Learning from Experience - Characterization of Dam Incidents

MARTIN W. MCCANN, JR., ADJUNCT PROFESSOR & DIRECTOR OF THE NATIONAL PERFORMANCE OF DAMS PROGRAM, DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING, STANFORD UNIVERSITY; AND POOJAN PATEL, GRADUATE STUDENT, DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING, STANFORD UNIVERSITY

ABSTRACT

Learning from the in-service performance of dams is an important element of dam engineering and safety. In many respects, dam engineering is an empirical, trial-and-error undertaking. While present day methods of analysis in geotechnical, structural, and geologic engineering are sophisticated, we continue to rely on observational evidence to understand a dam is responding to the constant hydraulic and environmental loading cycles that it experiences. This makes a great deal of sense since dam engineers are keen to point out, each dam site, dam design and structure are unique – one-of-a-kind systems. Therefore, modern dam engineering and dam safety rely on detailed, structure-specific monitoring to track the performance of individual structures. In addition, the profession also requires data on dam incidents across the population of dams to be gathered, archived, and evaluated. While individual dams are unique, documenting and evaluating the performance of the broader population provides a foundational basis for understanding dam performance and identifying experiences and lessons the industry can benefit from. An important element to develop the level of understanding required to learn from the performance of dams is to establish a data system that captures information that supports the advancement of dam engineering and safety. In this paper we describe an approach to characterizing dam incidents. The approach includes a graphical method to represent dam incidents. The method, known as an influence diagram, represents events in an incident, along with factors that contributed to the events in the timeline. A challenge with influence diagrams is the image cannot be easily search if retained only as an image. To address this, we have developed a scheme that defines the influence diagram in a text string, referred to as an 'influence string'. Additionally, we have written a code that makes it possible to read an influence string and generate an influence diagram on demand. In this paper, we lay out considerations for developing this data system and illustrate, through an example, an approach to capture information on dam incidents (in a database) and display the influence diagram for the user.

I. INTRODUCTION

Efforts to catalogue dam incidents and failures have been carried out for decades. In the U.S. this includes the work of Middlebrooks (1953), Babb and Mermel (1968); USCOLD (1975; 1988), among others. Typically, these data catalogues contain a listing (hard copy or digital) of simple data fields that document basic features of the dam (e.g., dam type, year constructed, height) and a characterization of incidents in terms of whether the dam breached or not, the type of incident (i.e., flood event, earthquake, embankment piping, etc.), and possibly some key words. Generally speaking, the characterization of dam incidents is often limited; there are only a few data fields that are used and within a field, preset terms or keywords are used.

In traditional dam incident data characterization schemes, the relationship between events that occur in an incident and the role of factors that contribute to the occurrence of one or more events. In this paper, factors that play a role in the occurrence of an event during a dam incident sequence can cover a wide range of topical areas. For instance, a factor that might influence (contribute to) the failure of a structural member in a tainter gate could be the decades of cyclic loading the member experienced over many decades, couple with the slow, but steady corrosion at a critical section, and the ongoing failure to maintain or repair the gate. These factors collectively could lead to the failure of the structural member at the time of a flood or icing event. In this paper we describe the elements of a database system to characterize (document) dam incidents. The elements of the system are described and illustrated in an example.

II. THE NATURE OF DAM INCIDENTS AND FAILURES

Generally, forensics investigations of a dam failure or major incident (minor incidents are typically not investigated in detail) point out there was no single event or factor that led to the failure – no smoking gun. Rather, they typically find that a combination of events and/or factors contributed to the sequence of events that played out and the incident timeline. In addition, there also find that factors that were external to the incident itself (were not causally related to the flooding that occurred for example), but contributed in some way (possibly in a major way) to the occurrence of one or more events in the incident sequence. Examples of factors that play a role in events that occur during an incident are; time of day (when a project is not manned), weather conditions that make a project inaccessible, or the failure of a particular structure or component as a result of an external load (e.g., an earthquake) ***and*** the extensive deterioration that advanced over many decades.

Another factor that may play a role in a dam incident is the original design. The occurrence of an incident may reveal that the original design was not adequate to deal with the circumstances that occurred (see the discussion of the Spencer Dam failure later in this paper). In this instance, the design practices of the day were a factor, a contributor to the strength characteristics of structure at the time of the incident. The message here is simply - the occurrence of dam incidents is a function of:

- physical events that occur in sequence (in combination) to result in a particular outcome (i.e., damage, breach of the dam, etc.), and
- what we will broadly refer to as factors that define the design, and operational conditions at the dam at the time.

