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A DECADE OF LEARNING FROM OUR PAST AND PREPARING FOR OUR FUTURE: THE ASDSO DAM FAILURES AND INCIDENTS COMMITTEE

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1. IMPORTANCE OF DAM FAILURES AND INCIDENTS

Whenever a dam fails or a major incident occurs, many questions are asked. Why did this happen? How did this happen? And perhaps the most important question: how can we prevent this from happening again? Trying to answer the last question has led to changes in policies regarding how we design, build, inspect, evaluate, monitor, operate, and maintain dams. And in recent history, it has led to a growing industry dedicated to ensuring that dams can fulfill their functions in a safe manner. Yet, despite these changes, dams continue to fail every year in the United States and internationally. We must ask ourselves whether we have really learned all the lessons we can from past failures and have incorporated the lessons into current dam design, construction, and operational practices.

The most devastating dam failure in the United States was the South Fork Dam that failed above the town of Johnstown, Pennsylvania on May 31, 1889, killing over 2,200 people. Despite the devastation, the idea that the government should enact laws that oversaw private industry was still resisted at the time, and there were no laws passed either nationally or locally [1] in reaction to this catastrophe. Unfortunately, modern history shows that a series of noteworthy dam

failures sometimes needs to occur in short succession in order for action to be taken. For example, in Pennsylvania, people still likely remembered the Johnstown Flood (Great Flood of 1889) when, in 1911, the Austin (Bayless) Dam in Potter County, Pennsylvania failed, claiming 78 lives. Shortly following this, in 1913, Pennsylvania became the first state to pass legislation related to oversight of dams [1].

Other states followed with their own state laws for oversight of dams, but often not until their own disaster. For example, at midnight on March 12, 1928, the St. Francis Dam failed and sent a 70-foot wall of water down the San Francisquito Canyon near Los Angeles, California. The flood took over 400 lives and left thousands homeless [2]. On August 14, 1929, the state of California enacted two key pieces of legislation. One, the *Civil Engineers Registration Bill*, required engineers to be licensed in order to approve certain designs [3]. Two, a statewide dam safety program was created, which evolved into the California Department of Water Resources, Division of Safety of Dams. The program gave the state of California oversight of design, construction, and maintenance of all jurisdictional dams [2].

While states continued to pass their own laws regulating dams, for several decades there were no federal laws, policies, or guidelines related to the oversight or design of dams, despite the fact that tens of thousands of dams were being built during the mid-twentieth century by federal agencies including the Natural Resources Conservation Service (NRCS), United States Army Corps of Engineers (USACE), Tennessee Valley Authority (TVA), and Bureau of Reclamation (Reclamation).

A series of dam failures in the 1970s finally changed dam safety regulation at the federal level. There were many notable failures in this time period, but the one that began the conversation in the halls of Congress occurred in West Virginia. On February 26, 1972, Pittston Coal Company's coal slurry impoundment dam #3 failed on Buffalo Creek, causing the deaths of 125 people [4]. This led to hearings in Congress and ultimately the passing on August 8, 1972 of the *National Dam Inspection Act*, Public Law 92-367 [5]. But to say that everyone in the federal government was on board with federal involvement in dam safety would be incorrect. President Richard Nixon, who signed the law, also heavily criticized it, saying that the federal government should not get involved and should instead leave dam safety to the states. The actual inspection portion of the *National Dam Inspection Act* went unfunded until further failures reiterated the need for proper funding.

The next major dam failure in the United States, which occurred four years later, was the failure of Teton Dam on June 5, 1976, causing 11 fatalities [6]. The failure was especially significant because Teton Dam was built by a federal agency, the Bureau of Reclamation, which was considered a premier dam builder in the United States. At 305 feet high, it was also the tallest dam to fail in United States history. This failure reinforced the need for federal guidelines and oversight of the

safety of federal dams. Accordingly, on April 23, 1977, President Jimmy Carter released a Presidential Memo on Dam Safety that called for, among other things, federal guidelines for dam safety [5].

And as if to ensure that we not forget the need to manage safety of our dams, 1977 also saw additional dam failures. The failure of Laurel Run Dam, along with several other dams that failed during the same flood event in Pennsylvania, killed a total of 85 people. Later that year, the failure of Kelly Barnes Dam in President Jimmy Carter's home state of Georgia killed 39 people [7]. These failures led to Carter working with Congress to fund the *National Dam Inspection Act*. One of the stipulations for states to receive funding was that they have an adequate state dam safety program [5].

This led to many of the pillars of dam safety which we have today in the United States. In 1983, the Association of State Dam Safety Officials (ASDSO) was formed so that officials from all states could meet and share best practices in dam safety. Reclamation's dam safety law was passed in 1978 to give the agency their own dam safety program and funding. The Federal Emergency Management Agency (FEMA) was founded in 1979 and in it a dam safety office was formed that oversaw the completion of the *Federal Guidelines for Dam Safety* [8].

Dam safety regulation is now in place in 49 of the 50 states. Design practices, analysis models, and understanding of primary failure modes related to dams have advanced greatly, resulting in measurably improved safety of new and existing dams. Significant investments have also been made to bolster emergency planning and preparation so that people can be quickly evacuated if a failure does occur. Practices for evaluating safety of dams have been evolving in the United States from a reliance on dam inspections and standards to assessing the risks of dams.

Knowledge of dam failure case studies is an essential element to the engineering practice of evaluating the risks of dams based on potential failure mode analysis. Case studies reveal dam failure and incident progression mechanisms, as well as frequency data used in probability assessment.

While this work is notable and has led to safer dams in the United States, much work is still required, and dams still too often fail. Based on an ASDSO database of failures and incidents, 296 dam failures occurred in the United States between 2005 and 2019, averaging about 20 dam failures per year [9]. While many of these were small dams, some of these failures -- such as the spillway failures at Oroville Dam in 2017 -- were highly publicized and the lessons captured afterward have had a large impact on the dam safety community. Yet the lessons from other well-known failures are gradually being lost to time. The large majority of dam failures and incidents remain obscure and have little to no investigation or documentation of lessons that might be learned. One example of this is Ka Loko Dam on the island of Kauai, which failed on March 14, 2006, killing seven people. A legal investigation was completed by a Special Deputy Attorney General, but the

report contained limited technical analysis, was used mostly for court proceedings, and was not widely distributed or discussed in the dam safety community [10].

