The Fontenelle Dam Incident: The Investigation, Likely Causes, and Lessons (Eventually) Learned

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Summary

The Bureau of Reclamation's 127-foot-high Fontenelle Dam almost failed by internal erosion during first filling in 1965. The reservoir contained 345,000 acre-feet (or 113 billion gallons) of water. Within 24 hours of the discovery of seepage, seepage had eroded a hole 70-feet-wide, 60-feet-deep and 200-feet-long in the downstream slope of the dam. It was only through prompt intervention and dumping of the reservoir that the dam was saved.

Like many seepage problems, the Fontenelle leak problem was related to the foundation (in this case the abutment) and the dam embankment interface with the foundation. This paper reviews original site investigations, geology, dam design, construction, seepage performance, the incident that nearly failed the dam, the subsequent investigation, likely causes of failure, the lessons learned at the time, and lessons for our time and the future.

Dam Site Geology

The Fontenelle Dam site is located in southwest Wyoming about 45 miles northwest of the town of Green River. The dam site is located around elevation 6400 within the Upper Green River Basin – a broad structural basin surrounded by higher mountain areas. The basin floor consists of three formations (from youngest to oldest) the Wasatch, Green River, and Bridger formations. These consist of shale, sandstone, and limited fresh water limestone. These formations are the result of sediment deposition and lie in nearly horizontal beds.

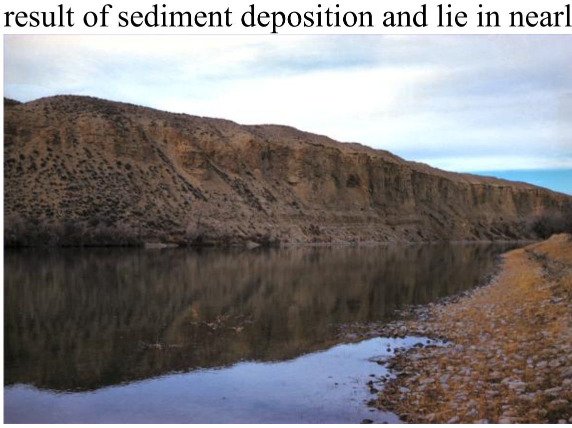

Figure 1: Cliffs at location of right abutment

Figure 2: Highly fractured sandstone at the right abutment.

Site reconnaissance began in the 1950's. The site selected is located within a wide-bottom, 5,000-foot-wide Green River valley with steep cliffs on the right (east) abutment (the location of the main erosion incident) (see figure 1) and a gently sloping left or east abutment. The foundation and abutment rock consists primarily of the Green River formation and has a grey-white or olive green appearance. The rock is exposed from the river up and beyond the future crest of the dam. At the dam alignment, the river is located at the foot of the right abutment cliffs. The Green River Formation rock at the site consists of shale, siltstone and sandstone. The rock is nearly horizontally bedded with a 1-degree dip to the downstream. In the steep right abutment, there are settlement cracks and relief joints (see figure 2).

An early site reconnaissance site report [1] stated that "With impervious formations underlying the reservoir … it seems certain that there will be no seepage from the reservoir." This report also stated that "Geologic conditions are favorable for construction of an earth dam."

Right Abutment Geology

The right abutment ranges in elevation from 6390 to 6519. Below elevation 6415, in the area of the grout cap, the rock is sandstone. From elevation 6415 to elevation 6442, the rock is nearly horizontal with lenticulary bedded shale and siltstone [2].

From elevation 6442 and 6505 (elevations of the most interest regarding the leak incident) the rock is predominantly massive, homogeneous, fine-grained, sandstone and siltstone. There is no evidence of bedding in this upper area. The upper area is continuous upstream. Downstream, it becomes increasingly bedded and lenticular with increasing amounts of platy siltstone and thin lenses of fissile shale [2].