Collectively these physical events and factors conspire to lead to the dam incident that occurred.

Efforts to chronicle dam incidents in a database typically use keywords in selected categories to identify and define the type of event that occurred. In addition, a short summary of the incident might be provided. See for example the USCOLD documentation of dam incidents and failures in the U.S. (USCOLD, 1975; USCOLD, 1988; among other examples).

As noted above, forensics studies of dam failures and incidents typically find there is often a number of events and factors that played a role in the occurrence of an incident and the final outcome. A traditional database format does not capture the relationship between the events that occurred and often does not identify factors that may have played a role in the initiation of the incident or in events that occurred in the course of the incident.

III. OBJECTIVE

The overarching objective of this paper is to describe the development and implementation of a framework to characterize dam incidents that provides detailed information about dam incidents in a searchable database that includes the identification of physical events that occurred during the incident and factors that were influential to the occurrence of events in the incident sequence.

Specific objectives are to:

1. Provide a means in a tabular and graphical format to display the relationship between events that occurred during a dam incident sequence.
2. Allow for non-physical factors that play a role in an incident to be included in its characterization.
3. Provide the user with expanded search capabilities.

In this paper we use the term dam incident sequence as a means of emphasizing the fact that a dam incident generally involves the occurrence of a series of events, a sequence, that initiates the incident and that is followed by other events, concluding in some outcome such as damage to a dam, or a dam breach.

To date our emphasis has focused on the events that relate to the performance of the dam and not on events that lead to particular consequences (e.g., injuries or fatalities, damage).

IV. A FRAMEWORK FOR CHARACTERIZING DAM INCIDENTS

In this section we outline the overall system that has been developed to characterize dam incidents in a digital database. The primary focus of this paper will be on the representation of the dam incident sequence in an influence diagram. However, for general context we will describe terms that are used and the general framework for characterizing dam incidents.

A. Terms

To begin, we define a series of key terms that are used in our characterization.

Dam Incident – An event that provides insight into the structural and/or operational integrity of a dam system.

Dam Incident Sequence – A series of events, a sequence, that includes an initiating event, which is followed by other events in series (and in some cases in parallel), terminating in some outcome that may result in damage to a dam, a dam breach, or even a satisfactory outcome, and possibly downstream consequences.

Events – This term is used broadly to denote physical events or actions (e.g., operator actions) that occur during a dam incident sequence.

Factors (Influencing Factor) – A general term used to identify conditions, physical or operational, that influenced the occurrence of events during a dam incident sequence.

Influence Diagram – A graphical method to display the relationship between events and factors in a dam incident sequence (see below for a more detailed description).

Some of these terms are described in a bit more detail.

Event - In our dam incident characterization scheme, an Event denotes a physical event or action that occurs during a dam incident sequence. These are best illustrated with some examples:

- Initiating Events – This is an event that begins, initiates, a dam incident sequence. An initiating event may be an external loading (e.g., earthquake, inflow flood event, wind waves). Initiating events can also involve a failure of an element of the dam system that occurs during normal or intrinsic conditions. For instance, the 1995 Folsom gate failure was initiated by the failure of a structural member during a normal gate operation. The failure of the structural member resulted in a failure of the gate and large release from the dam.
- Failure of elements of the dam system due to the common cause loading that occurs during an earthquake for example.
- Failure of structures or structural members (e.g., instability of a spillway training wall).
- Failure of mechanical, electrical/electronic components (e.g., failure of a hoist chain, failure of an emergency diesel generator to start).
- Operator actions or in-actions during a dam incident sequence (e.g., operator failure to open spillway gates in a timely manner, operator action to initiate the emergency action plan).
- Events that contribute to the progression or interruption of a failure mode (e.g., self-healing of a transverse crack in an embankment)

Factors - The term Factors is used to broadly denote a condition or circumstance that influences or plays a role in the occurrence of an Event during a dam incident sequence. The term itself is admittedly vague. Its choice is due in part to the fact there are a wide range of Factors that could influence the varying type of Events that occur during a dam incident sequence. For instance, the failure of structural members (e.g., elements of a tainter gate) or a mechanical component such as a hoist motor could fail during an incident due to their condition at the time; deterioration, wear and tear, lack of maintenance. The level of deterioration or wear is a Factor in the performance of a structure or component during the incident. Other examples of Factors that can play a role in a dam incident sequence are Owner Practices related to design and dam safety activities (e.g., periodic dam inspections).

