Who Designed the Ill-Fated St. Francis Dam?

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Abstract

The St. Francis Dam was built by the City of Los Angeles Bureau of Water Works and Supply (BWWS) in 1925-26 as a curved concrete gravity dam, approximately 200 feet high in San Francisquito Canyon, about 35 miles northeast of downtown Los Angeles. The reservoir provided an additional 38,000 acre-feet of storage from the Los Angeles Aqueduct. The dam failed catastrophically on March 13, 1928, killing at least 432 people, making it the most deadly American structural failure of the 20th Century. BWWS Chief Engineer and General Manager William Mulholland accepted complete blame for the failure, but who actually designed the dam has been clouded in mystery for almost 90 years. Recent research suggests that no site-specific rational design methodology was actually performed, only visual comparisons with some published cross sections of then-existing dams. More than a dozen separate investigations of the failure followed, all of which failed to ascertain the dam's actual maximum cross section or the fact that there were no stability calculations undertaken as part of the design. Recent evaluations have demonstrated that the St. Francis Dam exhibited extremely low safety factors in at least five different failure modes, including internal instability, overturning, arching, keyblock uplift, and reactivation of a megalandslide on the dam's left abutment

INTRODUCTION

A careful review of the 847-page Los Angeles County Coroner's Inquest into the Failure of the St. Francis Dam in March 1928 (LA Co Coroner, 1928) was made in 2009-10, while the author served as a Trent Dames Civil Engineering Heritage and Dibner Research Fellow at the Huntington Library in San Marino, California. Prior to this the author had spent several decades researching the St. Francis Dam failure (Rogers, 1992; 1993; 1995; 1997, 2006; and 2007).

The nine jurors were comprised of prominent engineers and contractors from Los Angeles, each volunteering their services for nothing. They included Los Angeles hydraulics engineer Irving C. Harris (foreman), mining engineer Sterling C. Lines, structural engineers Blaine Noice, Oliver G. Bowen and Chester D. Waltz, general engineering contractor William H. Eaton, Jr., real estate appraiser Harry G. Holabird, contractor and insurance executive Ralph F. Ware, and Z. Nathanial [Nate] Nelson.

Although none of the Jurors appears to have had any formal expertise in geology or foundation engineering, they possessed considerable technical training in civil/structural engineering and heavy construction, which is revealed in the technical content of their inquiries and the timeless wisdom of their concluding recommendations and findings, which have been quoted in countless articles, standards, and publications relating to dam safety, which advanced the need for external peer review of dams and establishment of the nation's premier state dam safety agency, the Division of Safety of Dams (DSOD) of the California Department of Water Resources (DWR).

The City of Los Angeles' Bureau of Waterworks and Supply (BWWS) engineers who had worked on the design, construction, and maintenance of the St. Francis Dam and two adjacent Powerhouses in San Francisquito Canyon were questioned at length about the St. Francis Dam in late March and early April 1928 in downtown Los Angeles. A number of glaring inconsistencies emerged from the testimonies of the various individuals queried by the jurors, the County's Deputy District Attorneys, and their technical experts, who produced their own report (Mayberry et al., 1928). Some of these inconsistencies with what the Inquest jurors felt was good practice are briefly summarized below.

BASE-TO-HEIGHT RATIO

BWWS prepared a preliminary design of the St. Francis Dam in July 1923, which was very similar to the gravity arch structure that they had recently designed, then called Weid Canyon Dam. Situated in the Hollywood Hills near the east side of Cahuenga Pass, it was referred to as the Hollywood Dam during construction, which began in August 1923. It was renamed Mulholland Dam when the structure was formally dedicated on March 17, 1925 (the body of water it retains is known as Hollywood Reservoir).

The original design envisioned concrete monolith rising 175 feet above the bed of San Francisquito Creek, with a "chopped toe," shown in Fig. 1. The maximum reservoir capacity was to be 30,000 acre-feet (ac-ft). In July 1924 the reservoir capacity was increased to 32,000 ac-ft by adding 10 feet to the dam's height, which required a wing dike extended westward about 600 ft from the dam's right abutment. City crews began placing concrete in August 1924. In July 1925 BWWS decided to raise the dam another 10 feet (to elevation 1835 feet), this time increasing the reservoir capacity to 38,168 ac-ft.

