ABSTRACT

Title of Thesis: THE ST. FRANCIS DAM COLLAPSE AND ITS IMPACT ON THE CONSTRUCTION OF THE HOOVER DAM

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This thesis will examine the construction of the St. Francis Dam, which collapsed within two years of its completion in the late 1920s, and its effect on the subsequent successful completion of the Hoover Dam from a Project Management perspective. Both dams were arch-gravity dams built in similar southwestern climates; this paper will attempt to illustrate why the St. Francis Dam collapsed while the Hoover Dam still stands today as one of the greatest civil engineering projects of the 20th Century.

The prevailing theory, based on findings shortly after the St. Francis Dam collapsed, was that the Dam's failure was totally due to the composition of the canyon walls. This thesis will establish a basis for the theory that in addition to unsuitable abutment walls, the failure of the Dam was also due to Project Management related errors. This thesis will show that the content of the concrete and the method in which it was poured caused it to crack, leak,

and ultimately collapse when the side walls disintegrated allowing all the water in the reservoir to be released at once.

THE ST. FRANCIS DAM COLLAPSE AND ITS IMPACT ON THE CONSTRUCTION OF THE HOOVER DAM

By

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I would also like to thank Gary M. Mullings from the National Ready Mixed Concrete Association for his help in interpreting the Compression and Petrographic Analysis performed on concrete samples from the St. Francis Dam and his explanation of early 20th Century dam-construction techniques.

I would especially like to thank Dr. Donald W. Vannoy for his early guidance with the direction of this paper and I would like to wish him a speedy recovery from his recent injury.

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Introduction

In the early 1900s, the southwest United States was on the brink of experiencing phenomenal growth. The wide-open lands of California, Nevada and Arizona were fertile and possessed a warm climate with a long growing season. Even the needed water was available in the lakes and rivers that traversed the region. But most of this water ended up in the Gulf of California or the Pacific Ocean. Civil engineers and their teams were essential to build dams, aqueducts and canals so the region would have a safe, reliable water source.

This paper explores differences between the project management organization and style used for the St. Francis Dam and that for the Hoover Dam. The two arch-gravity Dams were similar only in that they were both planned and constructed in the early part of the 20th century; the finished projects had dramatically different planning and construction procedures, methods, and teams. This paper reviews the projects' leaders, early planning, site selection and oversight, planning and design, construction and post-construction history.

The St. Francis Dam

William Mulholland, the driving force behind the St. Francis Dam

In 1877, William Mulholland moved to California and went to work for the Los Angeles Bureau of Water Works and Supply. He began work as a ditch digger for the primitive water system and, although self educated, eventually became the Bureau's Chief Engineer and General Manager.[1] Mr. Mulholland shaped the entire water supply system for Los Angeles, building dams, reservoirs, and a 225-mile Aqueduct which tapped the water from Owens Valley, an agricultural area to the northeast of Los Angeles. He guided this Aqueduct project through enormous technical challenges, including 52 miles of tunnels, which made him a living legend to the people of Los Angeles. "The Chief" as he was known, was a hard taskmaster whose knowledge and experience was richly interlaced with engineering theory gained through years of burning the midnight oil and perusing every available technical book and journal.[2] In literature discussing the St. Francis Dam, Mr. Mulholland is the most significant personage mentioned from the time the project was first envisioned to the day it collapsed. As Chief Engineer, he oversaw the design work done by the Los Angeles Engineering Department and was the individual primarily responsible for managing the construction activities for the Department.

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[1] Charles Outland, Man-Made Disaster: The Story of the St. Francis Dam, 20.

[2] Ibid, 21.

Early Planning and Site Selection for the St. Francis Dam

In 1902, the Los Angeles Bureau of Water Works and Supply began construction of the first large-scale water supply system in the West, The Owens Valley/Los Angeles Aqueduct.[3] During construction of this 225-mile series of canals and tunnels, which diverted water from Owens Valley, William Mulholland identified the San Francisquito Canyon as an ideal site to create a reservoir. He believed that a large reservoir at this site, only 30 miles from Los Angeles, would be able to provide a one year supply of water in case the Aqueduct failed or needed repair.

The site Mr. Mulholland selected for the future Dam was located on the old San Francisquito fault line which was easily visible in pictures taken to document the Dam's collapse (Plate 1, page 55).[4] Fault lines are indications of previous earth shifts and are typically the location of multiple soil conditions. For example, the nature of the spur of mountain against which the Dam abutted fluctuated so widely in composition that while no explosives were ever used to excavate for the Dam itself, roads leading to the Dam through the same mountain formation required extensive use of dynamite to prepare their path. Further, the canyon walls were so soft and fractured that blasting had not been necessary to prepare them prior to placement of concrete. Instead high-pressure hoses were used to sluice off the mountainsides and human labor armed with picks and gads were utilized to finish the job.[5] Geologists who examined the site after the disaster questioned Mr. Mulholland's site selection, and, as early as 1911, 11 years before Dam construction was started, Mr. Mulholland,

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[3] Ibid, 21.
[4] Ibid, 41.
[5] Ibid, 180.

in a letter to the Board of Public Works, described the canyon walls as having dangerous conditions which would make side hill excavation difficult.[6]

While living at a camp on the floor of the San Francisquito Canyon, he ordered the crews working on the Aqueduct to do test borings into the streambed and side walls to determine the feasibility of building a dam at the site.[7] The test borings taken by Mr. Mulholland showed that the west wall above the fault consisted of a conglomerate red material partially composed of sandstone. Ultimately, this soft conglomerate composition of the west canyon wall contributed to Dam's inability to hold back the pressure of the reservoir. Below the conglomerate, below the streambed and up the east canyon wall, mica schist, a gray rock severely laminated and interspersed with talc giving it a greasy feel, prevailed.[8] Although Mr. Mulholland was aware of the site's condition, he either misjudged or ignored the dangerous nature of the schist in the east canyon wall.

As we have studied in our Project Management Program, appropriate early planning is essential to the final success of a project. William Mulholland and his engineering team practiced good "Project Management" in examining the site conditions and doing test borings, but then turned around and ignored their findings by designing a Dam that was fundamentally unsuited to the site conditions.

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[6] Ibid, 37.
[7] Ibid, 34.
[8] Ibid, 34.

Project Organization of the St. Francis Dam

In today's Project Management environment the St. Francis Dam project would be considered an Owner-Builder / Design-Construct project. In this type of Project Management Organization, the Project Manager is the leader of engineering, procurement, construction, and support personnel and works directly for the Owner. Such an approach can work well when constructing complicated projects because one person can speak for all departments.[9] This approach can save both time and money but disadvantages exist that can be applied to the St. Francis Dam. For example, one disadvantage is that there are few checks and balances and the Owner (in this case, the Los Angeles civic leaders) is sometimes not advised or aware of design and construction problems. The St. Francis Dam was funded, designed, built, and operated by the Los Angeles Bureau of Water Works and Supply. And, all the plans for the St. Francis Dam were executed in-house by the Los Angeles Bureau of Water Works and Supply; the author could find no history of outside engineers having been retained to review the final plans.

Due to major unrest in the valleys affected by the diversion of water to Los Angeles by the Los Angeles Aqueduct and other diversion projects, the St. Francis Dam project from beginning to end was achieved with very little public scrutiny. Unlike other aqueduct and dam projects self-performed by the Los Angeles Bureau of Water Works and Supply, the St. Francis Dam was approved and begun without any groundbreaking ceremonies or published reports. In addition, the remoteness of the

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[9] Donald S. Barrie, Professional Construction Management, 32.

construction site and the lack of communication gave Mr. Mulholland the ability to build the Dam with little public oversight.

Lastly, no mention was discovered in any literature of any cost estimates or budget for the St. Francis Dam's construction. Therefore, no on-going review of the Dam's cost could be used to validate actual construction expenses compared to other dams that had been built with similar design/construction techniques. Instead, in such an atmosphere, Mr. Mulholland would have tried to complete the Dam as inexpensively as possible to please his bosses (the Los Angeles Water Works and Supply). Unfortunately, the result was that there was not a counter-balance to question the design or construction techniques.

Planned vs. Actual Construction of the St. Francis Dam

To overcome the presence of the conglomerate and the mica schist, Mr. Mulholland planned to tie the Dam into the canyon walls using trenching; however, ultimately, the trenching that was done did not suffice to properly stabilize the abutment and prevent seepage under the abutment walls. In March, 1925, pictures taken by Carl E. Grunsky, a well-respected engineer from San Francisco, hired by landowners in the area that would be affected by the Dam's construction, show that for at least 15 feet above the streambed there was no indication of trenching.[10] The Dam, at this point, was 15 feet above the streambed and work was viewed from the newly built road above the future high water level. His notes from this visit state: "It was noted that

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[10] Outland, 26.

there was no indication of trenching up the hillsides to provide vertical abutment faces."[11]

Additional irregularities were discovered post-disaster. Pictures of construction work and site investigation completed after the collapse showed that the toe of the Dam which was planned to extend 30 feet below creek level only extended 10 feet down.[12] And the base, shown on plans to be 176 feet thick was actually built only 156 feet thick[13]. In addition, extra stress, not engineered for, was placed on the Dam when, at some point during construction after the foundation was poured, the Dam's height grew from 175 feet with a water capacity of 30,000 acre feet to 185 feet and a 38,000 acre feet capacity.[14] Calculations to validate changes made to the St. Francis Dam when the additional ten feet of height were added do not appear in the records nor does any other documentation as to when or how it was to be accomplished.[15] Due to this change, the St. Francis Dam included the wing wall on the western end that did not appear on the original plans.

QuestionsRaised About the Composition of the Concrete Used in the St. Francis Dam

During the author's visit to the former St. Francis Dam site, several samples of concrete were obtained with the intent of performing a compression test and petrographic analysis. A road that now roughly follows the path of San Francisquito Creek provides access to the site and samples were taken from large fragments of

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[11] Ibid, 33.
[12] Ibid, 204.
[13] Ibid, Appendix I.
[14] Ibid, 29, 30.
[15] Ibid, 30.

concrete the washed down the valley after the collapse. These fragments are still in the same locations where they came to rest as shown in the survey on Plate 2, page 55.[16] These samples were chosen since the larger sections of the Dam still standing after the collapse and wing wall were dynamited by the Los Angeles Water Authority during the spring of 1929 to stem the interest of people who were traveling to the former Dam site for a look at the engineering disaster that had been the St. Francis Dam. Fragments 13 and 16 from approximately elevation 1750 were the sources of the fragments used for this analysis. Documentary photos show that the portion of the Dam containing fragments 13 and 16 was poured during December 1925 to January 1926.

Examination that was done on the St. Francis Dam samples by Penniman & Browne, Inc. and National Petrographic Services (Appendix A) showed that they were comprised of aggregate that was not homogeneously distributed and contained mostly smaller aggregate less than ½ inch in diameter.[17] In addition to the analysis that was done by the engineering firm, slides were produced from two other thin section samples for examination by the author and the Geology Department of the University of Maryland. These samples also showed a heterogeneous distribution of aggregate (see Plate 3, page 56)[18] and visible in the paste were many pieces of mica schist (see

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[16] A. J. Wiley, et all, Report of the Commission appointed by Governor C. C. Young to Investigate the Causes Leading to the Failure of the St. Francis Dam, 61.

[17] Thomas C. Simon, Report of Test on Concrete Cores Supplied by Client, 2.

[18] Geology Department photos of prepared concrete slides.

Plate 4, page 56**)**[19] The mica schist would have eroded from the eastern walls of the San Francisquito Canyon and been deposited in the river bed prior to having been excavated and mixed with cement for construction of the Dam. Larger schist aggregate can be seen in other concrete samples taken from the Dam (see Plate 5, page 57).

In conversations with Mr. Gary Mullings, Director of Operations and Compliance for the National Ready Mixed Concrete Association, the author asked about the possible effects of mica schist in both granular and larger aggregate forms on the strength of the final concrete. He stated that mica schist of any size would be harmful to the concrete due to

the laminated nature of the material. He was also surprised to hear that larger schist aggregate was visible at the St. Francis Dam site protruding from the remaining Dam structure and felt that the existence of appreciable quantifies of mica schist in the Dam could likely have weakened parts of the structure. The compressive strength of one concrete sample that could be prepared for testing was documented by Penniman and Brown (Appendix A) to be relatively low 1880 psi.

The petrographic analysis on page four of Appendix A showed that the concrete had an air volume of 3.44. Since the concrete was not air entrained, a 1% air content would have been expected. Higher air values would indicate that the concrete was not consolidated with the use of pneumatic vibrators as it was placed in the forms for

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[19] Ibid.

the Dam.[20] Significantly, archival photos of the St. Francis Dam construction do not indicate that pneumatic vibrators were used to consolidate the concrete (Plate 6, page 57).[21] (In a documentary video of the Hoover Dam construction, men are shown working vibrators in the concrete as it is being poured.[22] It is likely that the Hoover Dam concrete had a content close to the 1% expected air content.) For each 1% of air volume over the base 1%, 5% of the concrete strength is lost. If the air volume in the tested sample is any indication of the rest of the concrete in the St. Francis Dam, about 12% of the expected strength would have been lost only from this characteristic.

Evidence of Delayed Ettringite Formation in Concrete from St. Francis Dam and its Possible Role in the Deterioration of Concrete

The construction team and engineers who oversaw the construction, allowed the concrete to be poured in ways that played a part in weakening the structure. Instead of pouring concrete into separate forms which would be tied together with steel or grout, the

concrete was poured in massive waves with "hummocks" – bumps that were meant to provide a bond between layers in the dam (Plate 7, page 58)[23]. In his visit to the Dam in March, 1925, Carl Grunsky noted:

> The top surface of the concrete in place was uneven presenting the appearance of a number of small hummocks each of which represented a

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[20] Gary Mullings, personal conversation in April of 2004.
[21] Outland, 36.
[22] Hoover Dam, writ., prod. and directed. Stephen Stept.
[23] Ibid, 32.

> large batch of concrete several feet in thickness which had intentionally been allowed to set without leveling off in order to improve bonding with the next higher layer of concrete...[24]

No provision for controlling the concrete temperature during curing was provided and, predictably, contraction cracks appeared which became leaks as water filled the Dam. William Mulholland instructed the workers to caulk one large crack with oakum on the upstream side of the Dam to stop some of the leakage, other cracks he ignored and considered normal contraction or temperature cracks that would be expected in any large body of concrete.[25]

Not surprisingly, the author did not find any reference to ettringite as a possible cause or evidence of pre-damage to the St. Francis Dam concrete in any literature, since the first publication about concrete-damaging delayed ettringite formation appeared in 1945. It

noted that damage in conjunction with ettringite formation in hardened concrete was first identified in … pre-cast concrete elements which, during use, had been exposed to open-air weathering with frequent wetting.[26]

The petrographic examination (Appendix A) showed that significant amounts of ettringite was present throughout the sample. Ettringite is formed in concrete by a

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[24] Ibid, 33.

[25] Ibid, 51.