Feedback from dam failures is only impactful if the profession makes the effort to investigate new failures and incidents, and research failures and incidents of the past. The investigators and researchers must then educate others regarding the lessons from these events for them to be truly and widely learned. However, it is often difficult to share these lessons broadly across organizational and international boundaries. Compounding this issue, the dam safety industry is experiencing significant turnover in the United States, with high rates of retirement among senior engineers and regulatory staff. Much of the knowledge and experience gained from decades of building new dams and learning from failures will be lost unless these lessons are conveyed to the rising generation of dam safety professionals.

In order to help investigate, learn from, and disseminate lessons learned from dam failures and incidents, the Dam Failures and Incidents Committee (DFIC) was formed in 2010 (originally called the Dam Failure Investigation Committee). The mission of the DFIC is to discover and distribute lessons to be learned from past dam failures and incidents, and to support quality investigations of new failures and incidents. During over a decade of research and study, the DFIC has produced a voluminous body of work. This paper outlines the many ways the committee has done this.

2. DAM FAILURES AND INCIDENTS COMMITTEE (DFIC) FOUNDING AND MISSION

For countries interested in examining and learning from their own incidents and failures, it is valuable to understand how the ASDSO DFIC was formed, its mission, the projects it completes, and how it functions within the larger ASDSO organization.

The genesis of the DFIC occurred when its founding member co-authored a technical paper titled *Dam Failure Investigation Approaches* [11]. Seven major dam failures were reviewed. This paper showed that there was no standard methodology for conducting dam failure investigations in the United States. Shortly thereafter, the DFIC authored the initial version of the ASDSO *Dam Failure Investigation Guideline* [12]. This guideline shares lessons from previous dam failure investigations and is designed to assist state dam safety agencies and dam owners in making good decisions during the chaotic and high stress period during and following a dam failure or incident.

At the 2010 ASDSO national conference, a “Soapbox Session” was held to discuss recent and best practices for conducting dam failure investigations. State representatives shared their recent dam failure and investigation experiences. This soapbox led to the creation of the Dam Failure Investigation Committee (DFIC). In

2013, the Committee completed a Charter which renamed the committee the “Dam Failures and Incidents Committee” as recognition that both failures and incidents offer valuable lessons learned. The Charter assigned the following goals:

1. Maintain and update the *Dam Failure Investigation Guideline* [12] through ongoing committee research into past dam failures and investigation practices of others.

2. Collect and share lessons learned from past dam failures and incidents with the ASDSO membership.

3. Provide support to ASDSO and states during and following dam failures and incidents, with the goal of advocating for successful investigations by qualified and trained personnel.

4. Train the state dam safety officials and other ASDSO members in the best possible industry methods and practices for investigating and reporting on dam failures and incidents.

The committee is led by two co-chairs and is assigned a representative from the ASDSO Board of Directors. The committee has about a dozen official members and about two dozen technical advisors who occasionally work on projects. While the committee’s financial year follows the ASDSO fiscal year, its project planning schedule is different. Each year in September, the DFIC holds its primary annual meeting, where attendance has continued to expand, with 25 to 35 people participating each year. During this meeting, the past year’s accomplishments are recognized and new projects are discussed. At the end of the meeting, attendees sign up for projects to be completed in the coming year. Projects that reoccur are managed under permanent subcommittees. Other standalone projects have a team leader and team assigned. The committee leaders check with subcommittee leads and project team leaders throughout the year to monitor and support their efforts.

3. DAM FAILURES AND INCIDENTS COMMITTEE (DFIC) PROJECTS

The DFIC has undertaken numerous projects during the past decade, five of which are described below.

3.1 DECADE DAM FAILURES SERIES

The Decade Dam Failure Series (“Decade Series”) subcommittee of the DFIC is an initiative of the DFIC to provide ongoing research and presentations on past failures and incidents at each of the annual ASDSO national conferences. Dam failures and incidents that typically occurred during a decade or multi-decade anniversary of the conference event are covered. For example, Castlewood

Canyon Dam in Colorado failed in 1933, and in 2013 a member of the DFIC presented the case study during a concurrent session sponsored by the Decade Series. These decade dam failures are researched by both DFIC members and technical advisors, and an overview of the failure or incident, relevant findings, and lessons learned are presented at the annual conference General Session (typically 90-minute presentations), during Concurrent Sessions (15-30 minute presentations), or as posters, which include “lightning session” talks (5 minutes).

The ASDSO Conference Planning Committee has been very supportive of the Decade Series, and conference attendees consistently rate the series favorably. Each of the annual conferences since 2013 has included at least one Decade Series concurrent session, with the last two annual conferences (2019 and 2020) including three concurrent sessions. Since the Decade Series began in 2013, there have been a total of 70 unique failures and incidents presented, with the years of failures and incidents ranging from 1874 to 2019. The failures and incidents include events from across 30 states in the United States as well as international events in 13 different countries. The full list of Decade Series presentations is available online in Appendix A (link).

Every decade will have been covered by 2022. Despite the significant amount of case studies that have been researched, there remain many more noteworthy dam failures and incidents which can be studied and presented at future conferences. For example, during the next ten years, there can be more emphasis on learning from failures and incidents that are not currently as well known to the dam safety industry, as well as focusing on more international failures and incidents.

The Decade Series is a unique opportunity for young professionals to get involved with an ASDSO committee and learn research and presentation skills. It is often intimidating for young professionals to present to a room of experienced dam safety professionals. The Decade Series often pairs more seasoned experts with young professionals in order to provide mentoring opportunities. Poster presentations and lightning session talks are shorter in length, with a smaller audience, so they offer a good first chance to complete a case study.

Some lessons learned from conducting the Decade Series include:

- A team of dedicated researchers who stay committed during the course of a decade-long effort can produce voluminous output.

- It can be difficult for the DFIC to obtain information on failures and incidents that occur internationally, especially in countries where English is not the primary language.

- Dam failures have many facets such as mechanisms of failure, design/construction issues, emergency response, efforts to save the dam, consequences of failure, and the investigations.

- There are many significant failures and incidents of which the DFIC is not aware, especially international events and those that the news media do not cover.