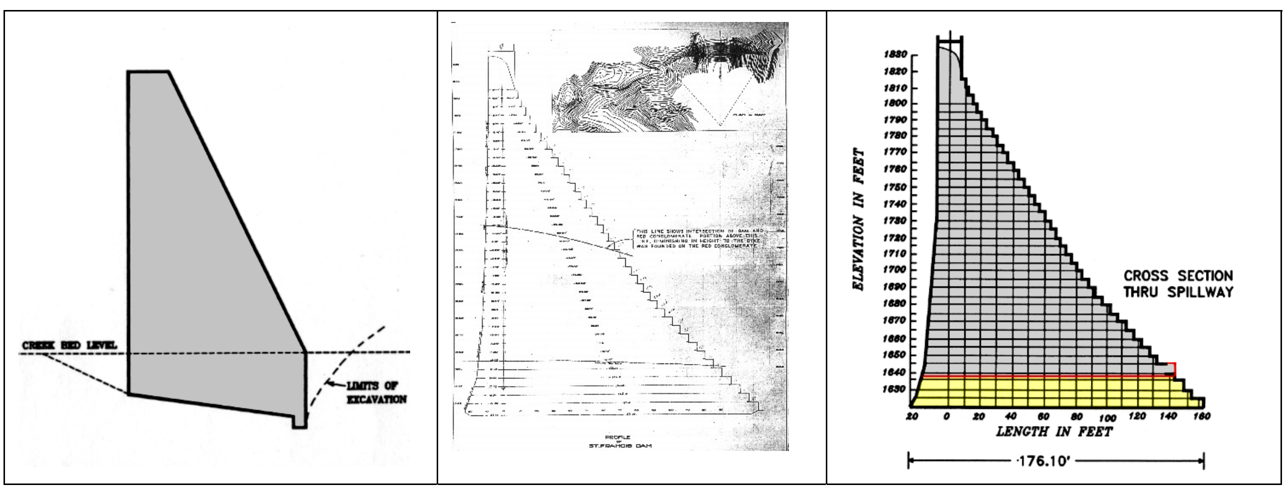

Figure 1. Left pane shows the original maximum section through the St Francis Dam, made in July 1923. Middle pane shows the as-built drawing released by BWWS after the failure, showing a flared toe, up to 175 ft wide at elevation 1625. The right pane shows the actual limits of the dam in red, with a base width of 148 ft.

The dam was subsequently raised 20 vertical feet, about 11% of its original height (175 ft) without any corresponding adjustment of the dam's base width. The elevation of the stream bed was about 1655 ft, and the maximum depth of excavation was about 16 ft, to an elevation of

1639 ft. The last step is clearly observed in construction photos at the time (Outland, 1977), five feet below Outlet No. 1, at an elevation of 1645 ft. The cross section presented by BWWS to all of the investigative panels after the failure was not an accurate portrayal of the dam's maximum section, especially with regards to estimating the factor of safety with regards to cantilever overturning (even ignoring uplift).

These discrepancies resulted in erroneous evaluations of the dam's static stability by most of the investigative panels in 1928 (Rogers, 1992; 1995). Rogers and McMahon (1993) showed that the dam's maximum section became unstable in cantilever overturning when the reservoir rose to elevation 1830 ft, seven feet below the spillway sill. Although ignored in the original design, the arch stresses began exceeding 7000 pounds per square foot (psf) at elevation 1822 ft, increasing to 10,000 psf at elevation 1830, five feet below spillway crest. The reservoir had been brought up to within 4 ft of the spillway for 17 days in mid-May 1927, but was not filled to capacity until March 2, 1928, 10 days prior to the failure (Fig. 2).