Table I provides a list of different categories of Factors, a description of each and examples. Note, the table is not intended to be a collectively exhaustive list.

Influence Diagram - An influence diagram is a graphical tool that is used to display the relationship of events and factors in a dam incident sequence, beginning with the initiating event and concluding with the final outcome or conclusion of an incident. An influence diagram is a visual tool to represent dependencies among variables. Influence diagrams have been around since the early 1900s (Wright, 1921) when they were proposed as an effective method for visual representation of contributing variables and their influence on an outcome of interest. Influence diagrams were developed as a qualitative tool to represent many interconnected factors that influence a certain event or decision (Diffenbach, 1982; Howard and Matheson, 2005) The ability of influence diagrams to represent diverse and dense information in an easy-to-interpret format makes their application versatile. Thus, they have been used widely as an effective visual communication tool.

TABLE I

Categories of Factors That Influence/Contribute to Events that Occur During a Dam Incident

Factor Categories	Description	Examples
Owner Practices	This refers to the current or past dam safety policies and practices of the dam owner, the approach to dam, the manner in which dam safety activities are carried out, the periodic evaluation of dam systems.	a. What design standards and practices were applicable at the time the dam was built. b. Inspection practices c. Engineering practices
Regulatory Practices	This refers to current or past dam safety policies and practices that defines what is required, what is good practice as it relates to design, inspection and evaluation of the safety of dams.	a. Design reviews and periodic evaluations b. Regulatory standards c. Inspection practices
Organizational Structure	This refers to how an owner's organization is structured as it relates to dam safety. It includes the priority an organization puts on dam safety, the authorities of the chief dam safety engineer, etc.	a. Role/importance of dam safety in the organization. b. Operator, engineer authorities with respect to make decisions related to dam safety issues.
Dam System Characteristics and Conditions	Physical features of the dam system, its design, redundancy, condition, etc. A part of this also has to do with how a system has been maintained and operated over the years, whether deterioration has occurred, is instrumentation maintained, etc.	a. Physical and design features of the dam structures, systems and components. b. Level of wear and or deterioration of structures, systems or components. c. Redundancy of systems such as electric power. d. Capabilities to draw down the reservoir
River/Reservoir Characteristics	Refers to the features of the river where the dam is located. Important features could include the characteristics of inflows to the dam (e.g., is it flashy), is there a potential for icing, wind waves, landslide waves, etc.	a. Features of the reservoir or river that relate to the characteristics of flood or other events (icing). b. Is the reservoir flashy? c. Is there potential for debris (boats, logs, etc.)
Dam Operations	This relates to how a dam system is operated with respect to day-to-day operations (e.g., manned or unmanned, remotely operated), the manner in which inspections and routine maintenance are performed.	a. Are there operators onsite (what part of the day). b. If operators are not onsite, how close are they to the dam in the case of an emergency? c. Is the dam system remotely operated? d. How often is the dam system inspected? e. What communication capabilities exist?
Emergency Operations	In the event of an incident at a dam, operating procedures will address actions to be taken by the operator. This includes the implementation of the emergency action plan.	a. Operating procedures in the case of emergencies at the dam. b. Emergency action plan

B. Representing Dam Incidents

The system for representing dam incidents consists of the following elements:

1. Dam Incident Narrative – A description of the dam incident. Depending on the information that is available, the description may simply be a summary, with reference to documents that provide additional details.
2. Timeline of Events – This is a chronological listing and associated time stamp of the Events that occur during a dam incident sequence.
3. Event Description – Table listing the Events that occurred during a dam incident sequence. This includes the date, time, and a description of each Event, and the Factors that contributed to their occurrence.
4. Factors Description – Table listing the Factors that contributed to or influenced the occurrence of Events involved in the dam incident sequence.
5. Influence Diagram – An influence diagram of the Events and Factors involved in a dam incident sequence.
6. References (Supporting Documentation) – Supporting documentation can include reports, photographs, video, or as a minimum a citation to resources that were used to document the dam incident.