- The Decade Series includes case studies for individual failures and incidents, but, aside from human factors work done by DFIC members (described below), there have yet to be efforts to study cross-cutting themes or lessons learned that emerge when analyzing commonalities across multiple events.

- The DFIC has studied many more case studies at dams than at levees and canals. There are many levee failures that merit further research and documentation.

- There have been many more studies of failures than incidents (where the dam was not fully breached). Much can be learned from incidents where a breach was averted.

- On average, failures and incidents were studied approximately 50 years after the event. There were only four case studies in the Decade Series from the 1800s, but these were well known at the time. It can be challenging to obtain quality information years or decades after an event. The case studies that were completed many years after an incident rely upon documented investigations that occurred shortly after the failures and incidents, highlighting the importance of forensic investigations that gather perishable information.

- The historical research efforts have been successful. It has proven beneficial to provide researchers with “tips” for researching and presenting dam failure and incidents, along with a list of key areas to cover when developing a case study. The full list is available online in Appendix B (link).

3.2 ASDSO DAMFAILURES.ORG WEBSITE

In September 2015, ASDSO, in cooperation with the FEMA, released the “Lessons Learned from Dam Incidents and Failures” website (also known as DamFailures.org). The primary goal of this website is to convey educational information relating to and resulting from dam failures and incidents in an innovative, user-friendly manner. It is not intended to be a comprehensive database, but rather an educational resource. The website addresses a wide range of failure modes, dam types, and dam safety practices, including lessons learned relating to a spectrum of dam safety topics including engineering and design practices, human factors as they relate to dam failures and incidents, emergency planning and response, operation and maintenance, and other dam safety regulatory issues. The target audience is also broad and includes dam safety engineers, operators, dam owners, regulators, emergency managers, academia, and students.

The DamFailures.org website allows users to access a series of web pages that address specific lessons learned with corresponding case studies (see screenshots of the website home page and a typical case study page in Figure 1). Each web page is peer reviewed and includes a brief narrative as well as pertinent graphics, photographs, videos, and links to best practice resources and supporting technical papers. The web format of DamFailures.org allows ASDSO to share information that has traditionally had limited distribution via conference presentations or proceedings. As of July 2020, the website included over 20 lessons learned supported by 30 case studies of dam incidents or failures that occurred both within the United States and internationally. The website also provides free access to several ASDSO on-demand training webinars describing the basics of dam safety for engineers and dam owners.

Since its release, over 160,000 users worldwide have accessed DamFailures.org to learn more about various dam safety topics. Website usage has steadily increased over the past several years. In 2020, the average number of sessions exceeded 7,000 per month. The DFIC, in partnership with ASDSO staff, currently oversees maintenance and development of the website. Thanks to additional FEMA funding and volunteer efforts of the DFIC, the website content continues to be expanded and diversified. The DFIC has plans to add at least 10 more case study or lesson learned pages in the next year.

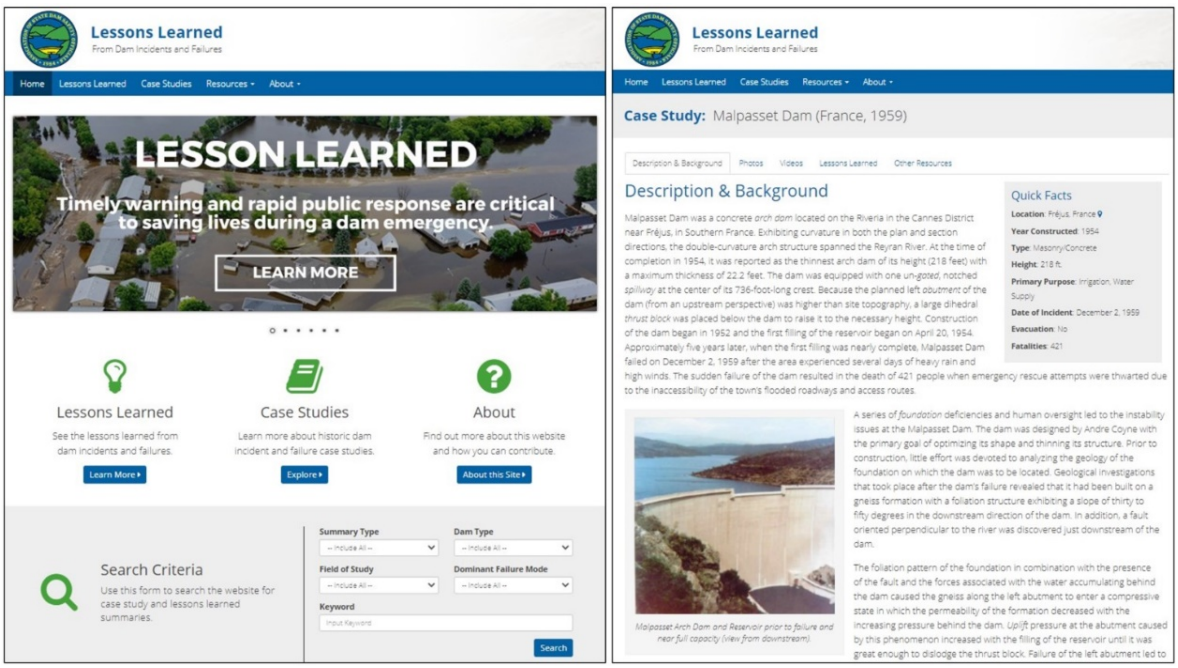

Fig. 1
Home Page and Typical Case Study Page on DamFailures.org Educational Website.

3.3 ASDSO Database of Failures and Incidents

The ASDSO Dam Safety Incident Database provides basic information on dam safety incidents and failures in the United States to ASDSO members, dam safety stakeholders, the media, and the public. It is available in a searchable format on the ASDSO website at damsafety.org/incidents. The database began as a cooperative effort between the Department of Homeland Security (DHS) Dams Sector and ASDSO in 2010 (after a few years, DHS was no longer able to support the database, but ASDSO has continued the project). The initial database contained a limited number of dam failure records from a previous ASDSO dam failure database effort. In 2010, ASDSO began to gather dam safety incident information (both failure and non-failure) from the state dam safety programs. The majority of the incident records have been collected from state programs following the year in which they occurred. Some states have been able to provide historic incident information and ASDSO continues to obtain as much information as possible. The database is not considered comprehensive of all dam safety incidents, both historic and current, and reflects only the data that ASDSO has been able to collect. Much of the identifying information on specific dams is obtained from the USACE National Inventory of Dams (NID). Data on the information fields collected can be found on the ASDSO website.

