam, and important records were lost, unorganized or unavailable. While the dam appeared to be well maintained, no provisions were made to pass or prepare for ice run events. Furthermore, NebDSP predominantly relied on its dam inspection program to bring dam safety issues to the attention of the dam owner; latent vulnerabilities such as performance during ice runs floods are not addressed in the state's inspection reports.

2. The Panel believes that NebDSP and NPPD underestimated the potential of the dam to cause life-threatening flooding at the downstream house and property in the event of dam failure.

   There was a lack of recognition that the house, Strawbale Saloon and RV campground situated just downstream from the dam would be at risk if the dam failed. One reason is that the Downstream Hazard Potential Classification (DHC) for the dam was "significant" when, in the panel's opinion, it should have been "high." Its Significant DHC rating resulted in less dam safety regulation including no requirement for an Emergency Action Plan (EAP). If the dam were designated a "High" hazard potential dam, there would have been a requirement for an EAP and there might have been a requirement to modify the dam to increase flood handling capacity.

The following lessons should be learned from this failure (see Chapter 7 for a full list):

- Engineers working on dams, bridges and other infrastructure facilities at rivers in cold-weather regions need to assess whether the rivers are susceptible to periodic severe ice runs. If this susceptibility exists, it should be addressed in design. Dam facilities should be designed to be operated safely during these extreme weather events. Warning systems are one potential measure to reduce risk where ice runs form.
- More research needs to be done on the dynamic nature of rivers in cold weather regions, including ice run formation, frequency, movement, damage, and how infrastructure like dams should be designed, maintained and operated to withstand ice run loading.
- Dam inspections, while valuable, are not adequate dam safety evaluations in themselves. Evaluations must include review of critical documentation and records. Potential Failure Modes Analysis at an appropriate level should be conducted as part of a dam safety review. Once the potential failure modes (PFM) are understood, inspection checklists should be modified to identify signs these PFMs are developing and/or the dam is vulnerable to them.
- Dam owners should maintain a complete and organized set of electronic records for their dam(s). A concise history of the dam with reference to key records and past incidents is invaluable.
- One of the most important responsibilities dam safety regulators have is to periodically assess the areas downstream of low and significant hazard dams to evaluate whether the hazard classification is appropriate. Documented formal procedures (including reviewing data such as aerial or satellite photography and verifying during the site inspection) should be adopted.
- For dams with people at risk downstream, Emergency Action Plans should be developed and exercised.
- Dams should have operation plans that include operations during extreme events.

CHAPTER 1: INTRODUCTION

1.1 Introduction

Spencer Dam, located on the Niobrara River in north central Nebraska, failed suddenly during a major ice run during the early morning hours of March 14, 2019. As described in this introductory chapter, an investigative panel was formed to identify the causes of the failure and provide lessons learned (presented in Chapter 7) to prevent future similar failures and for the benefit of the profession and society.

1.2 Panel Formation and Authorization

The failure of Spencer Dam prompted Tim Gokie, the Division Chief of the Nebraska Dam Safety Program (NebDSP) to review the Association of State Dam Safety Officials

(ASDSO) Dam Failure Investigation Guideline [See Reference. 1.1]. Following some discussion of investigation alternatives, the NebDSP leadership contacted the dam owner, Nebraska Public Power District (NPPD), to recommend that ASDSO lead an investigation of the failure. NPPD agreed that the failure should be investigated by ASDSO.

ASDSO's Guideline recommends the following questions be addressed in determining whether an investigation is needed:

1. Did the failure cause loss of life or injuries?
2. Did the failure cause significant economic, cultural, or environmental impact beyond that of the dam owner? Are there likely to be lawsuits to recover damages?
3. Is the dam regulated by the State?

In April 2019, ASDSO began contract negotiations with NPPD to perform an independent investigation. ASDSO established a Spencer Dam Oversight Group to guide the investigation. The Oversight Group consisted of ASDSO's president at the time, Roger Adams, PE, the executive director, Lori Spragens, ASDSO's staff technical specialist, Mark Ogden, PE, the chairs of ASDSO's Dam Failures & Incidents Committee, Dusty Myers, PE and Advisory Committee, Greg Paxson, PE. The team leader of the Oroville Dam Spillway Incident Independent Forensic Team, John France, PE also joined the Oversight Group.

ASDSO issued a Request for Proposals for potential panel members. The Oversight Group developed a process and evaluated the submitted proposals.

On May 30, 2019, the Oversight Group selected the following Spencer Dam Investigation Panel members:

Mark E. Baker, PE

Principal, DamCrest Consulting (Panel leader, dam safety programs, and human factors)

Robert Ettema, PE, PhD

Department of Civil & Environmental Engineering, College of Engineering, Colorado State University (ice and hydraulic structures)

Martin Teal, PE, PH, D.WRE.

Senior Vice President, WEST Consultants (hydrology and hydraulics)

John Trojanowski, PE

President, Trojanowski Dam Engineering (hydraulic structures, concrete dams)

Abbreviated resumes can be found at DamSafety.org/SpencerDamReport.

Additionally, the following individuals were engaged in the investigation:

Irfan Alvi, PE

President and Chief Engineer, Alvi Associates was the technical advisor for human factors.

James T. Pawloski, PE

Owner of James T Pawlowski, PE, LLC, was the technical advisor regarding state dam safety program regulatory issues.

To ensure investigation independence, neither the State of Nebraska nor NPPD had any input on the selection of the investigation Panel leader or Panel members.

1.3 Purpose and Scope of the Investigation

The purpose of this failure investigation was to examine and evaluate the physical causes of the failure, the human and organizational causes that contributed to the failure, and the lessons learned from the failure to prevent similar occurrences in the future. The scope included identifying the likely failure mode, how the failure contributed to the loss of life and damages downstream, what upstream conditions affected the dam, how operations and maintenance contributed to the failure, and how human factors contributed to the failure.

1.4 Focus and Limitations of the Investigation

The Panel's focus was limited to evaluating how and why Spencer Dam failed on March 14, 2019. The Panel did not investigate the damage to or failure of many bridges during this event. The emergency actions of NPPD in response to the failure were only reviewed up to the moment when the Highway 281 Bridge immediately downstream of the dam was closed. Damage to the interior of the powerhouse was not investigated other than to identify high-water marks.

The Panel reviewed a large amount of data and observations provided by the dam's owner and the state. Both entities were forthcoming with data and observations. During Panel interviews, interviewees spoke with apparent candor. It is possible that additional information could come to light after the investigation was concluded that could have impacted the Panel's opinions and findings.

The Panel's effort to reconstruct the events of March 13 and 14 were hampered by having only partial eyewitness accounts of the overall failure and events occurring upstream. While the dam's operators were at the dam, the failure occurred in the dark and with blizzard conditions prevailing, resulting in the view upstream being limited by artificial lighting to about fifty feet. There were only patchy eyewitness accounts regarding the initial appearance of ice movement, which began around midnight. The dam experienced the full brunt of ice at about 5:15 AM. Using the evidence, the Panel was able to gather, the appendices of this report include descriptions of the range of events that might have taken place. Chapter 4 of this report describes the most likely sequence of events leading to the dam's failure.

1.5 Methodology

In general, the Panel conducted the investigation following the methodology stipulated in the ASDSO Dam Failure Investigation Guideline [See Reference 1.1]. The Panel also drew from the experience of the Independent Forensic Team for the Oroville Dam Spillway Incident of 2017.

The Panel performed a dam-site visit on August 5 through August 9, twenty weeks after the dam failed. During the site visit, the Panel:

- Conducted interviews with the dam's regulators, engineers, operators, and one local resident who lived 10 miles upstream from the dam;
- Inspected the site;
- Toured the river via airboat from the Highway 11 Bridge 10 miles upstream of the dam to a point one mile above the dam;
- Drove to downstream bridges and the town of Niobrara; and
- Reviewed and copied dam files and historical photographs from a loose collection at the Spencer Dam powerhouse office.

The Panel developed and submitted an extensive data request to the dam owner (NPPD) and the dam regulator (NebDSP). Both organizations provided the panel with many electronic scans of Spencer dam data. The electronic files provided were not descriptively named or arranged in folders, making them difficult to follow. NPPD had files that NebDSP did not have and vice versa. Some dam records in the powerhouse were lost in the 1966 ice run event.

To collect additional historical information regarding Spencer Dam, the Panel sent research-request letters to 18 north-central Nebraska libraries and two local historical societies. Advertisements were placed in local newspapers to request information from the public about the dam's failure and the associated ice run and flood. This research yielded important information, mostly in the form of newspaper articles about the past performance of Spencer Dam and previous ice events. Additionally, the Panel reached out to the state office of the U.S. Geological Survey, the Omaha District of the U.S. Army Corps of Engineers, and the local office of the National Weather Service, as well as the Nebraska Department of Transportation, which oversees the bridges in the dam's vicinity. These organizations provided additional information to the Panel. The Panel also set up a webmail address so it could receive direct communications; but received little information.

Because the Panel members were not located in the same vicinity, there was only one "in-person" Panel meeting besides the site visit. Consequently, the Panel relied on frequent electronic mail correspondence and conference calls for sharing information and ideas.

A numerical hydraulic model of the Niobrara River was completed, which included a dam-break analysis and is described in Appendix H. Additional hydraulic computations were performed and are listed and discussed in Appendix K.

In February and March 2020, a second round of interviews (by phone) was conducted with NPPD and NebDSP staff.

Both NPPD and NebDSP reviewed the report in final draft to identify factual errors. Comments received resulted in factual changes to the final version of the report but did not change the Panel's findings conclusions and recommendations.

1.6 Report Organization

The report consists of seven chapters and eleven Appendices. The chapters are relatively brief and represent the Panel's opinion of the most likely chain of events and causes of the failure. The appendices are more detailed and serve to describe the in-depth research performed by the Panel and to explore the evidence and many plausible scenarios that may have led to the failure of Spencer Dam. Also, the appendices are fully referenced. It is the Panel's intent that the average reader can understand the chapters' narrative and that the more technical reader can go to the appendices to explore topics in greater depth and know where to go for more information.

1.7 Terms Used

This report uses several terms that need definition. Table 1.1 lists the terms and their definition as used by the Panel. Many of the terms concern river ice. Some terms require a brief comment and the appendices explain the usual meaning of the term. The lexicon of ice terminology has yet to develop formal definitions of some forms of ice. Readers are referred to the online glossaries provided by ASDSO (https://damfailures.org/glossary/) and USSD (https://www.ussdams.org/dam-levee-education/glossary/) for terms generally used in the context of dams and dam safety.

Term	Definition used by the Panel	Comment
Anchor ice	A coral-like growth of ice formed on the bed of a channel conveying supercooled water and frazil.	Much has yet to be learned about anchor ice.
Braided river	A river having multiple smaller channels separated by small islands or bars	Usually wide and shallow, typical form for rivers carrying a large sediment load.
Dike	The earthen embankment forming part of Spencer Dam.	Dikes retain water in run-of-river reservoirs and may guide flows of water.
Frazil ice	Discoid ice crystals formed in supercooled water.	In ice literature frazil ice is commonly just called “frazil.”
Ice floe	Large pieces of broken ice whose maximum plan dimension is comparable to the width of a channel or flow opening, or even larger (lakes and seas).	This term is widely used in sea-ice and lake-ice literature but lacks formal definition for river ice.
Ice rubble	Pieces of broken ice that vary in maximum plan dimension up to nominally 20 feet.	This term is widely used in ice-related literature but lacks formal definition for river ice.
Ice run	Flow-driven, multiple layers of ice rubble moving along a river.	This term also is used (in the literature) to describe downstream drifting of single

		pieces of ice broken from an ice cover or slush ice and ice pans that eventually accumulate and freeze together to form an accumulation cover.
Ice slush	Drifting, detached anchor ice mixed with frazil.	In frigid weather, ice slush freezes to form rounded ice pans that may accumulate to form an ice cover.
Incremental	A gradual change.	As in change in water level.
Tainter (radial) gate	A radial gate used on spillways.	The terms “radial” and “Tainter” are interchangeable. Spencer Dam records use the term “Tainter.”
Supercooled water	Water whose temperature drops slightly below the freezing temperature of water.	Water in most rivers exposed to frigid weather supercool a fraction of a degree.

1.8 Acknowledgements

The Panel acknowledges the following organizations and individuals for supporting the investigation:

- The dam owner (NPPD);
- The Nebraska Dam Safety Program (NebDSP);
- Nebraska Department of Transportation;

- U.S. Army Corps of Engineers;
- U.S. Geological Survey;
- National Weather Service;
- ASDSO Executive Staff;
- James Pawloski and Irfan Alvi;
- The ASDSO Oversight Group volunteers: Roger Adams, John France, Dusty Myers and Greg Paxson; and
- Google Earth®

The Panel especially thanks History Nebraska, whose research of local newspapers was essential information about past ice run and failure/damage to Spencer Dam.

1.9 References

1.1 *ASDSO Dam Failure Investigation Guideline.*

https://damsafety.org/sites/default/files/DFIC_Investigation_Guide_12-10-11_0.pdf

CHAPTER 2: BACKGROUND

2.1 Dam Location

Spencer Dam was located on the Niobrara River in northern central Nebraska (NE) about 5 miles southeast of the town of Spencer, NE. The dam was constructed in 1927 to produce hydropower. The closest city to the dam is O'Neill, NE 25 miles south of the dam. The dam was 37 river miles upstream from the Niobrara River confluence with the Missouri River (See Figure 2.1) and was positioned between Boyd County to the north and Holt County to the South.

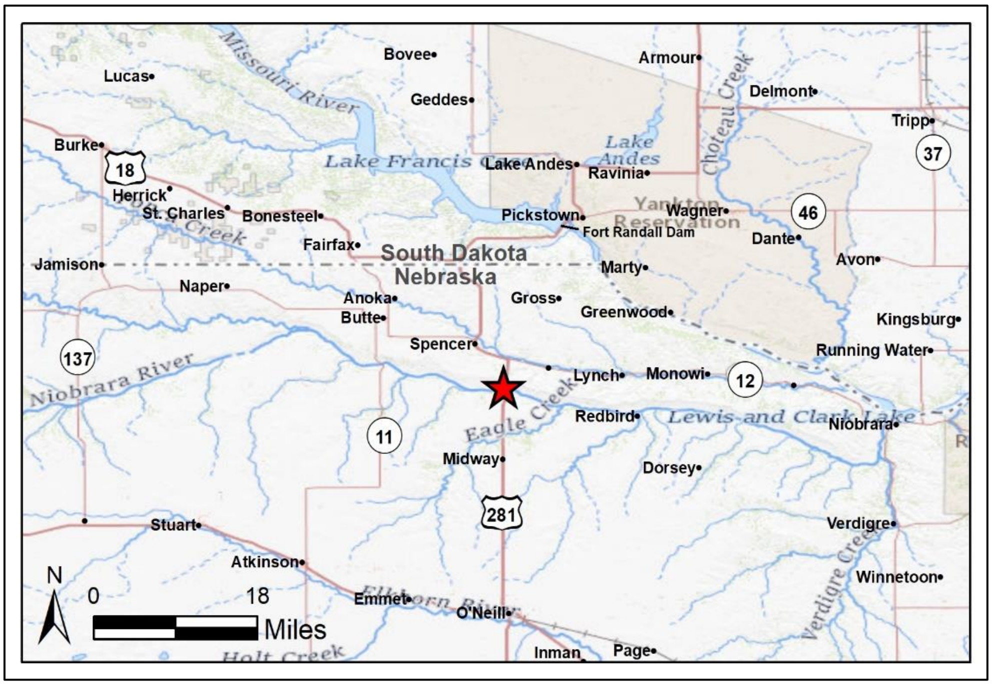

Figure 2.1 - Spencer Dam site located in north-central Nebraska along the Niobrara River near Spencer, Nebraska — Source: WEST Consultants

Spencer Dam was the only active hydroelectric facility along the main stem of the Niobrara River, which flows from west to east across most of far northern Nebraska before entering the Missouri River near the town of Niobrara. The dam site is located 224 miles northwest of Omaha and is 1/3-mile upstream of the State Highway 281 Bridge (see Figure 2.2).

Figure 2.2 - Aerial view of Spencer Dam and Vicinity – Source: Google Earth

2.2 Project Features

The dam consisted of two primary elements: a 3,200 foot-long earthen embankment (called the dike in this report) which had a maximum height of 26 feet; and, a multi-bay buttress-type concrete spillway structure with one ice/trash bay with a 10-foot wide lift gate, four 33.5-foot wide Tainter (also sometimes called “radial”) gates (Figure 2.3), and five 33.5-foot-wide needle-beam stoplog bays (Figure 2.4). Each needle beam stoplog bay contained five needle beams and six stacks of wood stoplogs. The needle beams were operated by the positioning of a pneumatic jack between a welded bracket on the side of the needle beam and the operator walkway (Figures 2.5, 2.8 and 2.9). A hydroelectric powerhouse was also located adjacent to and north of the spillway (Figure 2.3).

In the Panel’s opinion, Spencer Dam had been well maintained over the years leading up to 2019. Appendix A provides a summary of the repairs completed since 1994. Appendix D provides a history of inspections, and Appendix E discusses the most recent features of the dam and their condition. The project’s features included an embankment dike, a spillway, a powerhouse, a switchyard, a parking area, and a maintenance building (Figure 2.6).