[26] W. Lerch, "Effect of SO_3 Content of Cement on Durability of Concrete," Jochen Stark and Katrin Bollman, Delayed Ettringite Formation in Concrete, 1.

reaction between calcium sulfate, calcium oxide and aluminum oxide containing phases of the cement and water. Primary ettringite formation during the initial stage of hydration is seen as a positive affect because it regulates setting of the concrete.[27] The above is illustrated in the following formula and graph:

$$\underset{\text{Calcium Oxide}}{\mathbf{3\ CaO}}\quad \underset{\text{Aluminum Oxide}}{\mathbf{Al_2O_3}} + \underset{\text{Calcium Sulfate}}{\mathbf{3CaSO_4}} + \mathbf{26\ H_20}\qquad \underset{\text{Ettringite}}{\mathbf{3\ CaO\quad Al_2O_3\quad 3\ CaSO_4\quad 32\ H_20}}$$

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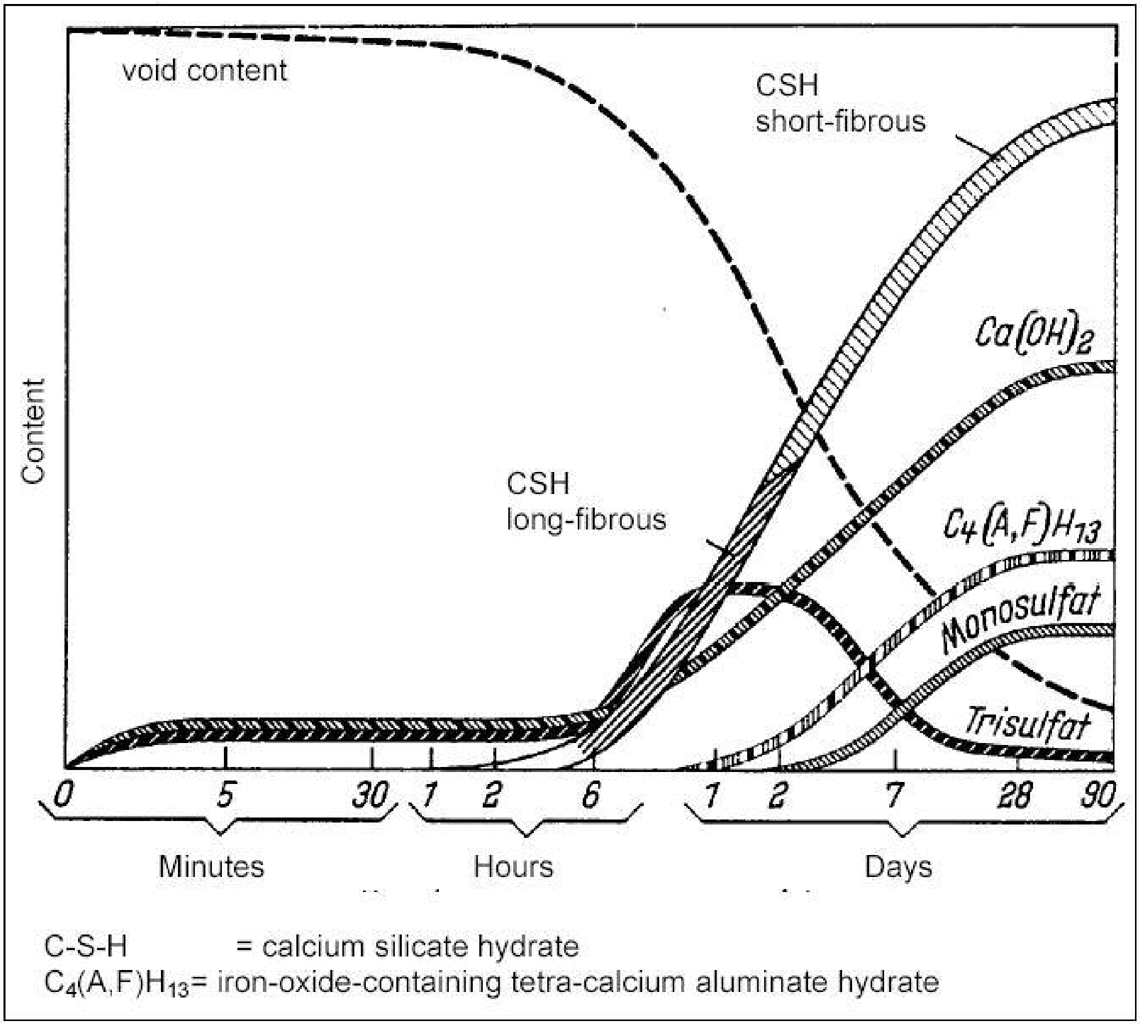
[27] Jochen Stark and Katrin Bollman, <u>Delayed Ettringite Formation in Concrete</u>, 1.



Tiime versus changes in modal % minerals in a
Concrete mixture that is maturing normally.[28]

This reaction ends as soon as the sulfate concentration, needed for forming the ettringite, decreases below the required limit. From this point the remaining C_3A (gypsum) reacts with a portion of the already formed ettringite to create monosulfate, calcium hydroxide and iron-oxide-containing tetra-calcium aluminate hydrate.

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[28] Ibid. 2.

In concrete stored or permanently used in a dry climate, ettringite is hardly detectable even after years of use. When a high degree of ettringite is present, it is generally associated with severely disintegrated concrete. Such secondary ettringite formations, also known as delayed ettringite formations (DEF), is believed to be a result of improper curing of concrete where the normal ettringite formation is suppressed. The sulfate that remains in the hardened concrete is rehydrated and eventually reacts with calcium and aluminum also remaining in the cement paste causing the paste to expand. The expansion can create gaps around the aggregate (larger gaps around larger aggregate than around smaller aggregate) which may be later filled with ettringite.[29] (Concrete is composed of Portland cement, water, and aggregates.)

Concrete Experts, Int'l (CXI), an organization that has world-wide experience in diagnosing DEF, identifies four criteria that can be used to identify concrete deteriorated by DEF.

- The presence of gaps completely encircling aggregates would indicate a problem with the cement paste or its curing process.
- Gaps that are proportionally wider around larger aggregate than smaller aggregate
- The absence of any external sulfate sources
- High temperature heat curing history.[30]

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[29] Concrete Experts Int'l, "Delayed Ettringite Formation in Concrete," 1.
[30] Ibid.

The St. Francis Dam concrete history exemplifies many features identified as typical DEF criteria:

- During the petrographic examination, gaps were visible around many pieces of aggregate.
- The concrete was poured in a very dry, hot climate with no attempt to control the heat produced during the initial set.
- And, there is no known external sulfate source that could have been introduced into the concrete to start secondary ettringite formation.

Damaged concrete often contains ettringite deposits in voids and cracks similar to what the author found in the St. Francis Dam sample. These ettringite deposits do not necessary indicate that DEF caused the cracks but they could be a consequence of the cracks' existence. "Every concrete contains weak points and micro damage to the internal structure, e.g. pores, distorted transition zones between aggregate and hardened cement paste, cracks. They do not necessarily impair the quality of the hardened concrete (strength, modulus of elasticity etc.), but they can promote the transport of moisture and phase forming components and therefore aid ettringite crystallization." [31] One likely cause of the cracks in the St. Francis Dam could be the way concrete was placed in the Dam, in large wide lifts. "…fairly high concrete temperatures can … occur during concrete placement under elevated external temperatures …, especially in massive concrete elements."[32] The expected contraction cracks would have left voids around aggregate and these cracks could

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[31] Stark, 11.
[32] Ibid, 7.

have invited ettringite growth. Excess sulfate remaining in the cement paste after the high temperatures accelerated curing could have then formed ettringite in the existing voids. "With a subsequent drop in temperature after the initial curing phase, the monosulfate becomes metastable so that, if there is sufficient water available, ettringite can be formed again. These processes take place under the conditions of high temperature and a concurrent moist environment."[33]

Another theory for the formation of the cracks is that the ettringite formed in the hardened concrete as moisture penetrated the Dam from the filled St. Francis reservoir which created micro structural damage because of the crystal growth or an increase in volume. The transformation of monosulfate into ettringite can produce a volume increase of 2.3.[34]   In either case, the ettringite would have been a contributory cause of the concrete deterioration in the St. Francis Dam.

Further Mr. Mullings felt that the ettringite noted on pages 2, 5, and 6 of the "Report of Tests on 5/29/03" and visible in cracks and voids in other pieces of concrete was interesting in that it indicates microscopic cracks may have existed from the time the St. Francis concrete cured. He also believed the practice of pouring five foot lifts without any concern about cooling the concrete would have definitely had caused contraction cracks due to the heat of hydration (Portland Cement + Water = Heat) within the cement paste. Because the cement in the middle of a five-foot deep concrete pour is insulated by the concrete around it, temperatures of 150 degrees or

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[33] Ibid, 7.
[34] Ibid, 20.

higher would have been generated. When the internal temperature is 35 degrees higher than the ambient air temperature, temperature cracks would have occurred in the concrete. Even if the outside air temperature was 90 to 100 degrees, the difference in temperature would have been very significant. Mr. Mullings agreed with the authors' conclusion from examination of current literature that the ettringite is an indication that cracks existed within the Dam due to the methods used to place the concrete and/or the heterogeneous distribution of aggregate in the concrete.

St.Francis Dam Collapse

Despite deficiencies in the Dam's design planning and construction, it was completed in May 1926 and filled. Leaks began as soon as the reservoir was filled to the height of the 1725-foot level, the approximate contact point between the schist and conglomerate – the San Francisquito fault line.[35] The leaks saturated the side walls and leaks from near the top were diverted to the stream bed by installing two-inch diameter pipes down the slope of the Dam where it met the canyon walls. Due to residents' concerns over the Dam's increasing leakage, Mr. Mulholland was called upon to check the Dam frequently. In early March, 1928, The Dam had been filled, for the first time, to within three inches of the top (Plate 8, page 58)[36] On March 12, 1928, Mr. Mulholland personally visited the Dam and declared it to be sound and described the cracks and leaks that worried the residents and prompted his visit as inconsequential and due to normal setting of the Dam. A picture taken from the upstream side of the Dam during Mr. Mulholland's visit shows the reservoir clearly

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[35] Outland, 44.
[36] Wiley, 33.

full with the waters at level of the outlet openings below the walkway (see Plate 9, page 59).[37] Another picture taken at the same time from the downstream side of the Dam shows the leak at the wing wall connection to the main structure with water spilling through the outlet openings on the eastern side of the Dam (see Plate 10, page 59).[38]

Early in the morning of March 13th, two years after its completion and 12 hours after Mr. Mulholland's assurances, the St. Francis Dam collapsed. The collapse is commonly believe to have begun when the west wall above the fault line, saturated from leaks, blew out. A 185-foot wall of water rushed toward communities downstream of the Dam. At least five hundred people died and 4.8 million dollars in losses were claimed against Los Angeles. In the aftermath of this tragedy, Mr. Mulholland and the Los Angeles Bureau of Water Works and Supply were not interested in a close investigation of the failure of the St. Francis Dam. Instead, every attempt was made to pay off those who could prove losses, rebuild the power and water diversion infrastructure where possible, and move forward with only one man – Mr. Mulholland -- scapegoated for the collapse.

Conclusions Drawn from the St. Francis Dam Project

In Project Management courses, future managers are taught about risks and how to control them. To reduce risk, project managers should incorporate thorough

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[37] Outland, 63.
[38] Ibid.

planning, redundancy and suitable project documentation. Literature has shown that proper planning was absent during the entire construction process for the St. Francis Dam. First, during the initial planning for the St. Francis Dam, Mr. Mulholland never called in a second party to verify his site selection or design. And, second, he was willing to make changes to the structural design; for example, the lack of trenching, the increase in the reservoir's capacity, and the use of oakum to solve a structural defect. Unfortunately, Mr. Mulholland was willing to take unacceptable risks to get this project completed at a low cost and on time.

The second element necessary to ensure successful projects is redundancy.[39] The St. Francis Dam project lacked redundancy in its on-site construction management and inspection functions. Adequate inspections independent of the owner/contractor were absent during the Dam's construction. Also, since this was not a Design-Bid-Build project, the design was not verified by contractors bidding on the project of by outside engineers hired to comment on the plans. It is important, especially with a project with as many uncertainties as the St. Francis Dam, to have more than one group responsible for critical issues. This could have provided an opportunity for questions about the abutment walls and concrete composition; subsequently followed by discussions of possible solutions and adjustments to procedures.

According to Frederick Gould, "project documentation is important in the event that any claims or disputes occur in the future."[40] In addition, documentation from

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[39] Alexander Laufer, Simultaneous Management, 78

[40] Frederick Gould, Managing the Construction Process, 178.

previous projects is used in planning subsequent projects. It’s common knowledge that changes in plans after construction has started are not new to the engineering profession. When actual conditions differ from what is expected, modifications of the original designs are necessary. However, in this case, further evidence of the lack of proper project management is shown in the scarcity of appropriate documentation of the rationale for deviations from plans in the Dam’s construction. Several undocumented modifications were made that may have severely affected the Dam’s ability to withstand the weight of the water in the reservoir and its ability to prevent leakage from under the structure.

The Hoover Dam

The St. Francis Dam Causes Misgivings

The collapse of the St. Francis Dam caused the public to question the ability of any authority to build the infrastructure needed to provide safe, reliable water to the growing cities of the Southwestern United States. A quote from the Literary Digest written three weeks after the collapse sums up how the public then felt about large dams,

> " For the first time in history a high dam of massive masonry has failed, and every fear of the destruction pent up in such works is realized… . Here the highest embodiment of modern dam-building science crumbled in ruin, taking a total of hundreds of lives as the price of mistaken confidence in its strength… . Men have always been in awe of these vast forces, and often has bitter protest been made against the erection of a dam above populous communities. In every instance engineering science answered the protest and gave assurance that the waters would be safely controlled. The destruction of the Saint Francis Dam challenges that assertion."[41]

The Bureau of Reclamation within the Department of the Interior had the daunting task of restoring the public's confidence in large infrastructures. Ultimately, the Hoover Dam was able to accomplish such a Herculean task and transformed an entire region with the electric power and water provided through its enormous reservoir and hydroelectric power generation capacity. The Hoover Dam, begun in 1931 and completed in 1936, was the first in a chain of dams, canals, and aqueducts built to harness the Colorado River.

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[41] Outland, 173.

Walter Young, Government Project Manager for the Hoover Dam

The man in charge of planning for the Hoover Dam was Walter Young, a 36-year old engineer who had worked with the Bureau of Reclamation for 10 years when he was given the assignment to lead the investigative team into the Colorado River Basin. This team would spend three years mapping, sampling and testing the river gorge and canyon walls to find the best site to build the proposed Dam. Mr. Young had graduated from the University of Idaho in 1911 and immediately went to work for the Bureau of Reclamation building the Arrowrock Dam in Boise, Idaho. After working on the Arrowrock Dam until its completion four years later, he moved to Denver to join the Bureau's Dam Design Team. Six years later, he was chosen to head the testing program for the Hoover Dam, the most ambitious government-sponsored civil engineering task ever attempted in the United States.

Mr. Young's task didn't end with the survey which was completed in April 1923; subsequently, he worked for 10 more months with the other Bureau of Reclamation engineers back in Denver until the final cost estimates and plans were delivered to the Secretary of the Interior in Washington, D.C. on February 1, 1924. Then, for six years, Mr. Young worked on other projects and waited until contracts were signed and money appropriated for the Dam's construction.

Frank Crowe, Six Companies Project Superintendent for the Hoover Dam

Like Walter Young, Frank Crowe, joined the Bureau of Reclamation immediately upon graduating with a Civil Engineering degree from the University of Maine in 1905. In fact, Mr. Crowe and Mr. Young worked together on the Arrowrock Dam where Mr. Crowe acted as Assistant Superintendent of Construction. He was known for constantly devising new techniques to increase speed and efficiency and commanded respect from all those who worked for him. Another government engineer said of Mr. Crowe, "Nothing stumps him. He finds a way out of every difficulty. And he is not conceited."[42]

Unlike Walter Young, Frank Crowe left the Bureau of Reclamation after his promotion to General Superintendent of Construction for all projects undertaken for the U. S. Government. The reason he left was characteristic of Mr. Crowe. In 1925, the Bureau of Reclamation decided to have all construction services handled by outside contractors rather than Government employees (Owner-Builder / Design-Construct organization). This changed Mr. Crowe's status from that of a hands-on builder, responsible for solving, on a daily basis, complicated field problems, to that of a paper-pushing administrator. Mr. Crowe decided to join Utah-Morrison-Knudsen, a joint venture of three construction companies that had teamed up to bid on government dam projects. This combined company built dams in Wyoming, California, and Idaho during the 1920s and, as Superintendent of Construction, Mr.

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[42] Joseph E. Stevens, Hoover Dam: An American Adventure, 37.

Crowe gained the experience he would need to build the dam he had been waiting for – the Hoover Dam on the Colorado River.

Walter Young and Frank Crowe … The Leadership Team for the Hoover Dam

One major contrast is evident between the project management of the St. Francis Dam and the Hoover Dam. William Mulholland was the principle individual responsible for the St. Francis Dam construction. He was integral to the selection of the site, the design of the arched-gravity dam, its construction, and the Dam's maintenance until its collapse two years later. An entirely different management style is evident in the Hoover Dam project. It was led by Walter R. Young, the Hoover Dam project construction engineer, and Frank Crowe, Six Companies; Supervisor of Construction. These two individuals had conflicting assignments and contrasting personalities. But they worked together and completed the construction project on time and within budget. Their mutual respect and affection for each other can be seen in the nicknames they gave each other. Frank Crowe referred to Mr. Young as the "Great Delayer." And Mr. Young pinned the nickname "Hurry-Up" on Mr. Crowe, the hard-driven superintendent.