The database currently contains 1,074 total incident records - 390 failure and 684 non-failure. As shown in Figure 2, the large majority of the database records (73%) are for incidents from 2010 to 2019 (data for most of 2019 and 2020 has not yet been collected). We have learned, unsurprisingly, that many incidents occur over a period of days as part of a large hydrologic event and many of the failure incidents occur at smaller, low and significant hazard potential dams (84%). The data also confirms that failure and non-failure incidents continue to occur every year.

Information from the database has been very useful to ASDSO in answering questions from the media and others. Over the years, ASDSO frequently received inquiries about the number of dams that fail every year, and now the database provides a source of information with actual numbers for those requests. Dam safety professionals and others have used the database as a starting point for more in-depth analysis of dam failure and incident history. Figure 3 and 4 show summaries of incident mechanisms and dam failure drivers.

Some requests for incident data lead to requests for more detailed information. It was never the intent of the database to provide comprehensive information about a particular incident, but rather to be able to answer basic questions about the number of failure and non-failure incidents, etc. ASDSO currently does not have plans to expand the detail of the incident data, but is actively seeking additional incident information (both historic and current) to add to the database.

Q. 93 – R. 3

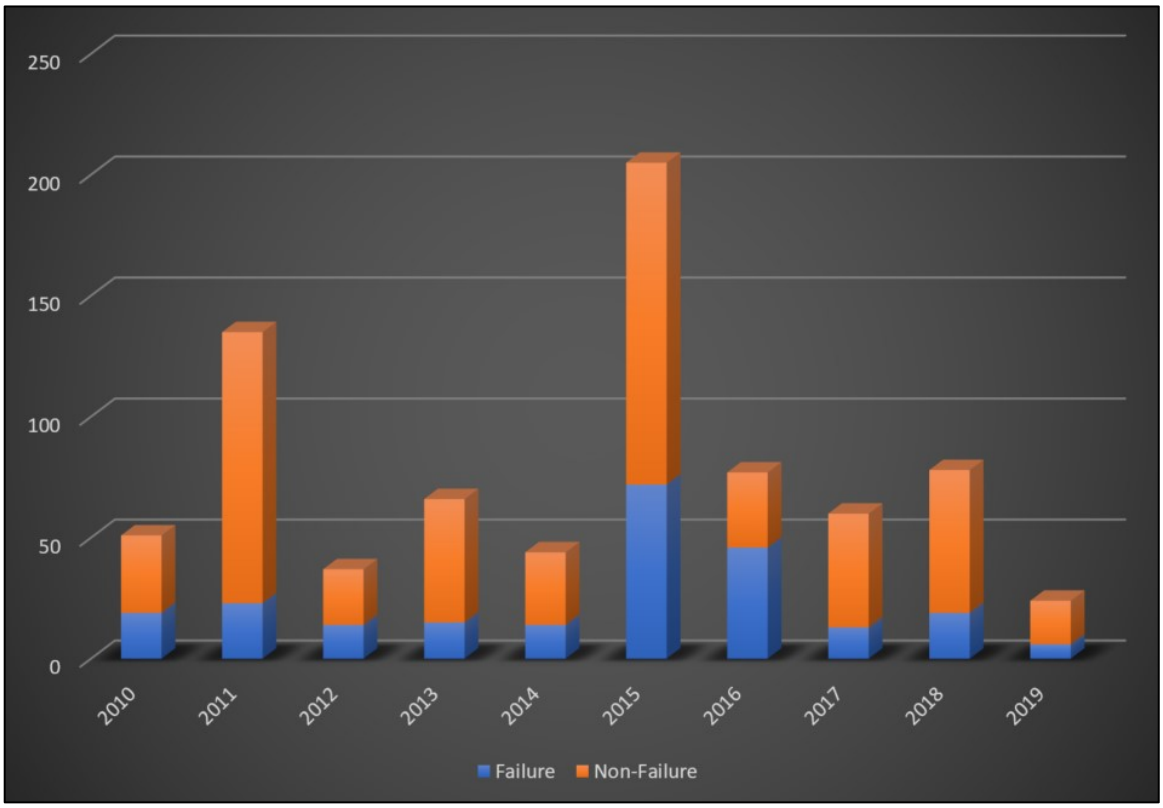

Fig. 2
ASDSO Incident Database Failure and Non-Failure Incidents (2010 – 2019)