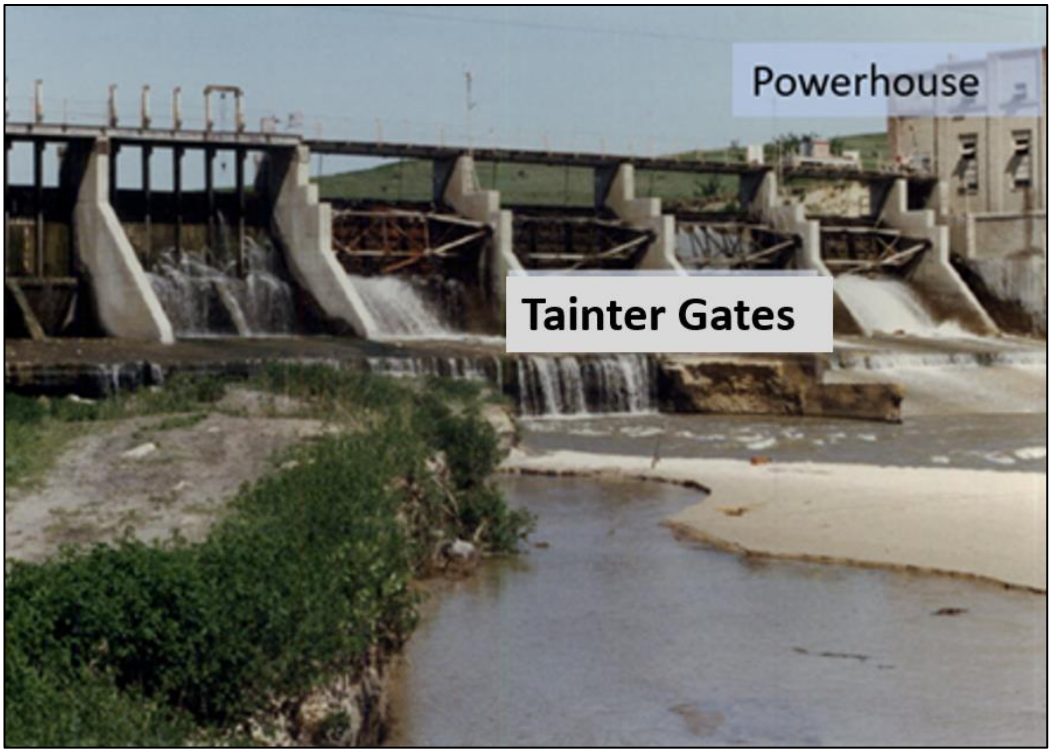

Figure 2.3 - Tainter (radial) gates - NebDSP photo

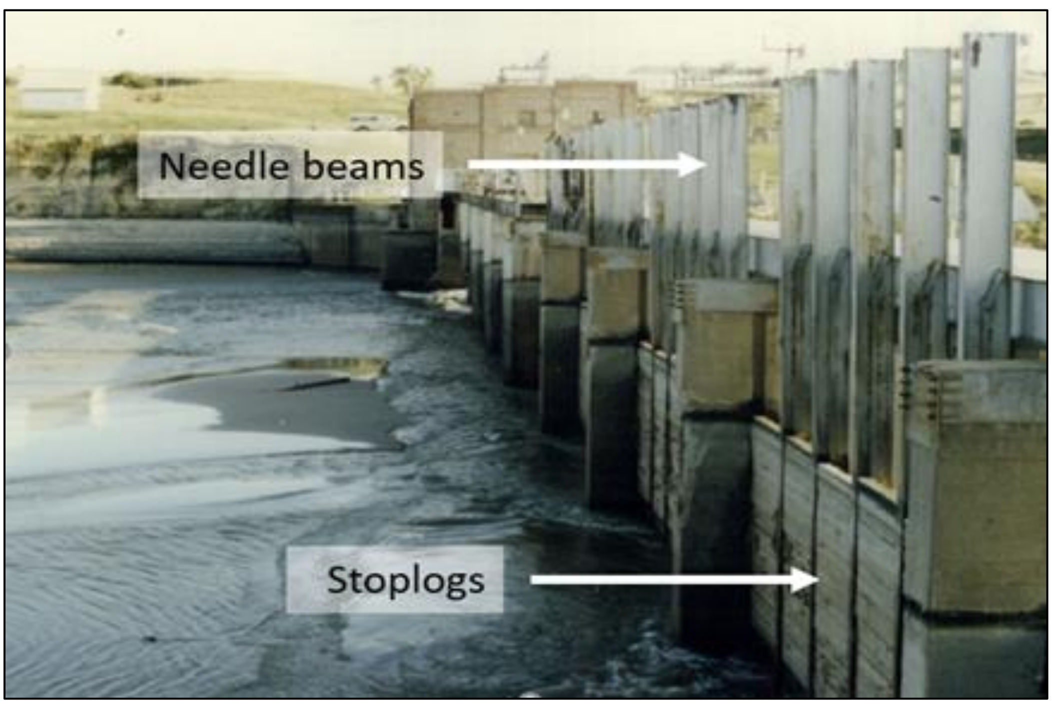

Figure 2.4 - Needle beams and stoplogs - NebDSP photo

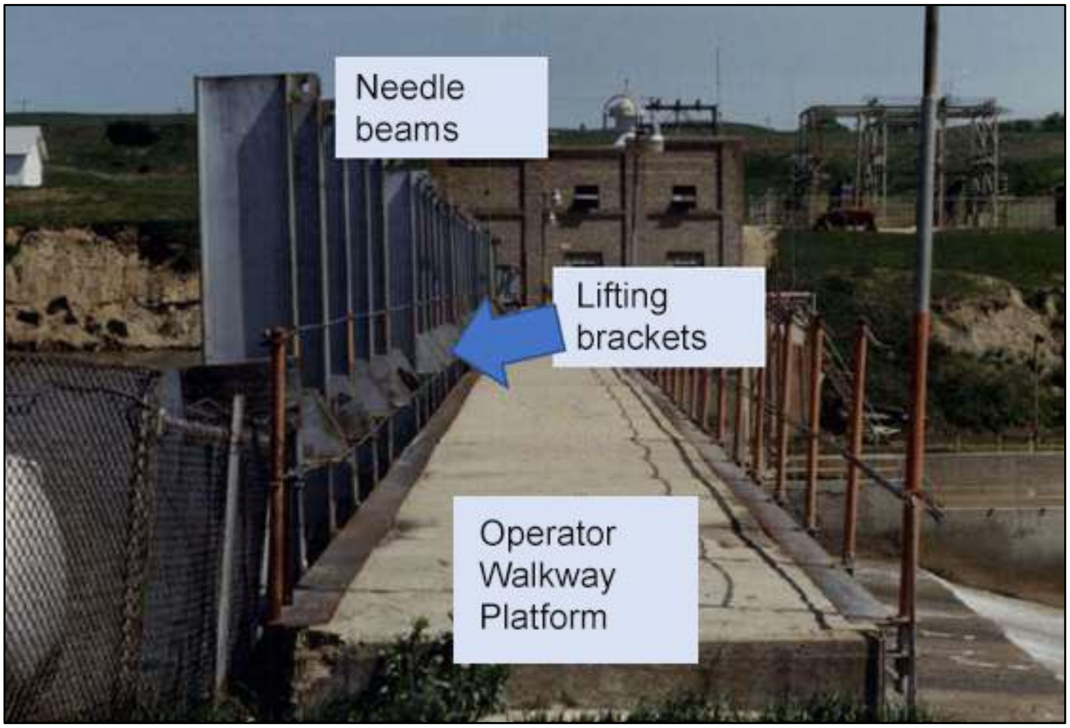

Figure 2.5 - Stoplog bays and needle beams at south end of spillway. NebDSP photo

Figure 2.6 – Aerial view of Spillway, Powerhouse and other facilities – Source: Google Earth

2.2.1 Reservoir

The reservoir was relatively small, typical of a run-of-river dam. Storage curves from 1999 indicate that the storage capacity at normal pool (elevation 1504.1 feet) was 8,300 acre-feet (AF). At the theoretical top of the dike the storage was estimated to be 16,500 AF. Whereas the storage below normal pool likely fluctuated significantly between the twice-yearly flushing of the reservoir sediment, it is believed that the surcharge storage above normal pool (about 8,200 AF) remained relatively constant since the reservoir level was only above normal pool during flooding.

The reservoir had two main channels that entered on either side of an upstream island (Figure 2.7). The north channel flowed directly towards the control structure. The south channel flow was diverted north along the dike towards the spillway control structure. The upstream island is large and was occasionally overtopped by flows that created minor secondary channels.

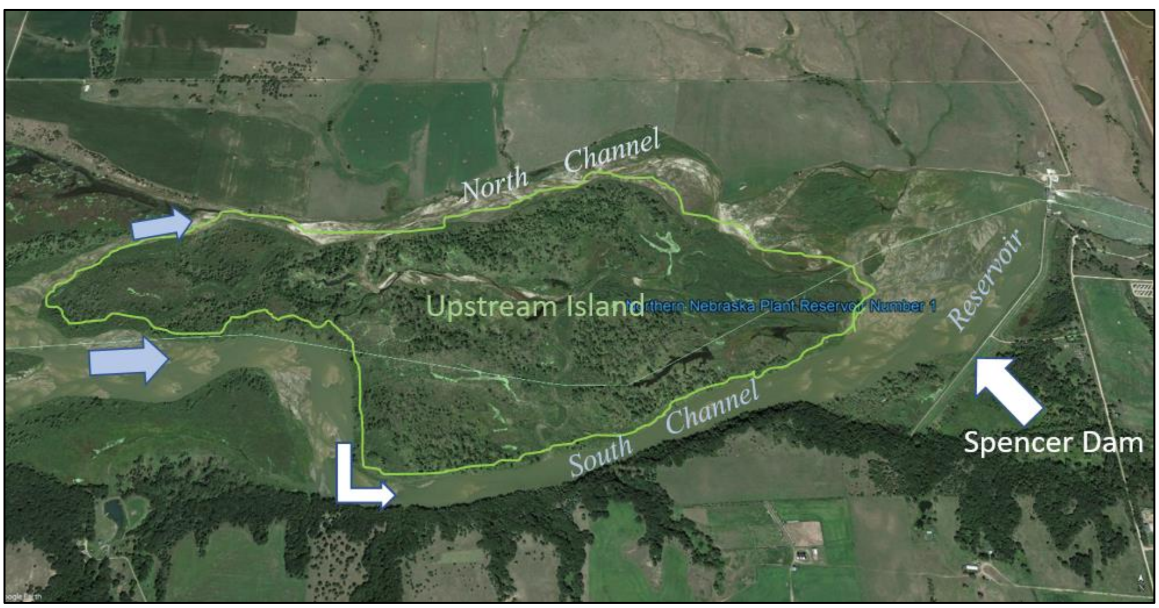

Figure 2.7 - Reservoir, upstream island and North and South Channels, source: Google Earth

Conditions associated with the upstream island were unknown immediately prior to the event. The fine sediment in the Niobrara River can easily deposit in slack water areas and erode where flow concentrates. At times the reservoir resembled a series of channels that approached the spillway rather than an actual reservoir. During spring and fall flushing operations, new channels would sometimes form in this area.

2.2.2 Embankment Dike

Spencer Dam had a 3,200-foot-long embankment dike located to the south of the spillway. The dike extended from the south end of the spillway to the south abutment. An access road to the top of the dike connected to the embankment near the midpoint along its length. The design crest was at elevation 1511.14 based on the current NPPD datum. However, a 2012 survey of the north portion of the dike [See Reference 2.1] indicates that the crest may have been more than a foot lower (below elevation 1510) at the north end. LiDAR data for the embankment, available through NeDNR and NRCS public records, seems to indicate there may be similar low crest areas in the south portion of the dike [Reference 2.2].

The dike was founded on river sediment. The northern portion had a clay core and a sheet pile cutoff extending down to shale. The cutoff and clay core were not constructed in the shallower southern portion of the dike. The southern portion of the dike was constructed with a mixture of sand and clay. Appendix E has additional details on the construction of the dam and dike.

Erosion of the upstream face of the dike had been an issue in the past, when flow from the south inlet channel had to turn north and flow along the dike before exiting through the spillway. The embankment breached in 1935 due to erosion of the embankment's upstream face (See Appendix C). Riprap had been added to the upstream face to protect against erosion. However, the bottom of the riprap was placed on top of reservoir sediment, making the protective layer vulnerable to erosion.

2.2.3 Spillway

The spillway had nine 33.5-foot-wide bays.

The first four spillway bays (immediately south of the powerhouse) were controlled by Tainter (radial) gates. Each gate opened to a maximum opening height of 6 feet. Of these gates, the three closest to the powerhouse were raised or lowered with Limitorque operators while the fourth was operated using a permanently attached travelling hoist. (All gates could be operated from inside the powerhouse.)

The last five bays had six stacks of stoplogs each (Figure 2.4). These wood timbers were held in place by five vertical, steel I-beams (Figure 2.5). These “needle beams” could be lifted by a portable jack to release the beams from a pocket in the spillway crest. As the needle beams were released, they swung downstream, releasing the stoplogs on either side. Each bay had a crest at elevation 1491.14 feet. Figures 2.8 and 2.9 describe the needle beams and their operation.

With all nine bays operating, the spillway had an estimated capacity of 38,000 cubic feet per second (cfs) at normal pool (elevation 1504.1 feet), and 65,500 cfs at the design top of dike elevation 1511.14 feet. This arrangement was estimated to have enough capacity to pass a 500-year flood (See Appendix E) which met NebDSP’s hydrologic capacity requirement for a significant hazard potential dam.

The spillway gates, hoists, and stoplog needle beams were all apparently in good operating condition before the March 2019 event. However, during the event the needle beams and stoplogs in the last two bays (Bays 8 and 9) were frozen in place by ice that had formed (See Appendix K). Also, Gate 3 shut partway through the event due to a broken lifting chain. The closure of these three bays (two stoplog bays and one Tainter (radial) gate reduced the discharge capacity of the spillway.

The dam was also designed with a 10-foot-wide ice/trash chute, controlled by a gate. The chute was located between the spillway and powerhouse but was not determined to be a significant factor in the flood operations.

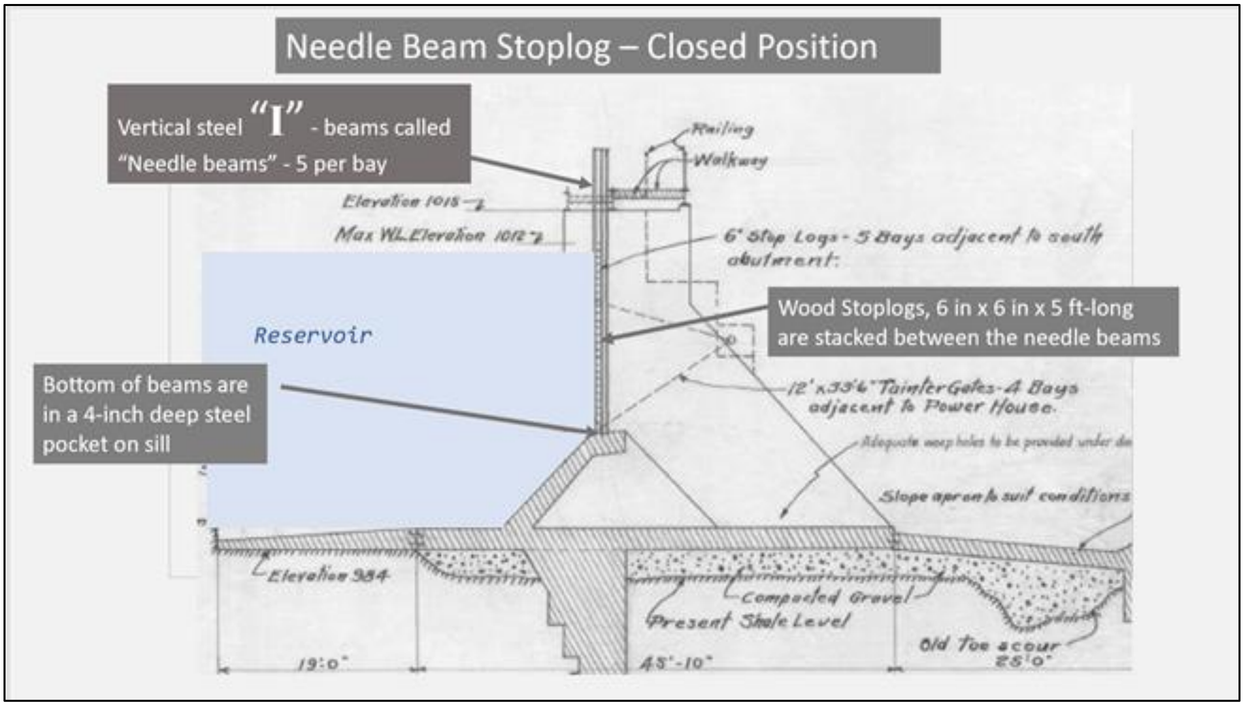

Figure 2.8 Needle Beam Stoplog - Closed Position - Source 1939 Spencer Spillway design drawing and Panel annotations.

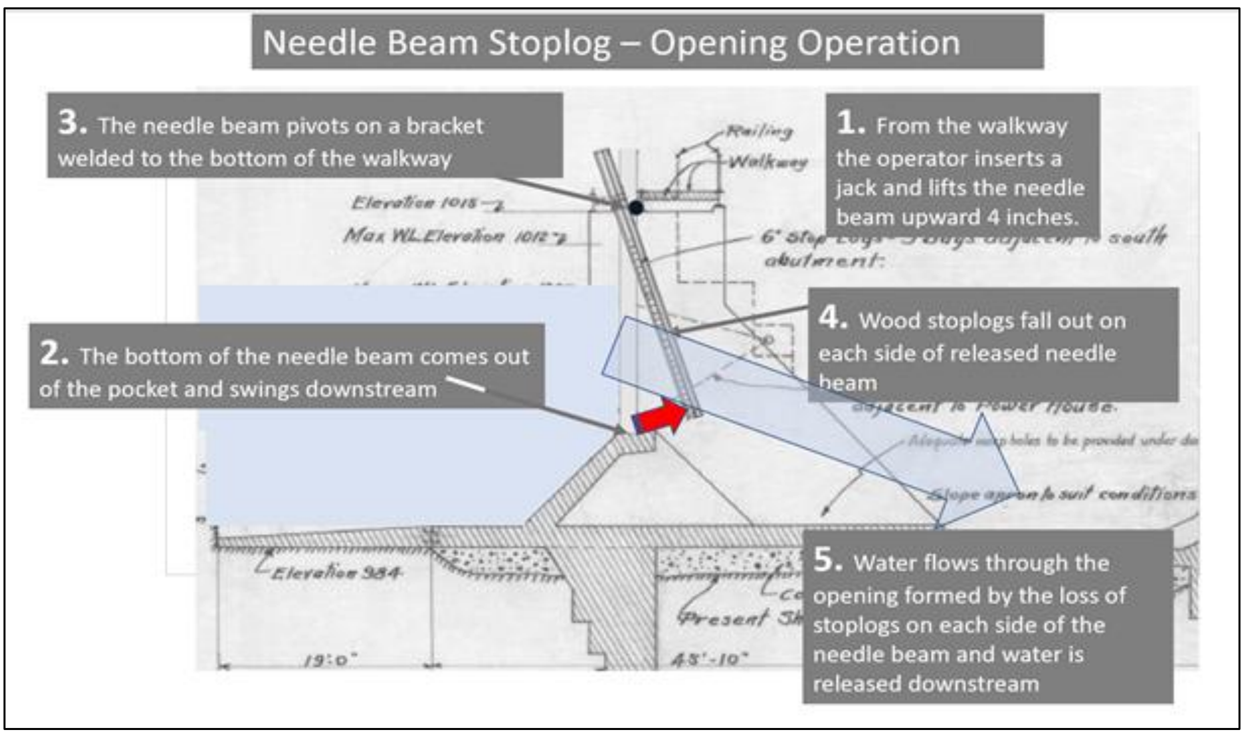

Figure 2.9 Needle Beam Stoplog - Opening Operation Sequence - Source 1939 Spencer Spillway design drawing and Panel annotations.

2.2.4 Powerhouse

The dam included a powerhouse on the north (left) abutment. The hydroelectricity facility housed two Westinghouse generators and Kaplan turbines with a maximum capacity of 3 megawatts (MW). Discharge through the turbines varied throughout the year with summer flows averaging 1,690 cfs. The powerhouse had a reinforced concrete foundation with a brick superstructure. Generation was stopped early in the evening of March 13th due to concerns about ice rubble clogging the turbine inlets. (See Appendix B).

2.2.5 Other features

The other features at the project included a switchyard, a parking area, and a maintenance building. These features were in good condition and had no known issues.

2.3 Owner

The Nebraska Public Power District (NPPD) is a publicly owned utility and a political subdivision of the State of Nebraska. NPPD is governed by an elected Board of Directors. It was formed in January 1970, the same year that the Spencer Dam came under its ownership. Although Spencer Dam generated hydroelectricity, the dam predated Federal Energy Regulatory Commission (FERC) regulation and therefore was not regulated by FERC. NPPD has a dam safety program structured around meeting the requirements of their other FERC-licensed dams although NPPD did not apply FERC requirements to Spencer Dam (See Appendix G for a description of NPPD and their dam safety program). NPPD owns eight dams besides Spencer Dam: four dams regulated by FERC and four dams regulated by NebDSP. In 2015, an agreement was signed to transfer the ownership of Spencer Dam to the Nebraska Game and Parks Commission and a coalition of five local natural resource districts. The transfer was delayed, however, and as of the 2019 dam failure event, NPPD was still the owner of the dam.

2.4 Regulator

The safety of Spencer Dam was regulated solely by the Nebraska Department of Natural Resources Dam Safety Program (NebDSP). The program regulates nearly 3,000 jurisdictional dams with approximately 7.6 full-time-equivalent employees. The main program functions are to inspect dams, ensure owners are responding to inspection findings, ensure all high hazard potential dams have an emergency action plan, and review plans for new dams or modifications to existing dams. See Appendix G for a full description of the NebDSP.

The state fulfilled their dam safety regulatory responsibilities for Spencer Dam through the following actions:

- Conducting state dam inspections every three years,
- Ensuring the dam owner addressed dam inspection findings and recommendations, and
- Reviewing plans and designs for dam repairs.

2.5 Dam Operations

Spencer Dam was a run-of-river hydroelectric facility. As such, it had limited storage volume and was not intended to store flood waters. Siltation of the reservoir further limited storage volume for normal operations but had negligible impact during flood events. The dam operators generally conducted sluicing operations twice a year (spring and fall) to allow for continued operation of the plant.

During normal operations, the NPPD operators worked to balance inflow with outflow by adjusting releases to keep the reservoir at normal pool level. These actions were based on the judgement of the operators, as the dam's written operating procedures mainly dealt with turbine and non-gate operations.[1]

The normal procedure for gate operation was to use the Tainter (radial) gates first, usually starting with Gate 1 (northernmost, closest to the powerhouse) and then proceeding with Gates 2, 3, and 4. If the water continued to rise with the Tainter (radial) gates fully open, the operators would then start releasing the needle beam stoplogs. Under normal conditions it would take 10-15 minutes to release a needle beam. Spencer operators were familiar with operations during normal spring ice breakup. Typically, they would leave ice on the reservoir as long as possible to help prevent buildup of frazil ice on the intake screens of the turbines (See Appendix F), and then pass as much ice as possible through the spillway gates. If ice started blocking some gates, other gates would be opened. Although the Tainter (radial) gates were heated (previously via propane, more recently via electricity) it was often necessary to clear the reservoir ice in front of the gates manually by cutting blocks of ice with a chain saw. These blocks would then be sent downstream through the trash/ice gate (lift gate) immediately adjacent to the powerhouse.

2.6 Downstream Areas

The following features are located downstream from the Spencer Dam site (distance is given in river miles):

- 1/3-mile downstream - Property owned by Mr. Kenny Angel. The property included a home, music venue, the Straw Bale Saloon, and an RV camping area. The home was constructed in 1965 and the other facilities were constructed within the last 25 years;
- 1/3-mile - State Highway 281 Bridge;

[1] Note that description of operations is based mainly on notes from interviews with the operators.

- 12 miles – Redbird Bridge, 503rd Ave. Holt County;
- 24 miles – Verdel Bridge, 514th Ave. Knox County;
- 38 miles – State Highway 12 Bridges - Two bridges over Niobrara River and Mormon Canal; and
- 38 miles – Village of Niobrara, NE.

2.7 Downstream Hazard Potential Classification

The downstream hazard potential classification (DHC) is a system of categories used in the dam safety industry to denote the severity of impacts downstream from the dam if the dam were to fail. The classification has nothing to do with the condition of a dam. The NebDSP uses a system of four (DHC) classifications:

- **High hazard potential** means that failure or misoperation of the dam resulting in loss of human life is probable;
- **Significant hazard potential** means that failure or misoperation of the dam would result in no probable loss of human life but could result in major economic loss, environmental damage, or disruption of lifeline facilities;
- **Low hazard potential** means that failure or misoperation of the dam would result in no probable loss of human life and in low economic loss; and
- **Minimal hazard potential** means that failure or misoperation of the dam would likely result in no economic loss beyond the cost of the structure itself and losses principally limited to the owner's property.