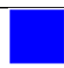
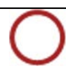
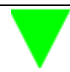
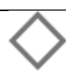
V. INFLUENCE DIAGRAMS

In our application for dam incidents, influence diagrams are used to display the relationship between Events that occur in a dam incident sequence and Factors that contribute to events. A feature of influence diagrams highlighted by this study is the ability to quickly visualize a dam incident sequence.

In an influence diagram is constructed using a series of symbols and connectors to present the progression of Events during a dam incident sequence and the Factors that influenced their occurrence. Table II provides a legend of the symbols that are used.

TABLE II

Influence Diagram Legend

Symbol	Description
	Initiating Event
	Event
	Operational Factor
	River Characteristics
	Outcome of the dam incident sequence (e.g., dam failure, damage)
	Dam Characteristic
	Consequence (property damage, injuries, fatalities, etc.)
⟶	Influence from a preceding Event
- - - ▶	Influence from a Factor

A. Digital Representation

To retain the influence diagram in a database, it is represented by an influence string. An influence string is similar to a Boolean expression that represents:

1. Events that occur
2. Relationships between Events in the dam incident sequence
3. Conditioning Events

4. Factors that influence the occurrence of an Event

The idea of the influence string follows the inferential notation used by Howard and Matheson (2005) and the scheme used by Dalton and Nutter (2020).

For simplicity, Events and Factors in an influence string are represented by uppercase and lowercase letters, respectively. Symbols such as "+", "*", and "|" are used to define the relationship between Events and Factors. A vertical bar denotes that an Event is conditional on the occurrence of an Event listed after the bar. The "+" symbol separates different groups of Events in the influence diagram, and a "*" denotes a Factor that influences the occurrence of an Event(s). In the database, the influence string is stored in a data field. When a user selects an influence diagram to be viewed, an algorithm reads and interprets the influence string and generates on-demand the influence diagram graphic for the user. Retaining the influence string in the database rather than a graphic image has a number of advantages:

1. Updates to the influence string can be readily made, and
2. The influence string can be queried for Events and relationships between Events and Factors, which would not be possible if only an image was stored.

An example of an influence string is shown in Equation 1.

$$G \mid F + F \mid D * E + E \mid C \; + D \mid C * p + C \mid B * m + B \mid A * r + A \mid I \qquad (1)$$

B. Influence Diagram Illustration

For a dam incident sequence an influence diagram begins with an Initiating Event, other Events that occur in the sequence, an incident outcome (e.g., dam failure or damage), and incident consequence(s), Factors). In the following example, there are eight E*vents – Initiating Event (I), Event A, Event B, Event C, Event D, Event E, Final Outcome (F), and Consequence (G)* – and three Factors – an *Operational Factor (m), River Characteristics (r),* and *Dam Characteristics Factor (p)*. The connectors represent dependencies, relationships between Events and Factors.

Figure 1 shows the influence diagram for the influence string in equation 1. The Initiating Event is the first event to occur that initiated a series of events. In the example, Event A follows the Initiating Event, Event B follows Event A and so on. In other words, each preceding event influences the occurrence of the succeeding event. In this example, Event B is influenced by River Characteristics (r) along with the preceding Event A. Factors can also be influenced by other factors.

