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The 1911 Bayless Dam Failure: Physical and Human Factors

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Abstract – Through various venues such as ASDSO's DamFailures.org website, many today in the dam engineering community know the basic story of the Bayless Dam failure that occurred over 100 years ago in the small town of Austin in north central Pennsylvania. The dam failed on September 30, 1911, resulting in the loss of 78 lives. In the immediate wake of this disaster, investigations to identify the contributing factors to this concrete dam failure were hastily prepared to quickly appease the public with answers. Limitations in the technological advancement of dam engineering at the time further prevented a comprehensive understanding of the failure's contributing factors.

Despite technological shortcomings, perhaps the most troubling aspect of this event is the fact that the disaster could have easily been prevented if warning signs had been correctly interpreted and there had not been a cascading series of flawed judgments and decisions over a span of more than two years. It also illustrates why effective dam safety regulatory programs are so important. This case study will revisit the lessons learned from both a physical and human factors perspective in hopes of providing a sobering reminder in how immature technology coupled with one or more unchecked flawed judgments and decisions, made by people who lack adequate technical expertise, can result in catastrophic consequences. Given that newsworthy dam failures have recently occurred which also likely involved flawed judgments and decisions, and which were preventable, it is evident that the profession still needs to learn from history in order to reduce the rate of future dam failures.

I. THE EARLY DAYS OF GRAVITY DAMS IN THE U.S.

In modern history, a "rational method" for the design of gravity dams was developed by French and British engineers between the 1850s and 1880s. This early work influenced prominent engineers in the United States like Edward Wegmann, who was involved with the design of New York City's New Croton Dam, which is now an ASCE National Historic Civil Engineering Landmark. He also authored *The Design and Construction of Dams* in 1888 with subsequent revisions and updates in seven more editions, the last being published in 1927. This book served as a primer over a span of more than 40 years in the latest technological advances for gravity dams in the United States. As such, Wegmann should be viewed as the father of gravity dam design in the United States.

In fact, Wegmann is credited with proposing the use of the simple right triangle with its vertical side facing upstream, the standard still in use today, as a more practical profile to construct than the stepped, polygonal, and curvilinear profiles being used by his French and British contemporaries. Not only was his profile simpler to construct, but it also required less material volume since he modified key assumptions regarding material unit weight and strength, the combination of these features making his profile comparatively less costly.

During the advent of a rational method, as a theory-based mathematical design method, it is probably more than a coincidence that there was a dramatic increase in the number of gravity dams built in the United States. Figure 1, which is based on data obtained from the U.S. Army Corps of Engineers National Inventory of Dams, illustrates the number of masonry and concrete dams built between 1600 and present. In the latter half of the 19th century and beginning of the 20th century when the rational method was in its infancy, there was a virtual explosion in the number of large gravity dams built in the United States. It should be noted that this data set does include other concrete dam types such as arch, multiple-arch, and buttress dams, however these other types represent a relatively small subset in comparison with gravity dams.

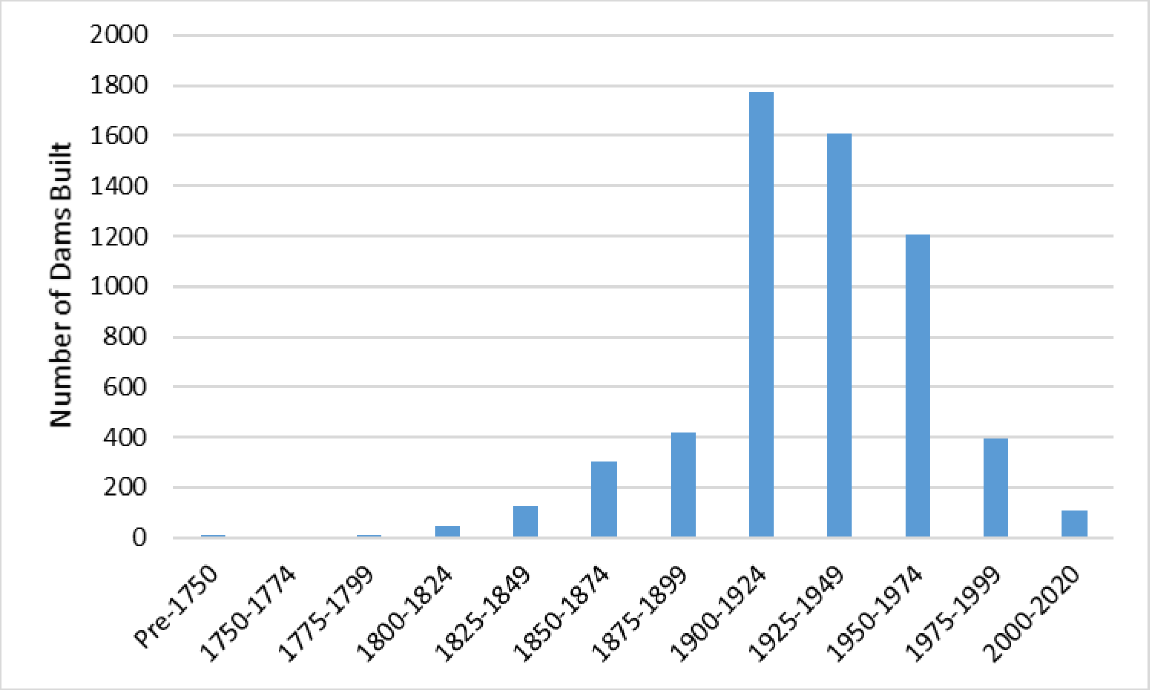

Figure 1. Number of Masonry and Concrete Dams Built in the United States.

As shown in the listing in Table 1, during this same time period, engineers began to place more confidence in the soundness of the rational method, with the trend toward ever increasing structural heights in wider stream valleys, which eliminated the added benefit of arch action for structural stability.

TABLE 1
U.S. Gravity Dams Over 100 Feet High Constructed Prior to 1920

Dam	Location	Date of Construction	Height (feet)	Crest Width (feet)	Base Width (feet)	Base/ Height Ratio	Crest Length (feet)	Plan
San Mateo	California	1887-1888	170	20.0	176.0	1.04	700	Curved
New Croton	New York	1892-1907	297	22.0	206.0	0.69	2,168	Straight
Wachusett	Massachusetts	1900-1906	228	25.8	187.0	0.82	1,476	Straight
Kensico	New York	1910-1917	307	28.0	235.0	0.77	1,843	Straight

However, as engineers were setting new gravity dam size records, several noteworthy failures occurred (see Table 2) during the late 1800s and early 1900s, including Bayless Dam, which put the profession on the defensive in the court of public opinion. When a dam failure was associated with a natural flood disaster, the profession and the public seemed less inclined to challenge the competency of the designer or the soundness of the basic design tenets. However, when a dam failure occurred during normal operating conditions (commonly referred to today as a “sunny day” failure) everyone was left to wonder whether or not the dam’s designer knowingly or unknowingly ignored one or more key design tenets or whether the tenets themselves should be put into question. These sunny day failures started a long running debate within the profession concerning the established fundamentals of gravity dam design and construction. Some aspects of the debate have not been well enough understood until the past few decades.

TABLE 2
Notable Early Era Gravity Dam Failures

Dam	Location	Date of Construction	Height (feet)	Length (feet)	Year(s) of Failure	Failure Scenario	Fatalities
El Habra	Algeria	1865-72	110	1,476	1872, 1881, 1927	Flood	209
Bouzey	France	1878-81	72	1,732	1884, 1895	Sunny Day	100+
Austin	Texas	1890-93	66	1,091	1900	Flood	8
Bayless	Pennsylvania	1909	50	544	1911	Sunny Day	78
St. Francis	California	1924-26	205	700	1928	Sunny Day	450+

Typically, when a failure did occur, a local governing body in the form of a coroner's inquest or criminal or civil trial would launch an investigation into its causes. Oftentimes, these investigations were performed in haste in an effort to quickly appease the public and curtail any growing broader fears with other similar structures. Uncooperative key witnesses, conflicting or inaccurate eyewitness accounts, and bias and limitations in the engineering profession's knowledge base all often served to mask the correct and/or full set of circumstances that led to failure. Unfortunately, these hindrances also kept the profession from avoiding the same mistakes on future projects.

Further diminishing the potential educational value of these incidents for future generations of owners, engineers, and regulators, their stories have become somewhat distorted with time or forgotten altogether. Fortunately, however, some individuals have devoted much time and energy to reinvestigate some of the more infamous concrete dam failures and thoroughly document their findings. Recent and easier access to digital copies of old documents through the internet, which in prior years were only accessible through a few libraries, have allowed an opportunity to obtain documents published at the time of each failure, some of which were authored by the central figures involved. Such reinvestigation efforts help serve to correct past inaccuracies surrounding a failure and maximize the learning opportunity.