Since the Phase 1 inspection in the 1970s, the hazard potential classification for Spencer Dam had always been “Significant,” presumably because the state highway bridge was just 1/3 mile downstream. While several state inspection reports since the 1970s cite that the dam’s hazard classification was “Significant,” no records were provided to the Panel from NPPD or NebDSP about how the hazard classification was originally determined. Also, there were no records revising or reconfirming this classification (although inspection reports list the dam as having a Significant classification). Because the homeowner's property was just 1/3 mile downstream from the dam, the Panel believes that the dam was misclassified, and it should have been classified as a High hazard potential dam. This concern is discussed further in Chapter 6.

2.8 Emergency Action Plan (EAP) and Inundation Map

The NebDSP requires all dam owners of high hazard potential dams to develop and exercise an EAP. The state has the authority to require an EAP for a Significant hazard potential dam but has not yet required a dam owner to do so. Spencer Dam, being a Significant hazard potential dam, was not required to have an EAP and did not have one at the time of the dam's failure. No inundation map for Spencer Dam existed before the 2019 event to show downstream areas that could be flooded if the dam were to fail.

2.9 Spencer Dam History of Incidents and Failures

Spencer Dam was constructed in the 1920s and had a long and storied history over its 90+ year life. Several of the dam's past incidents and failures were due to ice and could have been warning signs to the dam owner and regulator. The dam failed twice in the 1930s and was redesigned in the late 1930s. The spillway was rebuilt in the early 1940s, and the dam suffered major damage due to ice runs in 1960 and 1966. Brief descriptions of some of these events are given in the following subsections. (See Appendix A for a General Timeline of the history of Spencer Dam and Appendix C for a full description of past Spencer Dam incidents, failures and repairs.)

2.9.1 Ice-Related Dam Failure March 2, 1935

During the spring river ice break up, a log and ice jam formed about one mile upstream from the dam. This jam caused the channel of the river to shift to the south. As the water, ice, and woody debris flowed along the upstream slope of the dike to reach the spillway, it eroded the upstream side of the dike and produced a 200-foot-wide dam failure breach. The original dam was constructed without riprap protection. Instead, the upstream face was treated with oil, like a road surface. The dam failure flood inundated nearby lands and almost overtopped a bridge immediately downstream, but no flood damage further downstream was reported.

2.9.2 Spillway Sliding Dam Failure September 24, 1936

As the result of a high pool elevation, high water pressures developed within the foundation, and the entire spillway structure detached from its shale foundation and slid 30 to 50 feet downstream (Figure 2.8). The spillway was reconstructed in 1940 with foundation keys and anchors to prevent sliding.

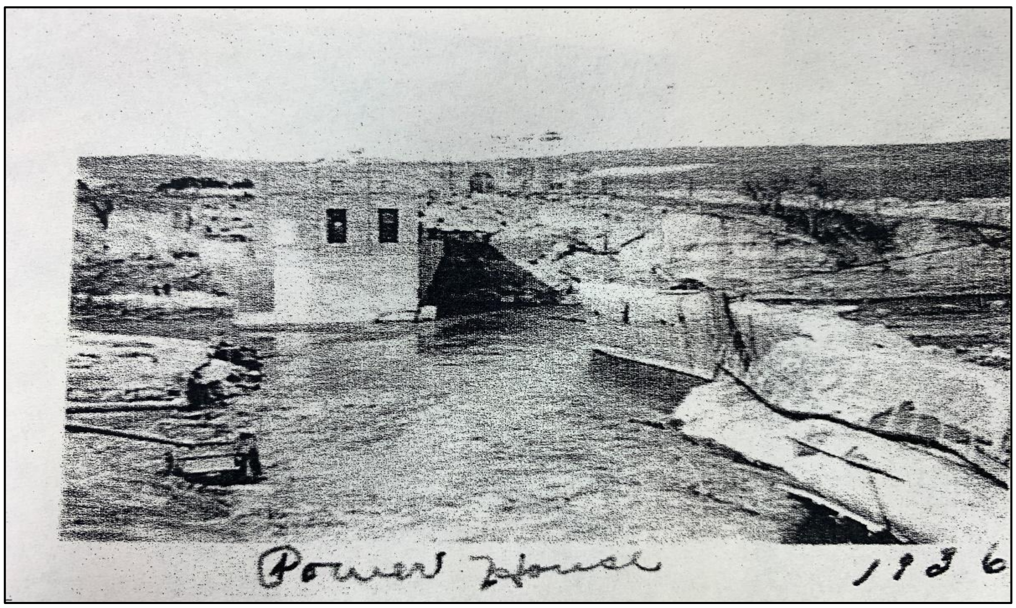

Figure 2.10 - 1936 Spencer Dam failure due to the concrete spillway sliding 50 feet downstream – NPPD photo.

2.9.3 Ice-Related Incident, March 26 & 27, 1960

Water and ice flowed from the south channel to the spillway located at the north end of the dike. The heavy flow eroded the upstream face of the dike. Crews were dispatched to repair the dike, and dam failure was averted. Damaged structures included: the dike (500 feet of erosion), #1 Tainter (radial) gate, concrete piers, and a trash rack.

2.9.4 Flood and Ice Jam Damage March 12, 1966

The operators of Spencer Dam anticipated an ice run due to an ice jam at the upstream Highway 11 Bridge. In an effort to avert damage to the dam, the operators emptied the reservoir. Despite their efforts, an ice-bearing flood rushed toward the dam. An estimated 10-foot-high wall of water and ice cascaded down the channels and over the “sand bars” (referred to in this report as the upstream island). As a result, Gate 4 was torn from its supports, and a large hole was punched in the side of the powerhouse, filling it with six feet of water. Gate 4 was deposited 200 yards downstream, and the dike and concrete piers were damaged. This flood destroyed most of the original plans and records that were stored in the powerhouse. Newspaper photographs from this event are shown in Figures 2.11 through 2.13.

Figure 2.11 - Caption: "SPENCER DAM IN FLOOD STAGE, ALL SYSTEMS GO IN THIS SHOT" - The height of the water can be seen as it flows over the top of the dam. No. 4 flood gate can be seen missing. Photo credit Holt County Independent March 17, 1966, page 4. Research source: History Nebraska.

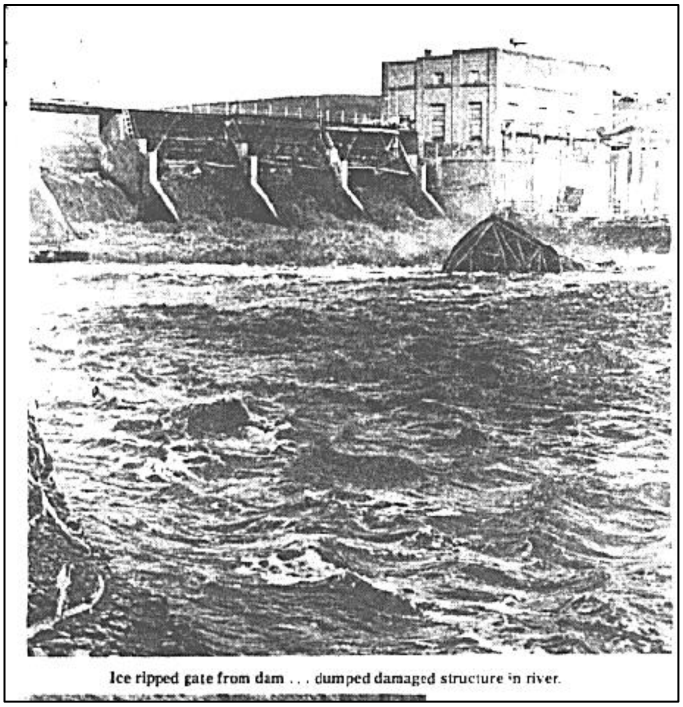

Figure 2.12 - Caption: "Ice ripped gate from dam. Dumped damaged structure in river." [Photo: Omaha World Herald March 15, 1966, page 11]. Research source: History Nebraska.

Figure 2.13 - Damaged window and ice – Photo: Omaha World Herald March 15, 1966, page 10. Research source: History Nebraska.

2.10 References

2.1 *Report on Niobrara River at Spencer Nebraska Power Plant*, by K.W. Dickey 10 008445 CD-20090506 ScanID-728550

2.2 NeDNR/NRCS LiDAR dataset, 1m bare earth DEM accessed from USDA Geospatial Data Gateway: https://datagateway.nrcs.usda.gov/GDGHome.aspx

CHAPTER 3: THE PHYSICAL SETTING OF SPENCER DAM

3.1 Introduction

This chapter describes the physical setting of Spencer Dam on the Niobrara River, Nebraska, and focuses on the following factors associated with the dam's failure:

- The geographic location of Spencer Dam;
- Weather patterns over Spencer Dam and the Niobrara River watershed;
- The channel characteristics of the Niobrara River in the vicinity of Spencer Dam;
- Ice formation on the Niobrara River upstream of Spencer Dam; and
- The layout of Spencer Dam.

Taken together, these factors indicate that Spencer Dam was vulnerable to the potential impacts of ice formation and movement consequent to the dynamic weather conditions known to occur in Nebraska.

An important feature of the natural setting in which Spencer Dam is located is the speed at which river ice can form and move. The location, weather patterns, and channel characteristics at and near the dam site can cause relatively rapid changes in ice conditions that complicate the design and operation of infrastructure like Spencer Dam, whose layout and design lacked the capacity to handle severe ice conditions.

However, little has been written or is understood about ice formation and movement along the Niobrara River or rivers in similar locations. Because ice played a prominent role in the failure of Spencer Dam, Appendix F was written to provide general background information on ice formation in rivers. Some of the information is of direct use for describing the physical setting of Spencer Dam on the Niobrara River.

3.2 Geographic Location

Spencer Dam is located on the Niobrara River near the town of Spencer in north-central Nebraska. The Niobrara River drains water from a portion of the higher, western elevations of the Great Plains down across the Plains until the river meets the Missouri River in northern Nebraska. The river generally flows from west to east. The river, though, flows north toward the town of Niobrara and the river's confluence with the Missouri River. Figure 3.1 outlines the river's watershed.

The watershed of the Niobrara River encompasses about 13,480 square miles, producing a mean annual discharge of about 1,750 cubic feet per second (cfs), and a maximum, historical discharge of about 39,000 cfs, at Verdel, Nebraska (USGS Gage 06465500). The average precipitation in the river's watershed varies from about 15 inches in the west to about 24 inches in the east. The flow hydrographs for the river indicate that the river stage rises and falls more quickly east of the town of Norden, Nebraska, a town about 100 miles west and upstream of Spencer Dam. These characteristics result from changes in soil type, thickness of underlying aquifer, terrain and increases in annual precipitation. Norden is approximately at the northeast fringe of the Nebraska Sand Hills, whose underlying aquifers contribute substantially to the base flow of the Niobrara River. About 70 percent of the river's total annual flow originates as groundwater entering through the bed of the river from the underlying Ogallala Aquifer.

Much of the land in the watershed is undeveloped, being used for row-cropping and cattle ranching. The extent of cattle farming is greatest in the more arid west than is the extent of row-cropping (mainly corn), which increases toward the eastern end of the watershed.

Upstream of Spencer Dam, there are a few dams on the main stem of the Niobrara River, but the dams had no or negligible effect on the ice run of March 13/14. The dams and their purpose are as follows:

- Box Butte Dam stores water for irrigation use. This dam was built in 1945 and remains in use.
- Dunlap Diversion Dam diverts water for irrigation use.
- Cornell Dam produces hydropower. This dam, about 160 miles west of Spencer Dam, was built in 1915 and operated by NPPD until 1985, when it was given to the U.S. Department of the Interior and became part of a national wildlife reserve.

Another dam exists on the Snake River, a substantial tributary of the Niobrara River. Merritt Dam, completed in 1964, is used primarily for storing water for irrigation use. This dam is about 130 miles west of Spencer Dam. Also, several small, water-storage dams and diversion dams exist throughout the watershed of the Niobrara River.

Upstream of Spencer Dam, two small but substantial rivers are confluent with the main channel of the Niobrara River. About 30 miles upstream of Spencer Dam, the Keya Paha River enters the Niobrara River. The Snake River enters the Niobrara River about 120 miles upstream of Spencer Dam. Table 3.1 summarizes the rivers in terms of the mean annual discharge.

Table 3.1. Approximate mean annual discharges of tributary streams to the Niobrara River near Spencer Dam

River	Mean Annual Discharge
Snake River, at confluence with the Niobrara River	130-180 cfs
Keya Paha River, at confluence with the Niobrara River	140 cfs
Niobrara River, at confluence with the Missouri River	1,720-1,760 cfs

For about 65 miles upstream of Spencer Dam there are seven bridges over the Niobrara River (Table 3.2). Downstream of Spencer Dam, to the river's confluence with the Missouri River, there are several bridges (including the bridge for Highway 281). This distance range encompasses the braided channel formed by the Niobrara River. The presence of these bridges is significant, because the bridges (including their approach embankments) narrow the river and can restrict ice movement along the river.

A noteworthy feature of the location of the Niobrara River is that it flows in a region that experiences frigid winters, as Figure 3.2 outlines. Consequently, the Niobrara River forms river ice, doing so every winter. The influence of frigid weather is amplified by the increasing elevation of the Niobrara River whose headwaters are in the high plains of northeastern Wyoming. The river's highest elevation is about 5,500 feet. The river's elevation at Spencer Dam is approximately 1,400 feet.

Table 3.2. Bridges over the Niobrara River within 65 miles of Spencer Dam

Route (other name)	Approx. Distance along the Niobrara River Relative to Spencer Dam
Upstream of Spencer Dam	
State HWY 11 (Butte Bridge)	12 miles
County 470th Avenue (Stuart-Naper Bridge)	25 miles
State HWY 137	38 miles
Karnes Road	44 miles
State HWY 7	52 miles
U.S. HWY 183	60 miles
Meadville Road (Old Hwy 7)	65 miles
Downstream of Spencer Dam	
State HWY 281	0.5 miles
508 Ave. (Redbird Bridge)	12 miles
514 Ave. (Verdel Bridge)	24 miles
State HWY 12	38 miles

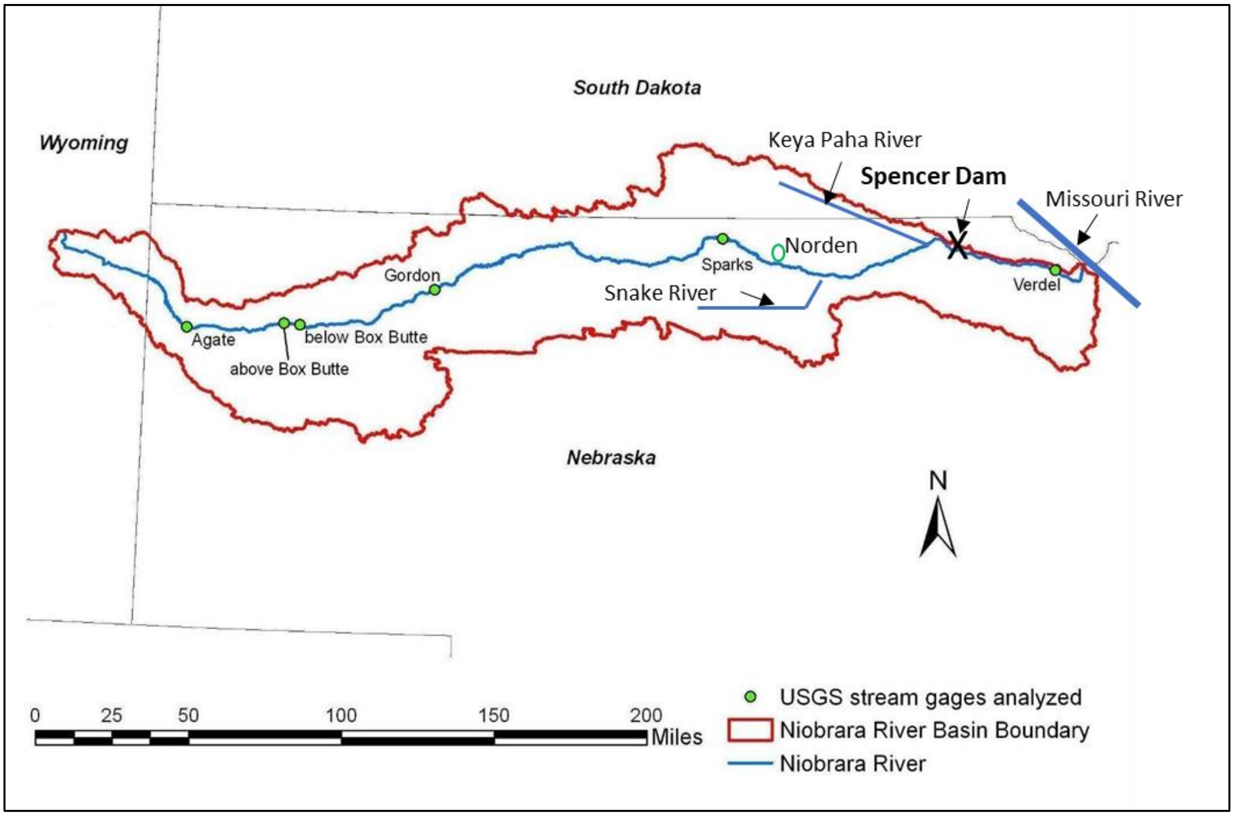

Figure 3.1. The course and watershed of the Niobrara River (Source: WEST Consultants)

3.3 Weather Patterns

The location of Spencer Dam is subject to some of the most dynamic fluctuating weather patterns in North America. This presents challenges for design and operation of infrastructure, such as the dam.

By virtue of Nebraska's mid-latitude range and mid-continent position, Nebraska experiences frigid winters that cause ice to be a common feature of rivers throughout the state. The warming periods associated with many springs in Nebraska may cause major ice runs and jams along the state's rivers. Even though the Nebraska Emergency Agency publishes online summaries of ice events (https://dnr.nebraska.gove/floodplain/ice-jamming-reporting), there is a substantial lack of documentation regarding the underlying causes leading to major ice runs and jams in Nebraska.

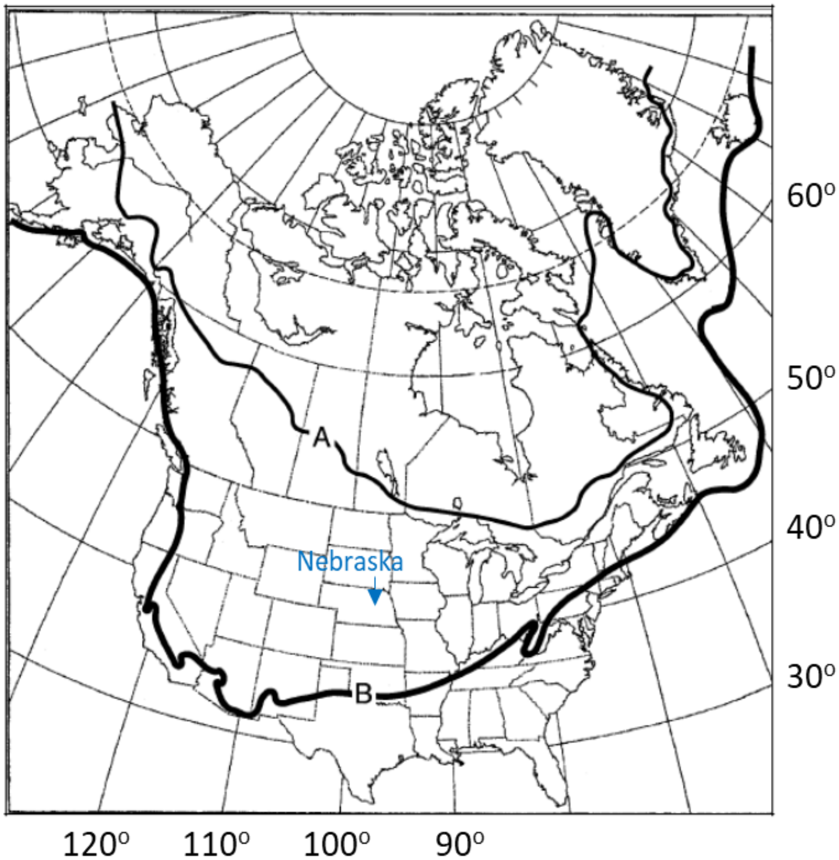

Figure 3.2. A schematic map outlining the cold regions of North America (latitude and longitude indicated). This figure also indicates the location of Nebraska. (Source: adapted from USACE 2002). The A-line in this figure is the southernmost boundary of the area where the average air temperature of the coldest winter month is -18°C (0°F) or less and ice forms covers over navigable rivers for at least 180 days of the year; the B-line is the southernmost border of the area where the average air temperature of the coldest month is between -18°C (0°F) and 0°C (32°F) and covers navigable waters for 100-180 days.