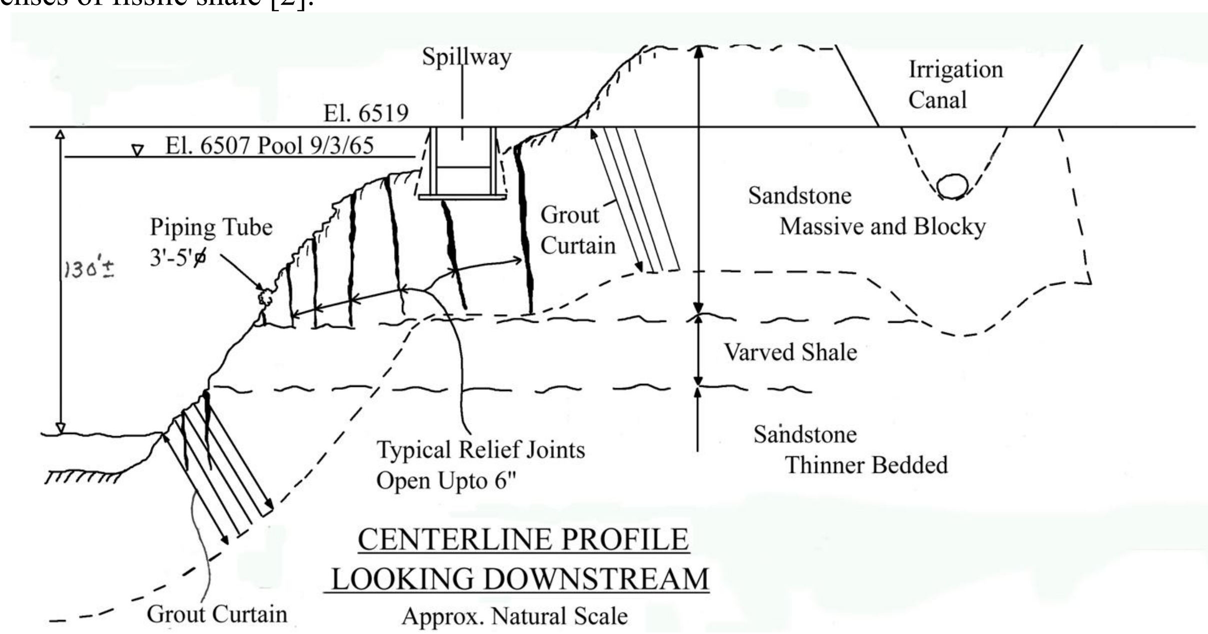

Figure 3: Section of the right abutment looking downstream

Relief joints, generally parallel to the valley, occur in the massive sandstone (see figure 3). These joints extend the full length and depth of the unit. They are formed due to removal of lateral support and aggravated by weakness in the underlying shale bed. [2-REF Geologic Appraisal of Right Abutment]

Dam Design

During the 1960s, Reclamation was designing and building many dams. An emphasis was on economy and expediency. The paper *Fontenelle Dam, Ririe Dam, and Teton Dam – An Examination of the Influence of Organizational Culture on Decision-Making*, Snortland, [3] provides a description of Reclamation's standard design/construction practices and methodologies of that time. For many embankment dams, a common general design included an impermeable core, more permeable shells, a cut off trench and a single line grout curtain.

A version of this general design was used at the 127-foot-high Fontenelle Dam (see figure 4). The Zone 1 core consists of a mixture of sand, silt, clay and gravel compacted by tamping rollers in 6-inch lifts. The Zone 2 shells were a mixture of free draining sand, gravel, and cobbles compacted by crawler-type tractors and placed in 8-inch lifts. And a Zone 3 (random) was included within the downstream Zone 2. It consisted of miscellaneous materials obtained from excavation, compacted by tamping rollers, and placed in 12-inch lifts.

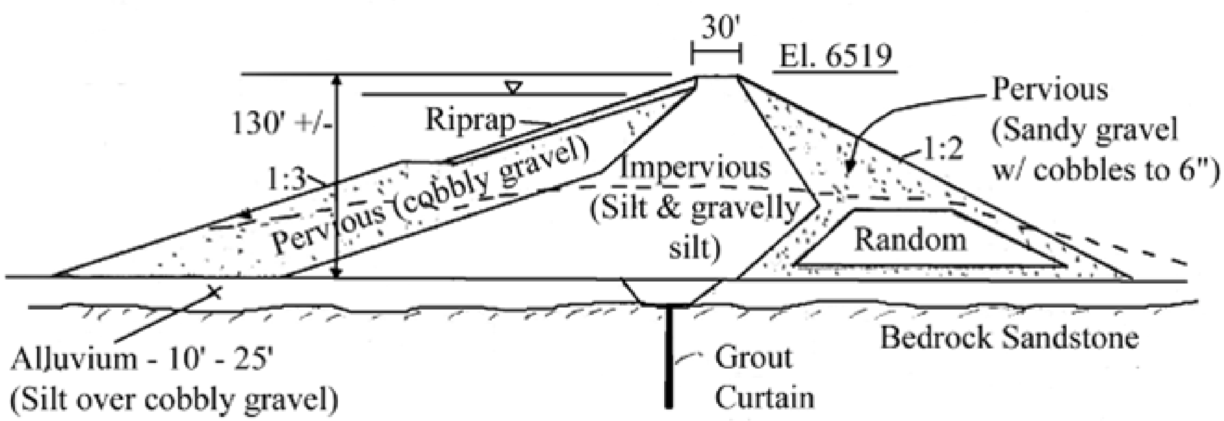

Figure 4: Fontenelle Dam typical cross section

The rock in the area was deemed adequate for upstream rip rap, however degradation over time was expected. The rip rap thickness was increased to 5-feet normal to slope and an extra 7,500 cubic yards were specified for stockpiling for future maintenance [4].

Abutment Design Considerations

The designers knew that "…this (right) abutment was going to require significant treatment". From the Design Considerations document:

> Special attention must be given to the contact between the cliffs and the right abutment. Rock spires, detached blocks, and loose, weathered rock should be removed to provide a solid and firm foundation. Overhangs and steep vertical or near vertical cliffs should be reduced to slopes of ½:1 or flatter under the Zone 1 portion of the dam. In short, all irregularities should be removed to give reasonably smooth foundation contours. Special compaction of the earthfill will be necessary against the exposed sound rock abutment [4].

Special compaction of earthfill materials was to be performed where larger equipment could not access, including, “the earthfill material abutting the rock cliffs of the right abutment” [4].

The designers planned to grout the vertical relief joints (see Grouting Program below).