Site Selection for the Hoover Dam

In 1919, Congress authorized a study of the Colorado Basin and the problems that would be involved in developing it. These documents provided engineers with the hydrological and geological data on the Colorado River and its canyons. In 1922, the most suitable site considered to build a dam was Boulder Canyon, in a river gorge that would provide the most water and silt storage capacity, had the best geologic and topographical features, and had good access to a railhead for supplying the project. Almost immediately the project was moved forward; of the five original sites identified (A through E) at Boulder Canyon, Site C was determined to be the only site where a 500 foot dam could be built. Barges anchored to the shore in the middle of the river became platforms for equipment used to drill into bedrock and men were suspended on cables from the sides of the Canyon to drill into the side walls to check its ability to support an arched-gravity dam, the only type feasible for a project this size.

For the author, one of the critical differences between the Project Management for the St. Francis Dam and the Hoover Dam were these tests and their assessment by a team of Bureau of Reclamation engineers back in Denver. Although the engineers considered it possible to build the dam at Site C, they concluded the conditions were not ideal. The engineers requested additional investigation of sites at Black Canyon, an alternative location that was 30 miles from Las Vegas, to determine whether a better location could be discovered. The engineers' persistence paid off, as a site in the lower region of Black Canyon proved to have less jointing and faulting than the bedrock located in Boulder Canyon. There was also less silt in the river channel and the narrower gorge would require less concrete to build the dam.[43] Site D, Black Canyon, was the final choice for the Hoover Dam. However, since the bill introduced in 1923 to build the dam was labeled the Boulder Canyon Project Act, the name of the dam remained "Boulder" even though the final site choice was Black Canyon. In contrast to the site selection for the St. Francis Dam, that for the Hoover Dam was layered with a variety of assessments which actually took into account the site conditions. And, these assessments were accomplished by multiple Bureau of Reclamation engineers.

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[43] Ibid, 25.

Project Organization of the Hoover Dam

In today's Project Management environment, the Hoover Dam would be considered a Competitively Bid Construction Project. As mentioned earlier, the Department of the Interior had discontinued major project construction utilizing Owner-Builder / Design-Construct project management style (that used in the St. Francis Dam project). The advantages of a Competitively Bid Project is that the contractor agrees to perform the work at a predetermined price, including profit (for the Hoover Dam, Six Companies estimated their profit margin at 25% of bid). This allowed the Government to benefit from price competition caused by the Great Depression. From the contractor's point of view, the positive is that the Owner has little influence over the details of the building process other than quality and schedule. For the Hoover Dam project, it allowed the contractor to use any means available to keep costs down and the project on schedule to maximize profits (as long as the quality of the project doesn't suffer).[44]

One negative present in this type of this Project Management Style is that the overall Design-Construct time is the longest of any approach. This is due to the need for a exhaustive design process before the project is put out to bid. However, the author believes this was a positive for the Hoover Dam project since the exhaustive design process guaranteed a completed Dam with little likelihood of failure. Another negative can be the Owner may have little influence over the performance of the

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[44] Barrie, 28.

work;[45] however, for the Hoover Dam project, the numerous inspections ensured the contractor performed work per plans and specifications.

Planning Plays a Role in the Success of the Hoover Dam Project

The importance of "Planning" is addressed in the first chapter of every Project Management book the author has studied; after researching these two projects, the author is convinced comprehensive and thorough planning is the basis for any project's success.

The Hoover Dam had a history which could serve as an example of how planning should be done to execute a difficult project. Not one, but two, experienced, educated and enthusiastic men were employed respectively on the owner's and builder's side to work on the Dam's construction. An examination of their backgrounds and managerial styles is a critical element when examining why this incredibly successful project was completed on time and within budget.

When Congress approved funding for the Hoover Dam, remembrance of the St. Francis Dam collapse was still vivid in the public's mind. Although mistakes in the St. Francis Dam design and construction had been identified, the plan to build another similar dam, over three times as high, seemed ambitious. Perhaps because of this, the planning and construction of the Hoover Dam project was dramatically different from that of the St. Francis Dam. For the Hoover Dam, planning was completed by the Bureau of Reclamation and construction was overseen by a group of reclamation

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[45] Ibid, 29.

engineers operating independently from the contractor selected to build the dam. The Dam was designed and the site selected in 1924 but construction could not begin until funding was approved and financing agreed to by Congress. Thus, there was plenty of opportunity for second-guessing of design, site selection, and the construction methods used.

In July of 1930, as the engineer most experienced with the Black Canyon conditions, Walter Young was chosen as the highest-ranking Government engineer assigned to the Dam site. He immediately moved to Las Vegas and began building the railroad spur that would carry men and materials from the Las Vegas junction to Black Canyon, and the infrastructure that would provide electric power to the construction town and Dam site. He also presided over construction of the worker's camp and performed all other administrative duties expected by the Owner (U. S. Government) to ensure the success of the project. This was truly a team effort, though. While Mr. Young toiled in Las Vegas to build the infrastructure between Las Vegas and the Colorado River Basin, other groups were planning the construction of the Dam itself. The author once again finds a stark contrast between the collaborative effort illustrated here and the management style present in the St. Francis Dam project which was primarily orchestrated by one individual.

Dozens of companies purchased plans and specifications for the Dam but only five bids were delivered to the Bureau of Reclamation in Denver by the March 4, 1931, deadline. Only two of the five bids included acceptable bonds and, Six Companies (a joint venture formed less than a month before bids were due) won the chance to build the dam. Six Companies included Frank Crowe's employers, Utah-Morrison-Knudson and he was assigned to be in charge of dam construction. It was his cost estimate, plus a 25% profit, that was used to calculate a bid for the dam. The final bid, at $48,890,955, was only $24,000 more than the estimate the Bureau of Reclamation engineers had worked out.[46]

Oversight of Construction had a Positive Impact on the Hoover Dam

Frank Crowe was both qualified and confident and his selection as superintendent put him in a position to prove those wrong who believed that the Dam and the weight of the reservoir it would create would collapse or cause a catastrophic earthquake. However, Frank Crowe was not alone in his management of the construction. As mentioned earlier, Walter Young, was an equally qualified engineer working in the government's interest on the owner's side. While working for the Bureau of Reclamation, Walter Young had led the surveying and drilling team in the mid-1920s, which examined both Boulder Canyon and Black Canyon. With his intimate knowledge of the site and experience gained working on other dam projects, he was well prepared to lead the team of 150 engineers charged with the responsibility of inspecting construction of Hoover Dam.[47]

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[46] Stevens, 44-46.

[47] Ibid, 203.

One of the most critical tasks this inspection team monitored was the placement of concrete in the dam. The contract written by the Bureau of Reclamation called for no more than five feet of concrete to be placed in any column or panel within a 72-hour period and no more than 35 feet of concrete depth to be placed within 30 days. The requirement that no concrete be poured in any more than five foot lifts was not set for the convenience of the Government inspection team or due to concern of the mixing capacity of concrete at the job site. Rather, the Bureau of Reclamation engineers had calculated that if the Dam was created in a continuous pour, the temperature of the concrete would be raised approximately 40 degrees by the chemical action of setting and, if the Dam were allowed to cool naturally, a period of as much as 150 years would elapse before the temperature of the structure matched that of the air surrounding it. During that period of time, temperature stresses would be set up and cracking would result from differential cooling.[48]

As seen in Plate 11, page 60,[49] pouring in blocks no more than five foot deep gave the Hoover Dam a different look than the pour did for the St. Francis Dam. Although both these dams were built in similar climates with arched-gravity designs, the way the concrete cooled in the St. Francis Dam (in large concrete pours with hummocks to provide tie-in between pours) likely contributed to its sudden break-up after one side

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[48] Ibid, 202.
[49] Ibid, 193.

wall of the canyon collapsed. Plate 12, page 61 shows the pieces of the St. Francis Dam spread at its base after the disaster.[50]

In addition to the restriction on the speed of pouring concrete, the Hoover Dam was designed with honeycombed one inch diameter piping through which river water and then ice cold refrigerated water was pumped until the concrete cooled and stopped shrinking (see Plates 13 and 14, pages 61 and 62). Grout was then used to fill the gaps between the blocks and gaps at the surfaces where the canyon walls and the blocks met. The network of pipes that the water was circulated through was also filled with grout, making the finished dam monolithic in look even though it consisted of many parts.[51] The volcanic tuff composition of the Black Canyon walls allowed the grout tie-in to work incredibly well for the Hoover Dam construction. A cut removed from the junction of the Hoover Dam and the canyon wall on the west side in the 1990s showed how well the slow cooling and grouting worked. Even under microscopic examination, the seam between the Dam and the canyon walls had disappeared and the chemical curing of the concrete has perfectly joined the concrete to the canyon wall. Conversely, the conglomerate rock and mica schist in the side walls of the San Francisquito Canyon would have prevented Mr. Mulholland from ever using grout to adequately tie the St. Francis Dam to the walls of the canyon.

Conclusion

When the author first started reviewing articles and books about the St. Francis Dam, frequent references were made that the Dam did not meet prevailing dam designs;

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[50] Wiley, 59.
[51] Stevens, 194.

other authors regularly excused St. Francis' design shortcomings as typical of 1920s dam construction. But, the extremely successful Hoover Dam design was completed in February, 1924 (the same year that construction began on the St. Francis Dam), and incorporated many design features strikingly absent from that of the St. Francis Dam. Certainly, the lack of incorporation of seemingly standard design features and construction techniques played a part in the collapse of the St. Francis Dam.

The Hoover Dam Project was an unqualified success and has met the test of time. The only caveat is that by today's standards, safety at the site was not a high priority and the resultant injuries and deaths would be considered unacceptable for a project today.

Comparison of the Construction of the St. Francis Dam and the Hoover Dam from the Perspective of Accepted Early 20th Century Concrete Dam Design

Introduction

When the author first read about the St. Francis Dam and began to compare its construction with that of the Hoover Dam, he spoke with engineers at the Ready Mix Concrete Institute who told him the St. Francis Dam was constructed in much the same manner as were most dams in the early 1900s. And, as mentioned earlier, books about the St. Francis Dam stated that the Dam's design met the prevailing design features and construction techniques.

Why then, the author thought, was there such a difference between the design and construction of the St. Francis Dam and the Hoover Dam? Here we have two similar arch gravity dams built within 10 years of one another, yet with copiously different features and radically different construction techniques. Perhaps, one reason was that Mr. Mulholland, the principle driver behind the St. Francis Dam, was a self-taught engineer whose "…knowledge and experience was richly interlaced with engineering theory gained through years of burning the midnight oil, and perusing every available technical book and journal."[52] In contrast, in the Hoover Dam Project, the Bureau of Reclamation employed dozens of engineers with experience in dam construction.

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[52] Outland, 21.

An examination of a book written in 1915 entitled Construction of Masonry Dams by Chester W. Smith describes early 1900s dam design and construction. Many dam design features and construction techniques detailed in this book were used in the Hoover Dam's construction but not in that of the St. Francis Dam. This book describes many dam design features and construction techniques used in the Hoover Dam which certainly contributed to its success.

Contraction Joints

In Smith's book, pictures of the Olive Bridge Dam (Plate 15, page 62)[53] show a dam under construction as early as 1910 with contraction joints and vertical steps. These features were both missing in the construction of the St. Francis Dam.[54] Contraction "cracks" did exist in the St. Francis Dam. Two of those cracks extended vertically through the Dam, one was 58 feet to the west of the outlet gates and another approximately the same distance to the east. Incredulously, these cracks had been packed with oakum and grouted after the Dam was completed; on Plate 16, page 63[55] the cracks are visible in the completed Dam from the downstream side. Not surprisingly, the cracks match perfectly the outline of the standing monolith after the failure[56] (**see** Plate 17, page 63).[57] Several other cracks occurred in the completed St. Francis Dam. One of these further to the east end of the Dam opened in late December 1927. Another crack

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[53] Smith, Chester W., Construction of Masonry Dams, plate opposite page 156.
[54] Outland, 176.
[55] Ibid, 45.
[56] Outland, 177.
[57] Wiley, 59.

occurred at the point where the western wing wall attached to the main Dam structure.

Both these cracks were also packed with oakum in an attempt to slow the leaks. It should be noted that, in general, the use of oakum and surface grouting is not a technique typically used in the construction of dams during this era.

An article in Electrical World entitled "Collapse of the St. Francis Dam Unexplained," circa 1928, stated that:

> "The dam itself contained no vertical joints as definite provision for contraction because it is not the policy of the Los Angeles Bureau of Water Works and Supply to make provision in dam design for contraction joints, but it is the policy to allow contraction cracks to occur where they will and subsequently to close them if necessary. This procedure is followed because it is the opinion of the Bureau's engineering department that cracks are very likely to occur elsewhere anyway, and it believed that it is the better policy to allow them to occur where stresses dictate rather than to attempt to fix them by expansion joints . . . In a structure of the St. Francis type it is common, according to the consensus of engineering opinion, that contraction cracks should occur approximately every 100 feet. This is borne out by the fact that the central portion of the dam that remains standing is slightly more than 100 feet wide, indicating that perhaps contraction cracks had something

> to do with the exact point at which rupture occurred when the site foundations gave way . . ."[58]

Since contraction joints were not included in the construction of the St. Francis Dam, the resulting contraction cracks could only be dealt with on the surface and not in the interior of the Dam structure.

In contrast, the Hoover Dam's contraction joints were grouted. The need for grouting, both for stabilizing the foundation and to seal the contraction joints between concrete sections is described in Smith's book,[59] and grouting machines are shown which were

specifically designed to do this work. Although grouting was used in many dams prior to 1915 and machines were in use specifically designed to do this work, no grouting was attempted during construction of the St. Francis Dam.[60]

__Cut-Off Trenches and Drains Prevent Uplift Pressure__

Smith also writes about the need to stop seepage under the Dam from undermining the foundation and creating uplift pressure on the Dam.[61] One way to do this would be to dig a cutoff trench at the upstream end of the Dam and fill the trench with concrete. Alternatively a line of holes drilled for this purpose could be pressure

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[58] Outland, 177.
[59] Smith, 48.
[60] Wiley, 10.
[61] Smith, 49.

grouted and the same result would be accomplished. Early in 1912, the Portland (Oregon) Railway, Light and Power Company built a dam in the western U.S. which included a cut-off wall over 60 feet deep created by pressure grouting. Five hundred and fifty five holes, 2 3/8” in diameter and over 60 feet deep were drilled and then grouted up to 200 psi to create a cut-off wall and seal the dam’s foundation (see Plate 18, page 64).[62]

Smith suggests that drains installed under the Dam behind the cutoff wall would relieve any pressure that could exert uplift pressure at or toward the toe of the Dam. Any water that passed through or under the curtain wall would percolate up to a drainage gallery and/or through a central drain and then out of the Dam at the toe. Foundation draining was necessary to control the water that would be expected to pass by the cut-off trench.

The following diagrams show the pressure that would have existed at the lowest upstream point of the St. Francis Dam and the Hoover Dam.

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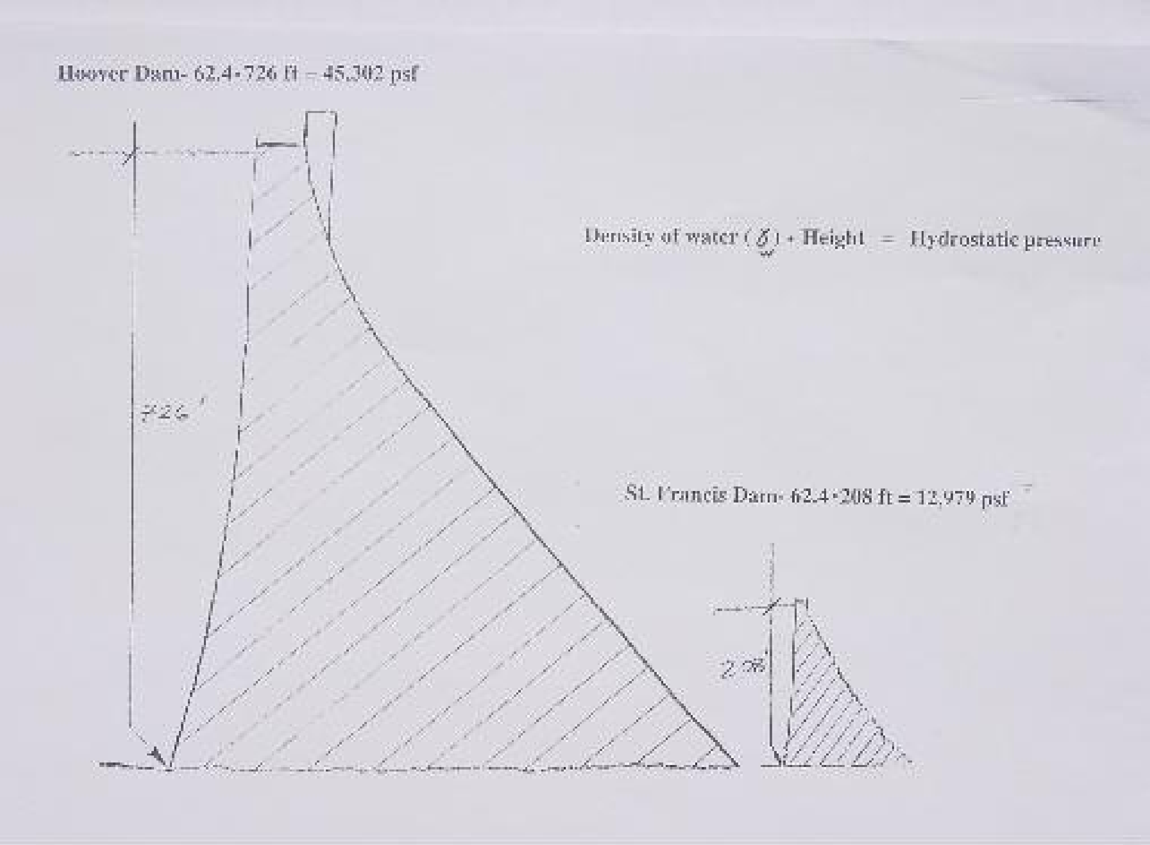
[62] Sherard, James, et al, Earth and Earth-Rock Dams, 212.