The topography of the western Plains, in which the Niobrara's watershed is located, sets the stage for the region's fluctuating weather patterns. The Rocky Mountains (or continental divide) act like an atmospheric dam, forcing hot air from the south and cold air from the north to pool up over the Plains, initiating dynamic fluctuations over the Plains, including Nebraska. The fluctuations include substantial variations in seasonal weather and may produce low-pressure systems that can generate storms. Such storms occur most frequently during winter and spring, when the atmospheric jet stream dips southward, and actively influences weather over the Plains.

Additionally, during winter and spring, the atmospheric expressway formed by the Plains may create fast-moving weather systems. If the fast-moving cyclones generate substantial rates of atmospheric-pressure decrease (bombogenesis), the cyclones become “bomb cyclones.” These cyclones cause Nebraska and surrounding states to experience large fluctuations of warmer and colder weather, especially as winter merges into spring. This was the case in March of 2019 (see Chapter 4 and Appendix H).

3.4 The Niobrara River at Spencer Dam

The Niobrara River in the reach containing Spencer Dam is an alluvial river whose characteristics reflect the interactions of the river’s water-flow hydrodynamics, sediment transport, the terrain through which the river flows, the weather patterns prevailing over the river, and the presence of bridges. Most reaches of Niobrara River, from about Norden to the river’s confluence with the Missouri River, form a braided channel with a bed largely comprising medium to fine sand. Figure 3.3 illustrates the river a short distance upstream of Spencer Dam and in the vicinity of Spencer, Nebraska.

The influence of ice on alluvial-river form (morphology) generally is unclear and not described in leading references (notably Alexander et al. 2009), though evidence of river-ice presence and movement is apparent from the type of vegetation found along the banks of the river’s main channel. Notably, the banks of the river’s active channels are vegetated by low vegetation such as grasses and small bushes.

Alexander et al. (2009) [See Reference 3.1] describe the hydraulic characteristics of the Niobrara River based on extensive data measured at USGS streamflow gage sites and provide a useful reference for obtaining a sense of how the river behaves hydrologically and hydraulically. The data this reference presents include characteristics of the river reach in the vicinity of Spencer and discharge data obtained from a gage station at Verdel, about 24 miles downstream from Spencer Dam.

Upstream of Spencer Dam, extending as far as Norden, the Niobrara River flows along a braided channel, marked by the frequent shifting of the river's main channel and the consequent wide floodplain formed by the river. Flow depths along the reach are shallow, ranging from about 0.25-3.0 feet during conditions of mean flow. Immediately downstream of the dam, the river flows for about five miles along a single channel that meanders from bank to bank. From this section on down to the confluence with the Missouri River, the river once more becomes braided. Both the braided and the single-channel reaches are marked by sand bars, which become vegetated islands in the case of the braided reaches.

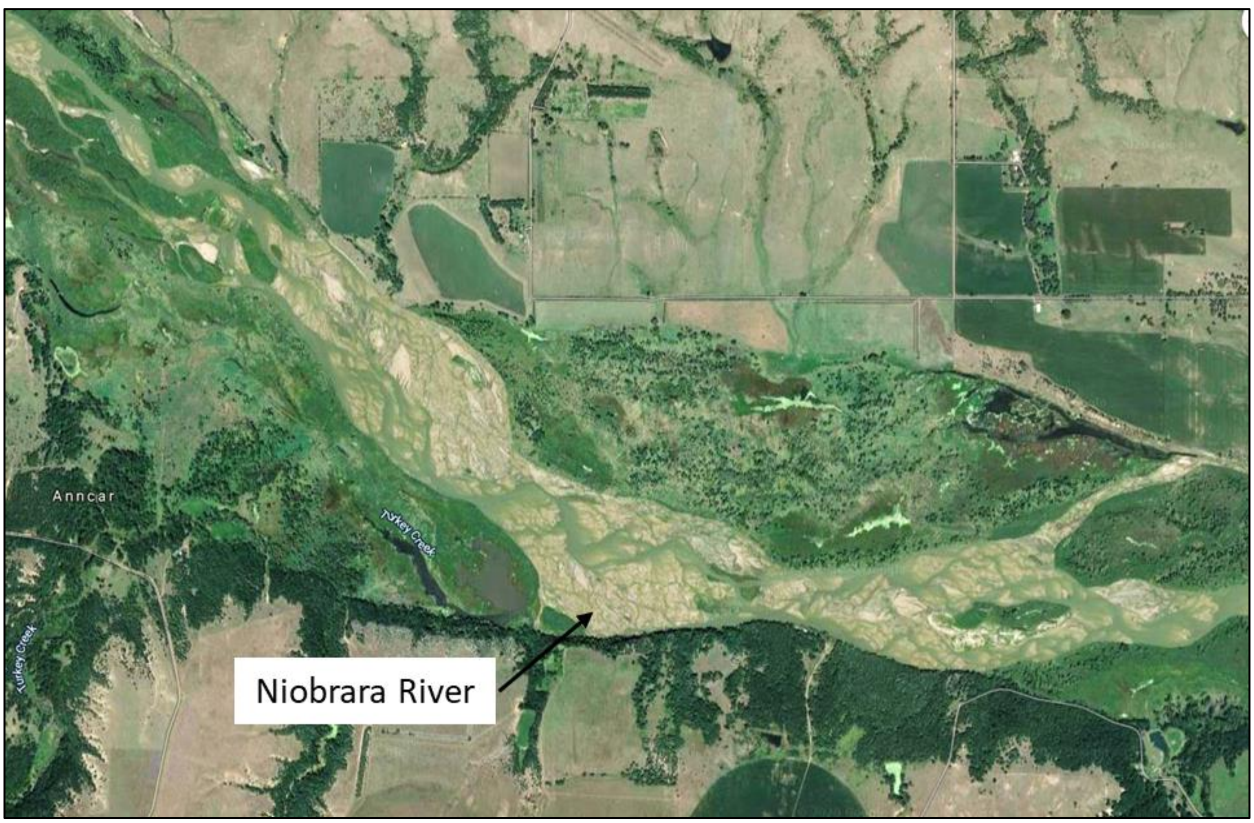

Figure 3.3. A satellite view of the braided channel a short distance upstream of Spencer Dam. The dam is not shown but is off the image to the right. (Google Earth Image).

The river reach from Norden to the Missouri River is relatively steep for a sand-bed channel and causes the reach to be braided in character. The bed of the Niobrara's main channel is marked by the formation of antidunes, bedforms that are continually mobile, shifting along and across the bed, and reflect the channel's substantial transport of bed sediment, mainly fine to medium sands, about 0.3-0.5 mm in diameter. Consequently, the river's channel is responsive to changes in flow velocity, such as occur during ice-cover formation and break-up.

A feature of the Niobrara River upstream of Spencer Dam is the presence of bridges. Each bridge typically confines the river to a single channel through the bridge waterway. Upstream of Spencer Dam, bridge waterways are about 300- to 500-feet-wide, nominally about a third of the overall width of the braided channel. The river's natural channel is irregular in width, in accordance with the river's braided morphology. This narrowing of the river at bridge crossings confines the river to a single channel and increases sediment transport through the bridge waterway. As explained in the next section, the narrowed channel makes bridge waterways potential locations for accumulations of drifting ice to develop. Figure 3.4 illustrates the river at the bridge crossing of Nebraska State Highway 11. The river at this location is narrowed significantly, then turns about 90-degrees and widens as it flows downstream.

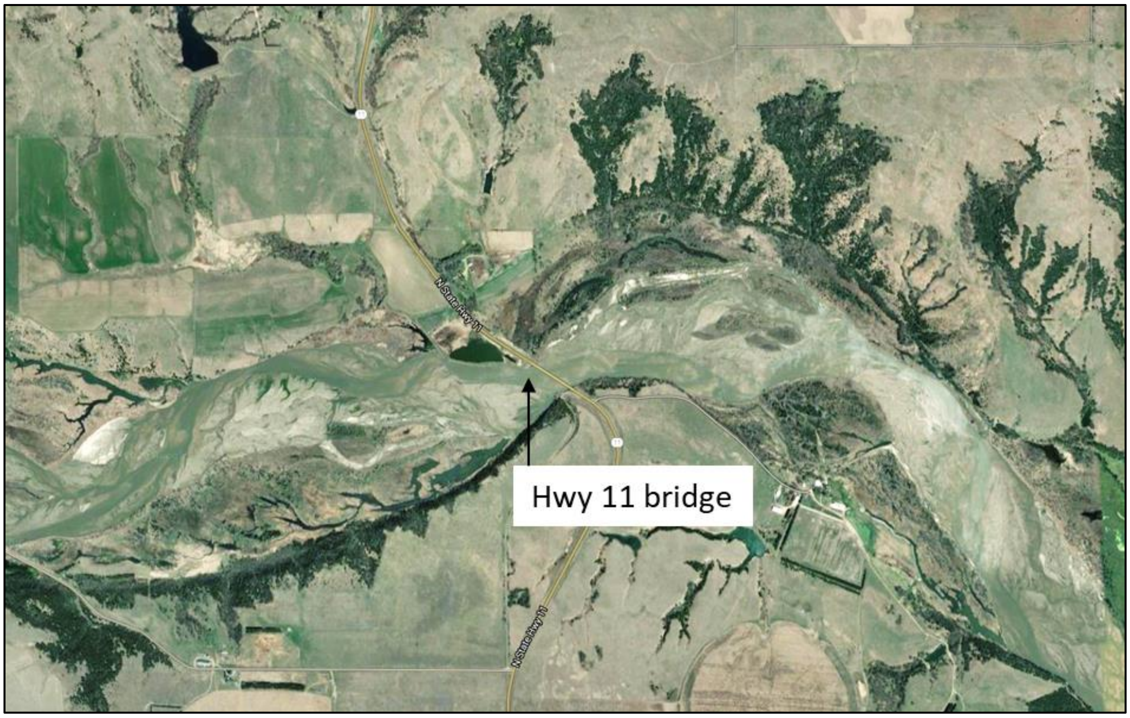

Figure 3.4. The Niobrara River at Hwy 11 Bridge. The bridge opening is about 500 feet wide (Google Earth Image)

3.5 Ice Formation and Movement in the River

This section concentrates on the main features of ice formation and movement along the Niobrara River from about Norden to the river's confluence with the Missouri River. Nebraska rivers, closely comparable to the Niobrara, are referred to when illustrating some aspects of ice in the Niobrara (e.g., the Platte River and its tributaries).

The braided morphology and readily erodible sand bed and bars of the Niobrara River downstream of Norden, and the dynamic nature of the weather patterns over the Plains, substantially influence ice formation, ice movement and ice accumulation along the Niobrara River at Spencer Dam. The influences are multiple and include the entire gamut of ice formation, break-up and jamming processes along rivers. The descriptions of ice formation and movement given here for the Niobrara River are expanded in Appendix F, which describes ice processes occurring in rivers generally.

Ice formation and ice movement in sand-bed braided channels are active areas of contemporary (and future) research. No descriptions exist of the ice-formation processes occurring over a winter leading to occurrence of an ice jam on the Niobrara River. The present lack of knowledge about ice formation in braided channels complicates the design and operation of run-of-river dams like Spencer Dam. Moreover, this lack also complicates the design and functioning of bridges over rivers like the Niobrara River. Other incidents related to ice-jams have occurred for run-of-river dams, but those incidents are infrequent and have never been thoroughly investigated and documented, e.g., the 1978 Markland Dam Incident on the Ohio River (Tuthill 1999, See Reference 3.2).

A point to emphasize here is that the period (or time scale) associated with each of the multiple influences is important when considering ice-induced failure of Spencer Dam. To begin with, the river's shallowness causes the water to cool relatively fast and enables ice to form comparatively quickly. The channel's swift currents and undular bed (the bed is marked by a variety of alluvial bedforms such as ripples, dunes and antidunes) mix water and affect the nature of ice formed. The currents also move ice rapidly, peeling it from the channel's bed, and conveying it downstream as slush that may freeze. However, the river's braided morphology complicates the downstream movement of ice. There are many locations (e.g., bends and bars) that can impede ice drift, causing drifting ice to accumulate and jams to form. Relatedly, the swift currents impose substantial hydrodynamic forces on ice accumulations and the river's channel boundaries.

The river's sand bed and sand bars (and islands) erode and shift readily and, thereby, cause jams eventually to weaken and collapse. The presence of bridges along the braided reach between Spencer Dam and Norden, though, further complicates ice movement along the reach. The bridges are resistant points along the river. Ice congests and accumulates at the bridges and may choke flow (in the open-channel-flow sense), with consequences for bridge and bed stability and for the sideways diversion of flow. The relative periods associated with ice formation, drift and accumulation, compared with periods typical of sand-channel erosion, influence the manner whereby ice and water move along the river.

For the same weather conditions, shallower and wider channels, like the braided Niobrara River produce more ice, because their comparatively large water-surfaces and shallowness cause them to cool relatively quickly. Consequently, the river along this reach can produce large volumes of ice.

The amount of heat entering in a river depends also on the heat flux associated with groundwater seepage into the river flow. The Niobrara River receives a substantial amount of its baseflow from groundwater flow. Though the rate of inflow likely is sufficiently low that it does not significantly affect the rapid cooling of the river during frigid weather, the inflow likely is warmer than is the river water. This inflow of warmer water is important when considering anchor-ice formation and release, and the eventual weakening of an ice cover. Frequent cycles of formation and release of anchor ice may increase the overall volume of ice formed per unit area of the riverbed. The inflow of baseflow may increase during periods of snowmelt and rain. Increased baseflow may stress an ice cover, causing it to lift.

The channel characteristics of the Niobrara River influence how ice covers form then break-up. Ice covers form on the river through the combined action of accumulation of drifting ice slush and pans, and ice growth over regions of quiescent flow or no flow (e.g., over low bars and in back waters). The cover then thickens thermally, as ice crystals grow downward and fill cavities between accumulated slush and pans. Snow deposited on the cover's surface thickens the cover. Figure 3.6 depicts ice formation along the Platte River, whose morphology is like that of the braided reach of the Niobrara River upstream from Spencer Dam. Some open-water leads may remain in the cover, doing so at locations where groundwater flow enters the river at a pronounced rate or where turbulence is substantial and persistent.

Figure 3.6. Ice cover formation on the Platte River between Lincoln and Omaha, Nebraska. The cover formed as slush and pan accumulation and thermal growth of ice in quiescent areas, e.g., over a sand bar.

Most years, the onset of warmer weather causes the river's ice cover to warm, weaken and disintegrate, largely in place. During this process of thermal break-up, gaps between ice crystals enlarge, though the cover's thickness usually does not diminish notably. However, much less frequently, the fluctuations in weather patterns cause the ice cover to break-up dynamically. This mode of break-up is a mechanical break-up of the cover and produces pieces of broken ice usually termed ice rubble. For rivers the size and characteristics of the Niobrara River the largest length dimension of the rubble is nominally about 20 feet, though the rubble is highly variable in plan size.

Once an ice cover breaks up along the Niobrara River, the river's channel characteristics affect the movement of the resulting broken ice (ice rubble) along the river, and the occurrence of ice congestion, jam formation, and the manner of subsequent failure of a jam. Figure 3.7 illustrates the congestion of drifting ice rubble on the Loup River, Nebraska.

Figure 3.7. The congestion of drifting ice rubble moving along the Loup River, a Nebraskan river like the Niobrara River.

The river's many bends and bars would hamper ice movement, as would the bridges across the river. At these locations the channel narrows, making it easier for drifting ice floes and ice rubble (or clusters of ice rubble) to lodge across the channel, or between the piers of a bridge. Studies show that ice movement along a river is affected especially by the ratio of ice-rubble length compared to channel width. Though ice strength and shape play roles, congestion and jamming occur at locations where channel width is less than about eight times ice rubble length.

The relative shallowness of the Niobrara River and the presence of bars in the wider regions of the river, as well as sharp turns in flow paths, would create locations where jams could initiate. Moreover, larger pieces of ice rubble and clusters of ice are less likely to negotiate turns and bifurcations around bars. Yet as a jam forms it retards flow, backs up water and may then produce an untidy series of accumulation steps that involve ice rubble being shoved and compacted at a downstream location of greater constriction.

Figure 3.8 shows ice rubble jammed in a reach of the Niobrara River. Though no photographs show such jamming upstream of Spencer Dam during the event, this photograph gives an impression of jam development along the river.

Figure 3.8. Ice rubble jamming on the Niobrara River during March 2019. The jam shoves rubble into a jumbled mass and pushes rubble over the channel's banks.

The Niobrara River's bed of erodible sand is susceptible to bed scour, notably when local velocities increase. Therefore, scour may occur at the toe of ice jams formed along the Niobrara River and cause more flow to pass beneath the jam. The development of scour consequently may cause a jam to collapse. Flow-induced erosion and collapse of the Niobrara's sand banks adjoining the jam also act to weaken jams along the river.

In the latter case, a jam may form at an upstream location then release only to re-form at a location downstream; this process may occur for several cycles. The release of an ice jam may produce a surge of water and ice rubble, especially if the release is relatively sudden. Channel characteristics play a pronounced role influencing the suddenness of a release. If the channel's bed were to scour quite quickly, jam failure could be swift. A channel's steepness increases flow velocity and, thereby, affects bed scour and the hydrodynamic loading of the jam. Furthermore, channel steepness affects the hydraulics of the surge resulting from the sudden failure of an ice jam.

3.6 The Layout of Spencer Dam

Spencer Dam extended across the full width of the Niobrara River. Figure 3.9 is an aerial view of the dam before its failure. This view depicts the river a short distance downstream of the view in Figure 3.3 and shows that water flow, sediment and ice arriving at the dam had to pass through the dam's gated spillway and two hydropower turbines.

As described in Chapter 2, the dam consisted of a long earth embankment dike (herein called dike) that extended from one side of the river's floodplain to the other side, and arced northeastward, directing flow along the embankment and toward the dam's powerhouse and spillway. The dam's spillways were designed to pass water flow during floods, but were not designed to handle bed sediment or river ice passage. The spillways comprised four Tainter (radial) gates, each 33.5 feet long and 13.0 feet high, and five stoplog bays, each 33.5 feet long and 13.0 feet high. Note that although the Tainter (radial) gates were 13 feet high, the gate openings were limited to 6 feet. Each stoplog bay had five vertical, steel H-beams (termed needle beams) that held a stack of timber planks between each pair of needle beams (six stacks total for each bay). Figure 3.10 illustrates the Tainter (radial) gates and the needle-beams.

The spillway also included a narrow trough (10 feet wide) designated as an ice chute. Such chutes are common for navigation dams on the Mississippi, Ohio and Illinois Rivers, and can be used to pass small quantities of ice (such as ice blocks cut upstream of the gates at Spencer Dam) but are considered essentially useless during major runs of ice. The layout lacked an ice bypass sluice or spillway.

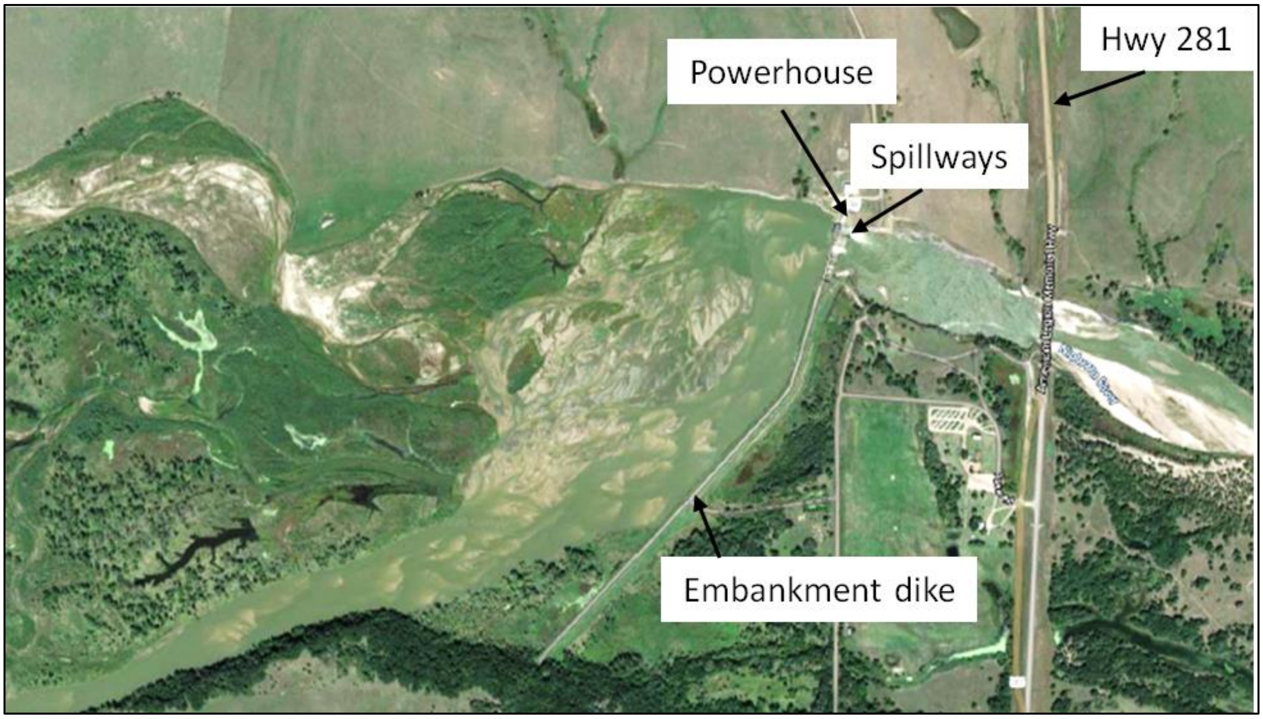

Figure 3.9. The layout of Spencer Dam on the Niobrara River. North is up. The west end of this view is about 0.5 mile downstream of the east end of the view shown in Figure 3.3 (Google Earth Image).