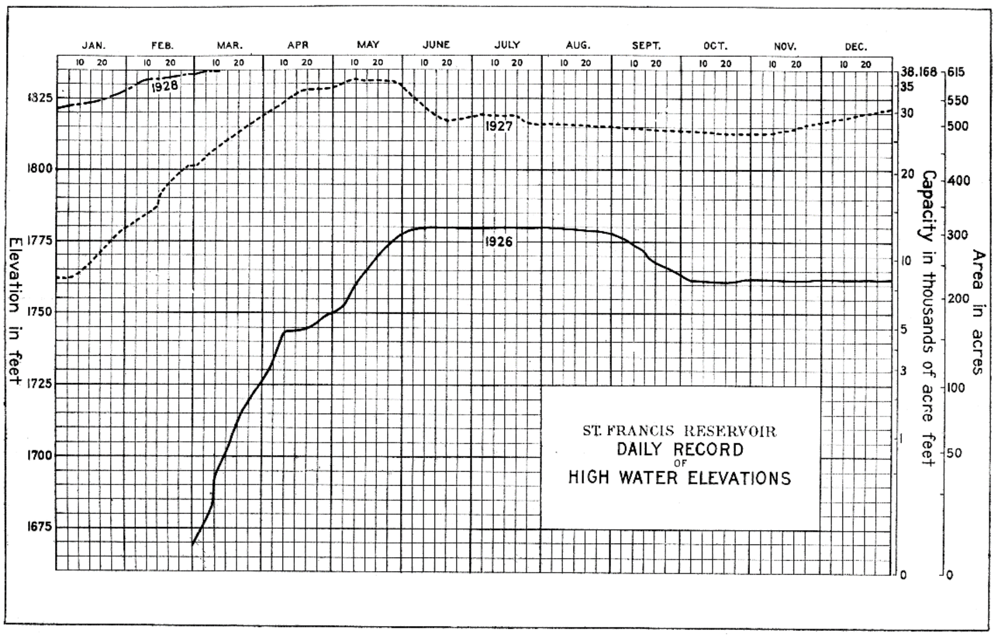

Figure 2. Daily record of reservoir elevations between March 1, 1926 and March 13, 1928. Note the reservoir was not filled to capacity until March 2, 1928, 10 days before the failure (Committee Report for the State, 1928).

ASSUMED COEFFICIENTS OF FRICTION

One of the most vexing aspects of the St. Francis Dam failure was the sheer size of the dam's displaced blocks of concrete. Some weighing as much as 10,000 tons were transported more than a kilometer downstream of the dam, and water was observed to be seeping from the dam's concrete monoliths for weeks after the failure, testifying to the fact that mass concrete was nearly as impermeable as most had assumed.

For these reasons, a significant number of questions probed into the coefficient of friction assumed by the dam's designers. W.W. Hurlbut, the senior BWWS Office Engineer stated that his office assumed the same coefficient of friction on St. Francis that had been employed at

Hollywood [Mulholland] Dam; a value of 0.667, or the tangent of 33.7 degrees. The queries then shift to how that figure was estimated, which Bayley stated came from Hollywood [Mulholland] Dam, which was founded on sandstone, and the "*proper friction was assumed to be two-thirds*" (0.667).

No effort was made to determine the coefficient of friction at the St. Francis Dam site that Hurlbut "*was aware of*." Nor, did BWWS attempt any sort of laboratory test to evaluate the concrete-rock friction coefficient at St. Francis. The concrete-to-rock friction was assumed from figures cited in published literature prior to 1924. This became a significant issue in the reassessment of Mulholland Dam in 1928-33, because of its structural similarity.

The interface friction value was much too high for the slippery micaceous foliation of the Pelona Schist (but was reasonable for the Hollywood [Mulholland] dam site in Weid Canyon, comprised of sandstone). Bayley was asked about the coefficient of friction at the St Francis Dam site. He admits that "*it would be low, likely something between 0.25 and 0.30, as an "offhand estimate*." A more realistic figure would have been between 0.36 (20 degrees) and, at most, 0.58 (30 degrees). In his third examination, Bayley stated that the actual figure used in the design was 0.60, which would equate to 31 degrees.

There was no accounting for diminution in the coefficient of friction when the rock material was saturated. William Mulholland responded that he assumed the mass concrete was more or less impenetrable to seepage. The jurors also inquired about whether the BWWS design team performed a basal sliding analysis, using stand-alone sections (vertical strips) of the dam. They were informed that they had not.

PAUCITY OF FOUNDATION EXPLORATION

The poor quality of the arkosic Vasquez conglomerate exposed in the dam's right (western) abutment was confirmed when specimens of the gypsiferous horizons were observed to disintegrate rapidly upon submersion in a glass of water. Many hours were taken up with inquiries about how the dam site was explored and characterized, especially in regards to the quality of the rock exposed in its abutments.