Scale drawings of Hoover Dam and St. Francis Dam with calculations for hydrostatic pressure present at lowest upstream point of structures.

No cut-off trench was used in the construction of the St. Francis Dam; however, it did have holes bored 15 to 30 feet in depth at two lines 30 feet and 45 feet from the upstream edge of the Dam. The 10 to 20 holes were connected to the lowest main outlet pipe. Interestingly, all of these drains are under the part of the Dam that remained standing after the collapse. The Report to the Commission highlights the lack of drainage features in the following excerpt:[63]

> ...the ultimate failure of this dam was inevitable, unless water could have been kept from reaching the foundation. Inspection galleries, pressure grouting, drainage wells and deep cut-off walls are commonly

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[63] Wiley, 16.

> used to prevent or remove percolation, but it is improbable that any or all of these devices would have been adequately effective, though they would have ameliorated the conditions and postponed the final failure.

Smith's book also recommends the construction of drainage systems serving as inspection tunnels within the Dam to prevent uplift pressure on the structure.[64] The Olive Bridge Dam and other dams described in the book were built with such inspection tunnels and channels within the Dam leading to outlets at the toe. In the Hoover Dam, the author crawled/walked through similar tunnels and inspection stairways that had been built within the structure in an organized labyrinth manner. These tunnels were completely dry and ventilated through 4-foot diameter channels leading to the downstream face of the Dam. Although, the St. Francis Dam had four outlet pipes at 30-40 foot intervals, in addition to the lowest main outlet pipe, that passed directly through the Dam, but these were not designed nor used for the purpose of preventing uplift pressure on the structure. They were designed to lower the level of the water in the reservoir behind the Dam (**see** Plate 19, page 65).[65]

Use of Aggregate

Smith's book contains a description of how sand and aggregate should be graded and carefully selected for inclusion in the concrete mixture (as it was in the Wachusett Dam,

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[64] Ibid, 106.
[65] Outland, 202.

built from 1900-1901).[66] During construction of the Wachusett Dam, experiments were conducted to show the strength and permeability of mortar composed of various consistencies of coarse, medium and fine sands. The numerous experiments showed conclusively that mortar made with graded sand was stronger and more impermeable then concrete made with ungraded pit run sand.

The Hoover Dam aggregate came from a pit ten miles upstream from the construction site in Arizona, and at that site a $450,000 automated gravel screening plant was built to divide the pit run material into five grades of aggregate and sand.[67] There was also a stone crusher to reduce the larger rock to smaller sizes that could be used to build the Dam.[68] Pictures of the Arizona Sand and Gravel Deposit, Screening, and Washing Plant, and Blending Plant can be seen on Plate 20, page 66**.**[69] The Screening and Washing Plant was state-of-the-art and the vibrating screens, sand washers and classifiers, belt conveyors, etc. could all be controlled by the Central Plant office. This aggregate and sand was delivered to concrete plants adjacent to the Dam where it was mixed in exact proportions with Portland cement and water to provide a consistent mix resulting in concrete that would meet the specified 2500-3500 psi requirement.[70]

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[66] Smith, 57.
[67] Stevens,181.
[68] Department of the Interior, 9.
[69] Bolder Dam Service Bureau, Inc. 1934, 8.
[70] Ibid, 184.

For the concrete at the St. Francis Dam site, with the exception of supposedly eliminating any large aggregate (cobbles) over six inches in diameter, no grading, washing or

screening took place before the sand and aggregate taken from the stream bed was mixed with Portland cement and placed in the Dam. It would not be expected that concrete made from material extracted directly from a stream bed would have a heterogeneous mix of sand and aggregate. In fact, the stream bed would have larger aggregate where the stream runs fast and increasingly finer aggregates and sand toward and on banks of the stream. As aggregate is excavated from the river bed, deposits would constantly change depending on where the stream meandered through the valley over the past millennium. The test on concrete from the St. Francis Dam revealed the concrete to be 2000 to 2700 psi, when it could be tested. The Report to the Commission stated that at least core out of four tested for the Report broke apart during preparation and ultimately was not tested.[71]

Site Selection

Site Selection is, of course, of greatest important in the creation of any dam. Smith suggests that four criteria be used to assess potential dam sites. These are:

- whether or not rock exists over the entire site of the dam,
- whether the rock is hard and sound enough to serve as a foundation, and free from seams or joints that would permit an objectionable amount of leakage,

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[71] Wiley, 20.

- the depth (a) of earth or loose material overlaying the rock, and (b) of disintegrating or unsatisfactory rock that would need to be excavated in order to reach sound, tight rock, and
- the character, amount, and location of the supply of stone and sand to be used in the concrete.[72]

To determine whether a site meets these criteria, borings must be taken at many locations and the results interpreted by competent geologists. Only in this way may the best location be found to locate a dam.[73]

The site selection for the St. Francis Dam began in 1911, during construction of the Los Angeles Aqueduct. Mr. Mulholland had workmen sink shafts and tunnels into the red conglomerate on the west side of the St. Francisquito Canyon to determine if it was suitable for acting as a dam abutment if the need arose. From those investigations and his own tests of the red conglomerate as an amateur geologist, the site for the St. Francis Dam was selected.[74] Mr. Mulholland did not have the site investigated by geologists to confirm that it was suitable for placement of a dam and reservoir. Further investigation would have shown the disintegrative nature of the red conglomerate that existed on the west abutment.

Investigation after the collapse showed the red conglomerate to have rock-like qualities when dry but after only a 20 minute immersion in water, a 1 ½ inch diameter

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[72] Smith, 5

[73] Ibid, 12.

[74] Outland, 37.

sample would break down to a mushy granular mass.[75] The composition of the east wall and river basin was no better; it was composed of severely laminated mica schist interspersed with talc. The schist had little resistance to slipping and possessed the strength of a deck of cards that is pushed obliquely on a table.[76] Neither substance would pass Smith's criteria that the rock be hard and sound enough to serve as a foundation, and free from seams or joints that would permit an objectionable amount of leakage.

In addition, judging from the change in depth that Mr. Mulholland decided to build the foundation, little was known about the composition of the river bed. The foundation of the St. Francis Dam was not dug to bedrock. Similarly, the abutment walls were not securely tied into the canyon wall to stop seepage along those planes. On the east side the concrete was poured up against the mica schist and into a small notch that was cut from the canyon wall (Plate 21, page 66)[77]. On the west side, where the canyon walls were made of conglomerate, a cut-off trench three feet by three feet was hand dug into the side wall with shovels and picks.[78]

Finally, the supply of sand and aggregate from the riverbed of the San Francisquito Creek, which may have proved adequate for the construction of the Los Angeles Aqueduct a decade earlier (a structure through which water flowed rather than one

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[75] Wiley, 20.
[76] Outland, 180.
[77] Wiley, 49.
[78] Ibid, 9.

that acted as a barrier in which concrete would endure higher stresses), was inadequate to build an arch gravity dam to the engineering standards of the 1920s.

The site selection process for the Hoover Dam adhered to Smith's criterion. Test borings were done at several locations over many years before the Reclamation Service began a final three-year survey of Black Canyon and Boulder Canyon to determine the best

location in the Colorado River Basin to place Hoover Dam. Also, the Hoover Dam was excavated to bedrock in the river bed and the abutment walls were carved out hundreds of feet across to provide a solid mating surface for the sides of the Dam. The west abutment can be seen on Plate 22, page 67.[79]

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[79] Department of the Interior, Construction of Boulder Dam, 1934, page 26.

Analysis of the "Report of the Commission"

Review of Omissions in the "Report of the Commission"

In modern times, whenever a major catastrophic event occurs that might have a basis in human error, there must be investigations to ascertain the cause of the failure and determine how the same type of catastrophe can be averted in the future. In the Spring of 1928, the City of Los Angeles, the State of California, the State of Arizona, and many other organizations were investigating the St. Francis Dam failure and, with the Swing-Johnson (Boulder Dam) Bill before Congress, Dr. Elwood Meade, Chief of the Bureau of Reclamation, was sent to Los Angeles to help determine why this arch gravity dam failed.[80] Of all these inquiries, one document, the first to be published after the collapse, is the most quoted in articles and books about the collapse. This report, commissioned by the Governor of California, C.C. Young, was compiled by four engineers and two geologists from California, headed by A.J. Wiley, an engineer from Boise, Idaho.

In Governor Young's instructions to the Commission he states that,

> The prosperity of California is largely tied up with the storage of its flood waters. We must have reservoirs in which to store these waters if the State is to grow. We cannot have reservoirs without Dams. These Dams must be

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[80] Outland, 171.

> made safe for the people below them. All this is both elemental and fundamental.[81]

The six men on the Commission first met on March 19, 1928, seven days after the Dam's collapse. The report, which included 13 pages of written material, two pages of letters from Governor Young, two pages of rock and concrete tests comprised of one conglomerate rock test and four concrete core tests, and 31 pictures and maps, was completed in five days. Not surprisingly, the report concluded that:

- The failure of the St. Francis Dam was due to defective foundations.
- There is nothing in the failure to indicate that the accepted theory of gravity dam design is in error or that there is any question about the safety of concrete dams ... when built upon even ordinary sound bedrock.

And, most importantly,

- ... Water storage, with its necessary concomitant dams and embankments, is particularly essential of California resources ... The police power of the State certainly ought to be extended to cover all structures impounding any considerable quantities of water.

That the conclusion of the Report of the Commission mirrored the tone of Governor C. C. Young's instructions did not surprise me; however, the author did find many important details in the report were found that didn't seem to be factored into the conclusions.

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[81] Wiley, 5.

The Report mentions that leakage did occur through the main structure of the Dam but called that leakage, as well as leakage through cracks in the wing wall, "unimportant." However, leaks under the Dam are called "much more important." The Report states "Rumors of muddy water seeping under or around the Dam before its failure are in circulation but the Commission has been unable to verify them."[82] Through its inclusion of admitted rumors, the Commission gives more credence to leakage under and around the Dam versus that through the Dam.

The foundation of the Dam is stated to have been excavated to an elevation of 1630 or 20 feet below streambed level.[83] The St. Francis Dam design, plan, and profile, included on page 29 of The Report (see Plate 19, page 65), shows the Dam foundation was to be 30 feet below streambed level or at elevation 1620. If bedrock conditions were found to be different from what had been planned, this modification to the plan would not have been a reason for concern, but the Report does not give any reason or explanation for the discrepancy in foundation depths. Likewise the Report states that under *portions* of the west abutment and about 25 feet from the upstream face, a cut-off trench about three feet wide and three feet deep was excavated. No mention is made as to why only portions and not the entire abutment was built into a cut-off trench.

Drainage from under the Dam is discussed but only to describe the system that was installed under the main section of the Dam. The Report states that "...this drainage

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[82] Wiley, 7.
[83] Wiley, 9.

system is included under the portion of the Dam which remains standing; this is probably merely a coincidence... "[84] No explanation is given as to why the entire Dam did not have a drainage system to relieve uplift pressure and to state that it is a "coincidence" that the drainage system was only under the upright structure has no basis in the facts known at that time.

The concrete aggregates are reported to have come from the streambed without washing or grading but the concrete is immediately excluded from having played a part in the disaster.[85] Later in the Report, the concrete is described as having an average crushing strength of 2400 psi[86] based on tests done for the Commission. The 2400 psi was based on three tests included on page 21 of the Report. This compression test report explains that four cores were to be tested but one core broke apart during preparation and "revealed a large laminated stone, which rendered this core unfit for testing."[87] One would expect that if 25% of the specimen cores could not be tested, some other test or an adjustment in the average concrete strength of the other cores would have been made.

The lack of any inspection gallery or pressure grouting are noted without explanation.[88] As for contraction joints, the Report stated "There were no contraction joints built into the Dam ... and, in any event, the failure cannot be attributed to their

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[84] Ibid, 10.
[85] Ibid, 10.
[86] Ibid, 15.
[87] Ibid, 21.
[88] Ibid, 10.

absence.[89] Again, the conclusions drawn do not have any basis in the facts known at that time.

Only the geological conditions of the Dam site are given more than a cursory examination within The Report. Over five pages of the 13 pages of the written Report are dedicated to examining the canyon walls and streambed before and after the collapse. Nor surprisingly, The Report's final conclusion was that the failure of the St. Francis Dam was due to defective foundations.

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[89] Ibid, 15.

Conclusions

Project Team

The prevailing emphasis in Project Management is to treat the planning, design, and construction phases as integrated tasks. This approach unites a three-party team consisting of owner, designer and construction manager in a non-adversarial relationship. The team should work together from beginning of design to project completion with the common objective of serving the owner's interest.[90]

Having studied the St. Francis Dam project for the past two years, three phases of the project seem to contradict Project Management principles that the author has been taught in the Project Management program. First, the project team was truly a one-man show. Second, the design and construction did not meet industry standards of the day. And third, during the final phases of the project, operation, and utilization, no one took the necessary steps to protect the investment and people who were at risk below the Dam.

In the early 20th Century, the Los Angeles Water Department followed the construction model of Owner-Builder.[91] In this type of organization, the City, County or State Public Works Department perform their own design and actual construction with their own forces. This is done to save money and to give the owner the ultimate control of the project. Up until the St. Francis Dam disaster, the Los Angeles

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[90] Barrie, Donald S. and Paulson, Jr., Boyd C., Professional Construction Management, page 35.
[91] Ibid, page 31.

Aqueduct and smaller reservoirs within the Los Angeles were built at great savings and had performed admirably. In contrast toe the project style used in the St. Francis Dam project, the Bureau of Reclamation had transitioned to a Design/Bid/Build construction model for large public works construction projects in this manner in 1925. It was determined that this was a more dependable style due to its built-in redundancies and checks and balances between the owner, designer, and builder.

William Mulholland, Chief Engineer and General Manager for the St. Francis Dam Project, was the driving force behind the project, although, there were many managers working with him, some of whom had worked on the Los Angeles Aqueduct, completed only 12 years before the St. Francis Dam Project began. The Los Angeles Water Works and Supply Authority was willing to give Mr. Mulholland a free rein in deciding what, how, or where the Dam was constructed as long as it received a water supply close to the city to protect its interests.

Without the checks and balances that are inherent in a Design/Build/Bid style, problems that arose during construction were ignored, addressed in a substandard manner, or diminished in importance.. For example, after the collapse, workmen came forward and claimed that the nature of the schist in the east wall had been brought up during construction of the Dam. Similarly, the differing nature of the red conglomerate in the abutment in the west canyon wall was discernable during construction.[92] And, since Mr. Mulholland did not regard the canyon walls'

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[92] Outland, Charles, page 31.

composition as a deterrent, his team of largely inexperienced dam builders concurred in the “Chief’s” judgment.

Without a strong project management team and open lines of communication within the team, a complex construction project, such as this, had little chance of success.