The dam's layout and the configuration of the dam's spillway suggest several hydraulic-engineering concerns:

- To reach the spillway section a major portion of the flow had to pass along the embankment dike, which functioned as an earthen dam and flow guidebank;
- The oblique angle at which the flow from the south approached the spillway, raises concerns about the discharge capacity of the spillway;
- Related to item b) above, the oblique angle of flow approach raises concerns about the spillway's capacity to pass ice rubble resulting from the dynamic break-up of the river's ice cover;
- The operation of the spillway's gates, especially the stoplog gates, prompts a question about the duration needed to fully open all the gates relative to the travel

times associated with surges of flow, particularly a surge resulting from the collapse of an upstream ice jam;

- The operation of the gates should be practicable at night and during frigid weather conditions (this was not the case at Spencer Dam).

The passage of bed sediment is known to be of concern for Spencer Dam. The dam's layout extensively blocked bed-sediment movement from upstream of the dam. The reservoir's original volume of 10,440 acre-feet at normal pool was reduced to 8,300 feet by 1999, even with semi-annual flushing. The resulting accumulation of bed sediment in the small reservoir (or pond) created by the layout required that the reservoir be flushed approximately twice annually, in the spring and the fall. Each flush took about two weeks and sent flushed sediment downstream of the dam.

The dam's layout posed problems for the movement of ice rubble conveyed to the dam from the reach upstream of the dam. When the rubble was weak and comprised smaller pieces, typically after a thermal break-up of the cover (or during freeze-up), the rubble would disintegrate when impacting the dam and its spillway. Evidently, such ice rubble was not particularly problematic (according to the dam's operators). However, when the rubble was relatively hard and large in piece size (as would result from the dynamic break-up of the upstream ice cover), the spillway experienced major difficulties passing the ice. For gate-opening widths of 33.5 feet and taking ice congestion to become problematic when the maximum length of an ice piece was about 33.5 feet/8[2], suggests that congestion and blockage could occur at gates when they attempted to pass ice pieces larger than about 4.2 feet in plan length. This estimate is made worse for large pieces of ice rubble obliquely approaching a gate opening; the opening's capacity to pass ice decreases as the angle increases relative to a line perpendicular to the opening.

[2] The value of ice-piece length being about 1/8th of flow width stems from research regarding ice-pieces arching and bridging across flow widths.

(a)

(b)

Figure 3.10. Two views of the spillway of Spencer Dam during sediment flushing: (a) the four Tainter (radial) gates; and, (b) the five stoplog bays with five needle beams and stacks of timber planks.

3.7 An Adverse Convergence of Factors

An adverse convergence of factors related to the physical setting of Spencer Dam led to an ice event that overwhelmed and failed the dam early in the morning of March 14, 2019. Though such an event could be deemed infrequent, the dam's mode of failure was foreseeable because the dam was on a river with a history of ice runs. Indeed, Spencer Dam had experienced prior major difficulties during the dynamic break-up of the ice cover upstream of the dam; notably in the years 1935, 1965 and 1966. The data record, though, is too short to assign a reliable frequency for this failure mode.

From February through early March 2019, frigid winter temperatures prevailed over the Niobrara River watershed (See Appendix H). The air temperatures at the town of Spencer were below average (NOAA 2019). This weather prevailed across much of Nebraska. For example, in Lincoln Nebraska, the air temperatures reached near-record lows (notably on February 21 and 25, and March 3 and 4). The lowest recorded values of air temperature there were about -6°F to -9°F. These weather conditions enabled an ice cover of substantial thicknesses to form on the Niobrara River. Estimates of ice-cover thickness upstream of Spencer Dam (based on observed thicknesses of ice rubble at Spencer dam) indicate that the cover was up to about 2 feet thick.

The likelihood of a dynamic break-up of the ice cover was heightened by the relatively thick and wet snowpack that lay on frigid ground in the watershed of the Niobrara River (see Chapter 4 and Appendix H). The snowpack was estimated to have a liquid water content of about one to two inches (USACE 2019, See Reference 3.3).

During the days preceding March 14, the air temperatures in the watershed of the Niobrara River were warming, indicating the onset of spring. The maximum air temperatures on March 11-13 were 39-49°F, though the minimums were 8-30°F. The warming weather led to increased snowmelt water runoff to the river and thereby to increased water flow in the river. For example, though the USGS gage was affected by ice-cover, the gage on the Niobrara at Verdel indicated that the river's discharge had increased continuously during March 11-13, particularly during March 13 (USGS Gage 06465500 Niobrara River); the discharge at this gage is indicated as having tripled from about 3,000 cfs on March 12 to 9,000 cfs on March 13.

A fast-moving large storm called Winter Storm Ulmer (named on 11 March) tracked northeastward during March 12-14. The storm underwent bombogenesis and became a bomb cyclone early on March 13 (See Chapter 4 and Appendix H). The bomb cyclone (Figure 3.11), pushed mild air and moisture northward, hastening snowmelt and adding about two inches of rainfall on the melting snow upstream of Spencer Dam. As evening developed on March 13, the rain became freezing rain, wind speeds became in excess of 60 mph and blizzard-like conditions prevailed as the bomb cyclone passed over the watershed of the Niobrara River.

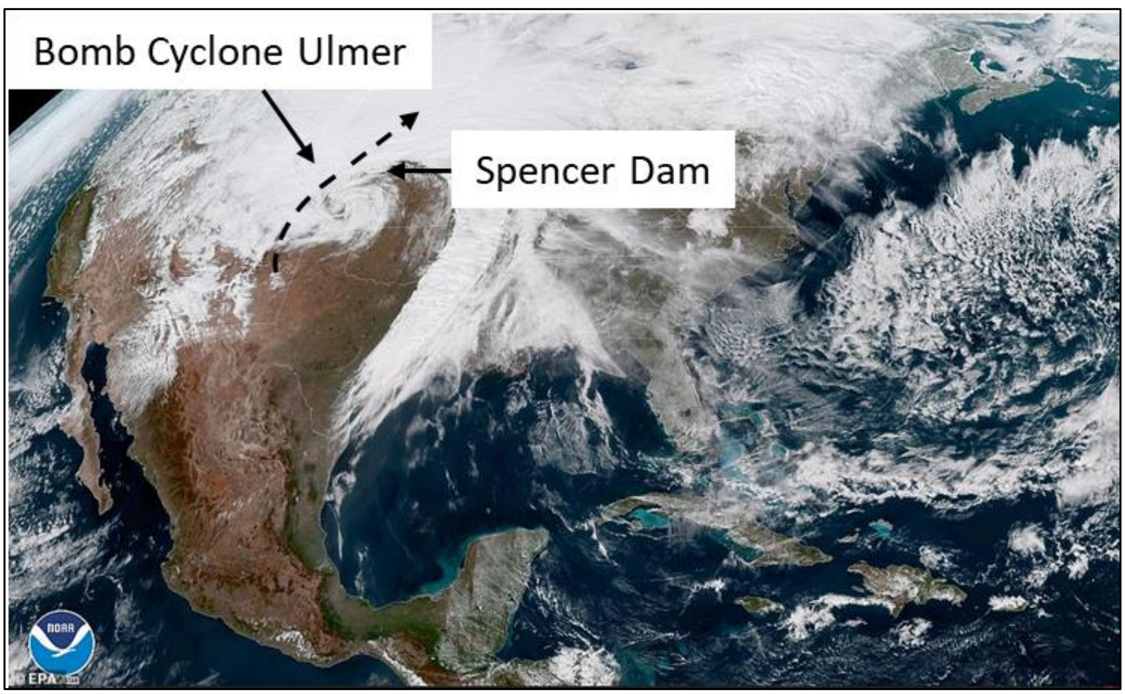

Figure 3.11. Winter Storm Ulmer becoming a bomb cyclone on Wednesday, March 13 (Source NOAA).

The rapid increase in water runoff entering the Niobrara River, whose ice cover was thick and intact, led to a dynamic breakup of the river's ice cover sometime during the evening of March 13. The resulting ice rubble drifted downstream until congesting and jamming at locations where the river narrowed, evidently (from photographs of stranded accumulations of ice rubble) doing so at several of the bridges upstream of Spencer Dam. The jams, formed during the evening of March 13, survived only until the early hours of March 14. The jams were unmonitored and unseen, except by chance observers who noticed locally rising water and ice. Once an upstream jam had formed then collapsed (owing to increased pressure from backed-up water and ice and erosion of the river's sand boundaries), ice rubble again surged downstream, amplifying the accumulations developing at downstream congestion locations. With each successive jam-formation and collapse event, the volume of accumulated ice rubble grew, and so did the magnitude of the surge of water and ice created when a jam collapsed. Though initially smaller volumes of ice rubble reached Spencer Dam, eventually, after the succession of jams, an enlarged volume of water and ice surged into Spencer Dam. These events happened at night and during conditions of freezing rain and blizzard.

3.8 Concluding Comments

The characteristics of the Niobrara River's channel (relatively steep, shallow and braided) lend themselves to the rapid formation of large volumes of ice. Climatic conditions prior to and up to the failure of Spencer Dam on March 14 resulted in a dynamic breakup of an ice cover formed during extreme low temperatures and runoff from rainfall on frozen ground and snowmelt during warming air temperatures associated with the formation and movement of a winter storm. The dynamic breakup of large volumes of strong and thick ice resulted in ice jam formation and collapse, perhaps multiple times, upstream of the dam. The Panel believed that it is very likely that one such collapse sent a surge of ice into Spencer Dam with catastrophic results, as Chapter 4 describes.

3.9 References

3.1 Alexander, J.S., Zelt, R.B. Schaepe, N.J. (2009), *Geomorphic Segmentation, Hydraulic geometry, and Hydraulic Microhabitants of the Niobrara River, Nebraska – Methods and Initial Results*. Scientific Investigations Rept. 2009-5008, U.S. Geological Survey, Reston, VA.

3.2 Tuthill, A.M. (1999). *Flow Control to Manage River Ice*. Report 99-8, U.S. Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Hanover, NH.

3.3 USACE (2019), website https://www.nwd.usace.army.mil/Media/Images.aspx?igphoto=2002109408

CHAPTER 4: HOW THE DAM FAILED

4.1 Introduction

What led to the failure of Spencer Dam on the morning of March 14? The failure occurred due to a combination of factors associated with the physical setting of the dam and reservoir, the conditions of ice and flow on the Niobrara River upstream from the dam, and the regional weather and storm development. The influence of these factors was compounded by the lack of warning provided to the dam operators; although advance notice may have allowed the operators to better react to the event, it is the Panel’s opinion that nothing they could have done at the dam as configured at the time would have kept the dam from failing given the magnitude of the combined flood and ice run.

This chapter discusses the local weather and river conditions leading up to the failure of Spencer Dam, the likely cause of the failure of Spencer Dam, and local consequences immediately downstream from the dam. The status and condition of the dam prior to failure are discussed in Chapter 2. General river and weather conditions prior to failure are discussed in Chapter 3. General consequences of the dam failure with a focus on downstream consequences are discussed in Chapter 5.

The subject of how the dam failed is discussed extensively in Appendix K, and is based on the detailed timeline given in Appendix B. While there are some details provided to the Panel that appear to be inconsistent, the Panel has evaluated various scenarios to determine which might be the most plausible.

The dam operators initially provided times for specific events to the Panel during their interviews. However, these times conflicted with the time stamps on photograph and video files from a smartphone that were taken by one of the operators. There is no reason for the Panel to believe the time stamps on these files would have been incorrect, because unlike some cameras, the smartphone constantly updates the time. Times stamps on the files were given more weight than the operators' recollection of time. With all that the operators were dealing with; it is likely the operators could not remember exact times five months after the flood when they were interviewed by the Panel.

4.2 Conditions Prior to the Event

The highly variable climate of the Northern Great Plains can generate extreme temperature swings and can produce precipitation that includes everything from heavy snow to severe thunderstorms. Temperatures are often well above average, only to quickly plummet as a strong cold front associated with a cyclone blasts through (See Appendix H for more detail). A wet fall season in 2018 and lower than normal temperatures in the winter of 2018-2019 froze the ground in much of the Niobrara River basin. The cold February and beginning of March temperatures combined with higher than normal river flows also promoted the formation of thick river ice. Just prior to Winter Storm Ulmer in March of 2019 (See Appendix H) there was also one to two inches of snow water equivalent on the ground due to a generally snowy February. The “bomb cyclone” produced by the storm made national news and produced blizzard or near-blizzard conditions in the Plains stretching from Colorado through Nebraska and into the Dakotas. The storm produced record precipitation in some locations and fluctuating temperatures that provided both rainfall (on the snowpack over frozen ground) and snow melt. These conditions swelled the flow of the Niobrara River (as well as many other Nebraska streams) and helped break up the solid ice cover that was present. The extreme flows generated by this confluence of events and the breakup and transport of strong winter ice by the flows had serious consequences for Spencer Dam.

4.3 Upstream River Channel

The Niobrara River is shallow and braided in many areas. There are numerous islands and sand bars within the natural channel. These features often overtop during high flows. Some dry land features have mature trees indicating infrequent overtopping, while others have only seasonal vegetation indicating more frequent overtopping. The river upstream from the dam is normally shallow and difficult to navigate in most places without an airboat. Figures 4.1 and 4.2 show the Google Earth images of the river reach between the Highway 11 Bridge (upstream) and Highway 281 Bridge (downstream) before and after the dam failure.

Ice forms on the river in winter. Chapter 3 provides a detailed discussion of potential ice conditions. Because the channel is wide and shallow, the ice that forms on the river covers a significant area. The ice on the river just prior to the events that failed the dam was reportedly two feet thick (Figure 4.3), although some photos taken after the flood showed pieces of ice that appear to be even thicker. Figure 4.1 shows how the channel would have looked before the March 2019 flood. The channel averaged about 1,000 feet wide. The after-flood image, Figure 4.2, indicates the flood flow averaged about 3,000 feet wide.

In a typical year, the ice on the river starts to melt in the spring before an ice run begins moving the ice downstream. The ice cover weakens during this melting period. Once the ice begins to move, it breaks into small, relatively soft pieces. There are several bridges in the river upstream from the dam. Ice jams at these bridges are generally not severe. Spring break-up ice also arrives at the dam. The dam operators told the Panel that, in a typical year, river ice passed through the spillway without incident.

The last known major ice run incident was reported in 1966 (See Appendix C). During that event, which also occurred in March, there was a four-day warming period that rapidly melted the snow cover creating a runoff flood. Although the river ice was also exposed to the warming trend, it was still thick and hard, and more prone to jams, as compared to the softer break up ice in normal years. When the ice started to break up during the increased river flow, an ice jam was reported at the Highway 11 Bridge, about 11 miles upstream from the dam. The dam operators were alerted to this condition in 1966 and the reservoir was "drained." However, there was no water surface elevation given for this drained condition. No such warning was provided in 2019.

The Spencer Dam operator on site the morning of the 1966 ice run described a 10-foot wall of water entering the reservoir at a flow that appeared to be twice the 22,000 cfs flow he had witnessed in 1960. The surge of inflow filled the reservoir and nearly overtopped the dam, even though the reservoir had been lowered. It caused the failure of one of the Tainter (radial) gates and punched a hole in the powerhouse wall. This event is important for both the similarities and the differences when compared to the 2019 event.

Figure 4.1 – Niobrara River between the Highway 11 Bridge (upstream) and the Highway 281 Bridge (downstream from the dam) before failure. From Google Earth (6/2018).

Figure 4.2 - Niobrara River between the Highway 11 Bridge (upstream) and the Highway 281 Bridge (downstream from the dam) after failure. From Google Earth (3/2019).

Figure 4.3 - 2-foot thick ice block (NPPD photo, March 2019).

The bomb-cyclone event associated with the 2019 ice run likely differed from the storm associated with the 1966 event. There was snow on the ground in 2019, but the 2019 storm, although initially bringing rain and enhance snowmelt, also brought cold, windy (blizzardous) weather. The 2019 ice was probably thicker and harder when the ice run started. The 2019 ice run was so severe that several upstream bridges were damaged or failed. The Highway 11 Bridge once again formed a major ice jam. The jam was described (by eyewitnesses) as at least 6-feet thick and backing up a half mile upstream of the bridge. The ice behind the bridge had pieces as wide as 20 feet as described by the eyewitnesses.

The reservoir's operators described the ice cover breaking up during the night (March 13) and being accompanied by high inflows and associated reservoir fluctuations. Although it was dark and impossible to see far upstream, the operators said that there were only occasional pieces passing through the spillway once the reservoir ice cleared.

The ice run from upstream had apparently not reached the dam while the operators were still at the powerhouse in the early morning hours of March 14.

Prior to dam failure, the peak flow at the Mariaville gage, 40 miles upstream was estimated to be about 29,000 cfs at around midnight (See Appendix H). The flow there was estimated to have peaked at about 31,000 cfs at 2:00 AM on March 14. Given that there were additional tributaries entering the Niobrara River for the next 40 miles, ice likely affected the flow by causing surges and blockages due to the formation of ice jams, and the gage may have failed before the flow peaked. Therefore, it is difficult to equate gage readings at Mariaville with flows at Spencer Dam. Closer to Spencer Dam, the Nebraska Department of Natural Resources (NDNR) maintained a stream gage at the Highway 11 Bridge but that gage also failed during the event. NDNR estimated a mean daily flow of 38,200 cfs for March 13. However, if a natural river flow of around 30,000 - 40,000 cfs had reached Spencer Dam just before it failed, it would not have been enough inflow to fail the dam given the spillway capacity, unless the spillway was blocked.

The Panel believes that a surge of flow much greater than the upstream gage estimate entered the reservoir and contributed to the failure. This surge may have been caused by the breakup of the ice jam at the Highway 11 Bridge that mobilized the river ice, or the breakup of one or more ice jams at other unknown locations between the dam and the bridge. The surge may have produced a wall of water and ice, like the 1966 surge, but possibly larger.

4.4 Detailed Account of Events that Failed the Dam

On the evening of March 13, 2019, preceding the dam's failure early on March 14, there were two dam operators on site. This arrangement was desirable to support operations during flooding. At 8:00 PM on the evening of March 13, the operators logged that they had opened all four of the Tainter (radial) gates in Bays 1 - 4 to their maximum opening of 6 feet. This was necessary for the operators to maintain the normal operating pool at elevation 1504.1 (all elevations are in feet using the current NPPD datum), and the reservoir occasionally dropped below this elevation during the evening. However, by midnight the reservoir was rising again, so the operators decided to start releasing the stoplogs by jacking needle beams. By 3:00 AM on March 14 the operators had managed to release all but one needle beam in Bay 5 (the first stoplog bay) and two beams in Bay 6. The three remaining stoplog bays still had stoplogs in place. However, by the time the dam failed, all the needle beams in Bays 5, 6, and 7 were released (most likely due to large pieces of ice hitting and dislodging the steel beams). All the needle beams and stoplogs in Bays 8 and 9 remained in place throughout the event, because they were frozen in place by ice on both the upstream and downstream sides (See Appendix K).

It had been raining most of the night, but at some point, after 3:00 AM, the rain turned to freezing rain. At 2:58 AM one of the operators shot a video of a piece of ice passing under one of the open gates. This video was intended to show how the gate was bouncing and the operating deck was shaking as the ice passed under the gate. It also showed one of the spillway gates was closed (in Bay 3). The operators told the Panel that Gate 3 closed (due to a broken lifting chain) around 2:00 AM and remained closed. According to the operators there was significant vibration on the operating deck due to the released needle beams dangling in the flow. The combination of freezing-rain ice on the walkway surface, wind, and vibration made the deck unsafe for the operators to walk across in order to access the spillway's south end to lift the remaining needle beams.

At around 4:38 AM one of the operators shot videos and snapped pictures of the trash-rake room in the powerhouse. The room's floor was beginning to flood (Figure 4.4). The floor is at elevation 1505.36, about 5.75 feet from the design top of dam, elevation 1511.14. At this time their access to the operating deck through the powerhouse was beginning to be cut off by the flooded floor. Also, at about this time, they decided to drive to the dike access road across the river and on to the dike where they could access the remaining stoplog bays from the south end of the spillway. The drive to the access road normally takes 10 minutes, but it likely took longer that morning due to unfavorable weather and road conditions.

Figure 4.4 – Water and ice entering the trash-rake room at 4:38 AM on March 14. The trashrack slots are behind (upstream from) the railing (NPPD photo).

Upon arriving at the gate to the dike access road, the operators noticed water on and around the access ramp and surmised that the dike was overtopping. Although it is unclear how much overtopping was occurring, they realized the overtopping was unsafe. The operators said that they did not see any ice in this overtopping flow. They then turned around and headed back to the powerhouse.