Almost all of the BWWS engineers who testified at the inquest were asked questions about the geologic characterization and appraisal of the dam site. The jurors had been given copies of the basic design plans, but nothing with any details about the dam site, except for plane table maps of the topography. The jurors asked about what sort of site exploration had been carried out on the dam site, "*for the purpose of determining whether they could put a dam up there?*" Witness after witness replied that "*they didn't know*." They were asked to produce "*a plan, a diagram, or a log, or by whatever name you may call it, of the formations taken from the core of the dam site?*"

The witnesses responded that there was "*a record of those wells which were put in there in connection with the drainage system under the dam. Those were drilled down away into bedrock*." Another witness told the inquest that a "shot drill" was used at the St. Francis dam site to drill the cores (shot drills employed steel ball bearings to grind through the rock, using a hollow cylinder drill bit). They were informed that "*those cores were taken and inspected on the ground by Mr. Mulholland and others.*"

The jurors then asked to "*see the cores*," but were told that the cores had been stored in one of the exploratory adits "*30 or 40 feet long in the left abutment just downstream of the dam*," and that these had all been lost in the landslide of the east abutment during the failure. No photographs of rock cores, field notes regarding the rock cores, or any sort of office sketch or drawings mentioning rock cores or samples were ever produced during the Coroner's Inquest, or in any of the dozen reports of investigation following the dam failure.

Records preserved the LADWP Archives suggest that 10 shallow borings were made in the channel of San Francisquito Creek to probe the depth of the channel gravels (Fig. 3). These were drilled in two parallel lines, along the dam's axis, three being 4 m deep and the remaining seven being 8 m deep. These are the same holes utilized as uplift relief wells beneath the upstream third of the main dam. The sloping abutments and wing dike were not explored by anything more than open trenches at the time of construction and were bereft of any uplift relief.

FOUNDATION EXCAVATIONS AND KEYWAYS

During his initial testimony BWWS Senior Office Engineer W.W. Hurlbut stated that he and his staff brought "*all of the blueprints*" they have of the St. Francis Dam to the Coroner's Inquest. When asked "*Was there any record kept of the position of bedrock before it was excavated into?*" he replied "*No, there is not.*" He was then asked "*There is no record to show how far you went into bedrock?*" and he answered "*No, no record to show that. There is the actual condition of the foundation – bedrock was cleaned and excavated into*." The only positions recorded were the rock-concrete interfaces, not the depth of cover excavated.

J. E. Shankland testified that the deepest point of excavation beneath the main portion of the dam approached a maximum depth of 9 m in the cofferdam trench, but "*shallower preceding downstream*." He estimates the depth of abutment excavations to have been about 3.6 to 4.3 m, after sluicing off loose materials with water hoses. He recalled excavating a cutoff trench about one meter deep and wide on the right abutment, which was "*feathered to zero, upstream.*" In addition, the steam shovel excavated a shear keyway for the dike section, which was about 4.3 m wide. On the left abutment Shankland thought his crews only excavated about 1.8 m into the schist, encountering "hard material," as determined by resistance to "*pick and shovel.*"

ALLOWANCE FOR UPLIFT RELIEF

A series of detailed questions were posed to W.W. Hurlbut and Edgar A. Bayley, the BWWS office engineers whom were credited with having designed Mulholland [Hollywood] Dam and St. Francis Dam. These questions reveal much about how both dams were designed based on accepted theories of gravity dam design published before 1922, and the various assumptions BWWS office engineers and that Chief Engineer William Mulholland made in regards to design decisions.

When queried about any design accommodation for hydraulic uplift on the Hollywood [Mulholland] Dam, Bayley stated: "*Mr. Mulholland also said there was another matter, the matter of uplift. Engineering authorities, best men, have various ways of handling the uplift. One way is a system of drain pipes near the upper toe, another is by gallery inspection, gallery with upright pipes. All are considered as practical ways of taking care of the uplift. It is a matter of opinion among the best authorities.*"

W.W. Hurlbut was then questioned about the "*records of the location of the drainage system of the dam*," which he said were prepared by Chief Surveyor Harold Hemborg. When asked if the uplift relief wells extended up the sloping abutments, he responded in the negative. Several more inquiries were made about limiting "*upthrust due to hydrostatic pressure on each* *side of the central section of the dam,"* but Hurlbut's answers suggest BWWS ignored the issue of uplift relief on the steeply sloping abutments. It was the two sloping abutments of the dam that failed catastrophically, not the main section. The enormity of this problem was not revisited in any significant detail until the untimely failure of the Malpasset arch dam in 1959.