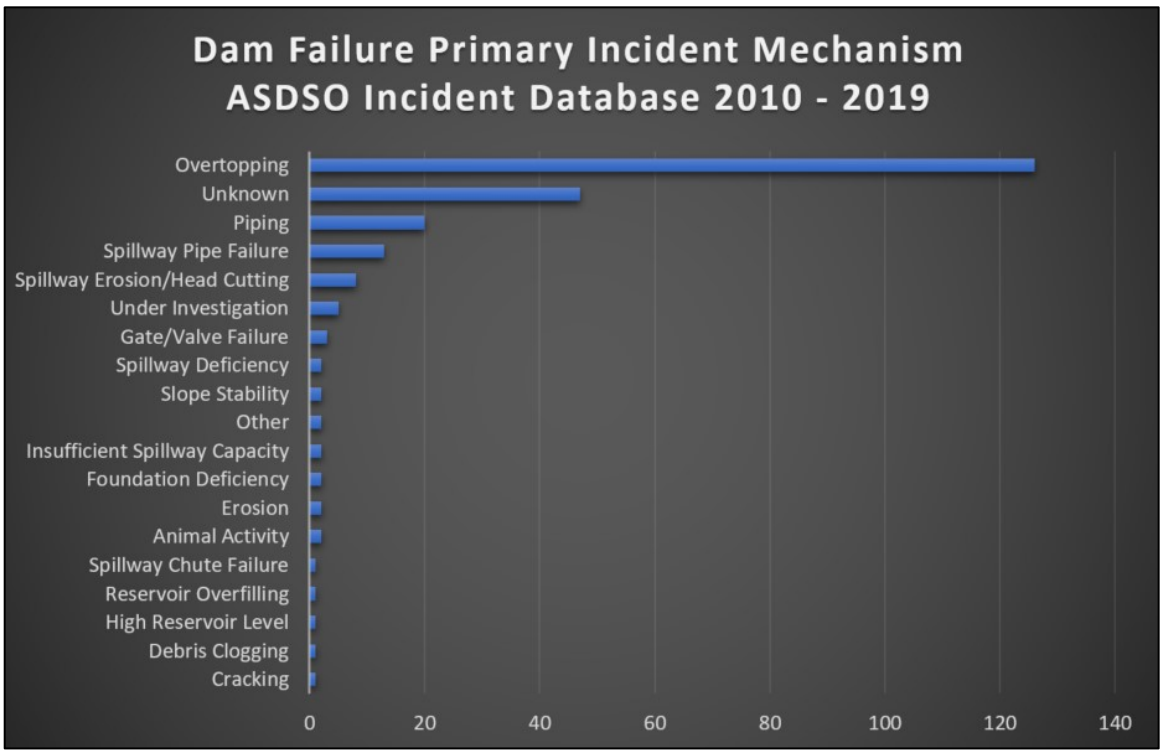

Fig. 3
ASDSO Incident Database, Primary Incident Mechanism (2010 – 2019)

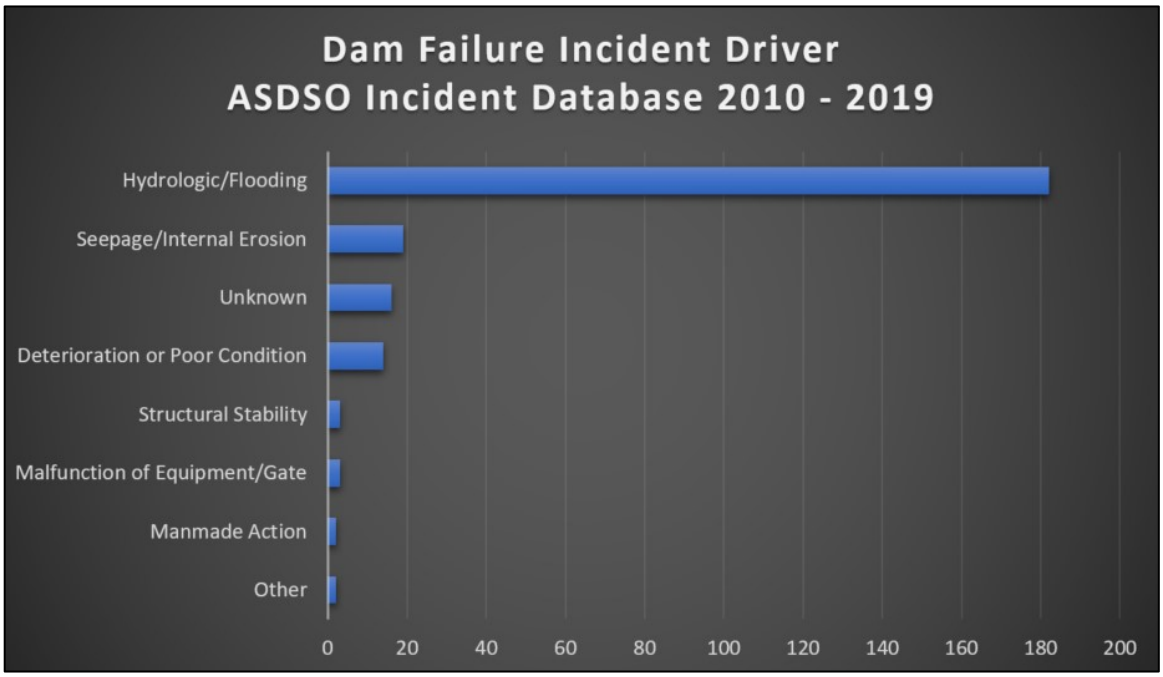

Fig. 4
ASDSO Incident Database, Incident Drivers (2010 – 2019)

3.4 HUMAN FACTORS RESEARCH AND APPLICATIONS

Dam failures and incidents are typically preceded by interactions of physical and human factors which go back years and often decades. These human factors include judgments, decisions, actions, and inactions at individual, group, organizational, and industry levels. The dam industry has always implicitly recognized the influence of human factors in dam failure and safety, but, prior to the work done by the DFIC, the industry lacked an adequate framework to systematically understand and manage the full spectrum of human factors. This is despite the fact that substantial academic research related to human factors has been done by psychologists and other social scientists over the past several decades, and in the past few decades this research has been increasingly and usefully applied by practitioners in fields such as aviation, health care, nuclear power, and the chemical industry.

In the dam industry, a milestone for application of human factors research occurred in 2010, when human factors were explicitly discussed during and immediately after the initial DFIC “soapbox” session on dam failures and incidents conducted at the ASDSO national conference. This discussion led to revision of the DFIC’s Dam Failure Investigation Guidelines to add guidelines for investigation of human factors [12] and initiated research into human factors by one of the DFIC members (Alvi).

During the past decade, members of the DFIC have continued to play a leading role in the United States and internationally in making human factors an active area of research and application in the dam industry. The output of DFIC members related to human factors has included numerous publications, conference presentations, webinars, and participation in forensic investigations. A brief chronology of this work is outlined below.

- At the 2013 ASDSO national conference, a member of the DFIC presented a seminal paper on human factors which used the failure of St. Francis Dam in California as a case study. This presentation generated much interest and discussion among the conference attendees [13].

- At the 2014 ASDSO national conference, three members of the DFIC (Myers, Alvi, and Baker) participated in a soapbox session on the failure of Big Bay Dam in Mississippi, discussing both the physical and human factors which contributed to the failure. This soapbox session was followed by a 2015 paper published in the ASDSO *Journal of Dam Safety* [14] and a 2015 presentation at an ASCE meeting in Baltimore [15].

- In 2015, another key milestone was a ASDSO webinar by a DFIC member which presented a comprehensive framework for understanding and managing human factors in dam failure and safety, illustrated with several case studies [16].

- At the 2015 ASDSO national conference, a member of the DFIC presented a paper on the failure of the Sella Zerbino secondary dam in Italy, which explicitly described both the physical and human factors contributing to the failure [17].