On the way back to the powerhouse, as the operators were driving towards the downstream resident's home, they directed their headlights on the house and honked their horn. After they stopped, they pounded on the door. They heard a dog barking. Finally, the resident opened the door. They told him the dam was going to fail and that he needed to get out. The operators said that they thought the resident clearly understood them when they told him he needed to leave “now.” It is important to note that the operators did not know the resident well. They may have briefly met him in the past but did not have his phone number and there was no emergency action plan telling the operators they needed to warn the resident. The operators told the Panel that, to their knowledge, there was never a discussion with the downstream resident about the hazards of living downstream from the dam.

As the operators were returning to the powerhouse, the operators saw three fireballs at the substation, indicating that the plant may have been flooded. By the time they arrived at the powerhouse, they observed a hole in the upstream wall of the powerhouse, but the reservoir had already dropped. They were unaware that the dam had failed and, seeing that there was nothing they could do there, they became concerned about Highway 281 washing out and called 911. They then headed to the highway bridge to warn people not to cross in the event it had been damaged by the flood.

Post-failure investigations showed a gage in the generator room that was 7-feet 7.5-inches above the floor (nearly 2 feet above the top of dam) that was half filled with water (Figure 4.5). A clock on the wall of the powerhouse office had stopped at 5:15 (Figure 4.6). Ice was piled on the dike and reservoir rim. The ice along the reservoir’s rim was about 6.1 to 6.3 feet above the top of slab on the north side of the powerhouse. This would put it at elevation 1515.7 feet (4.5 feet above the top of dam). It is not clear if the ice on top of the dike was 4.5 feet high or even higher, because no other usable measurements were provided to the Panel. The dike had breached in two locations: the north breach just south of the spillway was about 650 feet wide; the south breach, near the dike access road was about 800 feet wide.

Figure 4.5 – High water mark in the generator room – note that the water stain on the cabinet is the same elevation as the water in the gage (NPPD photo).

Figure 4.6 - Stopped clock in the powerhouse office (NPPD photo).

4.5 How the Dam Failed

While there were no eyewitnesses to the actual breaching, the Panel examined the available information to determine how the dam could have failed. Historical information related to prior similar events was also considered. The dam's operator in 1966 described a wall of water and ice entering the reservoir during similar ice run conditions. The Panel believes a similar surge occurred in 2019. However, in 2019 the reservoir was not lowered ahead of the surge, and the surge was likely larger.

4.5.1 Timing of the Breach and Possible Inflows

Based on the time stamp on photo files (e.g., Figure 4.6) the operators did not initially leave the powerhouse until at least 4:38 AM. According to the stopped clock on the wall of the office, it is believed the plant was flooded at 5:15 AM (Figure 4.6). The Panel does not know how long the dam overtopped before the clock stopped, or for how long after the clock stopped. The operators said they saw (by vehicle headlights) the hole in the powerhouse at about 5:30 AM. This observation apparently was after the dam had breached, but they could not see a breach due to darkness, and the reservoir had already dropped below the powerhouse wall.

Key times the Panel had to work with are the 4:38 AM flooding of the trash rake room, the 10 minutes (more likely 15 minutes given road conditions) it took for the operators to drive to the dike where they first saw the dam was overtopping, and the clock in the powerhouse stopping at 5:15 AM. This time span is only 37 minutes, during which time the reservoir went from about 5.75 feet or less below the top of dam to overtopping the dam. If the water went as high as the ice, it would have topped the dam by an estimated 4.5 feet.

The estimated reservoir storage from the powerhouse floor to the top of dam is about 7,000 AF according to a 1999 study [See Reference 4.1]. The estimated storage from top of dam to 4.5 feet of overtopping is also about 7,000 AF as estimated from that same study. The amount of ice entering the reservoir during the surge may have temporarily blocked the entire spillway. Even if the spillway were completely blocked by ice, this 10.25-foot rise in reservoir cannot be explained by flows measured at nearby river gages. A surge of 14,000 AF in 37 minutes requires an average inflow of about 274,000 cfs, not counting the flow going over the 3,200-foot long dike or through the spillway.

Therefore, it is likely that this surge was a localized event that would not have been captured by river gages.

Since the physical evidence indicates that ice rubble, and not necessarily water was approximately 4.5 feet above the dike's crest (Figure 4.7), the water level itself may not have been this high. The high-water mark measured in the downstream generator room of the powerhouse was 7-feet 7.5-inches above the floor at elevation 1505.36 (Figure 4.5). This observation puts the water level at elevation 1513.0 (about two feet above the dike). The discrepancy between water level and ice level could be explained if the surge pushed, rather than floated the ice over the dike. Floating ice would only be several inches above the water surface. As the ice was being forced over the dike and through the powerhouse wall to a height of 4.5 feet above the dam, the reservoir water surface may have only risen to a height of two feet above the dam.

Figure 4.7 – Ice stacked on the north end of the south breach. The elevation of ice measured in the reservoir rim upstream from the powerhouse was about 4.5 feet above the design top of dam elevation (from NPPD video).

If the surge pushed the ice to a level higher than the reservoir water surface, and the level of water in the powerhouse matched the reservoir water surface, the office clock may have stopped before the dam failed. The clock is believed to have been mounted on the wall about a foot or more below the high-water mark. The initial surge to the top of dike could have taken longer than the 15 minutes if it caused the clock to stop. Assuming the first surge took the full 37 minutes, the time between the last photo in the powerhouse (Figure 4.4) and the clock stopping (Figure 4.6), the estimate of 7,000 AF of inflow in 37 minutes would result in an average inflow of about 137,000 cfs (without considering any outflow). While this lower inflow seems more believable than 274,000 cfs, it would also result in less time for the reservoir water surface to rise two feet above the dike. Assuming two feet of water above the dam is the high-water mark just before the dike failed, even at the lower rate of inflow, the dam probably would have failed too fast to match the operators' account of the timeline.

How can this surge be explained, and was it one surge or more than one? The scenarios presented above may represent the extremes in possible inflows given the physical evidence. Other possibilities are discussed in Appendix K. It could be that more than one surge occurred. The surge or surges are likely related to the release of upstream ice jams either at the upstream bridge, multiple bridges, or in the river channel between the bridge and the dam. Figure 4.8 gives a sense of how much ice was in the river. This figure shows the ice on the south bank of the river upstream of the failed Stuart-Naper Bridge (owned by Holt County), about 25 miles upstream from the dam. This bridge failed from an ice jam. The depth of ice deposits was similar on the downstream side of the bridge.

Figure 4.8 – Ice deposits upstream from the Stuart-Naper Bridge. For scale, note the roof sticking out of the ice on the left side of the photo (from NPPD video).

Considering only the release of the ice jam at the Highway 11 Bridge (12 miles upstream from the dam) can give a sense of how ice approached Spencer Dam. An ice jam at the bridge was reported to extend a half mile upstream. It was about 3,000 feet wide, and probably had at least a 6-foot-thick layer of broken ice pieces up to 20 feet wide. The jam at the bridge, which is only about 800 feet long, caused the river upstream to rise. When the water surface was high enough for the north approach road embankment to overtop (Figure 4.9), the ice jam released, turning the downstream river from a 1,000-foot wide channel to a 3,000-foot wide channel full of ice and water that likely mobilized additional river ice downstream. There were likely ice jams formed and released along the way. These jams, possibly one associated with the upstream island, likely produced the surge into the reservoir.

Figure 4.9 – Highway 11 Bridge and north approach looking downstream. Note the ice trapped between guardrails on the bridge and along the far-left bank (from NPPD video).

4.5.2 How Two Breaches Formed

The embankment breached in two locations that the Panel has identified as the north (adjacent to the spillway) and south (near the access ramp) breaches. In past flooding, the dike failed or suffered erosion damage near the location of the 2019 south breach. It is believed that flow from the south channel, that is directed towards the dike, caused erosion of the dike in this location (Figure 4.10). The momentum of the ice-laden flow in 2019, which was much higher than the flow in the figure, likely caused run-up of ice and water onto the embankment, making this location the most likely spot for erosion damage and overtopping.

Figure 4.10 – Flow from south channel changing direction at the dike. (Corps of Engineers photo, 2015).

The location of the north breach had a surveyed crest elevation (from 2013) that was a foot or more lower than the remaining portion of the surveyed embankment crest (the survey ended at the access road). There may have been similar low crest areas south of the access road based on 2013 LiDAR as described in Chapter 2. The north breach location and any similar low areas in the south breach location would be a likely place for overtopping to occur for a uniform pool elevation. Given the relatively small reservoir, where the water surface during a flood may not be level, the two breach locations may have overtopped and failed nearly simultaneously.

Most dam engineers and dam safety professionals would probably picture an overtopping breach (with water only) much differently than one caused by mostly ice. In a normal situation, this dike could not be expected to survive a foot of overtopping considering the embankment shell material is sand. The sand on the downstream face would quickly erode leaving the steep clay core to either erode or collapse. It is believed that the overtopping was mostly by compacted broken ice (ice rubble) that contained some water as well as trees and other debris from upstream. The water within the ice rubble was not likely present up to the top of the ice surface. The ice may have gouged the embankment, weakening it for water erosion, although gouging was not identified elsewhere on the intact crest. An indication of the level of pressures exerted through the ice mass accumulated at the dam is evident from the deformations of the steel beams of the Highway 11 Bridge and the steel beams and gates at the spillway of Spencer Dam.

As the ice overtopped the dike, water contained within the accumulated ice likely dropped out on the downstream side of the dike as ice tumbled down the slope. Since the water was likely a small percentage of the overtopping volume of water and ice, only several inches of water overtopped the dike. This water flowing out from under the ice initiated a headcut erosion on the downstream toe of the dike that worked its way through the crest at the breach location(s); evidence for such a headcut exists in the remnant embankment. Portions of the embankment that remained standing after the dam breached show signs of this headcutting (Figure 4.11). Relatively flat road embankments, such as the one on the north side of the Highway 11 Bridge, were overtopped by significant amounts of water and ice without washing out (Figure 4.9). About a half mile of road was overtopped without significant signs of erosion.

With a small amount of water in the overtopping flow, it would take longer to fail the dike compared to being overtopped by several feet of water. It is also possible that the surge of inflow pushed 4.5 feet of ice up and over the dike all at once in a wall of ice and water without the gradual increase in reservoir depth. Long, uniform deposits of ice and local channels in the ice downstream from the south end of the dike that were observed after the failure could be signs the dike was overtopped by a thick layer of ice rubble for several minutes or more (Figures 4.11 and 4.12). With ice being deposited downstream from the south end of the dike the breach may not have fully developed until all the ice deposited downstream was forced out of the way of the flow. This sequence of events could have given enough time for the north breach to initiate.

Figure 4.11 – South end of south dike looking upstream showing the headcut erosion on the downstream slope of the dike (NPPD video).

Figure 4.12 – South end of the dike looking downstream. The dike is at roughly mid-height in the figure. Thick ice fields can be seen downstream (MPPD video).

Another more likely possibility is that the two breaches did not happen simultaneously. Since the embankment crest elevation was not uniform, it may have overtopped and failed at one of the breach locations first. Once the reservoir began to flow through the breach and the reservoir was lowered, the flow along the dike towards the breach became more concentrated. This produced high flow velocities along the upstream face of the embankment as water from the opposite side of the reservoir flowed towards the breach. That concentrated flow may have eventually resulted in a second breach that formed in the manner of the 1935 breach, by eroding the upstream face of the embankment until it failed.

It appears (from the photographic evidence) that large ice field deposits were associated with obstructions, such as bridges and roadways, which failed suddenly. There was apparently more ice upstream and downstream from the failed Stuart-Naper Bridge (Figure 4.8) than at the Highway 11 Bridge (Figure 4.9). This difference is likely due to a sudden drop in water level and release of ice when the Stuart-Naper Bridge completely failed. The release from Highway 11 Bridge was likely more gradual, as this bridge did not fail.

Also, there were no extensive ice deposits upstream from Spencer Dam, except on high points on the upstream island and along the banks. This observation may indicate that the ice run did not enter the reservoir before overtopping began, but instead came in the final surge, continuously flowing over the dam or through the breach without creating a stagnant pool where ice could settle behind the dam. Once flow from the wide swollen upstream river entered the reservoir, the reservoir became part of the river, because the available reservoir storage was insignificant compared to the inflow. The river quickly flowed through the breach once it formed, entraining ice accumulations in the reservoir.

The foregoing discussion of possible ways whereby the earthen dike failed contains considerable conjecture. This draws attention to important lessons learned and to topics requiring further investigation regarding river ice and weather interaction with run-of-river dams and other infrastructure, notably bridges. Chapter 7 summarizes these lessons.

4.6 Local Consequences from Embankment Failure

The discussion here focuses on the embankment-failure consequences locally near Spencer Dam. Chapter 5 of this report discusses the general consequences of the dam failure and focuses on consequences downstream of the dam.

The south breach of the dike occurred in the area of the dike access road, while the north breach was adjacent to the spillway. Figure 4.13 shows details of the downstream area prior to the flood. This figure denotes the approximate location of the two breaches and the “current” or new south channel through the south breach. The downstream house, occupied by one individual on the morning of March 14, is in the center of the new channel. This house and its occupant were swept away during the event. This resident was warned to evacuate after the dam operators first saw the dike beginning to overtop near the access road.

An extensive rubble-ice field formed downstream from the dike along the south bank as seen in Figures 4.11 and 4.12. This ice field is downstream from the portion of the embankment that remained intact, and it extends from the dike to the Highway 281 embankment approaching the bridge from the south. Because there was ice on top of the dike and downstream, it appears that a significant amount of ice overtopped the dike before it breached. It is not known if some of the ice was deposited downstream of the dike before or after it breached, but the ice could have been deposited as flow backed up behind the Highway 281 roadway embankment before it washed out. Failure of the highway approach embankment would have caused the flow stage to drop, leaving the ice higher on the south bank grounded. Similar ice deposits can be seen downstream from the roadway adjacent to the washed-out embankment (Figure 4.14). The ice downstream from the dike may have been deposited during overtopping of the dike, or in the high-water surge as the road embankment overtopped and failed.

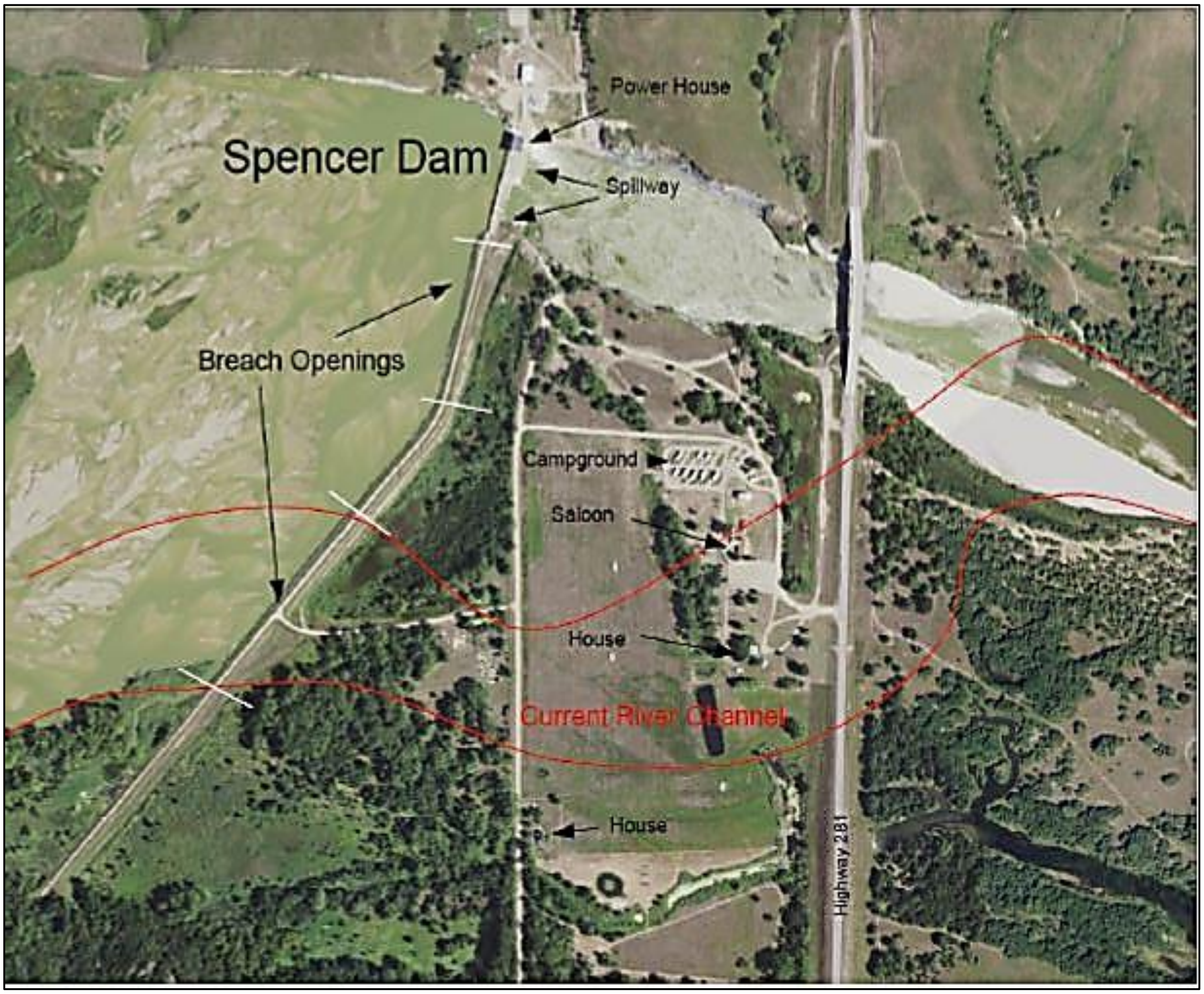

Figure 4.13 – Details of dam and area downstream showing dike breach locations and location of the river channel following the event (NPPD figure).

Figure 4.14 – View of washed-out Highway 281 approach ramp (looking south). Note the ice fields upstream and downstream from the road on the south bank (NPPD photo).

Ice was also deposited in a limited area on the north riverbank downstream from the highway (Figure 4.15). This ice was likely forced up on the bank from heavy flows coming from the south breach as the flow changed direction. However, most of the ice likely stayed in the flow as it moved downstream.

Figure 4.15 – Ice deposit on north side of river downstream from the highway (NPPD photo).

It is not known when the bridge's approach embankment washed out. However, before it washed out, the back-up of water and ice at the highway would likely have caused the residence downstream from the dam to become submerged. Flow from the south breach passed directly over the location where the house stood. It is apparent from photographs that the orientation and location of the north breach caused discharge from that breach to have flowed over the high ground north of the campground (Figure 4.13). Some of this flow may have also passed through the washed-out portion of the road to the south. Before the highway approach embankment washed out, flow from the south breach may have flowed towards the main river channel that passed under the bridge. An ice jam may have formed at the bridge before the approach embankment was overtopped and failed.

The two dam operators saw water in the area of the access road but did not see flooding in the area of the house when they were there to warn the resident. However, a road grade formerly connected to an older bridge (since removed) upstream from the house may have backed up flow while the operators were still in the area but overtopped before the resident could evacuate. Subsequently his evacuation route would have been cut off before the resident could reach the highway.

An image from an aerial reconnaissance after the dam failed (Figure 4.16) shows how the upstream island is prominent in the reservoir area, with just two main channels, the north (on the left side), and the south channels. It is believed the reservoir was not large enough to contain the 2019 flood. Though the spillway was estimated to have enough capacity to pass a 500-year flood (See Appendix E), it would have needed a much larger spillway, without gates, to pass the amount of ice and flow that entered the reservoir on March 14, 2019.

Figure 4.16 – View from above the upstream island looking downstream (east) towards the dam (NPPD photo). The run-of-river reservoir was small in comparison to the flooded river.

When evaluating the influence of the dam on the downstream consequences, three scenarios can be considered.

1. The dam as configured was incapable of passing the flood and subsequently failed;

2. If the dam were not there (was never built or was removed by the owners before the flood), the highway and the local structures including the house would likely have been washed downstream by the initial flood surge; and
3. If the dam were to have been reclassified as a high hazard potential dam and modified to pass a larger flood (up to 70 percent of the Probable Maximum Flood), it would have required an additional spillway, because there would be no economical way to alternatively enlarge the reservoir enough to contain a large volume flood. The flow from the river would have been passed downstream through this new spillway, which may have been a wide overflow spillway. If it could have passed the surge of ice and water the downstream highway embankment would likely still have backed up water, flooding the house, before failing the highway embankment.

It would be difficult to conclude that the area between the dam and Highway 281 was a safe place for a permanent residence. If the dam had been reclassified as high hazard potential, and it would have been cost effective to modify the dam (as opposed to breaching it), there would have been an Emergency Action Plan (EAP) that may have included earlier warning of the downstream resident and advanced warning to the dam operators of developing upstream conditions. However, as subsequently discussed (Chapter 7), the U.S. dam safety community does not have adequate understanding of how ice jams and ice runs can fail a dam. Without the information provided by this tragic event, modifications to pass extreme floods and associated EAPs may not necessarily be effective for ice related potential failure modes.