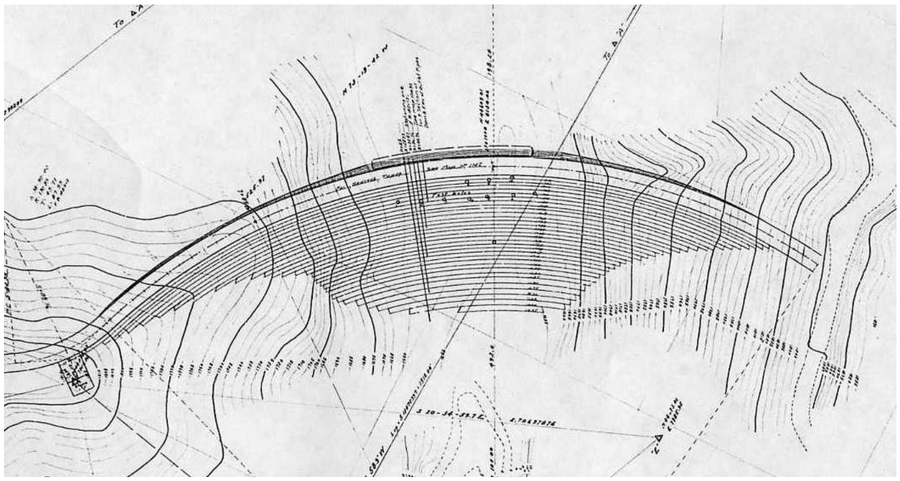

Figure 3. Plan of the dam dated November 1924, with the locations of the 10 test holes that were converted to uplift relief wells, split into rows of three shallow and seven deeper holes (LADWP).

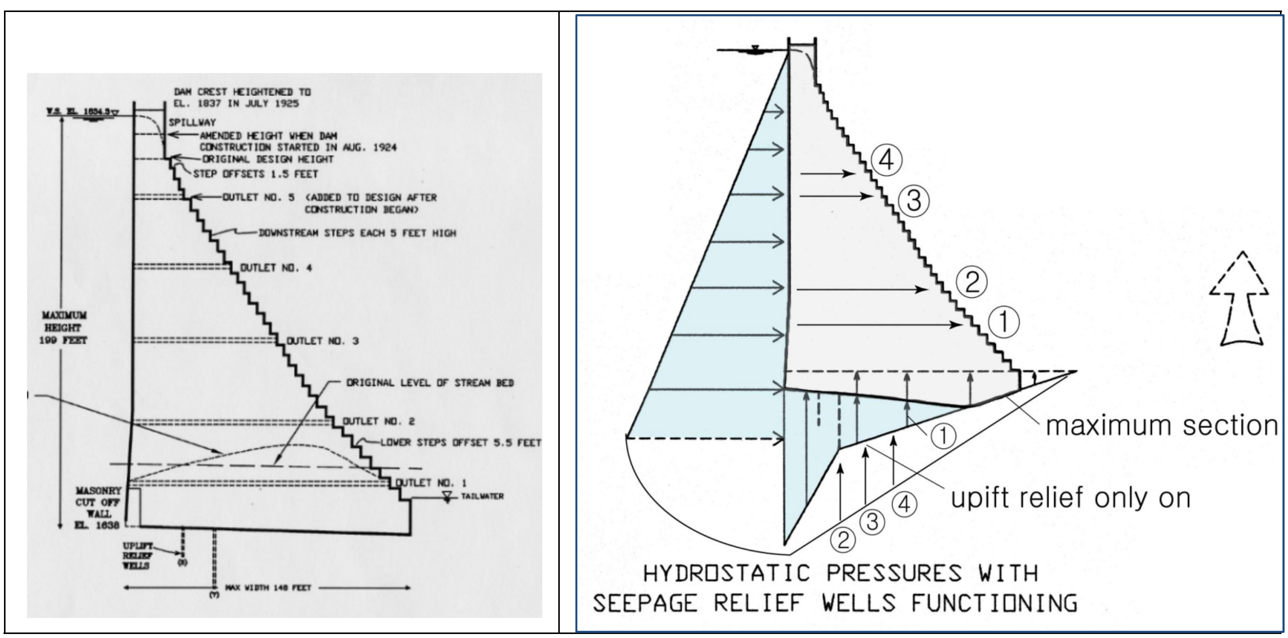

Figure 4. Left pane is a maximum cross section through the dam showing the locations of the 10 uplift relief wells beneath the upstream third (Rogers, 1995). Right pane shows the likely impact of uplift relief beneath the dam's main section, prior to caulking of the transverse shrinkage cracks in early 1928.