Design and Construction

As was stated earlier in this paper, many important design features common in other early 20th Century Dam were missing from the St. Francis Dam. The St. Francis Dam design was developed by the Los Angeles Bureau of Water Works and Supply Engineering Department. While it was similar in basic design to other concrete dams, the designers under Mr. Mulholland’s leadership left out necessary elements of masonry dam construction such as curtain walls, drainage systems and contraction joints. The inclusion of these basic features could have prevented or delayed the sudden total collapse of the structure just two years after completion. Similarly, pouring five-foot thick concrete slabs without consideration for heat of hydration was atypical for concrete construction at that time. Also, the use of large and inconsistent aggregate in the Dam’s construction, which can be seen at the Dam site in broken concrete pieces left when the Dam was dynamited one year after its collapse, exposes the mendaciousness of Mulholland’s expressed limit of using nothing larger than 6-inch diameter aggregate.

Operation and Utilization The St. Francis Dam began leaking as the reservoir behind it filled. Mr. Mulholland was aware of the leaks, yet was often quoted as saying, "Of all the dams I have built and of all the dams I have seen, it is the driest dam of them all."[93] By the time the Dam collapsed, two years after it had been filled, it was fractured transversely in four places. The leaks coming from these cracks were, for the most part, clear water -- which was seen as a positive by Mr. Mulholland because it meant that the foundation was not being undermined. When a new leak developed on the wing wall in early March 1928, 150 feet from its junction with the main Dam, Mr. Mulholland judged it to be another of the normal contraction or temperature cracks that could be expected in any large body of concrete. The engineer who installed a eight-inch drain to carry the water from the leak down the canyon wall, noted, "We dug down on the face of the dike in front of the crack and noted this water bubbling up like a stream as though it was coming through the crack in the concrete..."[94] Mr. Mulholland did not even seal this crack and commented after the collapse, "The dike leak was wholly an unimportant thing, had no significance at all..."[95]

On the eastern side of the Dam, the crack that occurred in late December of 1927, three months before the collapse, may have been caused by a movement of the schist against which the Dam abutted. Mr. Mulholland had been told of concerns people had about leaks in the Dam and saw the conditions himself, but even on the last day that the Dam stood with the reservoir filled and spilling over the top of the Dam, he

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[93] Ibid, 46.
[94] Ibid, 52.
[95] Ibid, 52.

didn’t order the outlet gates opened to relieve pressure on the Dam. Admittedly, opening the outlet gates probably would not have stopped the Dam from collapsing at this point. But why didn’t Mr. Mulholland try to lower the reservoir level as quickly as possible to ameliorate the quickly deteriorating situation? In statements he made to investigators to explain his actions on March 12th, he said that he felt some measures were needed to address the leakage but that he had not decided what they should be.[96]

One of the principles that is discussed in Simultaneous Management, is the need to control the project through inward and outward leadership.[97] Mr. Mulholland worked hard to get the project completed for his employer, the Los Angeles Water Works and Supply Authority. He understood how to control internal issues, such as managing the decision-making process and using his power to control the project to the extent possible, and his success in the construction of the Los Angeles Aqueduct and other water works showed that he understood how to move a project from design through construction. However, Mr. Mulholland did not pay enough attention to essential problems that were present from the start of the project such as the nature of the canyon walls and, also, those that escalated throughout 1927 and 1928 such as complaints about the leaks from neighbors. And, he did not take immediate action to address leaks that he later admitted warranted attention.

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[96] Outland, 66.
[97] Laufer, Alexander, Simultaneous Management, page 105.

His team either believed in what “The Chief” told them about the leakage or did not feel comfortable with exploring other reasons for the accelerating leaks. Dr. Laufer (the author of <u>Simultaneous</u> <u>Management</u>) suggests that a large project should have a decentralized organization that can reduce information overload and move the decision point closer to the information sources.[98] For the St. Francis Project, the Los Angeles Water Authority put too much power in the hands of Mr. Mulholland and errors in Dam design, site selection, construction, and operation came together to doom the project.

Mr. Mulholland ultimately took the blame for the Dam’s collapse when he said during the Los Angeles Coroner’s inquest, “Don’t blame anybody else, you just fasten it on me, if there is an error in human judgement, I was the human.” Later, he vacillated from this position when asked by the Coroner to explain the cause of the failure, by alluding to a totally unfounded theory that the Dam might have been dynamited. He said, “I have no explanation that could be called an explanation, but I have a suspicion, and I don’t want to divulge it. It’s a very serious thing to make a charge – to me it’s a sacred thing to make a charge even of the remotest implication.”[99]

The real cause of the disaster was not the Dam’s design, method of construction, erringite, or ignoring the significance of the clear water leakage (or dynamite). The root cause was the overriding desire of the Los Angeles city leaders and the

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[98] Ibid, page 137.

[99] Los Angeles County Coroner. Transcript of Testimony and Verdict of the Coroner’s Jury in the Inquest over Victims of the St. Francis Dam Disaster.

Governor, himself, to have a stable source of water so that the city and state could grow. In his final letter to Mr. A. J. Wiley, thanking the Commission for completing the investigation into the disaster, the Governor restates what he also said in a letter to them less than a month before ... “While fully cognizant ... of the appalling loss of life and great destruction of property caused by this frightful disaster, it is at the same time, self evident that the full development of this great commonwealth requires that her water resources be fully conserved. This can be done only by continuing the construction of great dams such as those that currently doing their work without sign of weakness.”[100]

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[100] Wiley, A. J., page 19.

Recommendations for Further Work

After testing of the concrete sample from approximately elevation 1750 at the western end of the Dam, showed the existence of ettringite and micro fractures in the concrete. It would be of interest to discover whether other portions of the Dam exhibit similar traits. ASTM C 856 – 95, Standard Practice for Petrographic Examination of Hardened Concrete, provides a procedure that could be used to do a more thorough study of the St. Francis Dam concrete. This standard outlines the procedure for obtaining, preparing, testing, and interpreting concrete samples from concrete structures. For study of large structures, ASTM C 856 – 95 suggests to, "...arrange them (the concrete specimens) in logical order to represent position in the structure and differences in materials, proportions and exposure or combinations of these."[101] A future researcher could, by obtaining several intact concrete fragments from other portions of the Dam, perform tests to confirm or disprove that the existence of ettringite found in the tested sample indicates that the balance of the St. Francis Dam concrete contained micro fractures that weakened the concrete.

The original intent of the author's trip to the southwestern U.S. was to investigate the St. Francis Dam site and visit the Hoover Dam to obtain a piece of concrete that had been extracted from that Dam. On previous trips to Hoover Dam when security was of less concern, walking down to a clean dumpsite would not have been a problem. A promising site on the Nevada side of the river appears to hold concrete that came from renovations to the original Dam structure. But at this time, due to stringent

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[101] Annual Book of AST Standards, page 433.

security restrictions, access to that location was not allowed. At some time in the future, a visit to that site could provide samples that would reveal difference in the concrete mix and ultimate strength from the concrete used in the St. Francis Dam.

Plates

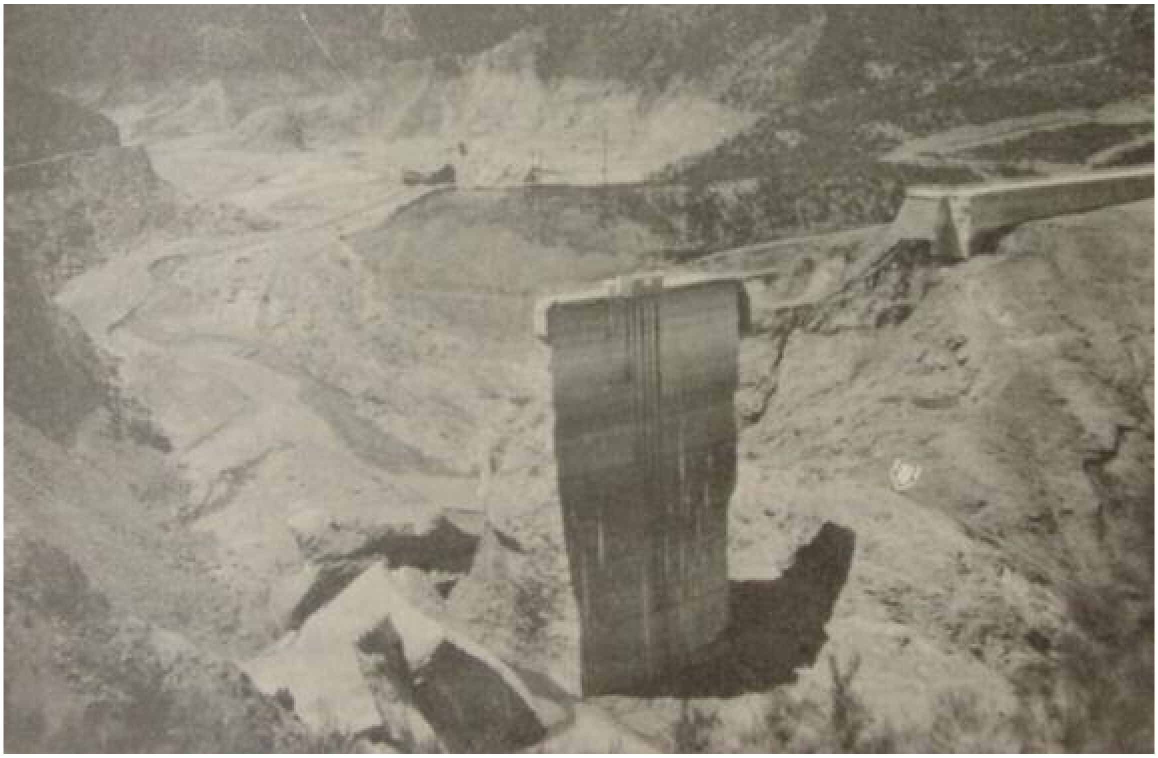

Plate 1 Fault line visible in picture taken after the St. Francis Dam collapse.

Plate 2 Location of St. Francis Dam fragments after the collapse.

Plate 3 Prepared slides of concrete sample showing heterogeneous distribution of aggregate.

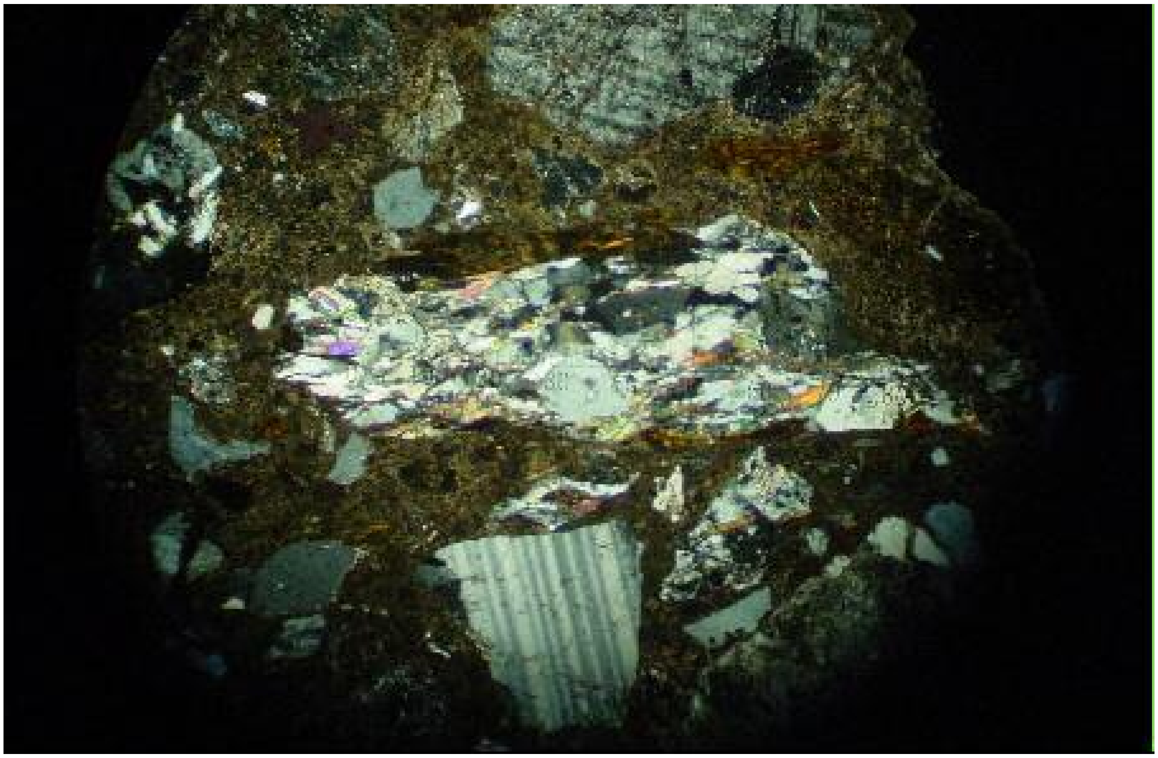

Plate 4 Prepared slide showing mica schist fragment magnified 10X.

Plate 5 Mica schist aggregate visible in concrete sample from the St Francis Dam.

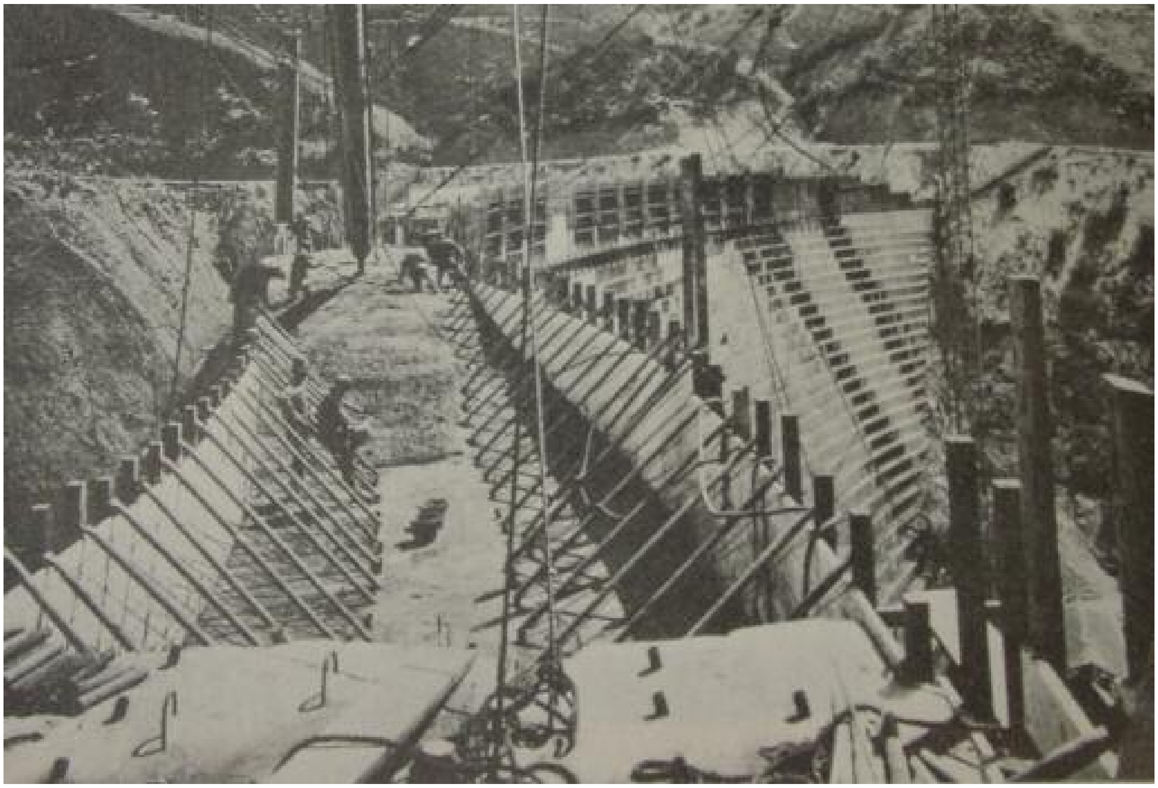

Plate 6 Concrete pour for the St Francis Dam.