- At the 2015 ASDSO Northeast regional conference, a member of the DFIC presented a keynote address which described the physical and human factors contributing to the failure of Ka Loko Dam in Hawaii [18]. This was followed by a presentation on this failure at the 2016 ASDSO national conference [19].

- Following the 2017 spillway failures at Oroville Dam in California, the federal regulator required that the owner retain a consultant team to perform an independent forensic investigation. Members of ASDSO, the DFIC, and the United States Society on Dams (USSD) participated in a task force to help define the scope of the investigation and recommend individuals to serve on the independent forensic team, and a decision was made by the federal regulator that human factors should be included in the investigation scope. A member of the DFIC served on the independent forensic team to focus on human factors, and the findings of the investigation included extensive discussion of contributing human factors and associated lessons to be learned [20]. To the DFIC's knowledge, the Oroville Dam investigation was the first investigation of a major dam failure or incident which gave the same level of attention to human factors as physical factors. The forensic report was followed by a 2018 ASDSO webinar which overviewed the forensic investigation and its

findings [21], followed by another 2018 ASDSO webinar which focused on the human factors findings [22].

- Following the 2019 failure of Spencer Dam in Nebraska, the owner contracted with ASDSO to perform an independent forensic investigation of the failure. The investigation followed the model of the Oroville Dam investigation, giving similar attention to physical and human factors. A member of the DFIC served as the investigation team leader and lead for investigation of human factors (Baker), another member of the DFIC served as human factors technical advisor (Alvi), and another member of the DFIC served on the Oversight Group for the investigation (Myers). The forensic report was completed in 2020 [23].

The work related to human factors completed by members of the DFIC during the past decade has been highly influential in the United States and internationally. Beyond the examples described above, many members of the DFIC and ASDSO have made dozens of presentations on dam failures at ASDSO conferences as part of the Dam Decade Failure Series, most of which have discussed both physical and human factors.

The Oroville Dam forensic report - particularly its human factors analysis and findings - have been widely cited in media, as well as papers, conference presentations, and books related to dam safety (e.g., [24]). In addition, the federal regulator for Oroville Dam, the Federal Energy Regulatory Commission (FERC), which has one of the largest dam safety programs in the world, is currently in the process of substantially revising its guidelines for inspection and evaluation of dams based on human factors lessons learned which were described in the Oroville forensic report.

The Spencer Dam forensic report, only recently published in April, has already had an impact on how the dam industry considers failure modes related to ice flows. The report also highlighted the lack of consistency across states in how dams are classified in terms of hazard potential based on downstream consequences. Discussions have been initiated on how best to address these inconsistencies.

3.5 ASDSO *JOURNAL OF DAM SAFETY*, QUARTERLY BOOK CLUB

A recent DFIC initiative is the Quarterly Book Club, published in each issue of the ASDSO *Journal of Dam Safety*. This Book Club reviews recent or older books pertinent to ASDSO members with the hope to share a reading list and promote lifelong learning in the dam safety industry. The initial book list was developed through an online survey of dam safety industry leaders. The results of that survey were presented at the 2019 USSD Conference [25], and the first two book reviews have been published in the Summer 2020 [26] and Fall 2020 [27] issues of the *Journal of Dam Safety*. A list of useful books specifically on dam failures and incidents is available online in Appendix C (link).

4. DAM FAILURES AND INCIDENTS COMMITTEE (DFIC): LOOKING AHEAD

4.1 CONTINUATION OF CURRENT INITIATIVES

The DFIC continues to be a very active committee. One of the key ways is by continuing with projects it has begun during the past decade. While the DFIC has built a voluminous body of work by investigating 70 failures as part of its Decade Dam Failure Series, there are still more failures and incidents to be investigated and new audiences to which to present these case studies. The DFIC will continue to make failure case study presentations as an important part of ASDSO national conferences.

In addition, lessons learned from past failures will continue to be published and widely disseminated. DamFailures.org will continue to expand its content as new case studies and lessons learned are added each year. This website is already seen as a trusted source for dam safety information, and with time and expanded content, the audience and usage of the website are expected to increase.

ASDSO, in conjunction with DFIC, will continue to track failures and incidents. As more professionals learn about the ASDSO Dam Safety Incident Database, the hope is that there will be increased reporting to the database. The DFIC knows that many failures and incidents still occur that never get reported. As ASDSO continues outreach, the hope is that the number of unreported failures and incidents will diminish and thereby improve the usefulness of the data.

The Dam Failure Investigation Guideline has been useful in recent forensic investigations. The DFIC sees its use expanding over time, but to make the guideline as useful as possible, it will need to be updated. The DFIC plans to update the guideline based on the lessons it has learned from recent investigations and will regularly update it as needed. There is also a need for a uniform dam failure investigation policy (discussed below) and this guideline will assist in that effort.

The importance of understanding human factors continues. One of the DFIC members (Alvi) will be looking at how human factors affected the failures of two dams in Michigan in 2020 as part of that dam failure forensic investigation team. The ASDSO monthly webinar program will feature a presentation in late 2020 on human factors which influence judgment and decision-making in dam engineering (link).

4.2 Effectively Sharing Lessons Learned

As noted previously, dam failure investigations and research advance the industry only if the lessons gleaned from these events are shared and learned by the industry at large. The DFIC has made considerable strides in reaching a larger audience via modern means such as the DamFailures.org website. However, disseminating the information is only the first step. We need to gain a better understanding of how to help others learn and apply the lessons we are sharing. For example, website usage statistics from DamFailures.org indicate that users spend over three hours looking at case studies on the site for every hour spent looking at lessons learned. With this information, the DFIC is making efforts to weave more of the technical lessons into the case study content rather than relying on users to follow the links to the separate lessons learned pages.

It may also be necessary, in this rapidly changing technological world, to adapt teaching methods in order to effectively train the next generation of dam safety professionals. A recent study found that young people in 'Generation Z' preferred learning new things by watching YouTube® or similar type videos over in-person group activities or printed books [28]. Future efforts to share lessons learned from dam failures and incidents will need to adapt to the rising generation and could possibly include new formats such as short instructional videos, webinars, or podcasts. The DFIC will collaborate with others both in and out of the dam safety community to understand these trends and adapt our efforts to share lessons learned from dam failures and incidents accordingly.