To that end, this paper presents information on the failure of Bayless Dam. Much has already been written by others about this event, but the purpose of this paper is to present known facts, to dispel prior misconceptions, and to illustrate the warning signs that were present which could have allowed this failure to be avoided. In many cases, these lessons reinforce the importance of current dam safety practices and remind us of their purpose.

II. BAYLESS DAM

A. Project Background

Bayless Dam was a 50-foot-tall by 544-foot-long concrete gravity dam constructed between May and November 1909 on Freeman's Run to supply water to the Bayless Paper Mill. The mill was located about one-half mile upstream of the town of Austin, which had a population of approximately 2,500 people.

An act passed in Pennsylvania on May 28, 1907 provided the Water Supply Commission with limited jurisdiction over the construction of encroachments in river systems declared "public highways" (i.e., navigable waterways). The jurisdictional limits on Freeman's Run in the upstream direction terminated about one mile downstream of the Bayless Dam and consequently the Commission had no knowledge of its construction.

The dam was designed by T. Chalkley Hatton of Wilmington, Delaware. The Bayless Pulp and Paper Company president, George C. Bayless, gave Hatton two objectives: 1) build a 200 million gallon (614 acre-feet) reservoir, and 2) do it within an $85,000 budget (about $2.4 million in 2021 dollars). After developing three different dam profiles, with subsequent iterations involving reduction in cross-sectional geometry to reduce concrete volume, Hatton was able to satisfy the maximum budget constraint.

As construction neared completion and it became apparent that the original $85,000 budget would be slightly exceeded, Hatton received pressure from Bayless to modify the structure to avoid and/or reduce the potential overrun. For example, the 36-inch control valve for the outlet works was replaced with a much less expensive wooden cap. During this same period, Bayless also began to direct staff at the construction site, initially unbeknownst to Hatton, to increase the storage capacity of the structure by raising the crest of both the dam and its spillway. Hatton conceded to nearly all of Bayless' demands even though they were not in accordance with sound engineering principles known at that time.

Upon construction completion around Thanksgiving in 1909, the total project cost was $86,000 which equates to an overrun of only 1.2%. The structure consisted of 15,780 cubic yards of concrete, 7,925 cubic yards of foundation excavation, and 6,360 cubic yards of earthen embankment placed against the upstream face.

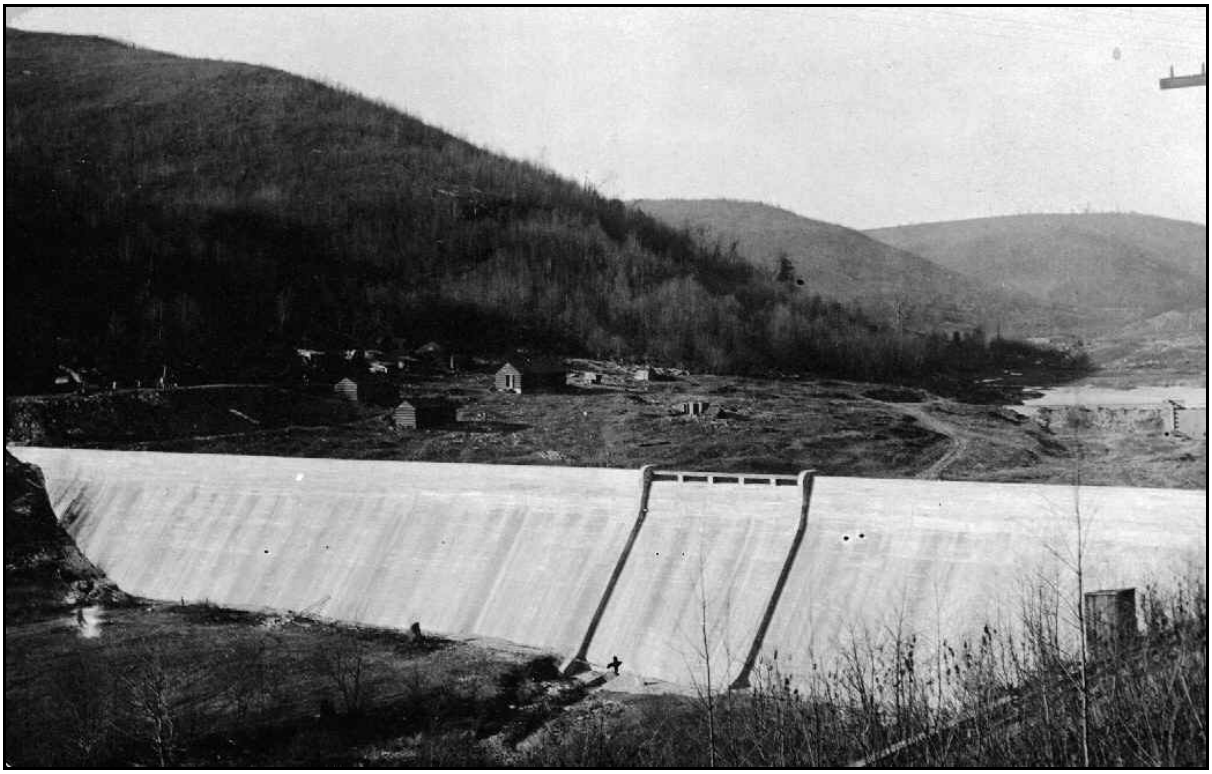

Figure 2. Bayless Dam, December 1909 (Source: Potter County Historical Society).

B. Failure Event Description

The dam was ready to be put into service on December 1, 1909. Before water was impounded behind the dam, two transverse vertical cracks developed at locations left and right of the spillway section. Each crack had about a 1/16-inch width opening. Hatton attributed these cracks to thermal contraction since there was no evidence of structural settlement.

In mid-January 1910, an unseasonably warm period combined with some rain caused rapid snowmelt runoff within the watershed. Within a period of three days the reservoir was filled and the spillway was activated for the first time. On Sunday afternoon, January 22nd, the first signs of trouble appeared, including a large landslide at the left abutment on the downstream side of the dam. Seepage flow, estimated to total about 600 gallons per minute, was present within the slide as well as at various locations along the toe of the dam. On Monday, the dam slid downstream with a maximum deflection of 18 inches at the toe and 31 inches at the crest. As a result of the movement, the dam fractured into six or seven distinct sections each bounded by large cracks that were pinched closed at the upstream face. This movement reportedly occurred over a period of eight hours. In response to this partial failure, the paper mill staff used dynamite to blast an opening in the upper portion of the dam near the right abutment as well as blast the wooden cap free from the downstream end of the outlet pipe to quickly lower the reservoir level.

In an Engineering News article published on March 17, 1910, dam designer Hatton attributed two main causes to the partial failure as given in the following excerpt: "…the failure of the dam to withstand the flood of Jan. 21 is probably due to two causes. One of these is that the great bulk of concrete which had been hurriedly built, some during freezing weather, and which had been completed but six weeks before the maximum pressure came upon it, had not set up so as to attain its ultimate tensile strength. The most important cause, however, was due to the water getting under the dam. This condition was not anticipated when building the dam, and all precautions which seemed to be necessary at the time were taken to guard against it".[1] He also offered further detail with "From the evidence thus far obtained the outward movement of the center of the dam was due to water getting under the foundation, softening up a stratum of clay or shale lying between two layers of rock, and permitting one layer of rock to slip forward about 18 inches upon the lower layer….The water getting under the dam at a depth of 6 ft. below the concrete base exerted a much greater upward pressure than was anticipated when the cross-section was designed and reduced the factor of safety against sliding to an unsafe limit".[1]