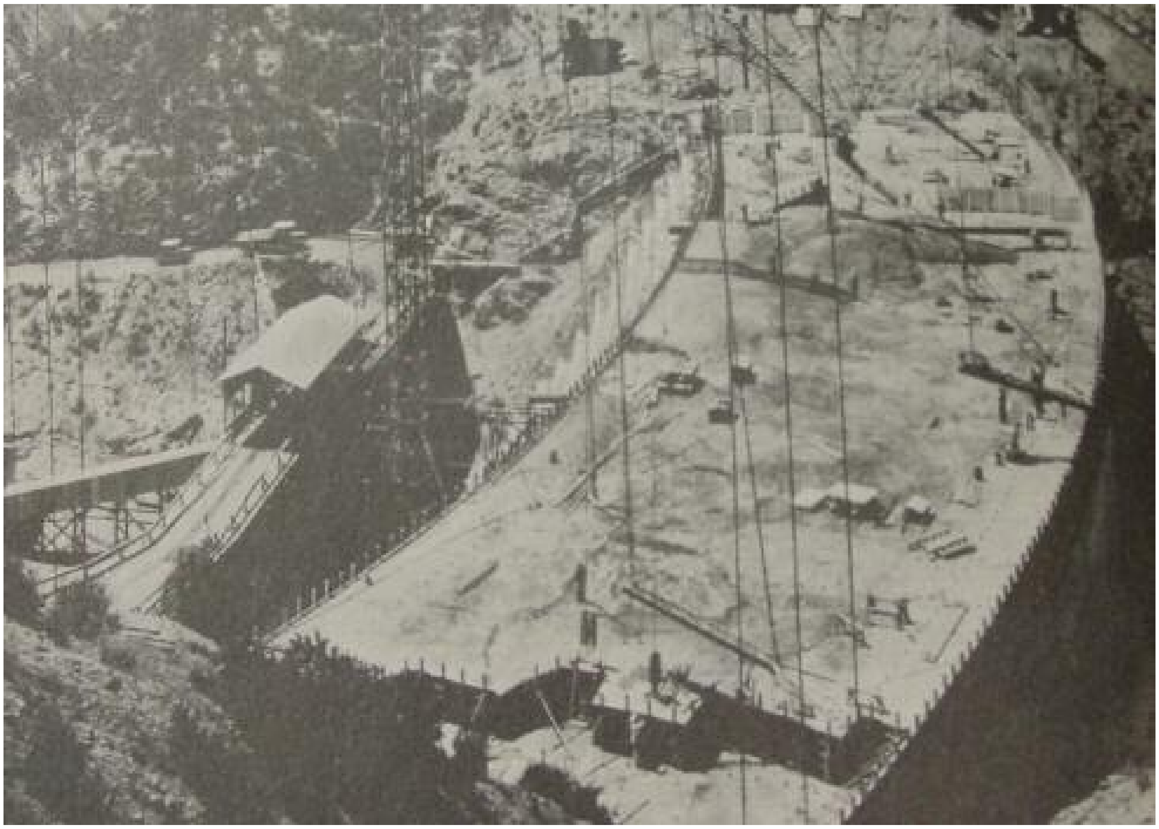

Plate 7 Early view of St. Francis Dam showing, “hummocks”.

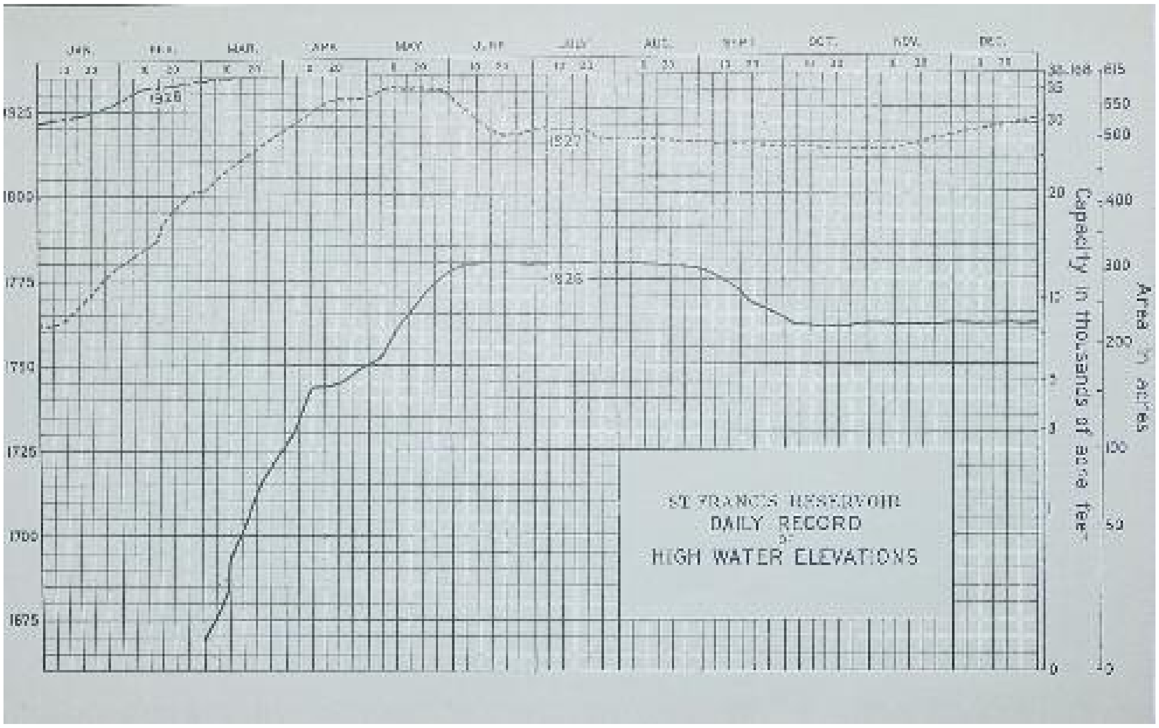

Plate 8 Graph showing water levels in the St. Francis dam on March 12, 1928.

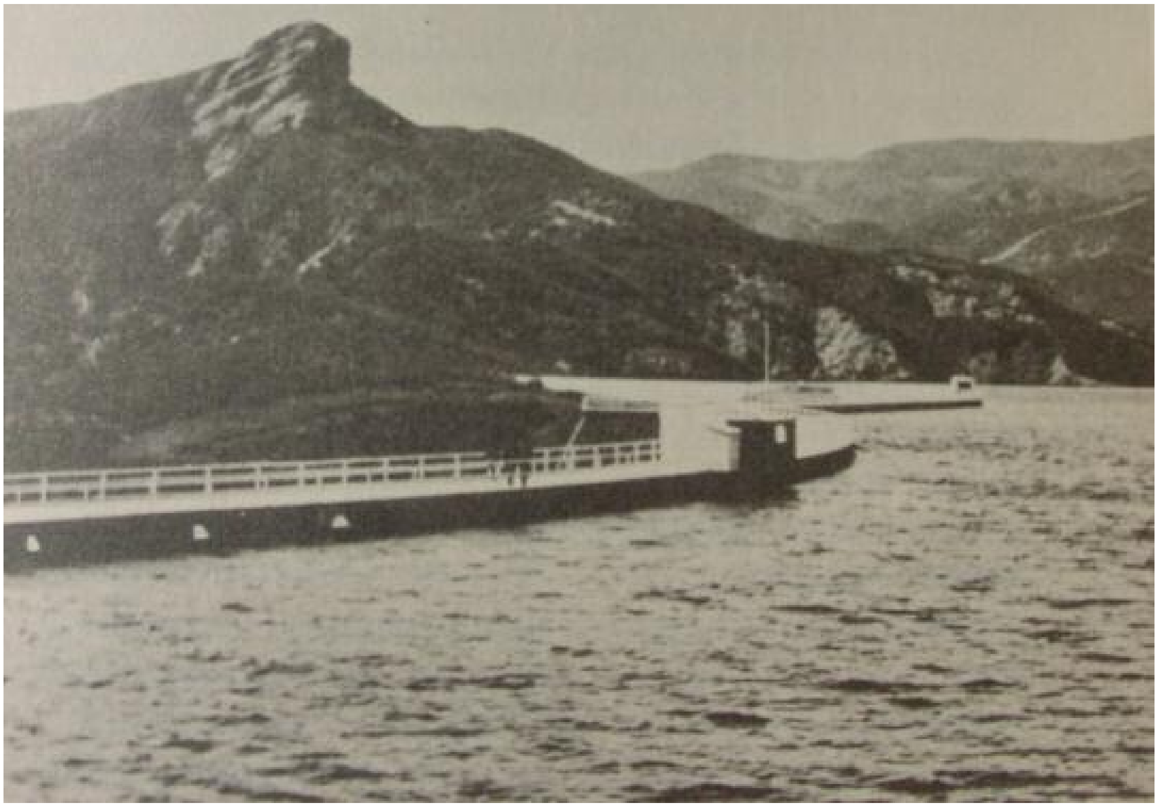

Plate 9 View of reservoir outlet openings at St. Francis Dam on March 12, 1928.

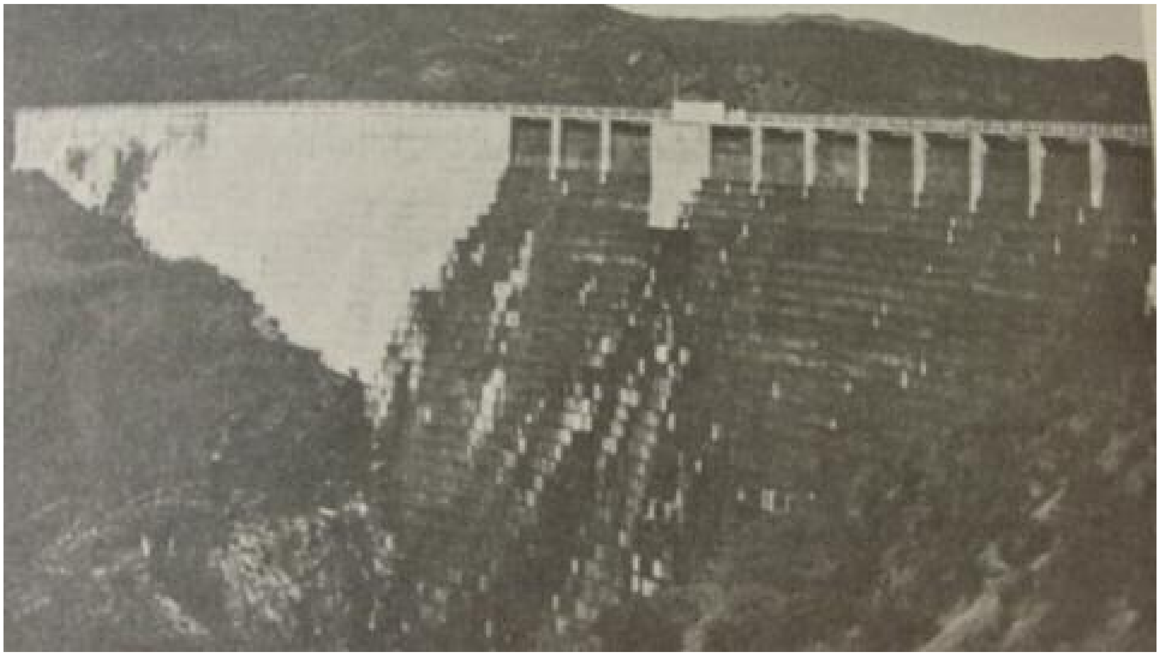

Plate 10 View from downstream side of St. Francis Dam on March 12, 1928.

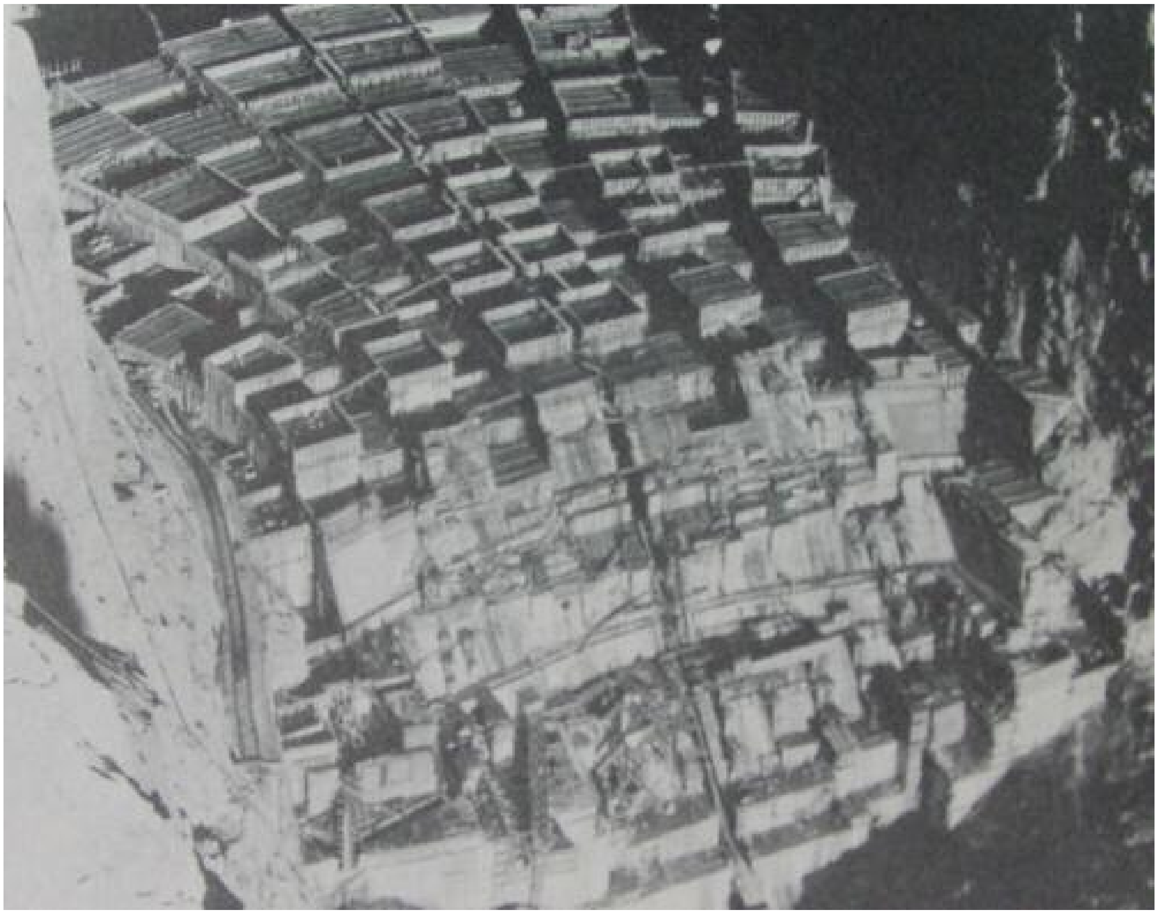

Plate11 Hoover Dam under construction.

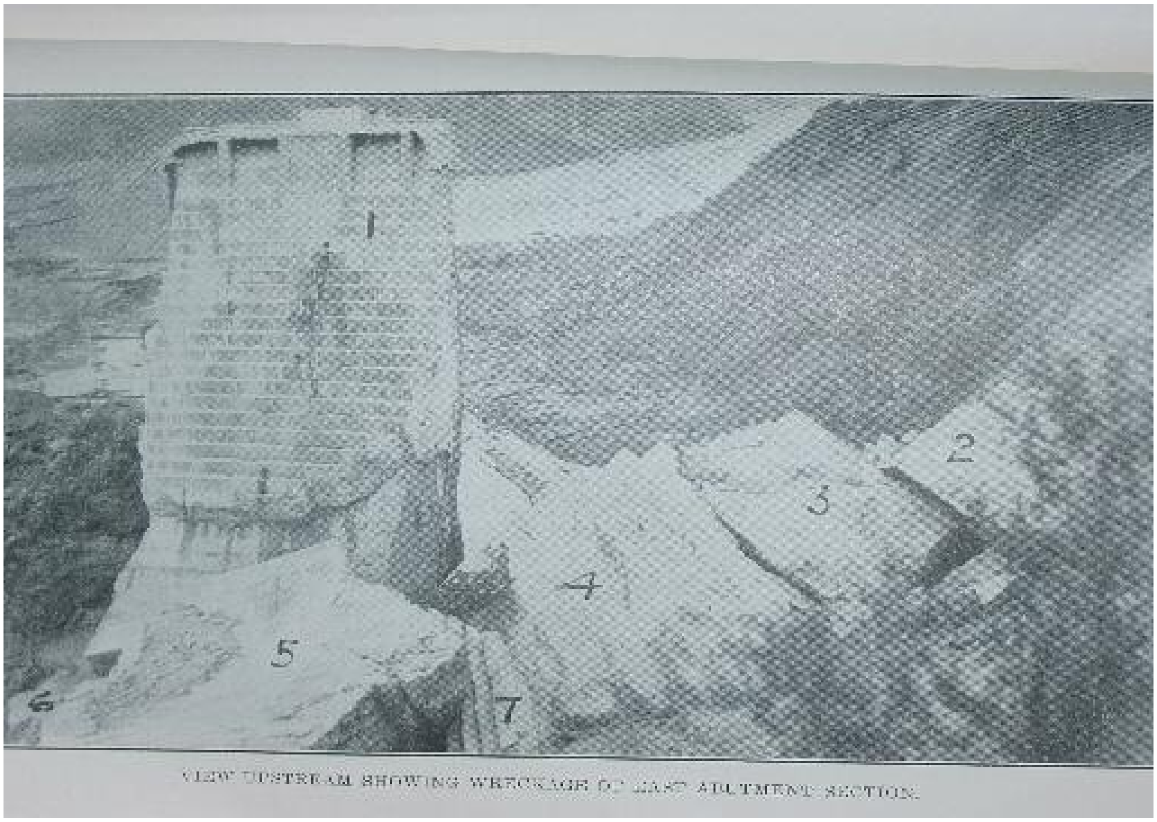

Plate 12 St Francis Dam after collapse.