A few days later, Edgar A. Bayley was recalled to the witness stand to answer more questions on uplift relief. He was asked "*What do you think about the practice of under-draining all of the dam, not just the bottom, but the side portions, as well, to prevent erosion, supposing a leak starts in the upstream face, if there was a series of drainage pipes in there to pick up that seepage and carry it to the canyon below, without erosion, would that not be a measure for safety?"* He responded *"I would consider that good practice as a measure of safety.*"

Bayley stated that he had not designed the St. Francis Dam, only Hollywood [Mulholland] Dam. When asked how he had accommodated the relief of "upthrust" into the design, he replied: "*there are several ways to take care of upthrust. One is by a gallery along the upper toe and another by a system of drain pipes and another by blocks of concrete to let the upthrust come where it will. In the Hollywood dam we took care of it by a system of drain pipes, and when I left there, there were many drain pipes installed.*" Bayley was likely referring to well casings installed in the exploratory borings beneath the main dam, connected to some sort of outlet pipe, similar to what was installed at St. Francis Dam.

Bayley cited the two principal references he used in the design of Hollywood Dam as being Morison & Brodie (1916) and Wegmann (1922). The answers provided by Hurlbut, Bayley, Hemborg, and Phillips suggest that BWWS never attempted to provide internal drainage within Hollywood or St. Francis Dams, nor did they provide uplift relief under the sloping abutments. Internal drains had been included in the Olive Bridge cyclopean masonry gravity dam in New York, but that was one of the only masonry dams so fitted prior to the mid-1920s.

GROUTING OF TRANSVERSE SHRINKAGE CRACKS

BWWS Office Engineer Edgar A. Bayley was then queried about the absence of expansion [contraction] joints in St. Francis Dam. Bayley stated that "*many engineers place these at 50 foot intervals, but Mr. Mulholland does not – he just grouts the shrinkage cracks after they occur*." He then conceded that "*the prevalent practice in current times has been towards employing expansion joints,*" and mentions other mass concrete dams then under construction, including: Exchequer, Don Pedro, Lancha Plana (Pardee), San Gabriel at the Forks, and Pacoima Dams. All of these projects were employing contraction joints. The Forks Dam was then under construction in San Gabriel Canyon, and was slated to be 29 times the volume of St. Francis Dam.

William Mulholland chose to forego the insertion of regular contraction joints, which would have required additional formwork and insertion of waterstops. When asked why BWWS did not employ water stops, Bayley replied these were not used "*because they are patented*." The alternative practice was to grout or caulk shrinkage cracks after they developed. The Governor's Commission opined that many existing concrete masonry dams had been built prior to 1928 without using contraction joints (Committee Report, 1928, p.15).

During the testimony of Edgar Bayley he laid the responsibility for handling shrinkage, stresses, keys, and post-construction grouting of Hollywood and St. Francis Dams on William Mulholland, the Chief Engineer. He asserted that Mr. Mulholland and other designers "*have done so without employing regular contraction (shrinkage) joints*, which are grouted after the concrete has cured some amount.

Significant shrinkage cracks developed in the St. Francis Dam as the mass concrete cured (BWWS employed a 4-sacks of cement per cubic yard mixture, the same as the US Bureau of Reclamation). BWWS Chief Surveyor James E. Phillips testified that "*the first prominent shrinkage crack was about 75 to 100 feet east of the right abutment thrust block*." Another crack developed "*58 to 60 feet west of the gates*" [outlet pipes], and another crack approximately the same distance on the other side, and one at about the "*quarter point*" of the main dam. Another transverse crack formed at the other quarter point (shown in Fig. 5).