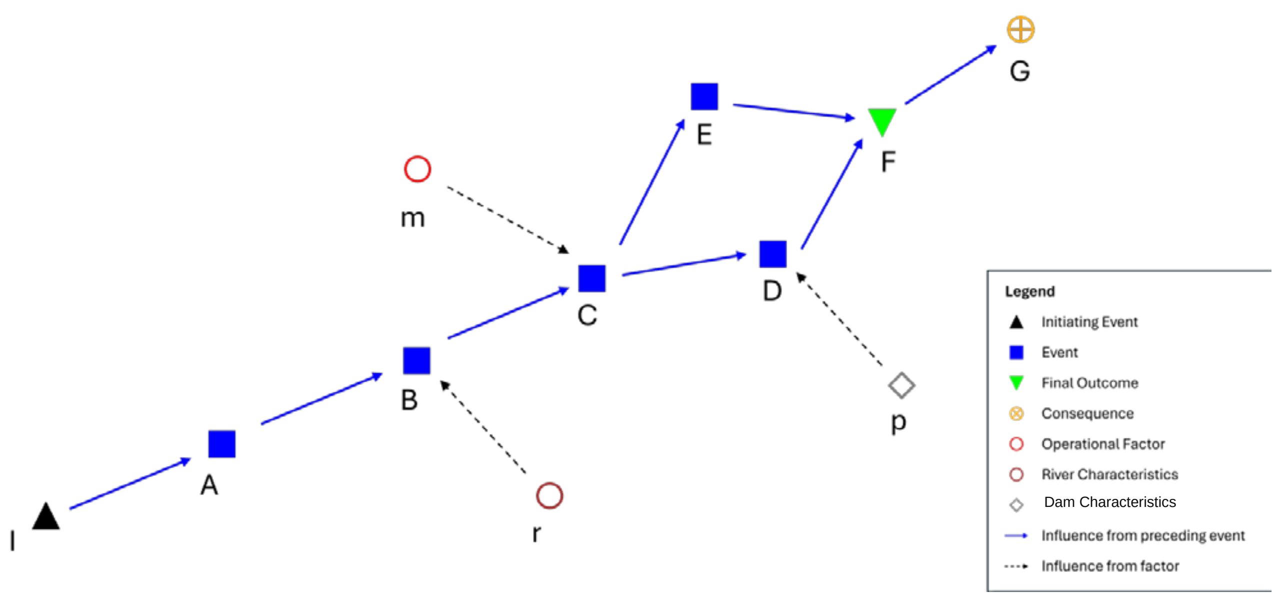


Figure 1. Generic illustration of an influence diagram.

VI. SPENCER DAM FAILURE – MARCH 14, 2019

To illustrate the application of the approach for characterizing dam incidents, the case of the Spencer Dam failure in 2019 is presented. Spencer Dam is located on the Niobrara River in north central Nebraska. The dam consists of a 400 feet long spillway, a powerhouse, and an earth embankment. The dam is owned by Nebraska Public Power District (NPPD).

Figure 2. Aerial view of Spencer Dam and Vicinity (ASDSO, 2020).

The dam failed early in the morning of March 14, 2019. In the evening of March 13, the dam operators had opened the four spillway tainter gates. In addition, they had also released stoplogs from some of the stoplog bays. Most of the stoplog bays could not be opened because of the icing on the river. A major ice run was reported on the evening of March 13 causing failure of the Stuart Naper-Bridge and damage to the Highway 11 bridge, both located upstream of the dam. Significant ice rubble and flood waters headed toward the dam causing some of the stoplog bays to be jammed, leading to water rising to the dike crest. This resulted in overtopping of the dike and erosion of the downstream side of the dike, eventually leading to the failure of the dam. The flooding that occurred resulted in destruction of several buildings immediately downstream of the dam, led to death of one resident, and caused damage or destruction of several bridges downstream (ASDSO, 2020). The key events that occurred during the dam incident sequence leading to the failure of Spencer Dam failure are listed in the Table III.

Table IV lists the timeline of events for the dam incident sequence from March 12 to March 14, 2019, and includes events starting from the increase of flow in the river, followed by actions taken by the dam operators, and the eventual failure of the dam.

Table V describes Factors that played a role in the Spencer Dam failure event.

The influence diagram for the Spencer Dam failure is shown in Figure 3.

TABLE III

Spencer Dam Failure – Major Events

Sr. No.	Element (Structure or Component)	Load/ Factor	Mechanism	Description of the Event/Failure	References
1	Stoplogs	Ice load and/or icing	Jamming	Ice rubble caused some of the stoplog bays to be jammed and water reaching the dike crest.	Spencer Dam Failure Investigation Report ASDSO (2020)
2	Dike	Ice load	Overtopping	This resulted in overtopping of the dike (with ice and water) and erosion of the downstream side of the dike eventually leading to the failure of the dam due to headcutting.	Spencer Dam Failure Investigation Report ASDSO (2020)
3	Dam Operators	Ice load and/or icing	Jamming	Inability to open or pull the stoplogs due to ice jamming	Spencer Dam Failure Investigation Report ASDSO (2020)
4	Dam Operators	Night	Darkness and low visibility	Due to limited visibility, operators could not determine the cause for the jamming of the stoplogs	Spencer Dam Failure Investigation Report ASDSO (2020)