A toe drain near the right abutment under Zone 2 was planned but not designed or constructed [4] because Zones 2 and 3 were thought to be adequately draining.

Grouting Program and Construction

The foundation of the mile-long dam consists of fine-grained and bedded sandstone. The designers specified an 80-foot-wide cut off trench and a single line grout curtain (see figure 5). The grout curtain extended 60 feet into the foundation. Grouting was performed on 10-foot centers in the trench with additional holes in areas of high grout take. A 3-foot by 3-foot notch was excavated in the bottom of the cutoff trench to cut-off seepage in the rock directly below the embankment fill. Following grouting the grouting program, this notch was filled with concrete and became the grout cap (see figure 6).

Figure 5: Top of grout curtain

Figure 6: Cutoff trench with grout cap

The cliffs on the right abutment required extensive stripping to bring the slope to ½ to 1 as called for by the design. This stripping was done by a dragline crane dragging its bucket up the slope. According to the project construction engineer, all joints were filled by puddling in a slurry of soil and water. The impervious material was hand-tamped for a width of 2 feet next to the abutment. Photos indicate rock overhangs and discontinuities were left in place during embankment placement (see figure 7).

Figure 7: Panoramic image of right abutment with embankment placement at approximate elevation of 6438. Note overhangs and discontinuities.

The grout curtain continued up the steep right abutment (see figures 8 and 9) where the rock was predominately massive, homogeneous, fine-grained silty sandstone and siltstone. The holes were spaced at 5- to 2-1/2- foot centers. Grout takes were heavy in the area of the spillway and right abutment. This massive character extends upstream with a more bedded character downstream. The grout cap was so steep in places that ladders were used for personnel to access the full length of the grout cap. A special challenge was grouting near the surface where excessive grout pressures would cause uplift of the upper-most rock. This was especially challenging in the steep right abutment. Sediment or other material in the cracks may have prevented adequate spread of grout.

Figure 8: Right abutment with Zone 1 at elevation 6438. Note shale layers overlain by sandstone.

Figure 9: Detail of Figure 8. Sandstone and grout cap at approximate elevation 6450.

A total of 7,913 sacks of grout were injected by gravity into joints. The largest take at one hole was within 6 feet of the surface at approximate elevation 6454. The take was 1,753 sacks [3]. It was common Reclamation practice to perform additional grouting following initial filling of embankment dams.

Changes During Construction

Earth Dam Section engineers visited the construction site in March 1963. In reviewing the progress of the grout curtain, they found that one hole took 457 sacks of grout. Another hole leaked out of the abutment 300 feet upstream of the grout curtain. Numerous surface leaks occurred on the face of the right abutment (both upstream and downstream). In their travel report, they stated, that, "…it cannot be determined definitely that an effective grout curtain has been established" and "… is not considered adequate" [5].

In response, they recommended the addition of a supplemental grout curtain in the right abutment about 10 feet upstream and parallel to the existing grout curtain. This supplemental grout curtain extended to elevation 6475 (about two-thirds of the dam height) and tied into the grout curtain in the spillway area.

The engineers also did a quick study to determine whether the Zone 1 could be widened where it abuts the abutment. No deep cutoff was considered necessary and only "…thorough stripping of the abutment will need to be done" [5]. The Zone 1 was constructed with an additional 80 feet in the upstream direction.

These extra actions (additional grout curtain and widened Zone 1) "…should provide adequate protection against seepage into the spillway chute" [5].

The construction was substantially complete in November 1963.

1964 and 1965 Reservoir Operations and Seepage

The reservoir only filled about half-way during 1964. Even with this low elevation, there was significant seepage through both abutments and in the downstream borrow area B immediately downstream from the dam.

In 1965, there was very high snowpack and runoff. Due to damage in the outlet works stilling basin, flows were limited through the outlet works and the spillway passed the majority of the high spring runoff event. The reservoir quickly rose up to 5 feet above the spillway crest and only 2 feet below the design water surface elevation. Seepage flows in 1965 totaled about 70 cfs and extended several thousand feet downstream.

Embankment Slides Near the Spillway

On May 7, 1965 seepage emerged from the abutment rock adjacent to the spillway saturated embankment fill and caused erosion. A 12-inch perforated CMP was installed in the bottom of the eroded area.

Again on June 26th, the material saturated and slid away (see figure 10) leaving an erosion hole 25-feet-wide by 50-feet-long and 10-feet wide at the upper end.

On July 8, the material slid for a 3rd time (figures 11 and 12). Seeping water was observed squirting from the rock formation in numerous places.

Figure 10: The second embankment slide to the right of the spillway on June 27, 1965

Figure 11: The third embankment slide on July 27, 1965

Figure 12: Third embankment slide. Seeps issuing from vertical cracks in sandstone.

Friday, September 3rd Leak

[See the historical documentary *The Race to Save Fontenelle Dam* by the author for a graphic depiction of the 10-day leak emergency. See the *Leak at Fontenelle* [6] for a written report and technical details.]

On September 3, the reservoir was 1.7 feet above the spillway crest. During his regular Friday leak observations at about 11:00AM, the Project Construction Engineer (PCE) observed a trickle of seepage about 50 feet to the left of the left spillway wall about halfway up the dam downstream slope. By 7:00PM the seepage had increased to 10 to 15 cfs. A 60-foot-long conical-shaped erosion hole had formed in the downstream slope of the dam.