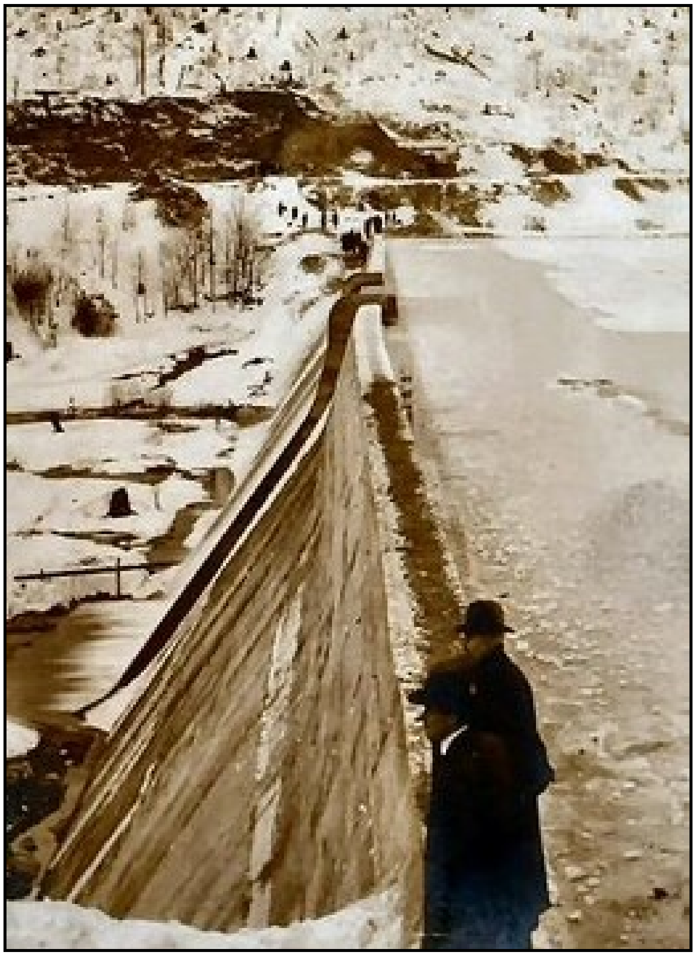

Figure 3. Partial Sliding Failure, January 23, 1910 (Source: Potter County Historical Society).

Immediately following the partial failure incident in late January, Hatton consulted with Edward Wegmann (described previously as the father of gravity dam design in the United States) about possible repair options and presented them to Bayless. During this same period, Bayless consulted with another engineer for a second opinion about repair options as well as an alternative interim measure which involved building a new timber-crib dam located near the upstream limit of the existing reservoir. The original intent for the smaller and consequently less expensive timber-crib dam was to provide water for the mill while the concrete dam was out of service for repairs.

In March 1910, during deliberations on how to proceed, the reservoir behind the derelict concrete dam was allowed to refill to a depth of 36 feet so that the mill could more quickly resume operation. Later this same month, the reservoir level rose to within two feet of the spillway crest. A trench was excavated along the toe of the concrete dam to collect resulting seepage for use at the mill. Bayless reasoned that by allowing the reservoir to partially refill "…we have practically proved that the dam has found a secure footing and will not slide further." [11] Bayless then proceeded with building the 30-foot-tall timber crib dam which was completed in June 1910 at a cost of $11,000 (about $300,000 in 2021 dollars).

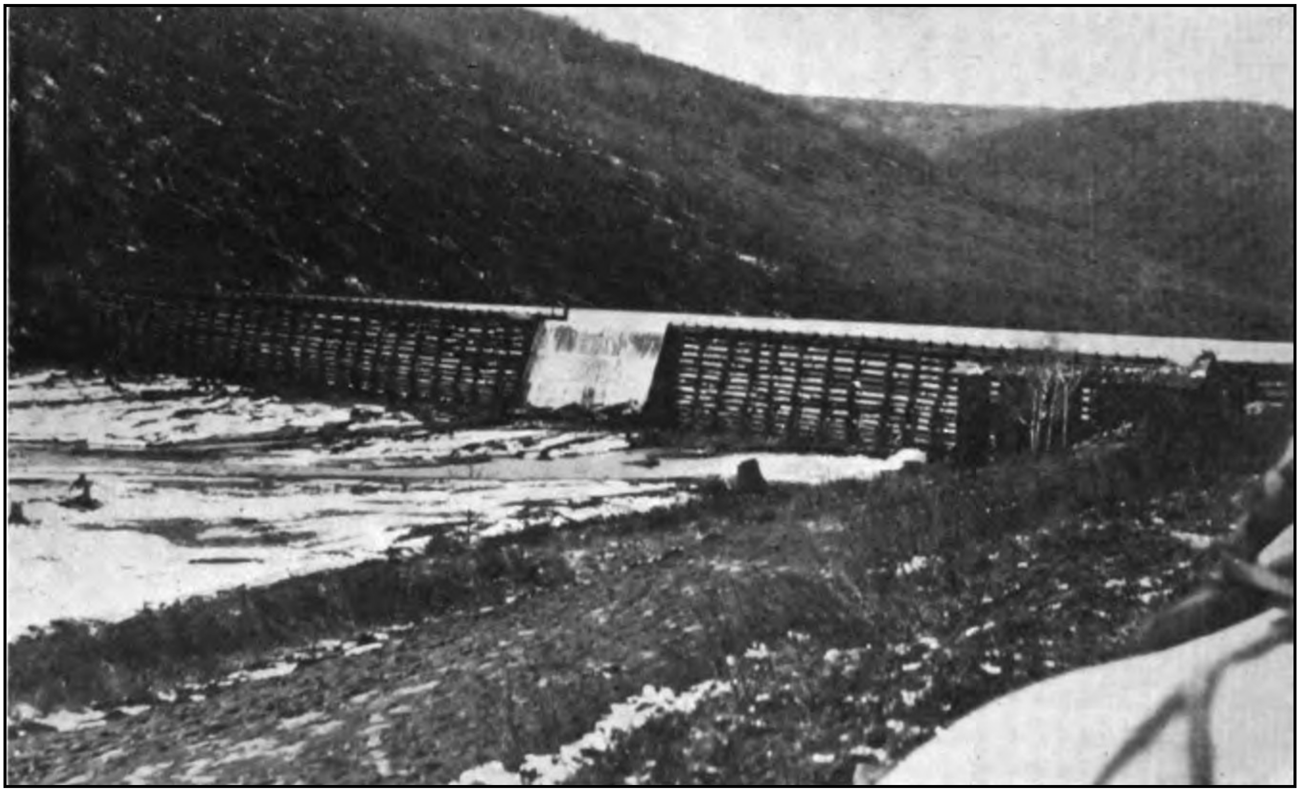

Figure 4. Timber-Crib Dam, Completed June 1910 [10].

In the first five months of operation, the timber-crib dam experienced seepage at the base along its entire length as well as up the right abutment. By December 1910, ten inches of settlement was observed along the entire length of the dam crest. Upon this news, Bayless directed the mill superintendent to empty the reservoir behind the timber-crib dam to investigate its condition and implement repairs. Later accounts indicate that strengthening this dam with timber, earth, and rock required a constant effort.

Bayless also confided in the superintendent that some directors were concerned that if the timber-crib dam failed that it would cause the concrete dam to fail as well. Therefore, to appease his stockholders and the Austin community, Bayless also directed the superintendent to blast an opening in the concrete dam near its spillway to limit its reservoir to a maximum 35-foot-depth. Once repairs were completed on the timber-crib dam, the reservoir behind the concrete dam was to be emptied so that the 36-inch control valve, which was originally called for by Hatton, could be installed at the upstream end of the outlet works pipe.

There is no record of the concrete dam's operation during the intervening ten months between December 1910 and September 1911. However, Bayless later stated that normally a reservoir depth of 40 feet was maintained behind the concrete dam during the drier summer months when natural streamflows and the impoundment behind the upstream timber-crib dam were insufficient to supply the mill. From what little is known, very modest repairs were made to the concrete dam leading up to and during September 1911 to prevent leakage through various locations within the structure, including closing two previous man-made breaches.

Due to heavy rains during September 15-17, 1911, the reservoir completely refilled to within inches of the spillway crest for the first time since the partial failure occurred in January 1910. By Saturday morning, September 30th, according to several eyewitness accounts, the reservoir level was within a half inch of the spillway crest and leakage both through and under the dam began to increase at an alarming rate. Against the pleas of two mill employees that witnessed the leakage, the mill superintendent refused to allow them to open the outlet works to lower the reservoir nor did he bother to visit the site to observe conditions firsthand. The superintendent's argument was that the reservoir must be kept as full as possible to help meet production demands at the paper mill. Sometime between 2:00 and 2:15 pm in the afternoon, the dam suffered a catastrophic failure as shown in Figure 5.

At the time of failure, no one from the mill was present at the dam site. The developing failure was first observed by two people passing by the dam in a car and by several residents living near the dam. Unfortunately, the failure occurred on Election Day and there were more people in the downstream town of Austin than usual. The first known warning to downstream residents was made by the "madam" of the local brothel near the dam. Her phone calls are credited with saving the lives of many of the estimated 3,000 people who were in town that day. Many of the individuals that perished in the flood either did not receive any warning at all or were not warned soon enough to allow evacuation.