TABLE IV

Spencer Dam Failure – Event Timeline

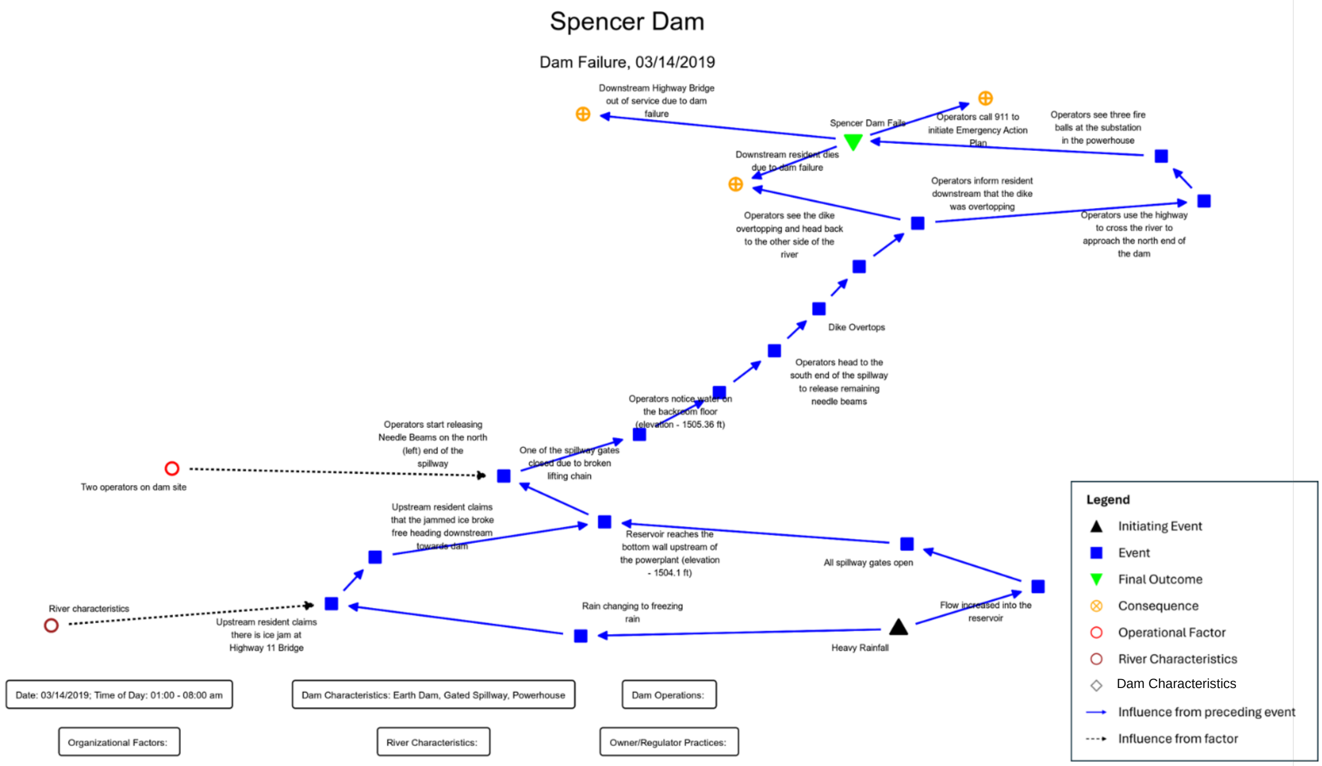
Timeline	Events
	Heavy Rainfall
03/12/2019 10:00AM	Flow increased into the reservoir
03/13/2019 08:00PM	All four spillway gates were open 6 feet (maximum opening as described by the operators)
03/13/2019 10:30PM	Reservoir reaches the bottom of the wall on the upstream side of the powerplant (Normal Headwater elevation - 1504.1 ft); For reference, the dam crest elevation is 1511.1 ft
03/14/2019 12:00-03:30AM	Operators start releasing Needle Beams from Stoplog Bays No. 1 & No. 2 (northbound end - left side) of the dam. Some beams were released and some were jammed (and could not be removed).
03/14/2019 01:00AM	A resident who was interviewed by the forensic team who lives upstream of the dam, near the Highway 11 bridge (about 10 miles upstream), claims that an ice jam formed at the bridge.
03/14/2019 02:00AM	One of the spillway gates closed due to broken lifting chain.
03/14/2019 03:00AM	Rain was changing to freezing rain.
03/14/2019 04:30AM	A resident who was interviewed by the forensic team who lives upstream of the dam, claims that ice that was jammed behind the Highway 11 bridge (about 10 miles upstream), broke free, heading downstream toward the dam. (Approximate)
03/14/2019 04:38AM	Operators notice water on the backroom floor (possibly located in the Powerhouse) - believed to be elevation 1505.36 ft.
03/14/2019 04:38AM	Operators release remaining needle beams from the south end of the spillway. They head to the dike access road on the south side of the river in a vehicle.
03/14/2019 04:55AM	Operators saw the dike was overtopping as they passed through the gate of the dike access road. Operators decide to head back to the highway. (Approximate)
03/14/2019 05:00AM	Operators inform a resident downstream that the dike was overtopping. (Approximate)
03/14/2019 05:05AM	Operators use the highway to cross the river to approach the north end of the dam. (Approximate)
03/14/2019 05:15AM	Operators saw three fire balls at the substation in the powerhouse.
	Dike Overtops
03/14/2019 05:15AM	The dam failed. This is the time at which the clock in the powerplant stopped.
03/14/2019 05:30AM	Operators check the powerplant by flashing lights at it. They saw bricks pop out of the back wall of the powerplant. The Operators call 911, and are asked to reach the north end of highway bridge to warn people.
03/14/2019 05:30AM	Downstream Highway Bridge confirmed to be out of service
03/14/2019 05:30AM	Downstream resident dies because of the dam failure