Recreationalists camping downstream of the dam were relocated, ranchers downstream were advised to leave the area, and the town of Green River was notified to be prepared to evacuate if the dam failed. By nightfall, the leak flows stabilized at 20 cfs.

Saturday, September 4th Intervention

By morning the eroded hole was 80-feet-wide, 60-feet-deep and 200-feet-long (see figures 13 and 14). A leak flow of about 20 cfs was coming out of the embankment at the contact with the right abutment rock at elevation 6447. Importantly, the flow was very muddy in color indicating internal erosion was actively occurring (see figure 13).

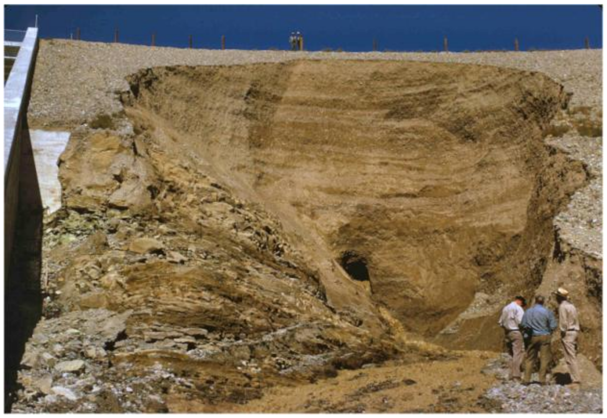

Figure 13: The erosion hole about noon on Saturday September 4. Note 4-foot-diameter leak exit tunnel adjacent to the right abutment rock.

Figure 14: Erosion hole about 4:00PM Saturday September 4. Dump truck is dumping rock to create a windrow at downstream end of erosion hole.

Two failure modes appeared likely:

<u>Failure Mode 1</u>: The ongoing piping of embankment materials within the dam continues. Larger and larger voids are created deep within the dam. The reservoir breaks through the upstream slope into the voids. The reservoir connects with the leak exit point and the pipe quickly enlarges. The crest breaks through and the reservoir is released.

<u>Failure Mode 2:</u> The widening and elongating downstream face erosion hole continues to enlarge in the upstream direction. The erosion hole envelopes the crest and then reaches the reservoir. The reservoir water pours down into the erosion hole, quickly erodes away remaining embankment core and releases the reservoir.

The Chief Engineer (CE) and his top engineering staff from Denver arrived at the site on Saturday morning September 4th. To address failure mode 1, the CE made the decision to dump the reservoir as quickly as possible. First the contractor working in the outlet works stilling basin had to remove as much as his equipment as possible. At 3:00PM, the outlet works were opened to 15,000 cfs. This would lower the reservoir 4 feet per day.

To address failure mode 2, the CE directed that a windrow of rock be placed along the left side of the bottom of the erosion hole (see figure 14). This would crowd leak flows against the abutment rock. The windrow was constructed first at the downstream end of the eroded hole by dumping and dozing rock as far up the cavity as considered safe. Rock was also dumped over the upstream edge of the eroded hole from the dam crest. Consideration was given to constructing a weir at the mouth of the slough to raise the elevation of the leak exit with a corresponding reduction in the hydraulic head – however, this was never constructed.

Sunday, September 5th Surging

By Sunday morning, 1700 cubic yards of rock had been dumped in the hole (see figure 15). As the rock tumbled down the 60 feet of embankment height, it brought with it embankment material. This rendered the rockfill relatively impervious and effectively dammed the leak. As the rock/soil berm enlarged, the leak exit point moved up and to the right along the contact with the abutment. This caused further sloughing of the upstream face of the erosion hole. The CE directed continued rock placement with perhaps complete filling of the erosion hole.

Figure 15: By Sunday morning September 5th a large rock berm was created in the left side of the erosion hole. However, the berm was dirty and blocked the leak exit forcing the exit point higher and toward the spillway.

Figure 16: At 3:00PM Sunday, there began a series of sudden surges of up to 35 cfs.

At 3:00PM, a series of surges began (see figure 16). These surges were up to 35 cfs. After each surge, the leak flow dropped significantly. Water pressure built up and then broke free causing the surges. The PCE thought the dam might fail and contacted the down of Green River by radio and told the authorities to be on heighted alert for evacuation. After an hour, the surges subsided and by nightfall leak flows were again steady.

Monday, September 6th Sinkhole

On Monday, reservoir releases continued. At 4:45PM a sudden and alarming event occurred. A 15-foot by 20-foot section of the crest road near the spillway suddenly and quickly collapsed (see figure 17). The sinkhole was in line with the downstream erosion hole. The PCE inspected the sinkhole by standing on the edge and peering down into the hole. He measured it and found it was 31 feet deep. Toward the bottom, it enlarged an additional 10 to 15 feet in the downstream and left direction - in the direction of the leak exit (see figures 18 and 19). He observed that water was exiting the abutment rock and percolating down through the bottom of the sinkhole.