The resulting flood wave that was released essentially destroyed the towns of Austin and Costello and took the lives of 78 people. In reaction, the County district attorney hired the Director of Engineering at Lehigh University, Prof. Frank P. McKibben, to investigate the cause of failure to determine what further legal action may be warranted. McKibben publicly released his findings in a little over two months in December 1911. His primary conclusion was "The failure of this dam is due to sliding as a result of faulty foundation, faulty design, faulty construction and faulty operation".[5] McKibben's detailed discussion of these factors along with his recommendations for future dams appears reasonably valid in light of the profession's knowledge base at that time. Concurrently, the Chief Engineer of the Pennsylvania Water Supply Commission, Farley Gannett, was tasked with conducting a similar investigation for the state's interests. Available documents suggest that Gannett reached the same conclusions as McKibben.

Figure 5. Catastrophic Collapse, September 30, 1911 (Source: Potter County Historical Society).

C. Fact Summary

At a meeting of the New England Water Works Association in Boston, Massachusetts on September 19, 1912, almost one year after the failure, Hatton presented a paper entitled "Some Features of the Construction and Failure of the Austin, PA., Dam".[6] The purpose of the paper was to correct erroneous statements by several of his peers regarding opinions publicly expressed on the cause of the failure and to support a key recommendation by McKibben and Gannett calling for state supervision of dams. Since Hatton was quick to publicly lay blame on himself for the failure, it seems reasonable to assume that his characterizations of the key technical aspects surrounding the disaster are likely to be reasonably accurate. The summary of the most relevant known facts given below are largely based on Hatton's own descriptions as well as on firsthand accounts by others.

1. **<u>Unconventional Design Features:</u>** Hatton devised some unique unconventional design features to mitigate the reduction in structure mass that was necessary to meet budget requirements. These features consisted of installing 25-foot-long and 1-1/4-inch diameter twisted steel rods on 2.66-foot-centers (see Figure 6) approximately 6 to 8 feet into the foundation rock "to increase the factor of safety against overturning".[6] Again, to further reduce mass, the dam's chimney section had a top width of only 2.5 feet with a very steep downstream slope. To prevent horizontal cracking due to tensile stress in this top portion of the dam, Hatton used ½-inch-diameter steel reinforcement spaced 4-feet-vertically and 2-feet-horizontally.

   To avoid being overly critical of Hatton for adopting an untested approach to his design, one should remember that at this point in U.S. history, many engineers engaged in this practice of using new and untested features in their designs. One possible reason is that engineers of the day were known to place much faith in scientific principles and associated mathematical analysis and design methods, which requires the assumption that one can adequately identify and quantify all the correct variables involved. Such practices led to the development of many new and highly valuable innovations during this period, but in some cases negative outcomes in the form of poor performance, inordinate cost, and catastrophic failure also occurred. It should also be noted that none of Hatton's peers criticized him for his unconventional practices, at least not publicly in writing. They did claim, with little basis to substantiate, that these unconventional design features may not have been constructed properly, but interestingly they did not necessarily question the features themselves.

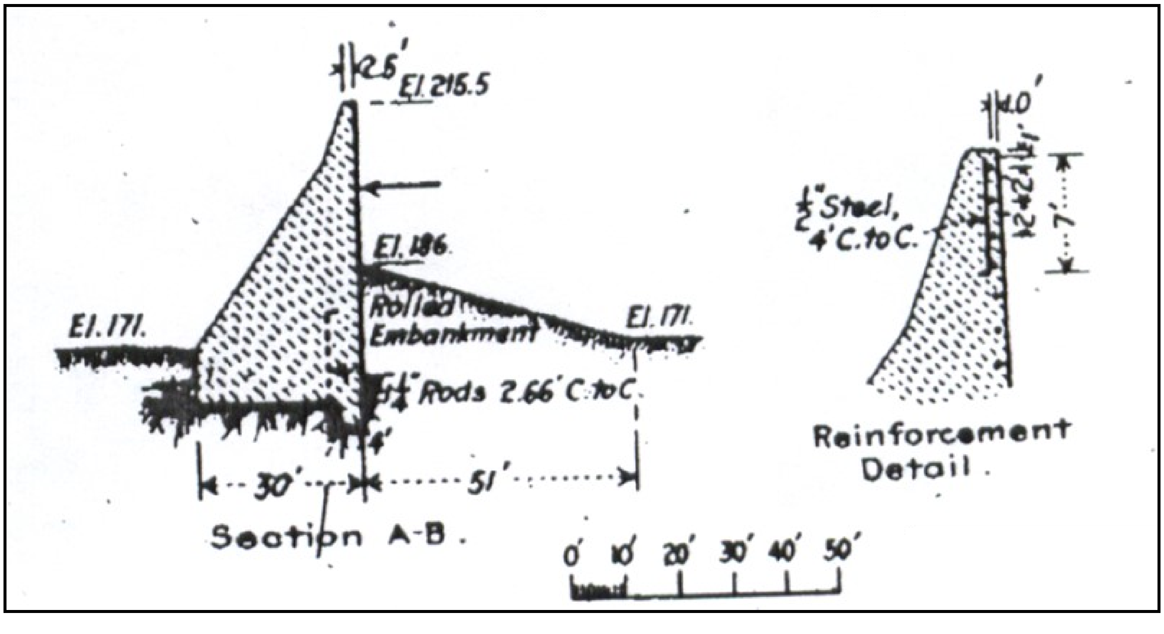

Figure 6. Non-Overflow Section [1].

2. **<u>Foundation Assessment</u>**: Hatton described what could be viewed at that time as a reasonable standard of care during design and construction in evaluating foundation conditions at the dam site. He reported

examining visible outcrops in the valley, digging test pits at the dam site, and drilling 2-inch-diameter holes from 10 to 15 feet deep on 15 to 20-foot centers throughout the entire foundation area. Hatton examined the drill holes to determine if water impounded by an existing dam located 860 feet upstream was being transmitted through the upper rock layers. He reported that the drill holes remained dry and concluded that the foundation was suitably impervious.

During foundation excavation, weathered sandstone and shale was removed until a minimum 2-foot-thick layer of competent sandstone was encountered. Today, with the benefit of hindsight, this criterion for establishing excavation limits for horizontal thinly-bedded sedimentary rock is viewed as woefully inadequate, but Hatton and some, but not all, of his contemporaries considered this approach acceptable.

Careful examination of the dam site following the 1911 collapse revealed that the weak plane that precipitated failure of the dam was within the rock foundation at clay-filled bedding joints between sandstone and shale units (see Figure 7). This failure mode was first evidenced during Hatton's inspection of the dam on January 25, 1910 by an 18-inch-wide vertical cleavage in the foundation rock located 12 feet upstream of the upstream face and running parallel to it. Hatton's further details on the failure mode are: "Since January 25, 1910, water has been constantly impounded by this broken concrete wall. The depth of this water has varied from 25 to 52 ft. During this period water has continued to leak through the underlying strata, and this leakage, going on at great pressure, must certainly have washed much of the shale and gravel away, leaving the heavy concrete walls with less and less foundation until the final collapse came on September 30, 1911".[6]

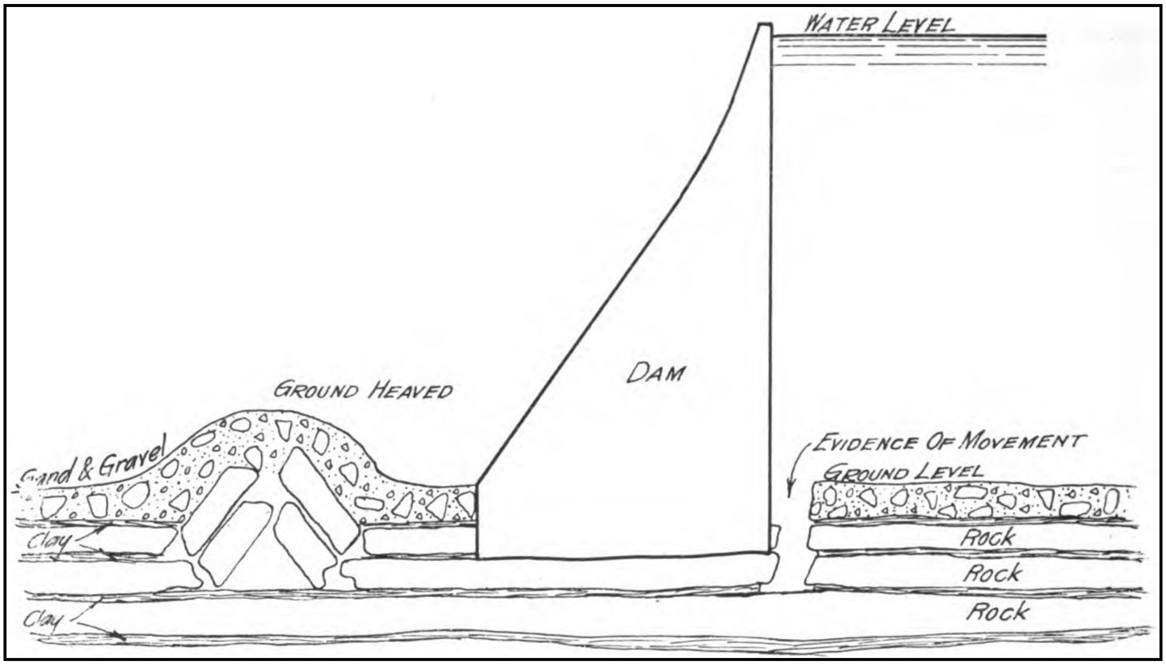

Figure 7. Schematic of Failure Mode – Slip Between Rock Layers [3].