TABLE V

Factors Associated with the Spencer Dam Failure

Factors	Description
Owner Practices	Nebraska Public Power District (NPPD) is the owner of the dam. The dam predates the FERC and hence is not regulated by them. NPPD did not apply FERC requirements to the dam although it has a dam safety program structured around meeting the requirements of their other FERC-licensed dams. 1. The owner acknowledged they were responsible for safety of their dams, they may have relied on NebDSP to identify dam safety related issues before they acted on them. 2. The operating procedures for the dam did not require operators to inform the downstream resident about emergency situations or hazards of living downstream of the dam.
Regulator Practices	Nebraska Department of Natural Resources Dam Safety Program (NebDSP) conducts dam inspections every 3 years. They ensured the dam owner addressed dam inspection findings and recommendations, and reviewed plans and designs for dam repairs. The dam had a "significant" hazard classification. There was no emergency action plan (EAP) as it was not required by NebDSP. 1. NebDSP relied on an inaccurate method for screening dams and determining the hazard classification. The method did not assume the downstream resident to be at risk in case of dam failure, even though the resident was located immediately downstream from the dike of Spencer Dam. 2. NebDSP is understaffed in comparison to many other dam safety programs. This limits their ability to perform inspections and update dam hazard classifications.
Organizational Factors	The operating procedures for the dam focused on hydrologic operations, but did not discuss gate operations (ASDSO, 2020). The operators had a vague knowledge of previous ice run events at Spencer Dam, but there was no specific provision in the operating procedures for handling this type of event. There are six contributing factors to this lack-of-knowledge: 1. General lack of precedent in the dam safety industry. 2. Lack of documented best practices for managing ice flooding events. 3. The most recent ice event occurred in 1966 and the information of this event was not available to NPPD or NebDSP. 4. There was no upstream ice monitoring system in place and the information on the ice formation observed by upstream residents was not relayed to the operators as there was no established protocol or communication channel. 5. The original dam design did not address the dam's vulnerability to major ice run loadings. The new spillway constructed in 1940 created more risk for ice rubble clogging than the original ungated overflow weir. The dam industry still lacks the understanding of ice mechanics and hence there is lack of guidance on mitigating this risk. 6. Until the 2019 event, the NebDSP had no knowledge of the Spencer Dam failure in 1935 due to ice run and the subsequent damages caused in 1960 and 1966. The limited knowledge was due to inadequate information management and the lack of focus on ice run performance in inspection reports. Operator experience was not passed on to successive new operators. A consolidated history of Spencer Dam (with references to key documents) was not established and maintained. Inspections were conducted during warm weather months and performance of dam during ice events was not observed.
Dam Characteristics	The dam system consists of a 3200-ft earth embankment (dike), concrete spillway (One ice/trash bay with 10-ft wide lift gate, Four 33.5-ft wide Tainter gates, Five 33.5-ft wide needle-beam stoplog bays), powerhouse (north of the Spillway); dam had been well maintained over the years leading up to 2019; erosion of the upstream face of the dike had been an issue in the past; spillway was designed to have enough capacity to pass a 500-year flood; small run-of-river dam reservoir. Storage capacity at normal pool (elevation 1504.1-ft) was 8,300 acre-feet (AF). The top of the dike storage was 16,500 AF. There were a number of hydraulic engineering concerns with the Spencer Dam design: 1. The ice bay/chute can handle small quantities of ice but is considered useless during major runs of ice.