4.3 Need for Uniform Dam Forensic Investigation Policy

The DFIC has supported the profile of ASDSO as an independent, credible organization for participating in, initiating, and conducting independent dam forensic investigations. Two recent major dam forensic investigations in which ASDSO and the DFIC had involvement were the Oroville Dam and Spencer Dam investigations. These investigations were substantially without controversy and garnered valuable lessons learned.

Yet, challenges remain to the performance of timely and successful dam forensic investigations. The dam industry in the United States lacks a uniform law, policy, guideline, or process for initiating and conducting investigations. After a major failure, it is usually unclear what the scope of the investigation should be (particularly the extent to which human factors should be investigated), how investigation team members should be selected in a way that assures independence and multidisciplinary expertise, and who should pay for the investigation. For example, it took more than four months to initiate the Spencer Dam Failure investigation, in part because of legal concerns. Precious data can be lost during such delays as people's memories fade and perishable evidence becomes lost.

How do we get over the hurdles that impede initiating and conducting investigations? Dam failures and incidents often have major financial, legal, and reputational implications for dam owners, regulators, consultants, construction contractors, and local communities. Findings from investigations may be adverse to the interests of one or more of the parties. Due to all of these factors, there may naturally be reluctance to fund or even cooperate with a forensic investigation.

Nevertheless, in order to advance the dam engineering profession and safeguard the public and environment, conducting independent forensic investigations for significant dam failures and incidents is necessary in order to reach unbiased and accurate conclusions regarding the physical and human factors that contribute to these failures and incidents, and to identify and disseminate the associated lessons to be learned.

As noted previously, there have been a substantial number of dam failures and incidents during the past decade. Yet, there have been very few formal forensic investigations released to the public during that same time period. The DFIC believes that there should ideally be a national policy or guidelines for getting “official” dam forensic investigations underway soon after a major failure or incident. Such a policy should address procedures for establishing an independent investigation team, funding of the investigation, liability of the investigative team, access to sites, subpoena power and confidentiality, preservation and gathering of evidence, report review processes, fact checking, acceptable uses of the forensic reports in legal proceedings, and communication with the media and stakeholders. With this goal in mind, the DFIC initiated efforts to help establish a national dam failure investigation program in 2018 in partnership with FEMA [29].

4.4 Additional International Collaboration

One observation made by the DFIC is that language barriers, and to some extent a natural tendency towards insularity among nations, limit international collaboration on work related to dam failures and incidents. Illustrating this, the DFIC’s work has generally been in isolation from work which may be underway by any similar groups in other countries around the world. Members of the DFIC have often found that their ability to learn about dam failures and incidents outside the United States has been limited when documents related to those failures and incidents were not available in the English language.

The DFIC hopes to find ways to overcome these barriers and share information and lessons to be learned across borders. In particular, the DFIC would benefit from having international participants who could assist in translating documents and provide avenues for the two-way sharing of lessons learned from dam failures or incidents in the United States or internationally with the broader dam safety community.

5. CONCLUSIONS

The DFIC has been highly productive over the course of the past decade due to strong leadership, effective meetings, interesting subject matter, and a sincere desire by the committee members to research and share valuable lessons learned from dam failures and incidents.

Henry Petroski, acclaimed engineering historian, writes that the concept of failure is central to advancement of engineering, specifically because engineering design has, as its “first and foremost objective the obviation of failure,” and failures and incidents are “unplanned experiments that can teach on how to make the next design better.” [30]

The dam safety industry has made remarkable progress in large part by learning from past failures and incidents. The majority of dams do not fail, but the relatively rare outliers are the ones that get the press: “To speak of engineering failures is indirectly to celebrate the overwhelming numbers of successes.” [30]

The DFIC’s original goal of developing a failure investigation guideline was accomplished and could have been the singular focus for the committee. However, the committee members realized that there were numerous ways that the DFIC could use its research into dam failures and incidents as educational tools to help drive the industry forward. The DFIC intends to continue these efforts, and will welcome collaboration with professional organizations in the United States (e.g., the American Society of Civil Engineers and the United States Society on Dams), as well as international partners, with the aim of contributing to improved dam safety on a global scale.

REFERENCES

[1] Rose, A. T. (2013). *The Influence of Dam Failures on Dam Safety Laws in Pennsylvania*, Association of State Dam Safety Officials, Proceedings of Dam Safety 2013. https://damfailures.org/wp-content/uploads/2015/07/104_The-Influence-of-Dam-Failures-on-Dam-Safety-Laws-in-Pennsylvania.pdf

[2] *St. Francis Dam Failure* (California, 1928). Lessons Learned Case Study on DamFailures.org website, Association of State Dam Safety Officials, accessed June, 2020. https://damfailures.org/case-study/st-francis-dam-california-1928/

[3] Wilkman, J. *Floodpath: The Deadliest Man-Made Disaster of 20th-Century America and the Making of Modern Los Angeles*. New York: Bloomsbury. Page. 237. 2016.

[4] *Buffalo Creek Dam Failure* (West Virginia, 1972). Lessons Learned Case Study on DamFailures.org website, Association of State Dam Safety Officials, accessed June, 2020. https://damfailures.org/case-study/buffalo-creek-dam-west-virginia-1972/

[5] Gee, N. (2017). *The Impact of Dam Failures on the Development of Dam Safety Legislation and Policy in the 1970's.* Journal of Dam Safety, 2017. https://damfailures.org/wp-content/uploads/2018/01/09-Impact-of-Dam-Failures-on-Development.pdf

[6] *Teton Dam Failure* (Idaho, 1976). Lessons Learned Case Study on DamFailures.org website, Association of State Dam Safety Officials, accessed June, 2020. https://damfailures.org/case-study/teton-dam-idaho-1976/

[7] *Kelly Barnes Dam Failure* (Georgia, 1977). Lessons Learned Case Study on DamFailures.org website, Association of State Dam Safety Officials, accessed July, 2020. https://damfailures.org/case-study/kelly-barnes-dam-georgia-1977/

[8] *Federal Guidelines for Dam Safety*. Federal Emergency Management Agency website, U.S. Department of Homeland Security. Site accessed July 2020, https://www.fema.gov/federal-guidelines-dam-safety

[9] ASDSO Dam Safety Incident Database Search, Association of State Dam Safety Officials website, accessed July, 2020. https://damsafety.org/Incidents