3. **Uplift Forces Neglected**: Hatton recognized that uplift forces can develop beneath a gravity dam but incorrectly assumed that a rolled embankment (see Figure 6) at the upstream face could provide an impermeable water barrier and essentially eliminate this force. He also incorrectly assumed this embankment would reduce the hydrostatic pressure against the dam, rather than increase the net loading on the dam. Hatton cannot necessarily be entirely faulted for this approach, since many other gravity dams constructed during this era also have this feature, presumably for the same reason.

   It should be understood that in 1909, uplift forces were one of the least understood components of gravity dam design and views on how to properly treat this force in design varied widely. The general view was that uplift forces could not develop at the dam/foundation interface to any significant degree since the dam by its own weight placed the structure in positive contact with its foundation. A contemporary of Hatton, J.W. Ledoux, gave further details into this thinking when commenting on the Austin Dam failure. “In making this calculation it is considered conservative to allow for possible upward pressure. Under the worst conditions this might amount to half the hydrostatic pressure, but no one allows for more than a third, which is even then considered ultraconservative”.[3]

As early as 1895, Maurice Levy, a French engineer, proposed a principle, rejected by his peers, that equated to applying full headwater pressure at the heel (upstream face) to tailwater pressure at the toe (downstream face) over the full area of any horizontal joint including the dam’s base. It wasn’t until the mid-1950s, through advocates like Karl Terzhagi and L.F. Harza, that the profession began adopting the present practice first proposed by Levy.

4. **Key Wall:** During the years that followed the failure, too much significance was placed by Hatton’s contemporaries and by others on the benefit provided by a 4-foot-wide key wall that projected 2 to 4 feet into rock at the structure’s heel. Hatton explained that the key wall’s purpose was to increase the factor of safety against sliding. He did not intend for the key wall to serve as a seepage cutoff. The rolled embankment was intended for that purpose. Some have claimed that the key wall was never installed. Hatton met this accusation by providing construction photos to prove its existence. Field investigations performed by the U.S. Army Corps of Engineers in more recent years also confirmed the key wall’s presence. Regardless, Hatton and some of his contemporaries failed to understand the very limited structural value of such a relatively-thin and very shallow key wall. They also failed to recognize that a rolled embankment would not reduce hydrostatic pressure against the dam, but on the contrary actually increase loading above that which water alone would impart.

5. **Crest Height Modifications:** The original design provided four feet of available freeboard, which was intended to accommodate up to a three-foot-high wooden flashboard system with one foot of remaining freeboard for normal spillway discharges. During the last two months of construction, Bayless directed Hatton’s resident engineer to raise the dam crest by two feet to increase available freeboard. A few weeks after, Bayless directed the resident engineer to also raise the fixed spillway crest by two feet, apparently to permanently increase storage capacity. Sometime shortly after these initial directives, Bayless again directed the resident engineer to raise the fixed spillway crest by another two feet to further permanently increase storage capacity. At Hatton’s strong objections, Bayless acquiesced to raising the fixed spillway crest by three and a half feet instead of four. This three-and-a-half-foot raise in the spillway crest increased storage capacity at normal pool from 200 to 260 million gallons (614 to 800 acre-feet). The raise reduced available freeboard from four to two and a half feet. Since these increases in structural height were performed near the end of construction, the dam’s base width was not increased accordingly. As a result, the dam’s structural integrity and stability was further diminished.

6. **Inoperable Low-Level Outlet:** The original design included provision for a control valve located at the upstream end of the 36-inch-diameter low-level outlet pipe to provide a positive means to regulate reservoir level for maintenance or emergency purposes. The design also included a gate house at the dam crest to operate the valve. The gate house was eliminated during the design phase to reduce cost. Toward the end of construction, as an additional cost-saving measure, Bayless directed the contractor, despite Hatton’s strong objections, not to install the 36-inch valve but replace it with a wooden cap at the downstream end of the outlet pipe. This modification essentially rendered the outlet works inoperable whenever the spillway was active or the dam impounded any moderate height of water. When the sliding failure occurred in January 1910, the first necessary response action was to lower the reservoir, which this modification prevented. To lower the reservoir in an expedited manner, the paper mill staff used dynamite to blast an opening in the upper portion of the dam near the right abutment as well as blast the wooden cap free from the downstream end of the outlet pipe. It is possible that these measures in themselves could have caused failure of the dam.

7. **Conventional Construction Practices:** Some have proposed that inadequate construction practices were a leading factor in the failure. Hatton countered these accusations by providing several photographs

taken during construction and by explaining in sufficient detail that thin weathered sandstone and shale layers were removed within the foundation, the remaining rock surface was thoroughly washed, and that the stone and concrete mortar for the cyclopean masonry was carefully prepared and placed in 25 to 45-foot-wide monoliths with multiple keyways in both horizontal lift and vertical monolith joints. The surface of horizontal lift joints was washed and swept with wire brooms to remove laitance. The cement content for the concrete mortar consisted of 1.25 barrels of cement per cubic yard which equates to 475 pounds per cubic yard in today's units, which is more than adequate for a mass concrete structure. Every load of cement delivered to the site was subjected to a series of property tests before being allowed to be used in the structure.

McKibben's findings challenged Hatton's one claim concerning horizontal lift joint treatment, with photographic evidence demonstrating that a keyway(s) was missing from at least one particular horizontal lift joint in one isolated portion of the dam, since failure had cleanly occurred along it.

8. **Structural Cracking:** Shortly after construction was completed, two transverse cracks appeared in the dam, one 39.5 feet left (looking downstream) and the other 51.3 feet right of the spillway. Both were approximately 1/16-inch wide and extended the full visible height of the structure. Since both cracks occurred before any water was impounded, Hatton correctly attributed their cause to thermal stress. These cracks likely had no influence on the mode of failure of the dam.

9. **Repair Recommendation:** Wegmann's repair scheme, developed in February 1910, basically consisted of buttressing the dam at its downstream face with rockfill. It also called for a masonry (concrete) or clay puddle cut-off extending down to impervious strata overlain with a clay puddle bank in the vicinity of the upstream face (see Figure 8).

   Some have opined that if Bayless would have elected to implement Wegmann's repair scheme that the September 1911 failure could have been fully averted. However, it should be recognized that Wegmann never visited the dam site and only served in a capacity of providing general guidance to Hatton. If Wegmann had been given an opportunity to personally inspect the dam site, he may have concluded that the dam was beyond repair given that such significant displacement had occurred over a substantial portion of the dam such that both the structural integrity of the dam body as well as its foundation rock underneath had been seriously compromised.

   Even though Wegmann was a well-established world-class expert in gravity dams, he was also limited by the profession's knowledge base at that time. In examining the schematic that illustrates his proposed repair scheme, it can be noted that, even though the foundation rock is comprised of thinly-bedded sedimentary rock, Wegmann neglected to consider a more conservative and very plausible uplift pressure condition. The note shown in the schematic at the dam's base reads "Upward pressure under base and joints of dam is assumed equal to 2/3 of hyd pressure due to head at up-stream face and decreasing uniformly to 0 at down-stream face." With the degree of displacement that occurred in the dam and its foundation rock, it is highly possible that preferential seepage paths within the rock joints could have been either partially or fully pinched shut at or beyond the dam's toe. Such a condition could cause full uplift over a higher than normal portion of the dam's base.