A photograph taken nearly three hours after the dam failed (Figure 4.17) shows a significant amount of flow passing over the spillway and through the north breach. At the same time, high flow was also passing through the wider south breach. Each breach was considerably wider than the spillway and the bottom of the channels formed by the breaches were lower than the spillway crest elevation. From this photo it seems clear that the flood, even hours after the dam failed, likely exceeded the spillway capacity. The downstream flow was so deep that only trees and no ground can be seen in the downstream area that is now an island surrounded by the north and south channels (submerged trees on the upper left of the figure). Hours after the dam failed, the flooding downstream was the result of the river flow and not the breach outflow that occurred nearly three hours earlier. The photograph confirms that, even without the dam, the structures immediately downstream would not have been safe during this flood.

Figure 4.17 – Photo of Spencer Dam taken at 8:04 AM on March 14, 2019 (NPPD photo).

4.7 References

4.1 NPPD-Sharefile-Dam Safety, File: 10 008445 CD-20090506 rrd ScanID-728615.pdf.

CHAPTER 5: CONSEQUENCES

5.1 Introduction

As the failure of Spencer Dam progressed, flows passed downstream through two breaches in the dam's earth embankment as well as through the spillway structure. Property and structures immediately downstream of the dam were impacted by the water and ice through the breaches as well as higher river levels (backwater) resulting from the increased flow. This chapter describes consequences of the Spencer Dam failure, upstream, immediately below and further downstream from the dam.

To aid in assessing consequences, the Panel developed a computer model (a one-dimensional model using HEC-RAS software, developed by the U.S. Army Corps of Engineers) to gain insight into flow along the Niobrara River downstream of Spencer Dam. Though this model was not configured to address the many uncertainties associated with an ice run and sequence of ice jams along the Niobrara River, the model yielded worthwhile information regarding flow-surge progress down the river.

5.2 Upstream Consequences

Although the flood and ice-run impacted properties, infrastructure and vegetation upstream, the resulting damages were not influenced by the presence of the dam. The USGS stream gage at Mariaville, NE about 40 miles upstream of Spencer Dam failed on March 13. The flood destroyed the Stuart-Naper (470th Avenue) Bridge and severely damaged the Butte (Highway 11) Bridge, located 25 and 12 miles, respectively, upstream from Spencer Dam. The Nebraska Department of Natural Resources stream gage located near the latter bridge was destroyed. The greatest impact of the failure was the concentration of flow into particular channels through the sediment deposits within the Spencer reservoir. These sediments would have been eroded by the flow and carried downstream along with the flood water and ice.

5.3 Consequences Immediately Downstream

This section describes consequences “immediately downstream” of the dam which includes the toe of the dam and property and structures just downstream, including the Highway 281 embankment and bridge crossing, about 1,500 to 3,000 feet downstream of the dike. This area is shown in Figure 5.1. As can be seen in the photographs in Figure 5.1 (a) and (b), all structures immediately below the dam were washed away.

In addition, the new flow path created by the southern breach (at the bottom of the photograph in Figure 5.1b) destroyed the highway embankment leading to the bridge. The bridge itself was left intact. Two new flow paths from the northern and southern breaches of the dam created channels evident in the photograph. However, it is also evident that the area between the two main flow paths was impacted by ice and water as it was swept clean of buildings, vegetation, and most other features. The extensive deposition of sand, and the patterns of deposition themselves, indicate flow paths and sand fans over the area and show that flow spread over the area as well as cutting into deposits to form new channels (Figure 5.1).

As was seen from ice deposits and damages further upstream from the reservoir, significant damage was caused by water and ice even without the effects of a reservoir or dam breach. Therefore, it is very likely that, were the dam not existing, similar impacts of removal of vegetation and formation of new channels would have occurred as observed elsewhere in the river. Even if the dam had not failed during the March event, and the dam had functioned as intended, it is possible that the ice-laden high flows released would have flooded some or all of the area just downstream of the dam, potentially causing damage or even destruction. The exact extent of such flooding is a matter of conjecture, however. Chapter 4 has additional discussion related to the inundation of the area immediately downstream from the dam.

(a)

(b)

Figure 5.1. Vicinity of Spencer Dam (a) Before (June 2018) and (b) After (March 2019) Failure (Google Earth)

5.4 Consequences Farther Downstream

The further downstream from Spencer Dam that the flood wave travelled, the more the peak flow would have decreased, or attenuated, as water and ice spread into the wide overbank areas of the Niobrara River and additional ice jams formed at downstream bridges. Because of sparse observations and measurements during the event, numerical hydraulic modeling was used to estimate impacts of the flood event for scenarios with and without the dam failing. Details of this modeling are provided in Appendix H. Photographs (See Appendix I), videos, newspaper articles, and social media posts after the event extensively document the flow's impacts near the Niobrara River between Spencer Dam and the town of Niobrara. It is worth noting that flooding and storm damage was widespread along many rivers and streams in north central Nebraska (which did not have dams) due to the adverse combination of weather-patterns and hydrologic and hydraulic conditions (Appendix H gives more details).

USGS stream gages were destroyed at Verdel, 24 miles downstream from Spencer Dam, and at Niobrara, about 38 miles downstream from Spencer Dam. The Niobrara gage was located at the Highway 12 Bridge, which was lifted from its foundations and destroyed by the flood. The Redbird Bridge, a county bridge south of Lynch, NE was damaged but survived.

In the village of Niobrara, buildings were flooded and destroyed by water, ice, and debris (Figure 5.2). The relatively large sizes and partially fragmented state of ice (fractures are evident in the large pieces) in the foreground of this photograph suggest that the ice originated close to the building against which the pieces came to rest. That is, these pieces were almost certainly not transported from the dam 38 miles upstream as they would have been broken up into much smaller pieces by the time they reached the village.

The amount, if any, that the dam breach at Spencer Dam would have exacerbated this flooding is difficult to quantify given the many unknowns, such as ice jam formation and release at the river’s bridges between the dam and the town. However, computer modeling indicates that, for a range of potential breach scenarios, there was no difference in water levels by the time the flood wave arrived at the village of Niobrara. This was true for results from simulations with both open water (no ice) and a stable ice cover. The modeling cannot account for additional flow attenuation due to the formation of ice jams at downstream bridges and within the river channel.

Figure 5.2. Ice and Flood Damage in Niobrara (Credit: Shane Greckel, used with permission)

5.5 Conclusion

The ice run and flooding in March of 2019 on the Niobrara River caused extensive damage to vegetation, property, and infrastructure both far upstream and downstream from Spencer Dam. The structures immediately downstream from the dam were destroyed by the dam-failure flood wave. However, it is equally clear, given their location, that they would have been destroyed by the ice run if the dam had not existed. The consequences of the dam's failure were felt most strongly immediately downstream of the structure (with loss of life and property just below the dam). Further downstream, the extent to which the dam's failure increased the damages is difficult to estimate, given the many uncertainties of what transpired during breach formation and in the following hours. However, based on computer modeling of open-water flow, and flow with a stable ice cover without jamming, the Panel estimates that flooding at the village of Niobrara was not increased by the failure of the dam.

CHAPTER 6: WHY THE DAM FAILED: HUMAN FACTORS

6.1 Introduction

In the past, failures of engineered structures during large natural events were often described as "Acts of God." Today, engineers know that structures need to be designed, constructed, and operated to have a low probability of failure for reasonably foreseen loading conditions and potential failure modes. Since structures like dams are conceived, designed, constructed, operated, and maintained by people and the organizations they represent, their incidents and failures evoke important human and organizational lessons learned beyond the physical processes of the failure itself.

Appendix J, Human Factors Methodology, provides a full description of how human factors were evaluated for this failure investigation. Chapter 7 describes Lessons Learned, many of which come from understanding the human factors that contributed to the failure of Spencer Dam.

As referenced in Appendix J, there are three defined categories of inadequacy due to human errors in risk management: ignorance, complacency, and overconfidence. Ignorance involves being insufficiently aware of risks. Complacency involves being sufficiently aware of risks but being overly risk tolerant. Overconfidence involves being sufficiently aware of risks, but overestimating ability to deal with them. The Panel found that there were two broad categories of human factors which contributed to the failure of Spencer Dam and the resulting consequences. These categories were (a) general ignorance related to the nature and risk of ice runs and (b) ignorance resulting in underestimation of the downstream hazard posed by the dam.

The Panel believes that, if the owner (NPPD) and State regulator (NebDSP) had better understood the potential hazards to and from the dam, the risks could have been mitigated by options such as removing the dam, modifying the dam to be able to handle major ice runs, removing the downstream properties in the inundation zone, and/or having an effective Emergency Action Plan to effectively warn downstream residents to evacuate when the dam was threatened. The Panel did not find that complacency or overconfidence were major contributing factors to the failure.

6.2 Ignorance of Ice Runs

Although the dam operators apparently had vague knowledge from brief discussions with previous operators that ice runs had occurred on the Niobrara River and had previously damaged the dam, there were no specific provisions for handling this risk. The operators were aware that the upstream brick wall of the powerhouse was previously damaged by ice. Although NPPD identified the plugging of canals due to ice buildup as a potential failure mode for some of the other FERC-regulated dams and canals, river ice runs were not identified as a potential failure mode. This is not surprising, considering that there exists a pervasive ignorance about ice run-related risks to dams in the dam industry generally, and for Spencer Dam specifically. The Panel identified six human factors that may have contributed to this ignorance.

6.2.1 Lack of Precedents in the Dam Safety Industry

There is a lack of reported dam failures attributable to ice runs in the dam industry. No dam failures due to ice runs have been reported to the ASDSO database of 380 dam failures (although the database is weighted towards incidents and failures since 2010). The National Performance of Dams Database shows just one dam failure from an ice flow in 1976. Note that for Spencer Dam itself, there were precedents as described briefly in Chapter 2 and in more detail in Appendix C (ice was involved with the 1935 failure of Spencer Dam and, in 1966, the dam's gates and the powerhouse were damaged by ice).

6.2.2 Lack of Documented Best Practices

The Bureau of Reclamation and U.S. Army Corps of Engineers Best Practices and Risk Methodology [See Reference 6.1] are used by many dam engineers but do not include potential failure modes related to ice runs. While static ice pressure against structures has long been documented as a design loading condition, there is a lack of design documentation for dynamic ice runs into smaller reservoirs that can block waterways and cause significant structural damage to dams.

6.2.3 Unavailable Information and Fading Memory

The Niobrara River's last documented major ice run was in 1966, 53 years before the 2019 failure. Only local senior citizens remember the last major ice run on the river. Whereas some of the information about these events was documented in local papers or in in the dam owner's files, information such as this was not available to NPPD and NebDSP as a consolidated dam history or an organized dam record.

6.2.4 Unavailable Warning Signs

No upstream ice monitoring system was in place. However, in the weeks leading up to the failure, at least one upstream resident near the river reported to the Panel that he knew that there was a thick build-up of ice cover on the river and that a major ice run was a possibility. This information did not reach the operators. Without a system in place, no warning was given. Still, for any forewarning to have been actionable, operators would have had to know that a major ice run could threaten the dam and would have needed a plan to deal with the run once the risk was recognized.

6.2.5 Lack of Best Practices for Passing Ice Runs at Dams

The original dam design did not adequately address the dam's vulnerability to major ice run loadings, nor did the 1940 replacement spillway project, and nor did the 1992 dam alternatives analysis. To the contrary, the new spillway, constructed in 1940 with nine 33-foot-wide bays, created more risk from ice rubble clogging than the original ungated overflow weir design. It is doubtful that industry dam design practices of the early- to mid-20th century had adequate provisions for successfully passing ice runs given that there is a notable lack of ice run guidelines for dams in our modern era.

Today, the dam industry still lacks adequate understanding of ice mechanics, thus the lack of guidance in the industry's technical literature on how to evaluate the risk. River ice formation, transport, and impact on infrastructure such as dams is inherently complex and difficult to model. More research is needed in this area. For example, one general resource for ice engineering is the U.S. Army Corps of Engineers' *Ice Manual EM 1110-2-1612* [See Reference 6.2], although it is not limited to dams and it inadequately addresses situations like that leading to the failure of Spencer Dam.

6.2.6 Ignorance of History

Until after the 2019 failure, NebDSP had virtually no knowledge that Spencer Dam had failed due to an ice run in 1935 or was badly damaged by ice runs in 1960 and 1966 (See Appendix C). NPPD had limited knowledge of these past events (such as the damaged upstream side of the powerhouse from the 1966 event). Past performance is an important indicator of possible future performance and review of these prior failures and incidents would have yielded valuable insight on the dam's ice run performance. Had these failures and incidents been known and analyzed as potential failure modes, the high risks to the dam would likely have been identified and the need to mitigate these risks would have been clear. The team identified the following contributing human factors for why the owner and regulator did not know or had limited knowledge about the 1935 failure and the 1960/1966 ice run incidents.

6.2.6.1 Inadequate information management

Dam records were destroyed in the 1966 ice run incident, although the incident itself should have had subsequent documentation related to the necessary repairs. Some remaining NPPD records were disorganized and not fully shared with the NebDSP. Although not required by the NebDSP, NPPD did not establish a Supporting Technical Information Document for Spencer Dam as is done for their FERC-regulated dams. When NPPD was formed in 1970 by the merger of three existing public power entities the new entity may not have fully reviewed the dam's history. Operator experience was not sufficiently passed on to successive new operators. Finally, no consolidated written history of Spencer Dam was established and maintained with references to key documents.

6.2.6.2 Inspection Reports did not address ice run performance

State inspections focused on discovery of observable deficiencies and not on latent vulnerabilities such as performance during ice runs (the inspection checklist had no items for ice run performance). The inspections were conducted in warm weather months and performance of the dam during ice events was not observed; therefore, ice loads and operations (such as plugging of the spillway) were not a focus of the inspection reports. Reliance on visual inspections to detect dam deficiencies and vulnerabilities is common in the dam industry, but may miss important, non-visible dam vulnerabilities.

6.3 Underestimation of Dam's Hazard to the Property Downstream

The Panel believes that the NebDSP and NPPD underestimated the potential of the dam to cause life-threatening flooding at the downstream house and property in the event of dam failure. The NebDSP classified Spencer Dam as having a Significant hazard potential, while the Panel believes that the dam should have been assigned a High hazard potential rating due to the presence of the occupied properties immediately downstream.

The house and property complex were located 1,600 feet downstream from the dike and along the access road to the dike. The complex consisted of a family home, a music stage, the Strawbale Saloon, and a privately-run RV campground. The house was constructed in 1965. The property was in the historic river channel that pre-dated the dam.

As discussed in Chapter 2, dam safety regulators typically use a system called the Downstream Hazard Classification (DHC) to separate their inventory of dams into several categories based upon the consequences if the dam were to fail. The DHC has nothing to do with the condition of a dam or the probability of the dam failing—only the potential consequences of failure if a dam were to fail.

The NebDSP uses four DHC categories: high, significant, low and minor. The NebDSP's high and significant categories are germane to this investigation:

A high hazard potential dam classification indicates that "failure or misoperation of the dam resulting in loss of human life is probable."

A significant hazard potential dam classification indicates that "failure or misoperation of the dam would result in no probable loss of human life but could result in major economic loss, environmental damage or disruption of lifeline facilities."

Spencer Dam was assigned a significant hazard potential classification rating in the early 1970s during the initial U.S. Army Corps of Engineers (USACE) National Dam Inspection Program and the dam was subsequently listed as Significant hazard potential in the many state dam inspection reports since that time. However, there was no comprehensive reevaluation of the downstream hazard that took advantage of newer information such as the "Risk Best Practices" referenced above or the Bureau of Reclamation's DSO-99-06, "A Procedure for Estimating Loss of Life Caused by Dam Failure." These guidelines include recreational users in the assessment for loss of life.

Had the dam been classified as high hazard potential, it would have been subject to greater dam regulation by the NebDSP. NPPD would have been required to develop an Emergency Action Plan for the dam and it may have had to be modified to pass a greater design flood. The NebDSP may have classified the dam as significant hazard potential and not high hazard potential for reasons explained below.

6.3.1 Anchoring Bias

The original hazard classification was performed by the USACE in the 1970s and it would have taken effort and justification to revise it. Once a classification is made by a reputable federal agency such as the USACE, it is easy for a state regulator to treat that classification as one that needs no review or update, or to simply defer to the prior classification. However, as time goes on, available information, methods for classification, and downstream development can result in a need for changes to the classification, regardless of the reputation of the original classifying agency.

6.3.2 Reliance on Inaccurate Models

The NebDSP relied on an inaccurate method for screening dams and determining whether additional hazard classification analysis was required. The method assumed that if any homes downstream of the dam are at an elevation above half the height of the dam at maximum section, then the homes are above any potential dam failure flood wave and thus out of harm’s way (not high hazard potential). The maximum section for Spencer Dam was at the concrete spillway. It also had a long and substantial embankment dike which extended south far from the spillway. The focus on the spillway maximum section may have led to inattention to the hazard posed by the dike. The dike was directly upstream of the downstream property and recreational areas and should have been considered as a potential source of high severity flooding in the event of dike failure, but the attention of the state and owner may have been focused mainly on the spillway and powerhouse because they were believed to be more significant structures.

6.3.3 Ambiguity in Language

There is ambiguity in the language used for state and federal classification of hazard. The NebDSP defines a high hazard potential dam as one where “failure or misoperation of the dam resulting in loss of human life is probable.” The Panel was told that for dams regulated by NebDSP, the term “probable” is defined as having a 50 percent or greater likelihood of occurring. The state’s DHC system closely aligns with the Federal Emergency Management Agency (FEMA) DHC Guideline 333 [See Reference 6.3]. In this FEMA guideline, a high hazard potential dam is also defined as a dam that would cause “probable” loss of life. However, in the discussion section of the FEMA guideline “probable” is not defined as a 50 percent or greater likelihood of occurring. Rather, the FEMA guideline discussion makes it clear that high hazard potential should not be assigned to a dam where persons are only temporarily in the floodplain (such as occasional recreational users). There were two permanent residents, a married couple, living just below the dike and their businesses generated visitors and overnight guests. Both overnight and permanent occupancy so close to the dam should therefore have warranted a high hazard potential classification rating. Furthermore, the FEMA guideline states that, “The classification should be based on the worst-case probable scenario of failure or mis-operation of the dam. Each element of a project must be evaluated to determine the proper hazard potential classification of a project.” In the Panel’s opinion, the hazard classification for Spencer Dam should have taken the dike into account.

6.3.4 Lack of Documentation

NebDSP has upgraded a total of 25 dams from Low or Significant to High DHC since 2005. NebDSP stated to the panel that they have a procedure for dam inspectors to check for downstream structures (e.g. homes) in the field when at a dam inspection. Engineers check current satellite imagery for downstream development when reviewing the inspection reports. The discovery of a downstream home or business would initiate a more detailed evaluation of the DHC.

For Spencer Dam, the NebDSP provided inspection reports restating the Significant DHC classification, but no other DHC records about the dam were provided to the Panel. The panel believes that NebDSP should better document each step in their DHC review procedure to ensure all dams are adequately reviewed.

6.3.5 Resource/Workload Pressures

The NebDSP has jurisdiction over almost 3,000 dams, and 600 of the dams are currently assessed to be in poor condition. The Panel believes that many responsibilities of the program and high workload relative to the size of the staff had the potential to negatively impact the quality of the program. Some of these impacts relate to downstream hazard classification verification. See Appendix G.

According to budget and staffing data compiled by ASDSO, the NebDSP program has fewer staff per dam and spends less per high hazard potential dam in comparison with many other state dam safety programs. The NebDSP stated that they also have trouble attracting and retaining engineers and, as a result, they have been using trained non-engineers in the regions to perform all low hazard potential dam inspections and about half of the significant hazard dam inspections (with peer review of the report by a licensed engineer). The most recent 2018 inspection of Spencer Dam was performed by two non-engineers.

Importantly, the program is behind schedule on updating hazard classifications for dams and for completing some significant hazard potential dam inspections. The program has begun working with dam owners to perform dam safety evaluations based on potential failure modes (not just inspection findings) and this will require more resources. In the Panel's opinion, the amount of training taken by NebDSP staff each year is not extensive and it was told that some training funds go unused every year because staff are too busy with program activities to use the resources.

6.4 Other Human Factors

Beyond the human factors noted above, which contributed to the risks posed to and from the dam, several other human factors had the potential to influence the judgment and decision-making related to the dam, and thereby contributed to the failure of the dam. These other human factors are described below.

6.4.1 Fatigue and Stress

During the night of March 13 and 14, 2019, the operators working at Spencer Dam experienced adverse working conditions (including wind, freezing rain, and snow). The operators also dealt with stress and fatigue. Their safe access to the spillway operating deck was cut off.

Although the dam operators were unable to open stoplog Bays 8 and 9 because they were frozen in place, and despite fatigue and stress, the Panel found no major mistakes, lapses or errors on the part of the operators. The ice run was so large that missing the capacity of Gate 3 (which closed due to a broken hoist chain), and stoplog Bays 8 and 9, probably did not affect the outcome; the dam would have likely overtopped and failed whether they were open or not.

6.4.2 Complexity

Operations of Spencer Dam to handle floods were complex because they often required at least two operators and were physically demanding. Gate operations sometimes required the operators to go outside the hydropower plant and check on the gates and lift motors. The stoplog operation was more complex and it helped to have two people, since there was a need to walk over 150 feet on the exposed high walkway, lug a 50 pound jack to the needle beam lifting bracket, chain the jack in place (so it wouldn't fall off of the catwalk when the needle beam kicked out), and operate a compressed air valve. The complexity was further heightened by adverse weather conditions and darkness.