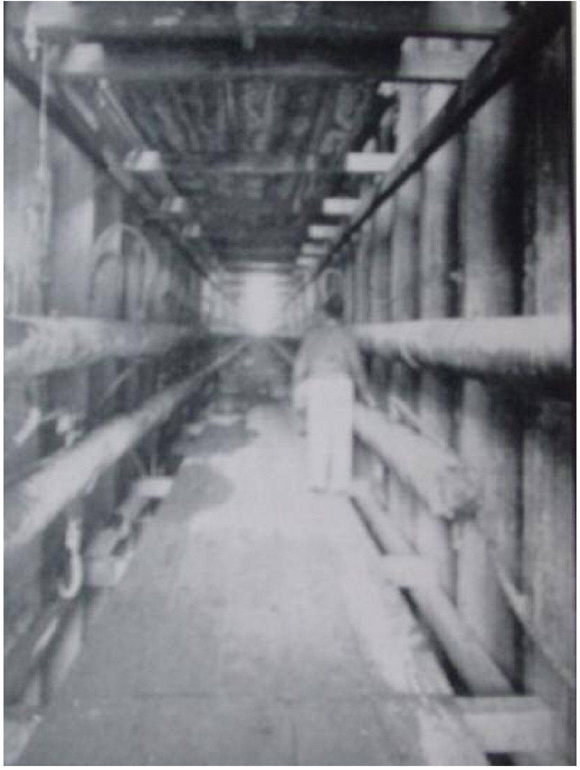

Plate 13 Walkway through the Hoover dam with supply lines for cooling pipes.

Plate 14 Three hundred foot long cooling plant (black building) located on lower coffer dam.

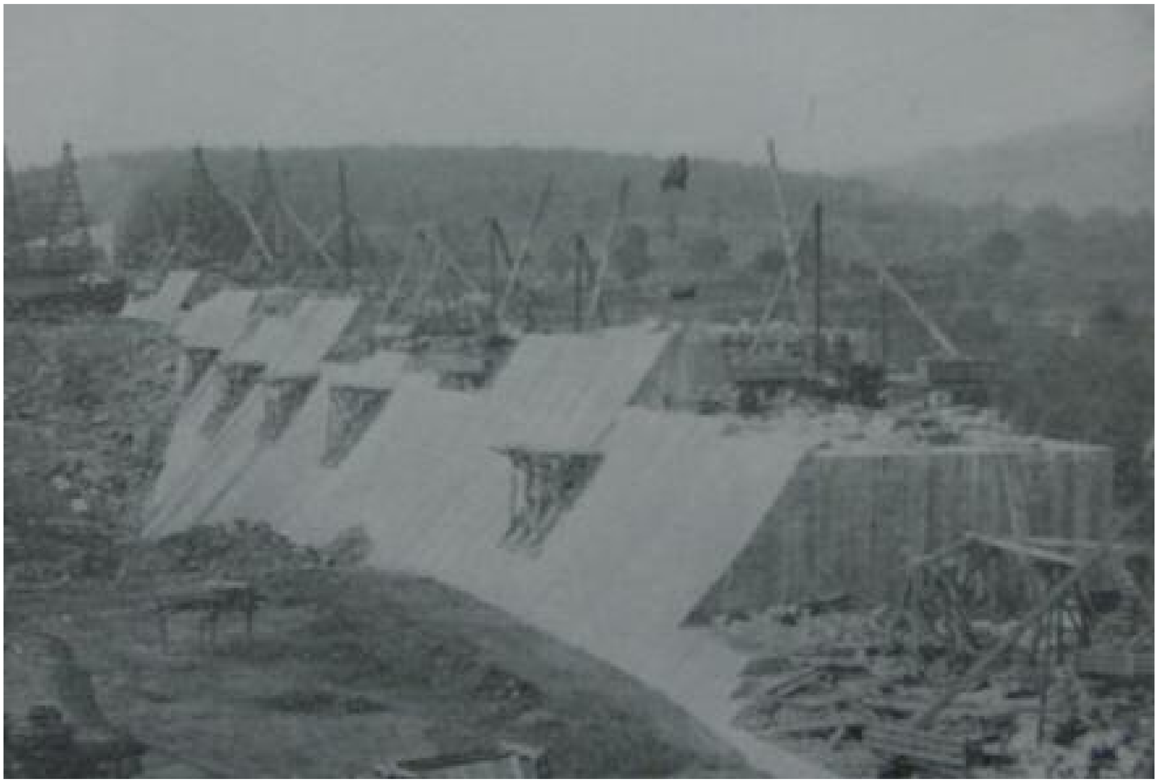

Plate 15 Olive Bridge Dam construction circa 1910.

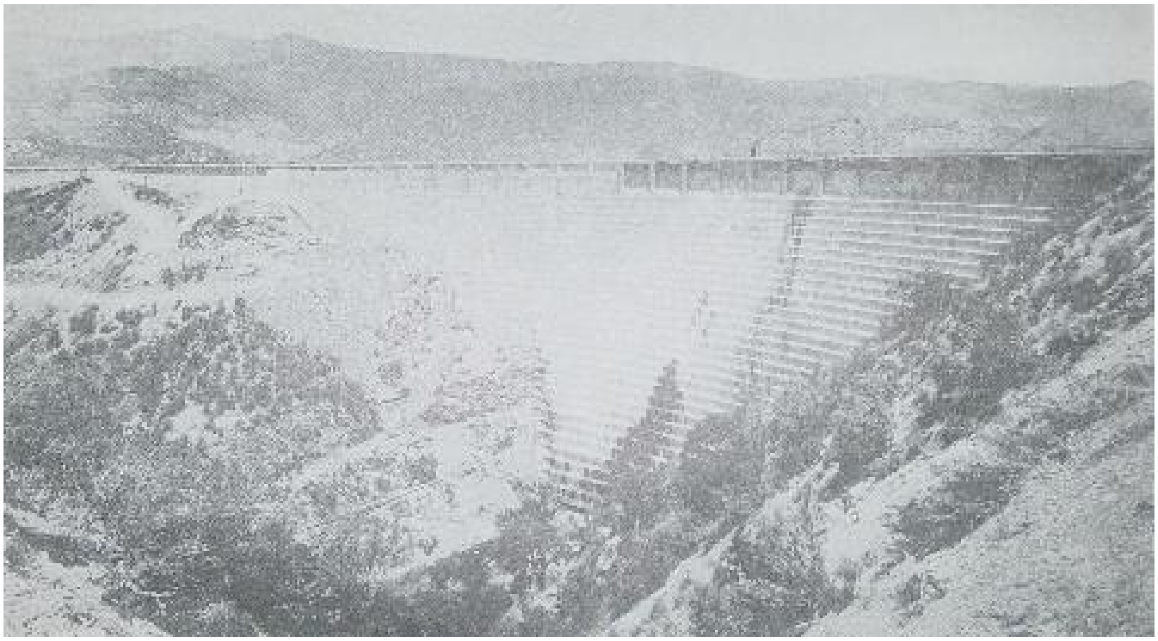

Plate 16 Cracks visible in completed St. Francis Dam.

Plate 17 View from upstream side of St. Francis Dam after collapse.

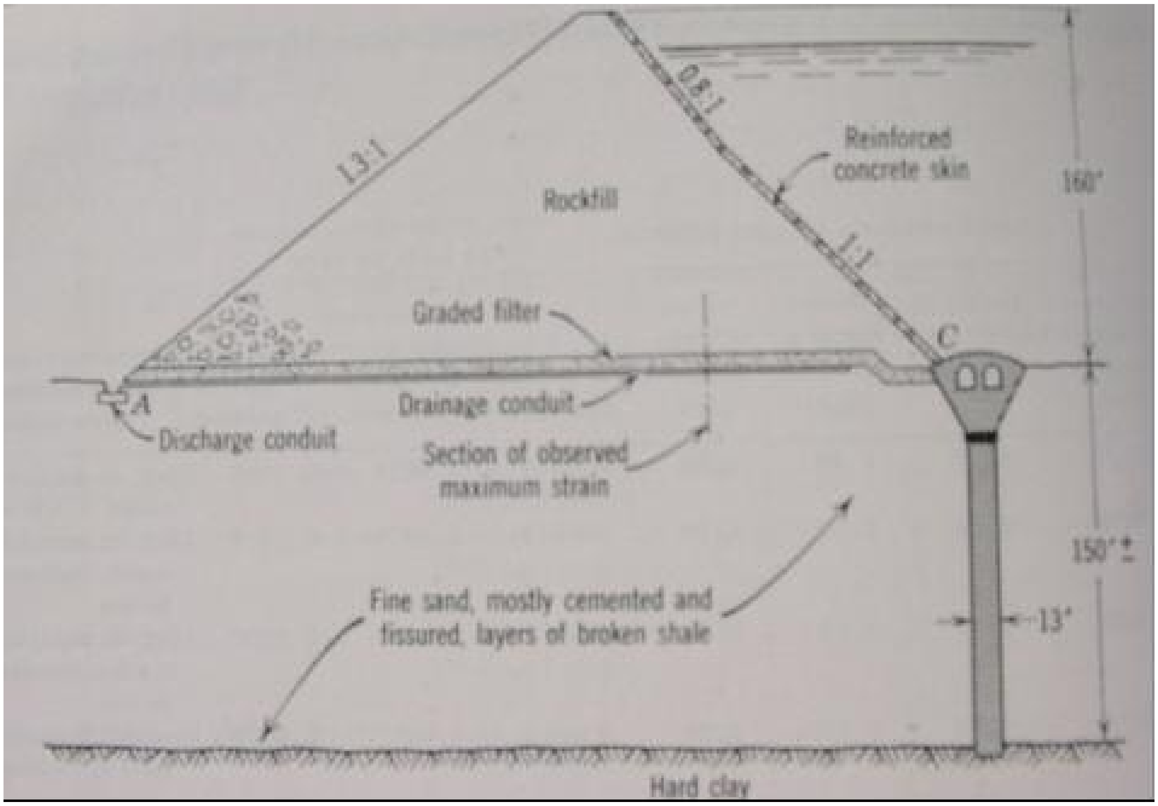

Plate 18 Example of generic cut-off trench under a dam.

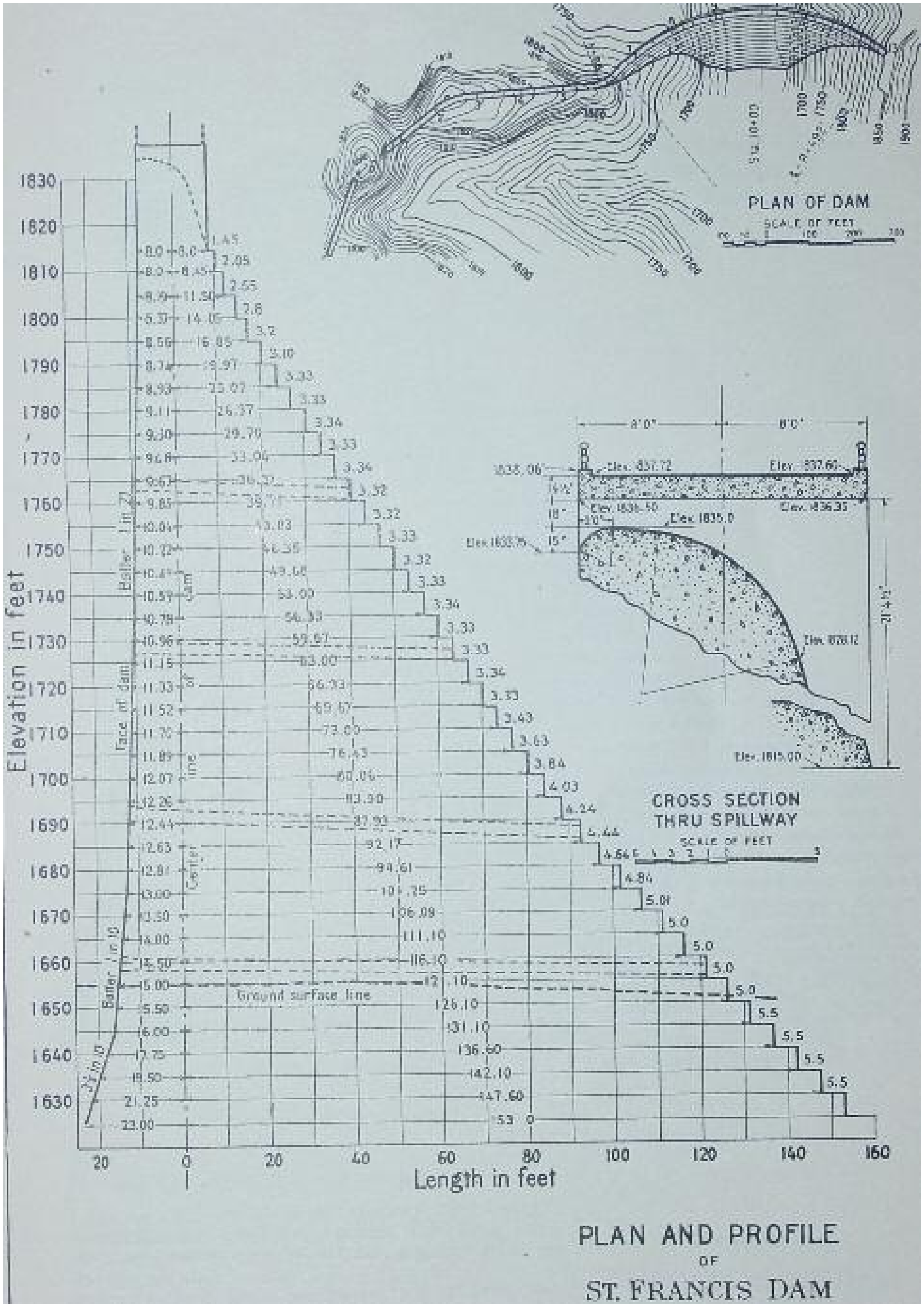

Plate 19 Drawing of St. Francis Dam showing outlet tunnels.

Plate 20 Hoover Dam sand and gravel screening plant.