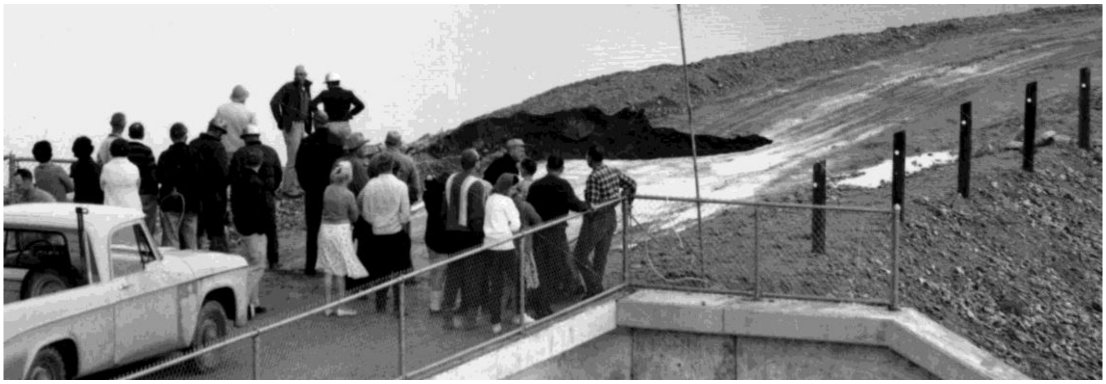

Figure 17: At 4:45PM Monday a 15x20 foot sinkhole suddenly opened up in the crest of the dam.

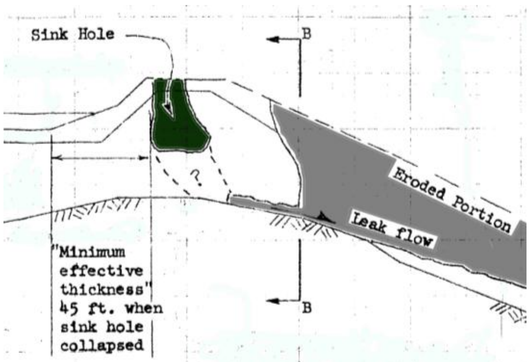

Figure 18: Section of the sinkhole looking left. The sinkhole was 31-feet-deep.

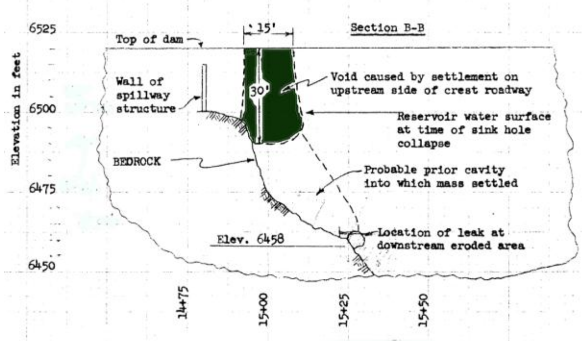

Figure 19: Section B-B of the sinkhole looking upstream.

The PCE decided to immediately fill the sinkhole with riprap bulldozed from the upstream face. This decision was later confirmed by the CE. By nightfall, the sinkhole was filled-in with rock and a layer of road base was added to allow for resumed travel along the crest road.

Tuesday September 7 through Sunday September 12

For the next six days, the reservoir lowered and leak flows diminished (see figure 20). A total of 3 feet of embankment width was gained for every one foot drop in the reservoir. On Wednesday, the reservoir lowered below the top of the wide Zone 1 berm adding 80 feet of embankment width between the reservoir and the leak exit. On Thursday, the rockfill in the sinkhole settled ceasing traffic across the crest road (see figure 21). The rock settled a total of 8 to 10 feet and additional rock was placed.

Figure 20: Erosion hole on Thursday September 9. Note diminished leak flows.

Figure 21: Subsidence of the rock placed in the sinkhole on Thursday September 9.

Leak flows diminished throughout the week. On Saturday September 11, leak flows were measured at 4 cfs. On Sunday morning a press release was issued cancelling the emergency.

Need for Investigation and Repair

Just 11 days following the end of the emergency, the CE announced an immediate repair of the dam. The repair program was 'carefully planned after thorough investigation to assure the safety of the structure.' The contract for drilling and grouting was awarded 12 days following the emergency.

The Wyoming Riverton Ranger Newspaper stated in an editorial:

> "The people of Wyoming deserve an explanation about why one-year-old Fontenelle Dam suddenly developed a leak that is forcing the release of thousands of acre-feet of water out of the storage reservoir. Why did the hole develop? Bureau of Reclamation engineers – who won the 1964 award for the outstanding engineering achievement of the year with the construction of the Glen Canyon Dam—haven't yet ventured to explain the misfortune at Fontenelle. [They said] the problem originated not in the dam structure itself, but in a weakening of the abutting cliff. This would give rise to speculation that geological soil tests prior to the dam construction were not all they should have been.
>
> Another possibility is that the lake filled too rapidly for accommodation by brand new structures.
>
> Whether the cause of the misfortune was geology, engineering, construction or an act of nature, a clear explanation of the cause should be given as soon as possible.
>
> The ability of Fontenelle Reservoir to fulfill its purpose should not be left in doubt."