   There are several other likely deficiencies with this repair scheme:

   - The apparent lack of understanding that the critical weak plane now existed in the slipped surface between bedding joints in the foundation rock and that only residual bedding joint strength was available to resist future loading;
   - The likely lack of effectiveness of the proposed seepage cutoff feature at the heel;
   - The lack of any type of drainage system to relieve foundation uplift pressure;
   - Neglecting to buttress the relatively-thin chimney section;
   - Neglecting to account for a more appropriate flood pool loading condition; and,
   - Neglecting to account for possible dam overtopping during flood events and its potential scour effect on the foundation rock.

Therefore, in the authors' view, this proposed repair scheme may only have delayed the failure of this structure, rather than prevented it. However, it may have reduced the vertical and/or lateral extent (e.g. chimney section only), and possibly even speed, in which failure developed, such that the release of reservoir water may have been less severe than that which resulted from the near-instantaneous and near full-length failure that did occur.

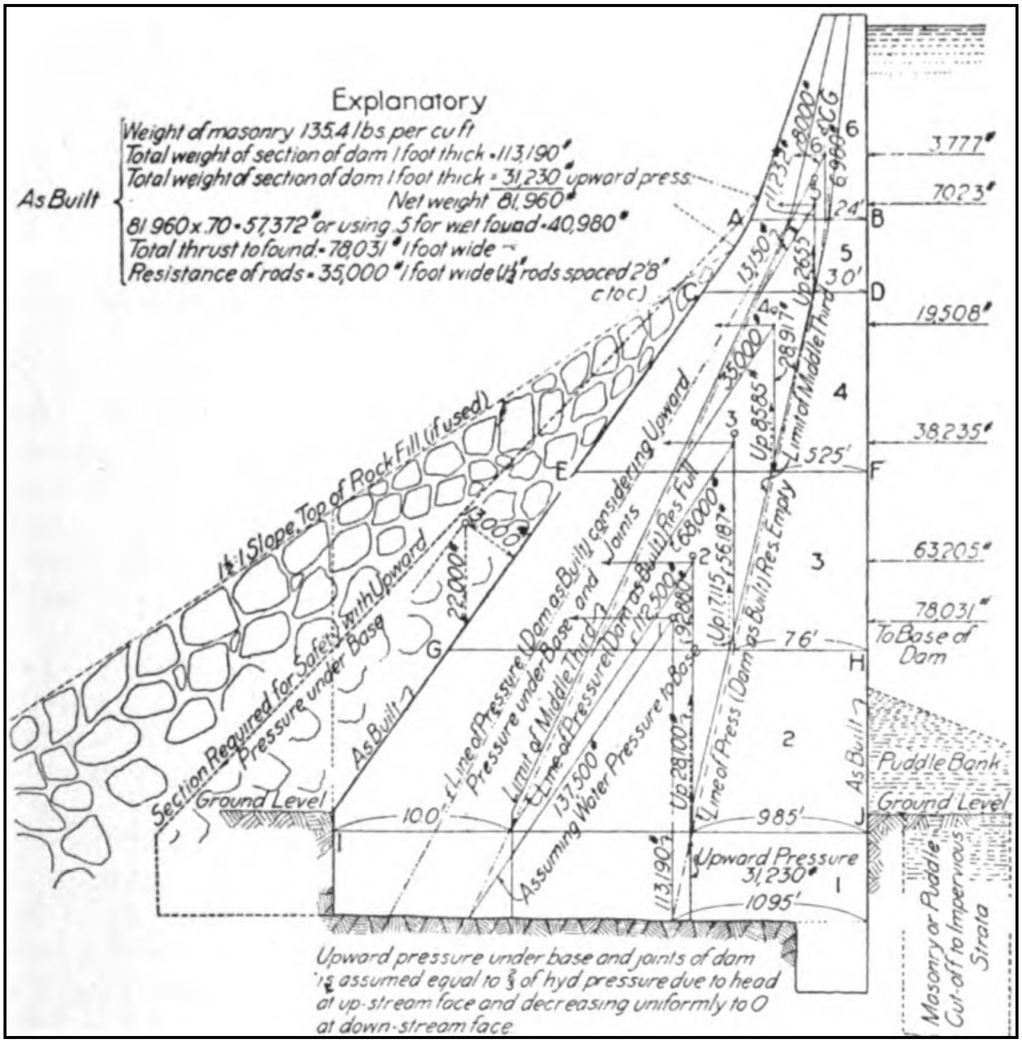

Figure 8. Proposed Repair by Edward Wegmann – February 1910 [2].

10. **Warning Signs:** By the accounts given, it appears that there was no formal plan for the first filling of the reservoir and associated dam performance monitoring. It is not fully known if such measures were even practiced then. However, it was common practice in those days to assign a person to serve as a "dam tender". The dam tender's sole duty was to perform water release adjustments and to monitor the condition of the dam and alert others to any noteworthy signs of changing conditions.
    Even without the benefit of a dam tender, there were ample warning signs observed prior to both the January 1910 partial failure and the September 1911 complete failure, that if acted upon more quickly, could have likely saved more, if not all, of those that perished as a result of this disaster. The observation of higher than usual rainfall or snowmelt runoff, landslides and seepage in the abutments, increases in seepage flow rates both along the toe and through cracks in the dam, and rapid increases in reservoir level all should have been cause to be on high alert and closely monitor conditions as well as give thought as to when and how to implement the evacuation of downstream communities, especially after the dam's integrity was placed into doubt after the January 1910 incident. The fact that no one from the

mill was present at the dam at the time of the 1911 failure, despite warning signs of changing and worsening conditions observed by mill employees that morning, demonstrates a lack of proper response to these warning signs.

11. **<u>"Sunny Day" Failure:</u>** The initial reporting of the January 1910 incident was characterized by Hatton and perpetuated by others as a "flood" induced failure. According to Engineering News [1], during the week of January 17th an unseasonably warm period, in combination with "some rain," caused the rapid melting of a heavy snowpack that resulted in the reservoir filling within three days. By Saturday, January 21st, the spillway was activated for the first time. Although this snowmelt event was likely unusual, no records suggest that the reservoir level ever exceeded the dam crest and if it did, it was not likely to a significant depth or for a significant duration, or such details would be expected to have also been reported. If the reservoir had been full prior to the snowmelt event, thereby preventing it from attenuating the heavy runoff, a true flood-induced failure and possible catastrophic collapse may have resulted. In either case, the use of a fully functional and adequately-sized low-level outlet may have helped to mitigate the situation. Hatton's describing the first incident as "flood"-induced leaves one to wonder if he was intentionally redirecting blame on a natural cause, although, to his credit, within a year he had publicly stated that the failure's cause lay at his feet.

    Again, in September 1911, even though heavy rains occurred for three consecutive days in the two weeks prior to the failure, the resulting runoff was attenuated by the available reservoir storage and leakage. On the day of failure, several eyewitness accounts indicated that the reservoir level was within a half inch of the spillway crest and that wind caused waves to occasionally pass over the spillway. This reservoir level was the highest the dam had experienced since the January 1910 incident. Of interest is that, within a very short period of time (less than two weeks) after the reservoir was returned to its full state, which was the same state that caused the partial failure twenty months prior, complete catastrophic failure occurred.

12. **<u>Reaction to the Failure</u>**: At the County coroner's inquest, key paper mill employees pleaded the Fifth Amendment and refused to give testimony as to why the reservoir was allowed to return to its original normal pool level (50 foot depth) without making any significant repairs to the dam, thus returning the loading on the dam to the same or similar condition that existed when it slid in January 1910. It may be that, since the dam in its compromised state was still able to successfully impound a depth of water up to 40 feet and greater, Bayless and the mill superintendent may have been lulled into a false sense of security. Bayless himself stated to Hatton back in December 1910 that "…we have practically proved that the dam has found a secure footing and will not slide further" [11].

    Bayless later explained in a statement to the New York Times [2], published three days after the September 1911 failure, that he viewed Hatton's repair scheme as only necessary if the dam was required to impound the full depth of 50 feet. He indicated that since the mill was able to function with a 40-foot-deep impoundment, they didn't see any need to perform the recommended repairs. This statement conflicts with the fact that at the time of failure, work was underway to restore the dam to its full function so that the reservoir could provide full storage. In fact, the first signs of failure occurred at the wooden forms that were still in place where concrete was to be placed to fill one of the two breaches previously created by blasting.