[10] Godbey, R. (2007). *Report of the Independent Civil Investigation of the March 14, 2006, Breach of Ka Loko Dam.* January, 2007, Volume 1. https://pinetreewatch.org/wp-content/uploads/2011/08/Kaloko-Report.pdf

[11] Baker, M.E., Graham, W.J., (2008). *Dam Failure Investigation Approaches*. Dam Safety 2008, Association of State Dam Safety Officials, Indian Well, CA. https://damsafety-prod.s3.amazonaws.com/s3fs-public/DamFailureInvestigationApproaches.pdf

[12] *Dam Failure Investigation Guideline* (2017), completed by the ASDSO Dam Failure & Incidents Committee, latest update in 2017. Previous version available at (2011): https://damsafety.org/sites/default/files/DFIC_Investigation_Guide_12-10-11_0.pdf

[13] Alvi, Irfan A. (2013). *Human Factors in Dam Failure*. Dam Safety 2013, Association of State Dam Safety Officials, Providence, RI. https://damfailures.org/wp-content/uploads/2019/02/Alvi_HumanFactors.pdf

[14] Myers, D., Ferguson, K., Alvi, I. & Baker, M. (2015). *Reexamination and Lessons Learned from the 2004 Failure of Big Bay Dam, Mississippi*, Journal of Dam Safety, 13:2. Lexington, KY: Association of State Dam Safety Officials. https://damfailures.org/wp-content/uploads/2019/02/Dam-Journal-V13-Issue2-Big-Bay-Dam.pdf

[15] Alvi, I. (2015) *2004 Failure of Big Bay Dam, Lamar County, Mississippi*, ASCE Geo-Institute Presentation. Baltimore, Maryland: American Society of Civil Engineers. http://alviassociates.com/yahoo_site_admin/assets/docs/Big_Bay_Dam_Failure_-_ASCE.176153201.pdf

[16] Alvi, I. (2015). *Human Factors in Dam Failure and Safety*, ASDSO Webinar. Lexington, KY: Association of State Dam Safety Officials. https://learningcenter.damsafety.org/products/human-factors-in-dam-failure-and-safety-on-demand

[17] Alvi, I. (2015). *Failure of Sella Zerbino Secondary Dam in Molare, Italy*, ASDSO Annual Conference. New Orleans, LA: Association of State Dam Safety Officials. https://damfailures.org/wp-content/uploads/2019/02/Sella_Zerbino.pdf

[18] Alvi, I. (2015). *Human Factors in Dam Failure & Safety, Case Study: Ka Loko Dam Failure,* ASDSO Northeast Regional Conference. Ocean City, MD: Association of State Dam Safety Officials. https://damfailures.org/wp-content/uploads/2019/02/Human_Factors_in_Dam_Failure_and_Safety_-_2015_ASDSO_NE.pdf

[19] Alvi, I., Richards, G., and Baker, M. (2016). *10th Anniversary of Ka Loko Dam Failure, Hawaii*, Presentation. ASDSO Annual Conference. Philadelphia, PA: Association of State Dam Safety Officials.

[20] France, J., Alvi, I., Dickson, P., Falvey, H., Rigbey, S. & Trojanowski, J. (2018). *Independent Forensic Team Report: Oroville Dam Spillway Incident.* https://damsafety.org/sites/default/files/files/Independent%20Forensic%20Team%20Report%20Final%2001-05-18.pdf

[21] France, J. (2018). *Findings of the Oroville Dam Spillway Forensic Investigation*. ASDSO Webinar. Lexington, KY: Association of State Dam Safety Officials. https://learningcenter.damsafety.org/products/findings-of-the-oroville-dam-spillway-forensic-investigation-on-demand

[22] Alvi, I. (2018). *Human Factors in the Oroville Dam Spillway Incident*, ASDSO Webinar. Lexington, KY: Association of State Dam Safety Officials. https://learningcenter.damsafety.org/products/human-factors-in-the-oroville-dam-spillway-incident-on-demand

[23] Baker, M., Ettema, R., Teal, M., Trojanowski, J. (2020). *Spencer Dam Failure Investigation Report.* Association of State Dam Safety Officials. April, 2020. https://damsafety.org/SpencerDamReport

[24] Oboni, F., Oboni, C. (2020). *Tailings Dam Management for the Twenty-First Century: What Mining Companies Need to Know and Do to Thrive in Our Complex World.* Springer, 2020.

[25] Mauney, L. (2019). *Dam and Levee Safety Leaders Library*. U.S. Society on Dams, 2019 USSD Conference and Exhibition, Chicago, IL. https://drive.google.com/file/d/1uhyhOHufftNNEczyTnNVNRftCOUaqE46/view?usp=sharing

[26] Mauney, L. (2020). To Engineer is Human: The Role of Failure in Successful Design, by Henry Petroski. *ASDSO Quarterly Book Club*, The Journal of Dam Safety, Summer 2020, Vol. 17, Issue 3, p. 44-45. https://damsafety.org/JDS-Summer2020

[27] Mauney, L. (2020). The Signal and the Noise: Why So Many Predictions Fail - but Some Don't, by Nate Silver. *ASDSO Quarterly Book Club*, The Journal of Dam Safety, Fall 2020, Vol. 17, Issue 3, p. 44-45. Pending publication, September 2020 https://drive.google.com/file/d/1QNOum074mu8cDrmSmYdAz-ebQ6ST6PQN/view?usp=sharing

[28] Pearson (2018). *Beyond Millennials: The Next Generation of Learners*, Global Research & Insights, August 2018. https://www.pearson.com/content/dam/one-dot-com/one-dot-com/global/Files/news/news-annoucements/2018/The-Next-Generation-of-Learners_final.pdf

[29] Baker, M., Alvi, I., Durgin, S., Mauney, L., Pittman, J., Wooten, L., and Roberts, T. (2018). *Establishing a National Dam Failure Investigation Program: Requirements and Approach.* Developed by Dam Failure & Incidents Committee, Association of State Dam Safety Officials. Sponsored by FEMA National Dam Safety Program, March 2018. https://drive.google.com/file/d/1-m4h0DsdsDjYVam1AsOCSceXlsGyKeNE/view?usp=sharing

[30] Petroski, H. (1994). *To engineer is human: the role of failure in successful design*. New York: Barnes & Noble Books, 1994.