Early Explanations of the Causes of the Leak

Paul Taylor, Reclamation's Regional Liaison Officer stated, "The leak in Fontenelle Dam came from a fissure that developed in the right, or west, abutment and not within the dam structure. Large areas on either end of the dam will be regrouted under a contract with Boyles Brothers of Salt Lake City, so as to insure all humanly possible against leaks in the future…to assure safety in the valley below." [7]

"Investigation of leakage and large scale erosion on the right abutment of Fontenelle Dam on the Green River in Wyoming has disclosed no fault in design and construction", says B.P. Bellport, chief engineer for the U.S. Bureau of Reclamation." [8]

"We are not prepared at this time to speculate as to the cause. However, we know there was some subsequent action within the abutment after completion that caused the leak." Chief Engineer.

"…it is obvious that a grout curtain failure was directly responsible for the September 3 leak." Regional Geologist. [2]

"There are probably as many theories as to why this condition occurred as there are individuals that have looked at the situation." Head, Earth Dams Branch [9]

Investigation

Two days following the lifting of the emergency, a geologist entered the leak hole in the bottom of the erosion hole. The hole extended about 20 feet into the embankment/abutment contact. There was no cracking found in the embankment.

Reclamation moved quickly to hire a contractor to excavate the embankment down to the elevation of the leak exit. The right 350 feet of embankment were removed (see figure 23) to determine the cause of failure and to perform a significant grouting program. The depth of the excavation was 65 feet.

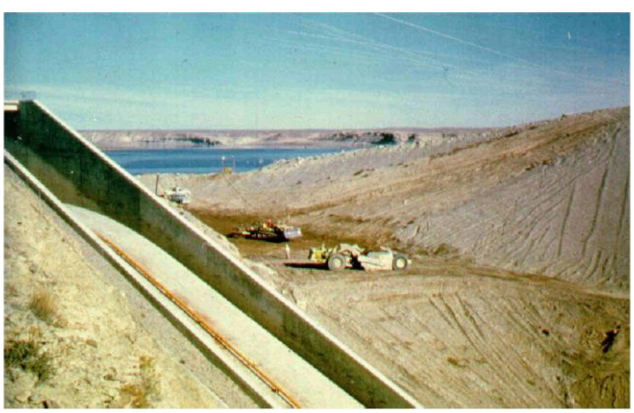

Figure 23: Section of dam removed for investigation and repair

The contractor used heavy equipment to remove embankment materials. For the final abutment cleanup, the contractor used air hoses to remove any remaining soil from the rock surface. A geologic investigation program was conducted with a report, a plan drawing, and several section drawings [2]. Three new holes were drilled for down-hole TV camera inspection. The camera showed that grout propagation may have been limited by debris in the joints.

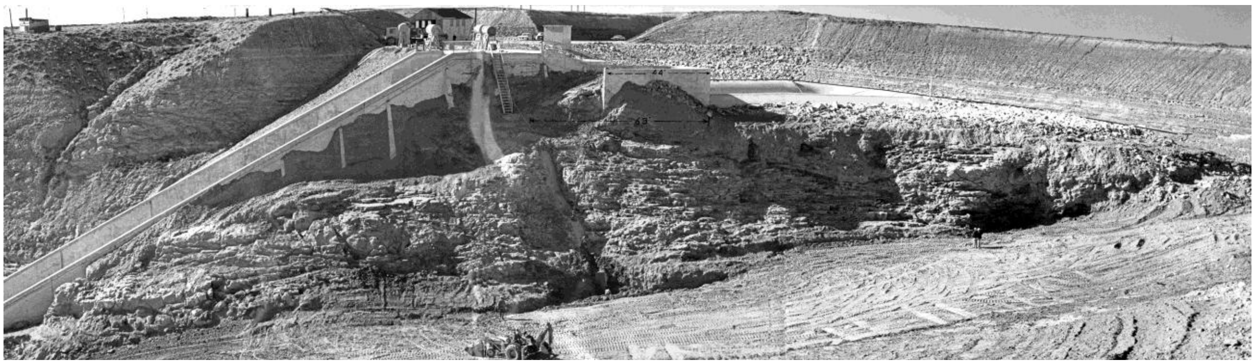

Figure 24: Panoramic photo of right abutment circa November 1965

A panoramic photo was made of the entire abutment (see figure 24) and more close-up photos were made of important relief cracks. A total of 29 “disturbing” relief cracks were mapped [10]. These cracks were mostly vertical, followed the contour lines and extended upstream and downstream. Crack widths varied up to 4-inches. One open relief joint (identified as location “B” in the reports and photos), was about 15 feet long and 85 feet upstream of the grout cap about 13 feet above the leak exit elevation (see figure 25). The crack was clean indicating possible transmission of seepage.