    All of this suggests that the risk of failure and its potential consequences were inadequately assessed and possibly even criminally ignored by those in responsible charge. The mill superintendent's wife later told reporters that when she asked her husband about any reservations regarding the dam's condition, he replied "I'm not exactly afraid of the dam, but you can never tell. I want my family to be on the safe side of the hill (referring to his home's location) if it ever does break" [11]. From the time of the first incident until the day of catastrophic failure, many of Austin's townspeople perceived the danger and regularly voiced their concerns. Unfortunately, these concerns fell on deaf ears, since Austin's police chief and mayor positions were held by prominent mill employees. As such, any concerns were downplayed by local public officials for the sake of keeping the mill in operation at minimal cost.

The most relevant factors contributing to the failure were an inadequate assessment of the foundation and an inadequate design, the latter being driven by budgetary constraints aggressively held by the owner in combination with wide varying views within the profession in how to properly address destabilizing uplift forces. Below is an excerpt of Hatton's own words as to the leading causes of the failure:

> "The failure of this dam was not the result of poor workmanship, but poor judgment upon my part. I should have sought the advice of a man more skilled than I in determining foundations for dams. Had there been such a state officer it might have resulted in saving this dam and my reputation.
>
> I was also too much influenced in my judgment by the necessity for keeping the expenditure within certain limits. I have since felt a very grave responsibility for my failure to advise my client early in my engagement that no paring down of this work should be countenanced. Had I done so, either the dam would not have been built, or it would have been built in accordance with my first design. The owner had no intention at any time of building a dam the safety of which he doubted, and no blame can be attached to him for its failure on January 23, 1910. He depended upon my judgment entirely, even though he may have tried to influence me to keep the expenditures down to the lowest possible limit.
>
> To the young engineer who is called upon to design an important structure, the safety or sufficiency of which he is not entirely satisfied with, I would strongly urge the wisdom of calling to his help the advice of an older engineer especially skilled in that particular line. Never sacrifice safety for cost, no matter how urgent your client may become. He does not realize the danger, and you should. If you cannot agree with him, resign your engagement, for sooner or later the reckoning will come".[6]

Hatton's words of wisdom are just as true today as they were a century ago. It should also be noted that he is clear to distinguish between his role in what occurred on January 23, 1910 compared to the tragedy that took place twenty months later on September 30, 1911. The January 1910 incident could have been a lesson, albeit a costly one, in how disaster was narrowly averted despite the design engineer's errors in judgment. Had the owner, the mill superintendent, the townspeople, and other stakeholders placed more value in erring on the side of caution by recognizing that, in its compromised state, the dam still posed some type of danger, even if not fully understood, since they had limited ability in preventing the reservoir and corresponding structural loading from returning to the level that preceded the first incident, then the ultimate disaster could have been avoided. To their credit though, up until this time, most failures like the South Fork Dam in Johnstown, Pennsylvania were coincident with a natural flood such that the possible dangers of a "sunny day" failure during normal operations was difficult for anyone to comprehend. This lack of knowledge, coupled with the pressure to reap a return on the initial investment in the dam, regardless of its questionable state, and to maximize mill production capacity by allowing the reservoir level to return to dangerous levels, sealed their fate.

III. HUMAN FACTORS

A. The Role of Human Factors in Dam Failure and Safety

Physical processes associated with loads on dams, and the behavior of dams in response to those loads, deterministically follow physical laws, with no possibility of physical "mistakes." Therefore, dam failures – in the sense of human intentions not being fulfilled – are fundamentally due to human factors, as a result of human efforts individually and collectively "falling short" in various ways.

Dam failures are typically preceded by interactions of physical and human factors which begin years or decades prior to the failure. These interactions are often not simple and linear, and usually generate warning signs which are not recognized, or not sufficiently acted upon, prior to the failure. The Bayless Dam failure perfectly illustrates this pattern, with the seeds of the eventual failure being planted during the planning and design of the project, and many warning signs which were generated by the dam being misinterpreted or dismissed over a period of almost two years before the failure.

A natural tendency is for systems such as dams to move towards disorder and failure, in line with the concept of increasing "entropy" in physics. Therefore, dams are typically not inherently "safe," and continual human effort is needed to maintain order and prevent failure. In the case of Bayless Dam, the efforts to prevent failure evidently fell far short.

With these observations in mind, the propensity towards dam failure can be viewed as being determined by the balance of human factors which contribute to failure ("demand") versus those which contribute to safety ("capacity"). Thus, applying a standard engineering metaphor, failure results when human factors demand on the system exceeds capacity, and safety results when capacity exceeds demand. For Bayless Dam, human factors placed a safety demand which far exceeded its capacity and generated a timeline which led to the dam failure and the destruction of two towns with a loss of 78 lives.

B. Pressures Which Drove Failure of Bayless Dam

The human factors contributing to safety "demand," and therefore the potential for dam failure, can generally be placed into three categories of primary drivers of failure:

1. **Pressure from non-safety goals** competes with the goal of dam safety. Such non-safety goals include delivering water, generating power, reducing cost, increasing profit, maintaining property values, meeting schedules, protecting the environment, providing recreational benefits, building and maintaining relationships, personal goals, and political goals. In the case of Bayless Dam, there were heavy pressures from the president of the paper company, and possibly also the shareholders in the paper company, to keep the cost of the project within a strict budget which was too tight to allow a safe dam design. In addition, operational decisions were made in the interest of maximizing the reservoir storage in order to supply water to the paper mill, which increased the loading on the dam and ultimately led to its failure. After the failure, Hatton, as the dam designer, acknowledged that he unwisely acquiesced to these pressures rather than pushing back and taking a firm stance that he was unwilling to design a dam with questionable safety margins. The dam's superintendent similarly acquiesced to pressures to keep the project's costs down and maximize the reservoir storage, while harboring enough doubt about the safety of the dam to want his own family to reside outside the potential floodpath of the dam.

2. **Human fallibility and limitations** include misperception, faulty memory, ambiguity and vagueness in use of language, incompleteness of information, lack of knowledge, lack of expertise, unreliability of intuition, inaccuracy of models, cognitive biases operating at the subconscious level and group level, use of heuristic shortcuts, emotions, and fatigue. Essentially all of the parties involved with Bayless Dam displayed fallibility across this spectrum, primarily reflected in their not having a good understanding of the physical behavior and potential failure modes of the dam, which resulted in numerous erroneous judgments and unsafe decisions. In addition, the state of knowledge in the dam engineering profession at that time was also lacking with respect to aspects such as uplift and potential for foundation shearing, while there was simultaneously some overconfidence in the dam engineering profession in the ability to accurately model concrete gravity dams, due to the recent advent of theory-based "rational" mathematical methods of analysis.

3. **Complexity** results from multiple system components having interactions which may involve nonlinearities, feedback loops, and network effects. Such interactions can result in large effects from small causes, including "tipping points" when thresholds are reached, and they make complex systems difficult to model, predict, and control. Complexity generally exacerbates the effects of human fallibility and limitations. While many laypeople and even engineers may perceive gravity dams to be relatively "simple" structures (a wedge of concrete holding back water), our modern understanding of gravity dam physics is that such dams can have complex interactions between factors such as uplift pressures within and under the dam, seepage, foundation deformation and stresses, and concrete deformation and stresses. These interactions can become more complex when a dam has already experienced significant deformations and partial failure, as was the case with Bayless Dam after it experienced partial failure in 1910, less than two years before it completely failed.

The primary drivers of failure lead to various types of "human errors," which can include categories such as "slips" (actions committed inadvertently), "lapses" (inadvertent inactions), and "mistakes" (intended actions with unintended outcomes, due to errors in thinking). In the context of dam safety, mistakes are the most common type of human error which contributes to failures. Many such mistakes were made with Bayless Dam.

Human errors and the underlying primary drivers of failure noted above often lead to inadequate risk management. Inadequacies in risk management may be classified into three types:

1. **Ignorance** involves being insufficiently aware of risks. This may be due to aspects of human fallibility and limitations such as lack of information, inaccurate information, lack of knowledge and expertise, and unreliable intuition. Complexity can also contribute to ignorance.

2. **Complacency** involves being sufficiently aware of risks but being overly risk tolerant. This may be due to aspects of human fallibility and limitations such as fatigue, emotions, indifference, and optimism bias ("it won't happen to me"). Pressure from non-safety goals can also contribute to complacency.

3. **Overconfidence** involves being sufficiently aware of risks, but overestimating ability to deal with them. This may be due to aspects of human fallibility and limitations such as inherent overconfidence bias, which results in overestimating knowledge, capabilities, and performance.

In the case of Bayless Dam, there was certainly inadequacy of risk management due to ignorance. However, it is likely that at least some of the parties perceived the dam to pose an excessively high failure risk, which would mean that risk management was also compromised due to complacency and/or overconfidence. Hatton in particular, as the designer and the owner's primary consultant, seemed to display overconfidence prior to the failure, in contrast to the considerable humility he displayed after the failure.