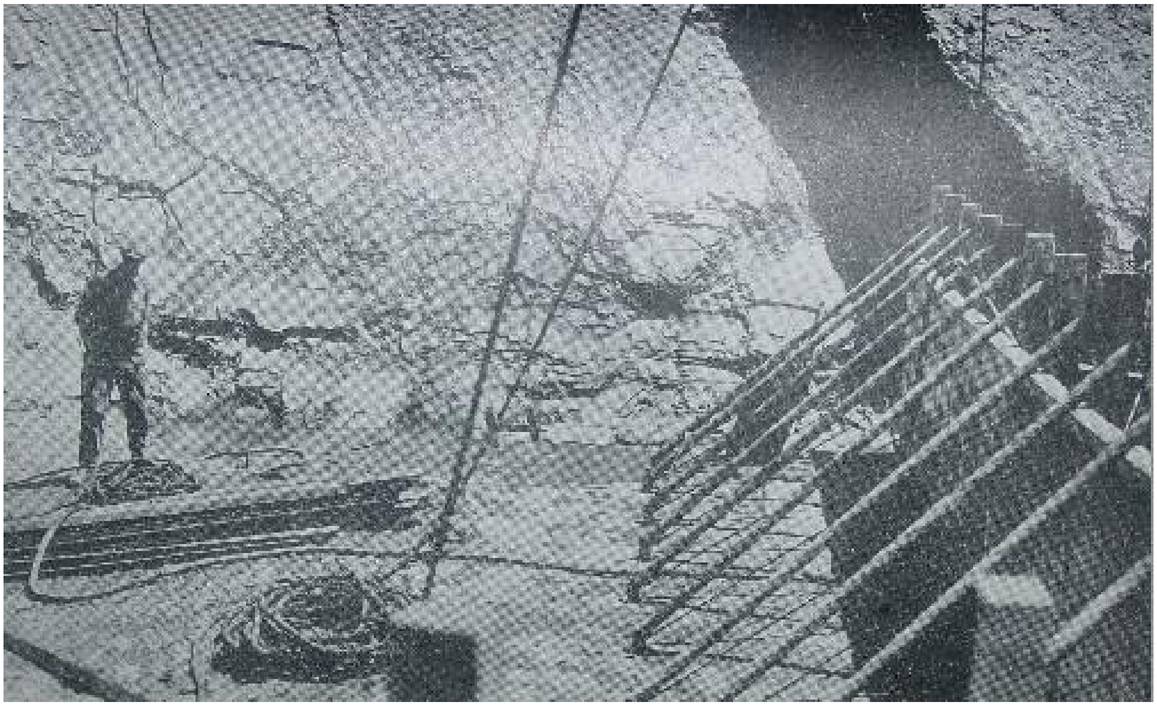

Plate 21 View of St. Francis Dam east abutment showing trenching up canyon wall.

Plate 22 View of Hoover Dam west abutment.

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Appendix A

NATIONAL PETROGRAPHIC SERVICES
4484 Willowbrook Road
Columbus, Ohio 43220
Phone: (614) 451-0231
Fax: (614) 451-0667

NPS-03-0611
June 16, 2003

DESCRIPTION Petrographic Examination of One Concrete Core

FOR Penniman & Browne, Inc.

PROJECT Thesis Project University of Maryland

REPORTED TO Penniman & Browne, Inc.
P. O. Box 65309
Baltimore, Maryland 21209-0309

Attn: Ayzik Vaynshteyn, P.E.
Laboratory Director

INTRODUCTION

This report covers the petrographic examination of one concrete core submitted by Penniman & Browne, Inc. The core's measurements (as received) and general remarks are as follows:

Core Diameter (inches)	Core Length (inches)	General Remarks
$2\frac{3}{4}$	~5 - 7	Photos 1 & 2. The core section was intact, but there was no indication of the top or bottom orientation of the core; both ends of the core was broken and uneven. An extensive fracture was noted oriented parallel to the core's length. This fracture appeared to be mostly within the cementitious matrix, but was observed disrupting one coarse aggregate particle. A very fine fracture was observed oriented parallel to one end of the concrete core.

Reportedly, the concrete core section was extracted from a 110 year old dam that collapsed.

EXAMINATION

A slab was cut from the concrete core parallel to the core length. A plane surface was then lapped according to standard procedures. The prepared concrete sample was then examined microscopically, and the observations are as follows:

The concrete section was intact. The coarse aggregate observed on the prepared concrete sample did not appear to be homogeneously distributed, and most of the coarse aggregates appeared to be $\frac{1}{2}$-inch or less in size. Some areas of the prepared concrete section appeared to be contain mostly fine aggregates and the finer range of the coarse aggregates. A number of microfractures oriented parallel to one end of the core (the left end of the core in photos 1 & 2) were observed in the area directly below the ruptured (broken) end of the core. An extensive fracture, oriented perpendicular to the ends of the core section, was observed through most of the core length (Photo 3). Some microfractures were noted adjacent to and paralleling this extensive perpendicular fracture. Throughout the body of the concrete a number of randomly oriented microfractures were observed within the cement paste and along the peripheries of some aggregates (Photos 4 & 5), and in a few instances fracturing weaker aggregate particles.

The parameters of the air-void system were determined according to ASTM C-457, and the resulting data are given in Table I. The concrete was non-air-entrained. The majority of the voids observed were irregularly shaped. Some white secondary deposits were observed within a number of the voids. The cementitious matrix was mostly white in color, and contained very little unhydrated cement. A number of areas within the cementitious matrix appeared weak and deteriorated.

The unprepared portions of the concrete core sample were easily broken with a geology hammer and the freshly broken surfaces were examined. The freshly broken surfaces exhibited secondary deposits of ettringite (Photos 6 & 7).

The coarse aggregate was composed of natural rock that ranged from rounded-to-subrounded-to-subangular in shape. The maximum nominal top-size of the coarse aggregate was approximately 1-inch. The composition of the coarse aggregate was mostly igneous in origin (granites, quartzite, etc.). The fine aggregate was natural and consisted primarily of quartz, some igneous rock and minor amount of mica.

CONCLUSION

For maximum durability of concrete structures subject to freeze-thaw conditions in a moist environment, adequate air-entrainment is generally recommended. The examined concrete was non-air-entrained (Table I). The one end of the concrete core sample exhibited microfractures oriented parallel to the ruptured end of the core. These microfractures are characteristic of freeze-thaw distress, and are generally precursors of future scaling.

Within the body of the concrete, a number of randomly oriented microfractures were observed within the cement paste and along the peripheries of a number of aggregate particles. The character of these microfractures and some observed secondary white deposits suggest a weakening within the cement paste and loosening of the bond between aggregate particles and the cement paste. Such features are generally associated with swelling of the cement paste.

White secondary deposits were observed lining a number of voids. Portions of the remainder of the unprepared concrete core sample were broken, and white secondary deposits were observed on the freshly broken surfaces (Photos 6 & 7). These secondary deposits exhibited the physical and optical characteristics of ettringite (calcium sulfoaluminate). Ettringite is a solid reaction product that has significantly greater volume than the solids entering into reaction. When a considerable amount of ettringite is produced, it can result in expansion and conceivable hydrostatic pressure could take place in the paste and/or voids in which the precipitations transpire. A high degree of ettringite is generally associated with severely disintegrated concrete. High degrees of ettringite are often associated with sulfate attack.

The extensive fracture (Photo 3), oriented parallel to the length of the concrete core, observed within the body of the concrete also indicates that the concrete was been experiencing a high degree of distress.

In summary, the examined concrete exhibited signs of mechanical disruption that most probably can be attributed to more than one agent. The observations noted in the examined concrete tend to indicate that a combination of freeze-thaw distress and chemical processes occurring in the hardened concrete are two major factors contributing to the deterioration of the concrete.

National Petrographic Services
Bonnie L. Awan
Bonnie L. Awan
Chief Petrographer

TABLE I

Parameters of the Air-Void System* for One Concrete Core Section Taken from 110 Year Old Dam.

Sample Identification	NPS-03-0611	ASTM Range
Air Content (% by volume)	3.44	
Paste Content (% by volume)	30.25	
Paste-Air Ratio	8.79	4 to 10
Specific Surface (sq.in./cu.in.)	139.37	600 to 1100
Void Spacing Factor (inch)	0.0429	0.004 to 0.008
Traversed Length (inches)	141.70	95.00**
Area Traversed (sq. in.)	15.75	12.00**
Total Points Counted	2846	1425**

* Determined according to ASTM C-457: Microscopical Determination of the Air-Void Content and Parameters of the Air-Void System in Hardened Concrete (modified point count method).

** These values are the minimums for 1-inch maximum size aggregate.

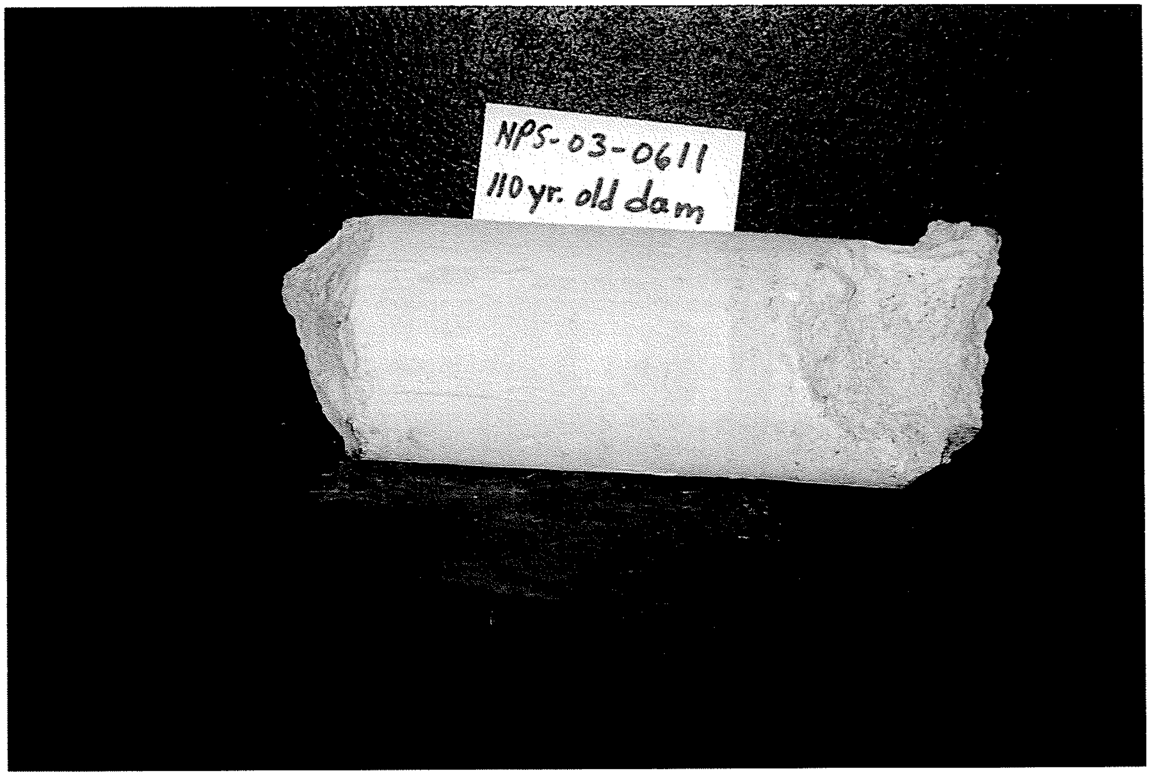

Photo 1. Core From 110 Year Old Dam: Concrete core sample as received. Note surface of core is covered with dried slurry resulting from the coring.

Photo 2. Core From 110 Year Old Dam: Concrete core sample as it appeared after it was washed off.

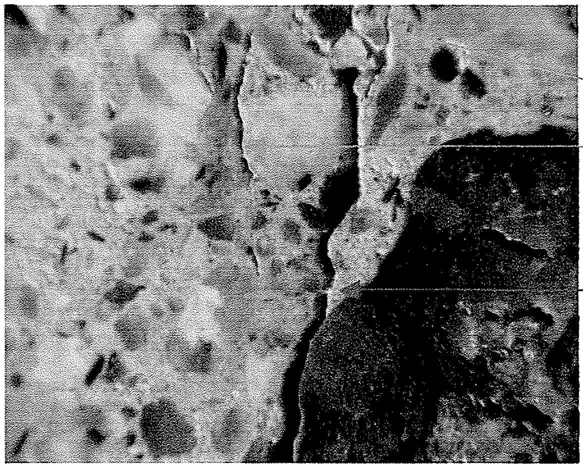

Photo 3.

Photo 3. Microscopic photo taken through a stereoscopic microscope of a polished (lapped) portion of the examined concrete sample.

The concrete exhibited an extensive fracture oriented parallel to the core length. The photo shows a portion of the fracture (red arrow) extending through the cement paste and along a portion of the periphery of a coarse aggregate. The 2 green arrows point out microfractures adjacent to the main fracture.

Note: The photo was taken at a magnification of 14X.

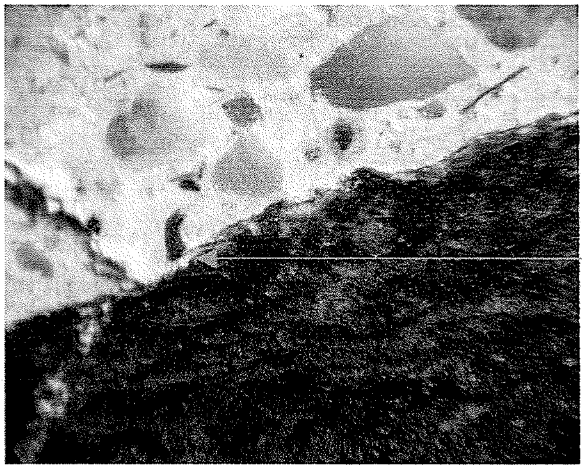

Photo 4.

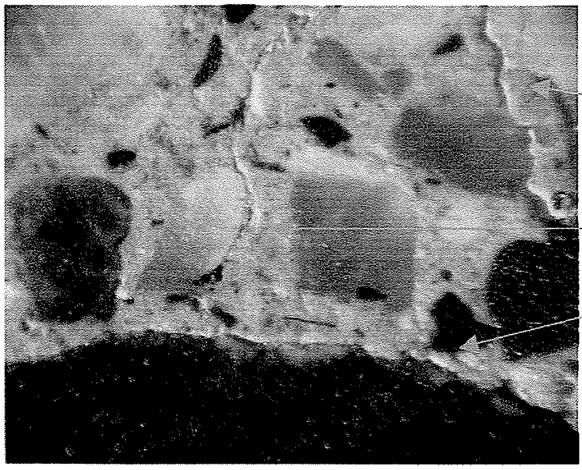

Photo 5.

Photos 4 & 5. Microscopic photos taken through a stereoscopic microscope of a polished (lapped) portion of the examined concrete sample.

The examined concrete exhibited a number of randomly oriented microfractures throughout the body of the concrete. These microfractures were observed within the cement paste and along the peripheries of some coarse and fine aggregate particles. Photos 4 and 5 are examples of the observed randomly oriented microfractures.

Photo 4 shows a microfracture within the cement paste and going along the periphery of a coarse aggregate. Photo 5 shows microfractures within the cement paste and along portions of the peripheries of a coarse aggregate and some fine aggregates.

Note: Photos 4 and 5 were taken at a magnification of 40X.

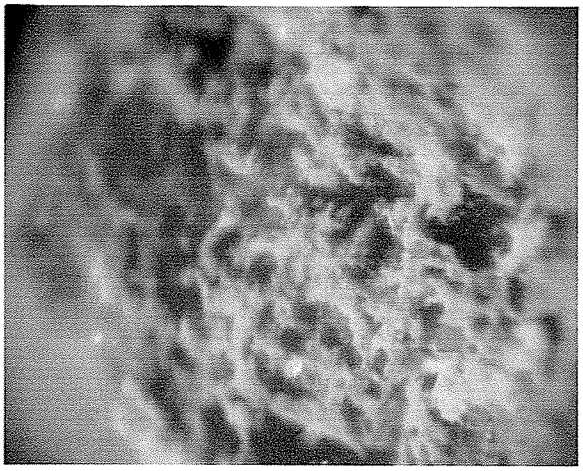

Photo 6.

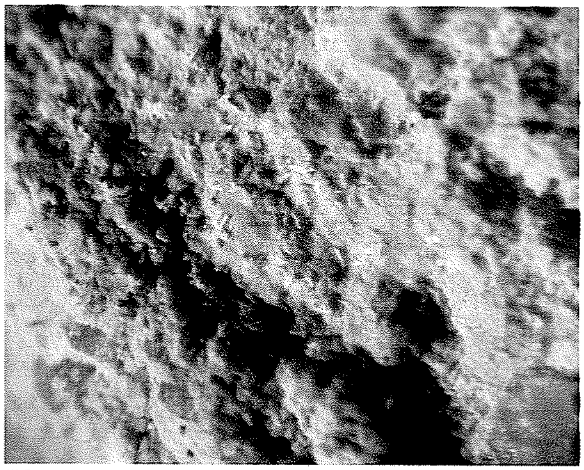

Photo 7.

Photos 6 & 7. Microscopic photos taken through a stereoscopic microscope of freshly broken surfaces of the concrete core sample.

White, needle-like ettringite crystals were observed on the freshly broken surfaces of the concrete.

Photo 6 shows an exposed smooth aggregate surface with ettringite crystals adhering to it.

Photo 7 shows a freshly broken concrete surface with white, needle-like ettringite crystals displayed on the broken surface.

Note: Photo 6 was taken at a magnification of 52X. Photo 7 was taken at 30X magnification.