Factors	Description
	2. A major portion of the flow had to pass along the dike to reach the spillway. 3. The oblique angle of the flow from the south end of the dam could limit the spillway discharge capacity and the ability to pass ice rubble. 4. The long duration needed to operate spillway's gates relative to the times associated with surges of flow (especially caused by breaking of upstream ice) were a cause of concern. 5. Spencer Dam spillway gate operations were not practical at night and in frigid conditions.
River/Reservoir Characteristics	Niobrara River flows along a braided channel upstream of the dam. The main river main channel shifts frequently creating a wide floodplain. During mean flow, river flows at shallow depths of 0.25-3.0-ft (which allows water to cool relatively quickly). The main channel transports bed sediments that are mainly fine to medium sands, about 0.3-0.5 mm in diameter. Hence, the river channel is responsive to changes in flow velocity caused. Upstream of the dam, the river has bridges which confine the river to a single channel through the bridge waterways (which are typically 300- to 500-ft wide. This narrowing of the channel increases sediment transport through the bridge waterway. The bridge waterways also act as a potential location for drifting ice to be jammed. The bends in the river serve as potential areas for ice build-up. The groundwater flow entering the river is relatively warm as compared to the river water during frigid conditions. This groundwater flow (which increases during periods of snowmelt and rain) can cause the ice formations to loosen up and release. Frequent cycles of ice formation and release increase the overall volume of ice formed. In most years, warmer weather causes ice covers to warm and disintegrate in place forming smaller chunks of ice. But occasionally, the weather patterns can cause ice to break up mechanically creating large chunks of ice also known as ice rubble (which can be as large as 20-ft long for Niobrara River). The built-up ice can break because of scour, flow-induced erosion, and breaking of the river's sand banks. The release of an ice jam can produce a surge of water and ice rubble, further aided by the steepness of the channel. Ice run events have occurred a number of times in the past. In March 1935: During the spring river ice breakup, a log and ice jam was formed one mile upstream of the dam. This shifted the river channel and caused erosion on the south end of the upstream face of the dike. In March 1960, water and ice flowed from the south channel to the spillway and eroded the upstream face of the dike. Crews were dispatched to repair the dike and dam failure was averted. In 1966, a major ice run occurred. There was an ice jam at Highway 11 Bridge (11 miles upstream of the dam) and the operators were warned about it. This prompted the operators to drain the reservoir preventing any adverse consequences. Operators did not receive any warning in the 2019 event. In 1966 event, the surge of inflow nearly overtopped the dam, caused the failure of a Tainter gate and punched a hole in the powerhouse.
Dam Operations	The dam is operated as a run-of-river hydroelectric facility and was not intended to provide flood control. Dam operators conduct sluicing operations twice a year (spring and fall). Operators manage inflows and outflows to keep the reservoir at normal pool level. The normal procedure for gate operations includes: Open the tainter gates first (starting from north end, closest to the powerhouse), followed by releasing the needle beam stoplogs. It takes 10-15 minutes to release a needle beam. Operators were familiar with operations during normal spring ice breakup. Tainter gates were heated. If necessary, ice blocks would be cut manually using a chain saw. There were two operators on site as that was the desired operating condition during flooding. The stoplog operations and gate operations required two people at a time because of the physical demands of the operations. The operating procedures for the dam did not require operators to inform the downstream resident about emergencies or the hazards of living downstream of the dam.



VII. IMPLEMENTATION AND FUTURE APPLICATIONS

The framework presented for archiving dam incidents in a digital database provides an opportunity to provide dam engineers with a broad information base for documenting these events in the future. Timeline information and influence diagrams in particular offer considerable information and insight for studying dam incidents as part of future research. For instance, a dataset of influence strings for dam incidents can be used as input to machine learning algorithms that may identify contributing factors and patterns of influence in dam incidents. This may help uncover hitherto unobserved contributing factors that might be otherwise difficult to observe when the events are studied in isolation. The observations made from such an analysis can identify broader trends in dam safety that can inform industry-wide practices.

VIII. ACKNOWLEDGMENT

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