6.4.3 Safety Concerns

When the reservoir started to rise after approximately 4:00 AM on March 14, the operators decided to try to open the last two needle beam bays (Bays 8 and 9). That would have required a 250-foot-long walk along an elevated and exposed walkway during freezing rain conditions. The operators were concerned about ice on the walkway, large chunks of ice hitting the gates causing the walkway to jump, and getting past the swinging steel needle beams in stoplog Bays 5, 6, and 7. Thus, they decided to drive to the dike and access stoplog Bays 8 and 9 from the south end of the spillway. This decision probably saved their lives, because the walkway was heavily damaged or destroyed by about 5:15 AM. After leaving the powerhouse after 4:38 AM, when the plant began to flood and arriving at the dike, they could see it was unsafe to drive on the dike, which by then was overtopping. Had they arrived earlier and driven to the end of the spillway; they may have never made it off the dike safely.

Despite knowledge that the dam would likely fail very soon, the operators decided to take the time to warn the resident. When the operators drove to the downstream home to warn the resident, they honked their horn and had to pound on the inner door to wake him. The resident was likely groggy with sleep. Although the operators were adamant that the resident understood that the dam was going to fail and that he needed to evacuate "now," he apparently did not evacuate in time and may not have understood or heeded the warning by the operators. Generally, there are dozens of reasons why people do not evacuate when warned, and any combination of them may have been applicable in this case [See Reference 6.4]:

- He did not comprehend the risk (lack of information) – He may not have perceived the dam as a threat since it had not harmed the house in the many past decades. As there was no EAP, he did not participate in the development of an EAP or develop a warning and evacuation plan for himself.

- He did not appreciate the high risk to himself (complacency) - He may have thought that, even if the dam failed, the flooding would go elsewhere or would not be severe.
- Ambiguity of language – The operators told him to evacuate “now,” but he may have thought he had at least several minutes to do so.
- Need for collecting pets or valuable items – He may have paused to collect pets (there was at least one dog at the home), memorabilia, or important papers.

6.4.4 Cost Pressures

Despite Spencer Dam only producing three megawatts of power (just 0.1 percent of NPPD’s generation capacity), NPPD had completed many repairs to the dam (See Appendix A), although none for the purpose of passing ice runs. NPPD continued to employ operators at the dam while the trend in the hydropower industry is toward remote plant operations. The Panel found no evidence that NPPD neglected the dam due to the pending transfer of dam ownership announced in 2015.

NPPD recognized that uprating the hydro turbine generators units may have triggered costly FERC regulation and, perhaps, expensive dam improvements. FERC regulation would also have triggered the development of a Supporting Technical Information Document and Potential Failure Mode Analysis, which adds costs. NPPD decided in the 1990s to forgo unit uprating and the dam was not brought under FERC regulation.

6.4.5 Pressure from Non-Dam Safety Goals

The Panel found no evidence of pressures on judgment, decision-making, or action during the failure event from non-dam safety goals. The generators were shut down early in the event. The dam does not store water and the water surface was not elevated before the event began. The reservoir is small and could easily be filled, even if they had lowered the reservoir before the flood as was done in 1966.

6.4.6 Overconfidence

Dam operators successfully passed normal reservoir ice through the dam's gates between 1966 and 2019. Annual success with passing pond ice and very limited river ice may have contributed to overconfidence that they could pass larger amounts of ice (including river ice runs). If there had been concern about plugging of the gates or opening of the stoplog bays, preventive measures could have been taken in advance such as opening all gates earlier in the event and freeing ice from stoplog bays. Further evidence of overconfidence involves the apparent modification of the gates and/or spillway structure that resulted in their restricted opening height of only six feet. Both the bay width and the gate openings were too small to pass the ice observed in the March 2019 event.

6.4.7 Unclear Roles

The NPPD staff interviewed by the Panel acknowledged that NPPD is responsible for the safety of the dam. NPPD initiated and completed many maintenance projects and projects to improve operations. However, because the NebDSP does dam safety inspections and issues findings and recommendations, NPPD may have at least partially relied on the NebDSP to identify dam safety-specific issues and requirements. This is an issue with many dam owners who may not understand that the regulators' abilities may be limited, and ultimately as an owner they have responsibility for owning a safe dam. Doing so goes beyond merely correcting negative findings from a visual inspection report and involves reviewing the dam's history and unique potential failure modes

6.5 References

6.1 *Risk Best Practices in Dam and Levee Safety Risk Analysis*, Bureau of Reclamation and U.S. Army Corps of Engineers https://www.usbr.gov/ssle/damsafety/risk/methodology.html

6.2 *Engineering and Design: Ice Engineering,* Engineer Manual No. 1110-2-1612, U.S. Army Corps of Engineers, https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1612.pdf

6.3 *Federal Guidelines for Dam Safety: Hazard Potential Classification System for Dams*, FEMA 333, April 2004, https://www.fema.gov/media-library-data/20130726-1516-20490-7951/fema-333.pdf

6.4 "Avoiding Disaster: Assuring Warning Compliance," Graham. https://damfailures.org/wp-content/uploads/2015/07/068_Avoiding-Disaster.pdf

CHAPTER 7: LESSONS LEARNED

Introduction

Lesson 1: Ice-run loading must be included in dam safety practices.

Lesson 2: The industry needs to improve Downstream Hazard Classification (DHC) practices to ensure the safety of people downstream.

Lesson 3: Emergency Action Plans (EAPs) and exercises are essential for effective warning and evacuation.

Lesson 4: Inspections by themselves do not constitute an adequate dam safety evaluation.

Lesson 5: Designers must incorporate knowledge of local conditions.

Lesson 6: State dam safety programs need to watch out for excessive workload and pay attention to maintaining the quality of their work.

Lesson 7: Engineers must learn about the history of their dams.

Lesson 8: Maintaining dam information is essential for conducting all dam safety activities.

Lesson 9: More river-ice research is needed.

Lesson 10: Warning systems need to be established for rivers that can produce major ice runs.

Lesson 11: Dams subject to flooding require flood operations plans.

Lesson 12: Adverse weather conditions must be taken into account in design of dam operations.

Introduction

The failure of Spencer Dam was a tragedy. The dam safety community has a responsibility to learn from this event and prevent future failures. By documenting and stating the Lessons Learned below, the Panel hopes that the dam safety industry will incorporate what the Spencer Dam failure can reveal about the status of dam-engineering practice and where the industry needs to improve.

Lesson 1: Ice-run loading must be included in dam safety practices.

Audience: Designers/Engineers/Regulators/Owners

Findings: There are thousands of dams in cold weather regions in 31 states of the U.S. (see Figure 7.1). Run-of-river dams or dams forming small reservoirs in cold weather regions can be vulnerable to large ice run events. Until the Spencer Dam failure, the dam safety industry did not consider that ice runs could fail dams. Ice runs are not included in Reclamation/USACE risk best practice methodology or in other well-used guidelines. Decades can pass between major ice runs, requiring research into river history to understand the true risk. There are so little available data at this point in time that it would be difficult to tie these events to realistic recurrence periods, but they are most certainly more likely on rivers like the Niobrara than other loadings such as the extreme floods that the dam safety industry designs for and routinely checks.

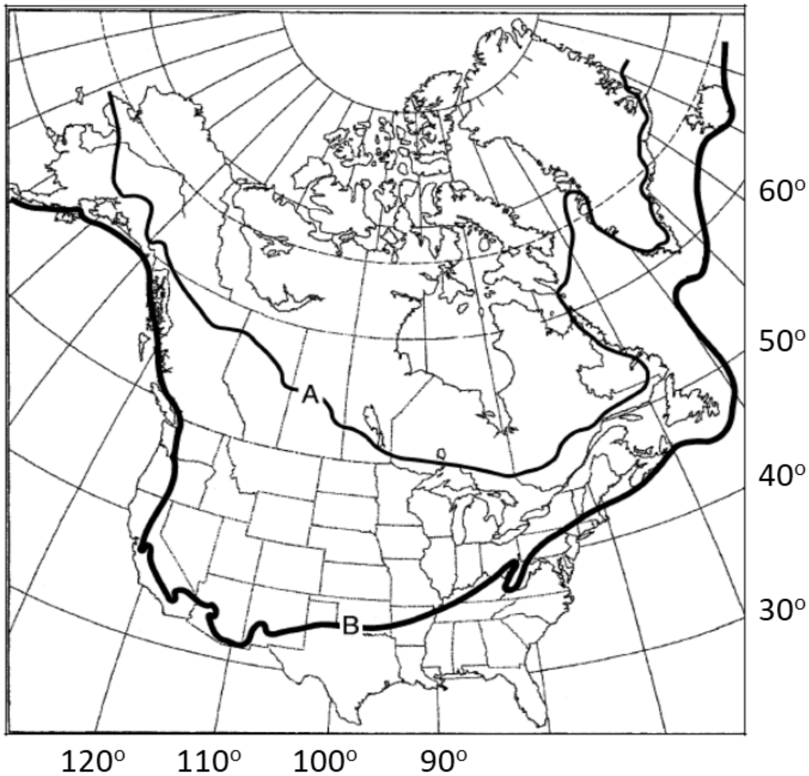

Figure 7.1. Cold regions of North America (latitude and longitude indicated). The A-line is the southernmost boundary of the area where the average air temperature of the coldest winter month is −18°C (0°F) or less and ice forms covers over navigable rivers for at least 180 days of the year. The B-line is the southernmost border of the area where the average air temperature of the coldest month is between −18° C (0°F) and 0°C (32°F) and ice covers navigable waters for 100-180 days. (Source: adapted from USACE 2002).

Recommendation 1A: The dam safety industry should develop a screening-level tool for dam owners and regulators in cold weather regions to determine which dams could be vulnerable to ice runs. Dam engineers need to screen dams with small reservoirs in cold weather regions for ice run potential. When the potential exists, engineers need to account for ice runs when evaluating the dam's performance. This would include evaluating the potential for waterways to plug with ice, and the ability to safely pass large surges that can potentially have peak inflows greater than peak rainstorm inflows.

Recommendation 1B: Ice runs should be added as a potential failure mode in the appropriate dam safety guidelines.

Lesson 2: The industry needs to improve Downstream Hazard Classification (DHC) practices to ensure the safety of people downstream.

Audience: Owners, Regulators/Dam Safety Engineers, FEMA.

Findings: In the opinion of the Panel, the hazard classification of Spencer Dam did not adequately account for the permanent resident and overnight camping 1,600 feet below the dam. There is confusion in the dam safety industry about the term “probable loss of life” in the FEMA 333 DHC Guidelines. The State of Nebraska interpreted the word “probable” to be a 51 percent or greater chance of occurring; however, the FEMA Guideline focuses on the tenet that occasional, non-permanent occupation of the floodplain does not justify high hazard potential classification. This seems inappropriate in areas of heavy recreational use.

The periodic review of the hazard classification at a low and significant hazard potential dam is a critical dam safety activity. There is often development downstream from dams (hazard creep). Tools are available to rapidly identify populations at risk (Google Earth and simplified dam break modeling). Because dam owners are responsible for the safety of the dam and want to limit their potential liability, they should want their dam to have a correct Downstream Hazard Classification

Recommendation 2A: FEMA should amend the existing DHC guidelines (FEMA 333) to clarify the term “probable loss of life.” The amended guidelines should more clearly address recreationalists (campers/hikers) and the presence of highways & roads downstream.

Recommendation 2B: States need to develop and follow technically adequate, documented procedures for periodically screening, evaluating and reassessing the DHC of low or significant hazard potential dams.

Recommendation 2C: Dam owners should alert states when they believe the DHC needs to be updated, or when they believe they may have been incorrectly classified. Dam owners’ engineers need to take DHC training.

Recommendation 2D: The dam safety industry should consider whether or when Emergency Action Plans and inundation maps should be required for significant hazard potential dams and for when there are people in the downstream flood plain.

Lesson 3: Emergency Action Plans (EAPs) and exercises are essential for effective warning and evacuation.

Audience: Dam owners and regulators

Findings: Spencer Dam did not have an EAP. The resident downstream from Spencer Dam received a warning that the dam might fail just minutes before the dam actually failed. He did not evacuate in time and lost his life.

EAP exercises are important for effective warning and evacuation.

Recommendation 3: Emergency Action Plans and exercises are critically important for effective notification, warning and evacuation of people downstream from dams. States should require EAPs and exercises for dams which have major consequences if the dam fails (such as significant hazard potential dams).

Lesson 4: Inspections do not constitute an adequate dam safety evaluation. Evaluations must include review of critical documentation and records. Dam owners need to know they are responsible for the safety of the dam.

Audience: Owners, Regulators

Findings: Dams have vulnerabilities which are not discoverable during visual inspections such as ice-related performance, poor erosion protection design, hydraulic performance during floods, and earthquake performance. Potential Failure Mode Analyses (PFMA) bring owners/regulators/engineers together to perform an evaluation of all vulnerabilities at a dam. These PFMAs need to be conducted or attended by well qualified dam safety engineers.

Dam owners may incorrectly view addressing the regulator's dam inspections recommendations as all they need to do to have a safe dam. Some owners may not fully understand that they, not the regulator, are responsible for the safety of the dam. Potential Failure Mode Analyses can be time consuming and expensive but can be scaled to the complexity of the dam and the potential risk.

Recommendation 4A: Potential Failure Modes Analysis at an appropriate level should be conducted as part of a dam safety review. Once the potential failure modes (PFM) are understood, inspection checklists and monitoring plans should be modified to identify signs these PFMs are developing.

Recommendation 4B: When transmitting dam safety inspection reports and other communications, regulators should remind the owner that they (not the State) are responsible for the safety of the dam including making any additional dam safety evaluations and repairs.

Lesson 5: Designers must incorporate knowledge of local conditions.

Audience: Designers/Engineers/Regulators

Finding: Ice runs were not considered in the design of Spencer Dam, despite local conditions being conducive to ice formation and runs.

Recommendation 5: Safety reviews of existing dams and design of new dams where ice buildup is common need to provide for ice loading by any combination of the following:

- Increased spillway capacity to handle ice affected discharge
- Increased dam height/freeboard/storage capacity to handle ice run events
- Embankments, structural members, and gates able to handle anticipated loading of flow and ice combined

- Other flow control or bypassing methods to deal with ice-laden flows such as wide uncontrolled spillways that will not plug with ice
- Designs for increased ice loads on structures

Lesson 6: State dam safety programs need to balance workload and resources while maintaining the quality of their work.

Audience: State Dam Safety Programs/State Government

Findings: Most State dam safety programs (DSPs) have jurisdiction over many hundreds, if not thousands of dams (NebDSP has jurisdiction over almost 3,000 dams). State DSPs have many responsibilities, including performing inspections (or ensuring the dam owner conducts inspections), reviewing new or existing dam designs, responding to incidents, periodically assessing the downstream hazard classification of dams, educating dam owners and staff, and ensuring that EAPs are developed and exercised. Much of this workload is repeated yearly and drop-in work (such as responding to dam incidents) can be disruptive. When state DSPs have too many responsibilities and too high of a workload, program stressors appear such as: excessively relying on screening methods, using incorrect technical criteria, falling behind in the state-of-practice, relying on non-engineers to do program work under peer review of engineers instead of having engineers do the work themselves, not taking enough dam safety training because of high workload, and falling behind on schedules. The Panel believes that the NebDSP was experiencing the above stressors prior to the failure of Spencer Dam.

Recommendation 6A: As a best practice, states should periodically request an independent peer review of their programs in order to identify weaknesses and to identify opportunities for program improvements.

Recommendation 6B: State DSPs should consider what dam safety work (such as dam safety evaluations based on potential failure modes and inspections) should be done by the state program and what work should be performed by the dam owners with guidelines from the state.

Recommendation 6C: State governments should adequately fund and support their dam safety programs.

Lesson 7: Engineers must learn about the history of the dams assigned to them.

Audience: Owners, Regulators, Dam Safety Engineers

Findings: Although there was historical information about previous failures of Spencer Dam and ice runs on the Niobrara River it was not readily accessible, and the Panel believes that the regulator and owner were not fully aware the dam had previously failed and been damaged by ice flows. Researching historical information takes time and effort, but it is extremely valuable when evaluating a dam and assessing its risks. Past incidents and failures often have a high likelihood of recurrence. The 2019 Spencer Dam failure was called "unprecedented" by some people even though failures or near failures had occurred in the past at Spencer Dam from similar conditions. A more thorough examination of events in the 1960s may have led to mitigation of the ice run risk.

Recommendation 7A: Dam owners should develop and maintain consolidated project histories for each of their dams which document important incidents, failures, modifications, and other notable events. This document should refer to other source documents.

Recommendation 7B: Owners and their dam safety engineers should be thoroughly familiar with the history of their structures (design, operation, maintenance, historical events including repairs and upgrades).

Lesson 8: Maintaining dam information is essential for conducting all dam safety activities.

Audiences: Dam Owners/Regulators

Findings: Without organized systems for maintaining information about their dams, dam owners and engineers run the risk of not understanding dam vulnerabilities and not being able to quickly assess a developing incident. At Spencer Dam, records were lost when the powerhouse flooded in 1966. In the course of this investigation, important records were found at the Spencer Dam powerhouse office that had not been made available to NebDSP. Although both the NebDSP and the NPPD had voluminous records about the dam, the electronic copies provided to the panel were not labeled by subject or organized. The NebDSP had some records that NPPD did not have and vice versa.

Recommendation 8A: Dam owners and engineers should keep records about their dams in an organized and clearly labeled system. This system should be kept electronically when possible in order to be more thorough, efficient, accessible, secure, and cost efficient.

Recommendation 8B: ASDSO should bring dam owners and states together to develop an effective and efficient dam record guideline. This guideline should include methods for the dam owner and state to share records. It should include establishing specific folder categories and naming conventions.

Lesson 9: More river-ice research is needed.

Audience: Institutions Managing River-Related Infrastructure, USACE, Bureau of Reclamation, Civil Engineers, Regulators of Infrastructure

Finding: Ice jams and major runs of river ice can severely affect river-related infrastructure, notably dams and bridges.

Recommendation 9A: Research is needed to determine how the design and operation of river-related infrastructure (dams and bridges) can mitigate or avert the adverse effects of river ice. In this regard, dam safety organizations and regulators should coordinate a plan to address issues related to river ice and its impact on dams.

Recommendation 9B: The design and operation of river-related infrastructure should account for sequences of winter and spring weather patterns that may cause ice jams and major ice runs to occur at the rivers where such infrastructure is located. Research is needed to define such sequences. The research should involve an international effort because weather patterns may encompass several countries. Also, several countries have river-related infrastructure subject to adverse effects posed by river ice.

Recommendation 9C: Research is needed to investigate ice formation and movement in channels of relatively complex geometry or containing low dams or bridges.

Lesson 10: Warning systems need to be established for rivers that can produce major ice runs.

Audience: Dam and Bridge Owners, River Monitors (USGS, NWS, USACE, state agencies), Forecasters

Finding: For Spencer Dam, significant ice run or jamming flows occurred for at least forty miles upstream of the dam. Forecasters had information about frozen ground and severe precipitation. The dam operators did not receive notifications from any individuals or agencies about ice conditions, relying only on what they were able to observe just upstream from the upstream dam face. The Panel is not aware of existing warning systems for potential ice runs.

Recommendation 10: All rivers that have produced ice runs should be monitored for development of ice runs and appropriate warning systems should be developed when there are critical dams or infrastructure on the river. The monitoring perhaps should be coordinated by the National Weather Service or the U.S. Geological Survey.

Lesson 11: Dams subject to flooding require flood operations plans.

Audience: Owners, Regulators

Findings: Spencer Dam had no apparent written plan for flood operations. While the operators could describe an operating sequence, this sequence was over simplified. There were no advance plans to ensure that all flood control features were operational ahead of the flood. Knowing the difficulties with releasing stoplogs if they are frozen in place, it would have made sense to check these features during daylight hours prior to the flood. As the flood was peaking, the operators were prohibited by adverse conditions from completing the opening sequence. While failure to release stoplogs at Spencer Dam likely did not cause the dam failure, stoplog release was a weak link in the flood operations.

Recommendation 11: Owners should develop comprehensive flood operation plans that include pre-flood inspection and preparedness, and a sequence of operation that allows greater operator flexibility and fewer risks as the flood intensifies. Weak links in the operations should be identified and addressed. These plans should be developed with input from regulators and other dam safety experts.

Lesson 12: Adverse weather conditions must be taken into account in design of dam operations.

Audience: Designers/Engineers/Regulators/Owners

Findings: Ice formation, blizzard conditions, and other weather factors can have a significant impact on the ability of dam owners and operators to carry out their responsibilities. In emergency situations, the ability to carry out these responsibilities can be the difference between life and death. Spencer Dam operations were extremely difficult during extreme weather conditions. The existing system for release of stop logs was solely dependent on manual operation of a hydraulic jack from a precarious position made potentially unsafe during extreme weather. Ice prevented the opening of stoplog bays.

Recommendation 12A: Avoid manual operation of gates as the primary operating mode in areas subject to extreme weather conditions. Provide methods for preventing ice build-up on regulating facilities.

Recommendation 12B: Avoid the use of complex, labor-intensive operating systems such as the Spencer Dam needle beam and stoplog system when there is the potential for freezing in place.

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