C. Inadequacy of Safety Culture and Implementation of Best Practices

Counterbalancing the drivers of failure noted above, the human factors contributing to system capacity for safety generally emanate from what is routinely referred to as "safety culture." The general idea of safety culture is that individuals at all levels of an organization place high value on safety, which leads to a humble and vigilant attitude with respect to preventing failure. For such a safety culture to be developed and maintained in an organization, the senior leadership of the organization must visibly give priority to safety, including allocating the resources and accepting the tradeoffs needed to achieve safety. It appears that the paper company had a rather poor safety culture, as reflected by its series of decisions which typically prioritized cost reduction and profit maximization over dam safety. This relatively weak safety culture may not have been atypical among dam owners during this period in US history.

Experience in dam safety shows that strong safety cultures naturally lead to implementation of numerous "best practices" for dam safety risk management. As a corollary, dam incidents and failures are typically preceded by long-term cumulative neglect of numerous accepted best practices. These best practices can be organized into two categories: 1) general design and construction features of dam projects, and 2) organizational and professional practices.

Best practices for general design and construction features of dam projects include application of generally-accepted best practices, design conservatism, customization of the design to the site, and reasonable budget and schedule contingencies to account or unforeseen conditions. Bayless Dam was lacking in all these aspects, with the design being generally unconservative, the foundation being inadequate with respect to seepage, uplift, and shear strength, and an overly rigid project budget with essentially no provision for contingencies.

Best practices for organizational and professional practices include having sufficient organizational staffing and budget resources, a humble learning culture which draws on expertise within and outside the organization, decision-making authority assigned based on responsibilities and expertise, emergency action planning, and vigilance with respect to warning signs. The Bayless paper company and the designer of the dam fell short in all of these areas: the paper company was focused on production and profits and didn't allocate the resources needed to design and manage a safe dam, both the paper company and the designer displayed overconfidence and made judgments and decisions well outside their areas of expertise, the president of the paper company made decisions to raise the dam and spillway to increase the reservoir storage without even consulting the designer, there was apparently no semblance of any kind of emergency action planning nor even a sense of responsibility in that regard, and numerous warning signs were ignored over a period of almost two years.

In summary, organizations which are capable of handling demands on safety from various drivers of failure have a strong safety culture and diligently implement numerous best practices. Such organizations are mindful, cautious, humble, oriented towards learning and improving, resiliently adaptive, and maintain high professional and ethical standards. They vigilantly search for and promptly address warning signs before problems grow too large, and they make effective use of available information, expertise, resources, and management tools to properly balance safety against other organizational goals. The Bayless paper company and the designer of the dam fell far short in displaying these attributes, and the result was a catastrophic dam failure which destroyed two towns and cost 78 lives.

IV. LESSONS TO BE LEARNED

The description given above of the Bayless Dam failure serves as a sober reminder of the duties of owners, engineers, and regulators charged with the safety of dams. Furthermore, dam failures and incidents continue to occur, as evidenced by the recent events at Oroville Dam (California, 2017), Spencer Dam (Nebraska, 2019), and Edenville Dam (Michigan, 2020). While the exact combination of physical and human factors that led to these dam failures and incidents were unique, they each have commonalities with the Bayless Dam failure from over 100 years ago. Many of the various factors that contributed to the Bayless Dam failure still have the possibility of occurring today. Below is a brief description of the key lessons to be learned from this engineering disaster:

1. **State Dam Safety Programs:** This failure resulted in an outcry for state supervision of dams to better protect the public. The principal investigator of the Bayless Dam failure, Prof. Frank McKibben, became a vocal advocate for state supervision. He did acknowledge that it should not be viewed as a panacea but as a means of additional oversight. On June 25, 1913, Pennsylvania's first dam and encroachment act was passed into law. This new law gave state officials the ability to regulate the design, construction, and operation of jurisdictional dams.

2. **Foundation Assessments:** At the time the Bayless Dam failure occurred, the critical importance of adequate foundation assessments for dams was just starting to be recognized. It would take several decades before the profession developed appropriate standards for foundation investigations and associated design practices.

3. **Loading Diagrams:** Proper development of site-specific loading diagrams and related assumptions is an important aspect for any dam design. Key assumptions include selection of dam and foundation material properties that are readily defensible and appropriately conservative. In 1909 and for several decades following, only the "reservoir full" and "reservoir empty" loading cases were considered in design in conjunction with very simple rules of thumb for material strength properties.

4. **Safety Factors:** Since certain parameters for hydrologic and structural analyses will always have some degree of uncertainty when assigning a design value, and since construction inherently introduces its own uncertainty as a result of varying levels of quality in the completed structure, appropriately conservative factors of safety need to be applied to mitigate this unavoidable variability.

5. **Peer Review:** Hatton would be the first to support the notion that no engineer, design team, or organization is infallible. Therefore, peer reviews should be a basic requirement for designs and certain structure modifications considered during construction. Some state dam safety agencies are well-equipped to perform this role. When this is not the case, either the owner or state should enlist the services of qualified independent experts to perform this duty.

6. **First-Filling Monitoring Plans:** Development and execution of first-filling monitoring plans should be employed for any new or rehabilitated dam structure to confirm its performance capability, within the degree possible, before being released for long-term service. A similar practice has been in use for decades by other engineering professions involved in fields such as shipbuilding and aircraft manufacture for the same reason.

7. **Surveillance Plans:** The value of surveillance plans is best realized if the owner's personnel are adequately trained in the various warning signs that indicate the possibility of changed and actionable conditions. The personnel should understand how the warning signs are related to potential failure modes, and not merely treat them as thresholds below which no action is required.

8. **Potential Failure Modes Analysis:** Designs for new and rehabilitated dams should include a potential failure modes analysis so that proper attention is given during design and construction to the most critical site-specific factors that could otherwise jeopardize the structure's safe performance.

9. **Failure Consequences:** Historic failures of both gravity and embankment dams have sadly demonstrated the destructive power of these manmade structures. Fortunately, with the advent of modern computers and software, engineers are now able to reasonably determine the potential consequences of failure for any dam. This has helped heighten the awareness of potential dangers as well as better equip stakeholders in emergency preparedness.

10. **Emergency Action Plan (EAP) Exercises:** The entire series of emergency response events that unfolded, starting with conditions leading up to the reports of failure, followed by the evacuation of mill employees and Austin and Costello townspeople, and finally the relief effort following the disaster's aftermath, is surprisingly well documented and a highly worthwhile study in itself. Dam owners and emergency responders would do well to learn as much as possible from what transpired during this tragic event and others like it.

    The benefits of EAP exercises are best realized when both dam owners and emergency responders are involved, so that weaknesses in protocol procedures and duty assignments can be exposed and corrected before a real emergency occurs. Dam owners should not lose sight that the value gained from such exercises can usually be readily transferrable to a wide spectrum of other types of potential emergencies and facilities.

11. **Low-Level Outlet Works:** Under some emergency situations, disaster can be avoided if the dam has an adequately sized and functioning low-level outlet works. As dams continue to age, owners need to recognize that the design life of the key components of the outlet works is much shorter than the dam body and therefore major maintenance or replacement should be performed on a shorter time interval.

12. **New Technology:** Since the failure consequences of significant and high hazard-potential dams are relatively severe, the profession's adoption of any new technology or unconventional design features for these structures (such as Hatton's unique and untested design of the chimney section that was adopted as a cost-saving measure) should first undergo thorough theoretical examination and laboratory and field trials to prove performance capabilities.

13. **Professional Societies and Other Educational Opportunities:** Even though, by his own admission, Hatton erred in his judgment in the design of the Bayless Dam, he should be applauded for his willingness to go before his peers at professional society meetings to explain, as best he could, his understanding of what went wrong and why. One of the great benefits of active involvement in professional societies is its forum for the exchange of information related to new technology as well as to practices which should be avoided.

    Furthermore, the site of the Bayless Dam failure has been preserved as the Austin Dam Memorial Park and was added to the National Register of Historic Places in 1987. Dam failure sites can provide important opportunities to honor victims, educate dam safety professionals, and raise public awareness of both the risk posed by dams as well as the numerous benefits dams provide. [13]

14. **Human Factors:** Dam failures are typically preceded by interactions of physical and human factors which begin years or decades prior to the failure. In order to counterbalance these factor; dam owners, consulting firms, and regulatory agencies should strive to foster a safety culture where individuals at all levels of an organization place high value on safety, which leads to a humble and vigilant attitude with respect to preventing failure.

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