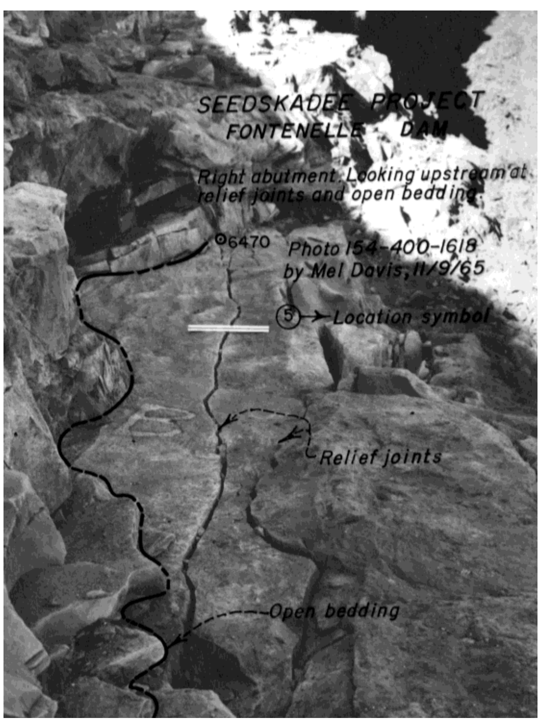

Figure 25: Relief crack in area “B” approximately 85 feet upstream of the grout cap at elevation 6471.4.

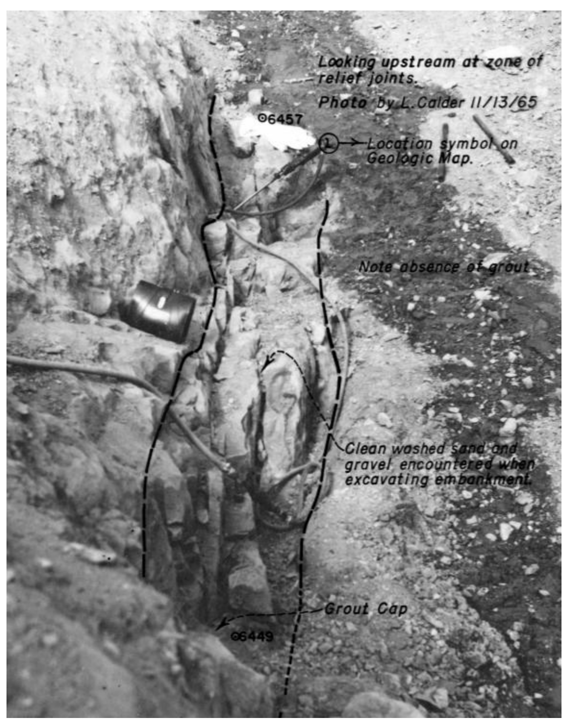

Figure 26: Relief cracks in area “G” just upstream of the grout cap at approximate elevation 6453.

Another crack system (location “G” – see figure 26) was located just upstream of the grout cap and the area was excavated down to elevation 6449. A clean sand and gravel deposit was located adjacent to one of these cracks. The embankment design engineer who visited the site stated, “This clean sand and gravel strongly indicated that flowing water had washed the fines away from the embankment material leaving only the coarser fraction” [10].

In addition, a geologist discovered a crack upstream of the embankment abutment contact in the canal inlet (at location “J” – see figure 27). This crack trended toward the leak area and “… surely appears to have transmitted water recently.” He stated that “…I feel quite sure that other cracks occur in the bedrock of this area.” [11]

Figure 27: Location “J”, one of the probable locations of water leakage into the right abutment from upstream of the dam.

The CE invited an inspection of the site by the U.S. Army Corps of Engineers (USACE). Their team visited the site on November 19, about 10 weeks after the incident.

Likely Causes of Failure

In 1984, Consultants Ralph Peck and Ralph Beene summarized the reasons for the incident as follows: “The lack of multiple defenses against piping of an erodible Zone 1 core may be regarded as the basic deficiency of the dam. The original design and construction placed unwarranted reliance on a narrow grout cap and a single line grout curtain as the sole line of defense against piping of fill material. This was inadequate in the face of the open-jointed, fractured rock, the locally unfavorable bedrock topography, the highly erodible embankment material, and the high seepage gradient above and beneath the 3-foo-wide grout cap. There was no dental concrete or slush grout applied to the fractured rock surface to prevent erosion of the fill material into or along the joints in the rock.” [12]

These causes were consistent with the USACE’s inspection report of late 1965 [13].

The author provides the following additional information consistent with the above likely causes and dam incident research conducted:

1. The selected site had challenging geology for successful containment of a reservoir. The near vertical right abutment included sandstone with numerous deep relief cracks parallel to the valley wall.

2. Due to a need to limit grouting pressures near the surface or because of debris in the cracks, the grout did not seal the near-surface vertical relief cracks upstream of the grout curtain.

3. The rock abutment was not prepared with the designer's intent. Rock irregularities and even overhangs were left in place during embankment placement. These irregularities prevented adequate compaction and bonding of the Zone 1 against the abutment. Although design engineers were generally discouraged from visiting Reclamation dam construction sites [3], the designer visited the site in 1963 and recommended that Zone 1 be widened in the upstream direction (a positive factor in preventing failure).

4. In early summer 1965, high runoff flows coupled with limited outlet works flows (because of stilling basin damage) caused the reservoir to rise quickly 5 feet above the spillway inlet crest and to within just 2 feet of the design water surface elevation. This subjected the new dam, foundation and abutments with new and relatively sudden and high water pressures. Seepage through these areas was extensive (70 cfs).

5. At the right abutment, reservoir water entered vertical relief cracks upstream from the dam, traveled through the cracks and impinged on the embankment core upstream of the grout curtain. The grout curtain in the right abutment dammed the relief cracks and caused high gradients directly into the Zone 1 core embankment upstream of the grout curtain.

6. Over several months, openings or loose areas between the poorly prepared (overhangs and no dental concrete or slush grouting) abutment rock and the embankment allowed seepage to travel toward the downstream along the contact past the grout cap. The lack of a filter allowed soil materials to migrate downstream with the seepage. The downstream shell was not sufficiently pervious to drain leak flows. No drainage zone existed. Part of the downstream slope near the spillway became saturated. Finally on Friday September 3rd flow emerged. Because all zones of the embankment were highly erodible, the cavity quickly enlarged through backward erosion, further reducing the seepage path. Eventually, the rate of seepage was only limited to the flow that could pass through the abutment cracks and free flow conditions existed between the crack exit points and the leak portal in the erosion cavity.

7. All available outlets were opened allowing the reservoir to lower 4-feet-per-day (a positive action to prevent failure).

8. The berm placed in the erosion hole (from above and below) slowed the rate of cavity erosion and kept the cavity from eroding into the crest and toward the east (a positive action to prevent failure).

9. Erosion and piping of embankment materials continued for the 10 days of the emergency. On Sunday September 5th (the third day of the emergency) the dirty rock berm covered the leak exit and caused leak flows to repeatedly fill up voids within the embankment and break free (surging). The soil roofs of the voids collapsed and on the 4th day, Monday, a 15-by-20 foot section of the crest collapsed into a sinkhole. Internal erosion continued for the following 6 days as noted by the 8-10 foot subsidence in the rockfill placed in the sinkhole.

10. The prompt and fast lowering of the reservoir (4-feet-per-day) lowered seepage pressures over the remaining days of the emergency. The pressures and leak flows subsided before the internal and external dam erosion could progress to full breach of the dam.

Lessons Learned

The USACE provided the following “Lessons for the Future” in their report [13]:

1. Designers must inspect earthwork and foundation conditions at key times during construction.
2. Fractured abutment rock deserves very conservative treatment.
3. Irregular rock surfaces should be smoothed out and all overhangs removed.
4. Locating a concrete spillway close to an abutment edge is not desirable.

The author offers the following additional lessons for consideration:

1. We should not rely on single defenses against piping. Modern embankment dam design includes multiple-defenses against seepage/piping including usually several of the following (as appropriate to the dam site): upstream membranes, dental concrete, slush grouting, favorable geometries for compacting using large equipment, laid-back slopes, filter zones, drainage zones, seepage collection and instrumentation.
2. Dams with highly erodible cohesionless soils with low plasticity can erode away very quickly. Emergency Action Plans should include relatively quick failure scenarios for appropriate failure modes of dams constructed of these materials.
3. Prompt mobilization of expertise, equipment, operators and material can make the difference between dam failure and no dam failure.
4. Failure mechanisms can be complex, interrelated, and multi-factorial. At this dam, two failure modes were advancing: backward erosion to the reservoir and internal erosion leading to voids connecting with the reservoir. While the constructed berm surely slowed the rapidly enlarging erosion hole, it dammed the leak exit and caused additional internal erosion which led to the sinkhole. Actions taken to stop one failure mode may accelerate another.
5. Large reservoir outlet works release capacity can help save a dam.
6. It is important to investigate incidents for effective dam repair, methodology/organizational improvement, and for sharing the lessons with the larger dam safety community to prevent future incidents.

Epilogue

In 1966, Reclamation blanket grouted the right abutment and installed a drain along the downstream embankment/abutment A total of 203,533 sacks of grout were pumped into 54,602 feet of hole in both abutments.

In 1967, the CE presented a paper about the incident at the International Committee on Large Dams, at Istanbul, Turkey [14]. This paper identified inadequate grouting as the primary cause of failure, but did not mention embankment/abutment interface concerns or lack of filter/drains. No other papers or conference presentations in the years following the incident are known.

During the period of 1965 to 1968, Reclamation's Regional Director of Region 4 (RD) thoroughly documented the incident in a document called *Leak at Fontenelle* [6] for potential publication in Reclamation's long-standing periodical at the time: *The Reclamation Era*. The document included his personal account, a 23-page assessment of the incident, 17 photographs, 8 figures and 2 tables. After management reviews, Reclamation decided not to publish the document [15]. The document and other first-person accounts of the incident were discovered by the author in Reclamation's Upper Colorado Region library in 2010 (42 years later).

Eleven years later (in 1976) and just 150 miles from Fontenelle Dam, Teton Dam failed resulting in 11 deaths and $1.2 billion (2008 dollars) in losses. Both dams had similar abutments, common design weaknesses, and experienced their problems on first filling. A post-Teton failure report by the General Accounting Office [16] stated that the similarities between the two dams were "striking". The report also stated that the designers of Teton Dam and the rest of Reclamation did not benefit from the lessons learned from Fontenelle Dam.

After the repair of Fontenelle Dam, it provided generally satisfactory performance until 1982 when subsidence, cracking, and significant new seepage occurred. After review of additional instrumentation data and an independent review, Reclamation designed and constructed a concrete cutoff wall from the crest throughout the length of the 5400 foot-long-dam at a cost of $58 million. Seepage performance has generally been acceptable since construction of the wall.

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