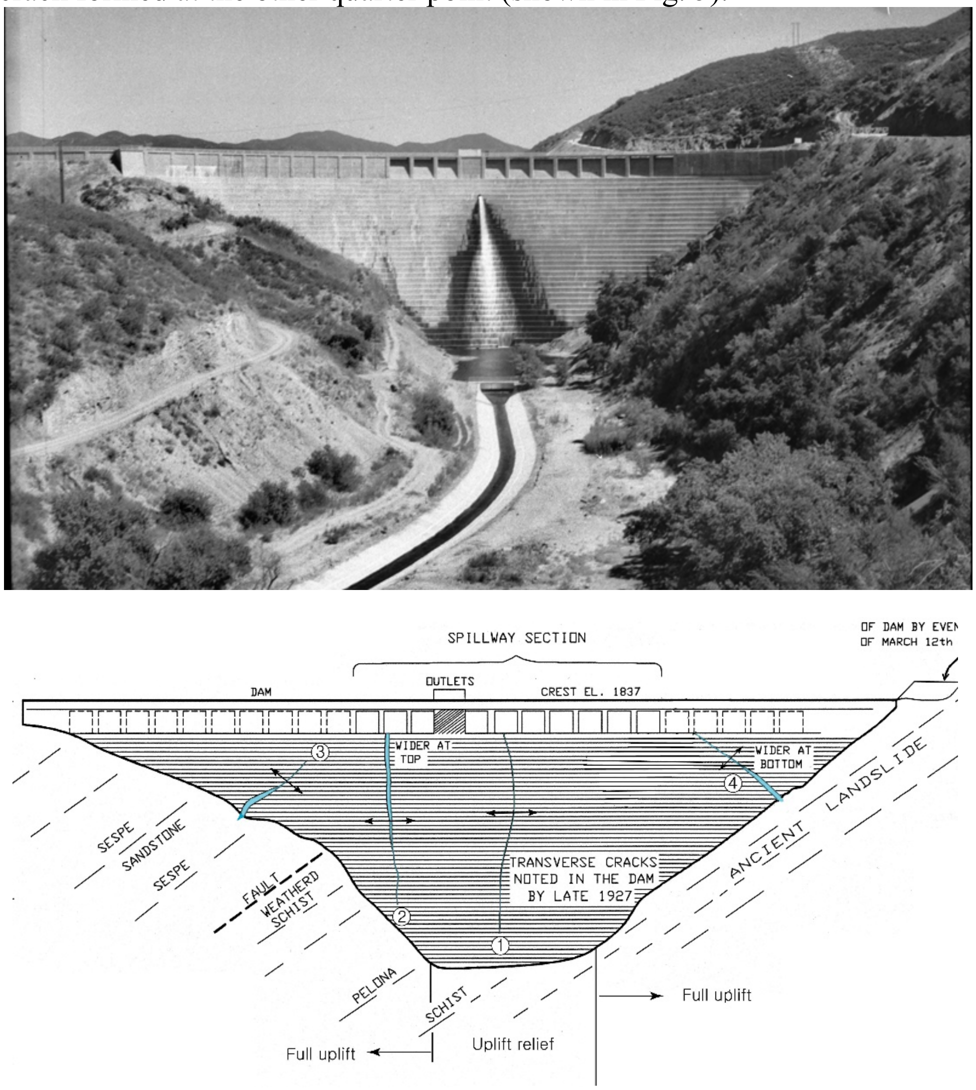

Figure 5. Stepped downstream face of the St. Francis Dam, as viewed looking upstream. Four prominent shrinkage cracks developed, shown in the lower diagram. These were caulked with oakum on the downstream face and grouted in early 1928 (author's collection).

Phillips stated that "*these cracks extended all of the way through the dam*." He noted that the apertures of most of the shrinkage cracks were initially between 1/8th and 3/16ths of an inch at the crest of the dam (Fig. 6). What engineers didn't understand at the time was that the width was inconsequential; it was the transverse connectivity with the dam's upstream face that impacted internal stability.

Phillips went onto describe how the shrinkage cracks were caulked with oakum; a mixture of hemp or jute fiber that was often smeared with tar, creosote, or asphalt to caulk seams in wooden ships and packing pipe joints. He noted that BWWS crews drilled holes into the dam and "grouted the big cracks." The oakum was placed on the downstream face of these cracks to keep the cement grout from "running out," as sketched in Fig. 7.

Figure 6. Upturned base of block #7, from the crest of the dam's left abutment. The open fissure is transverse shrinkage crack #4, shown in the lower half of Figure 1 (Mayberry et al., 1928).

LA Bureau of Power & Light (BPL) bus driver Henry Reiz described the various attempts to plug the tension cracks in the downstream face of the dam, stating "They put sacks to cork it," using "rope" to plug the crack at the face." Hemp rope was inserted into cracks "long after the dam was completed" (in January and February 1928). Reiz said that "*Mr. Jackson was the construction foreman*" involved with this work on the dam. Jackson had previously supervised the steam shovel and trucks used on the dam construction. All of the dam's visible shrinkage cracks were plugged from the downstream face, including the one on the dike section.

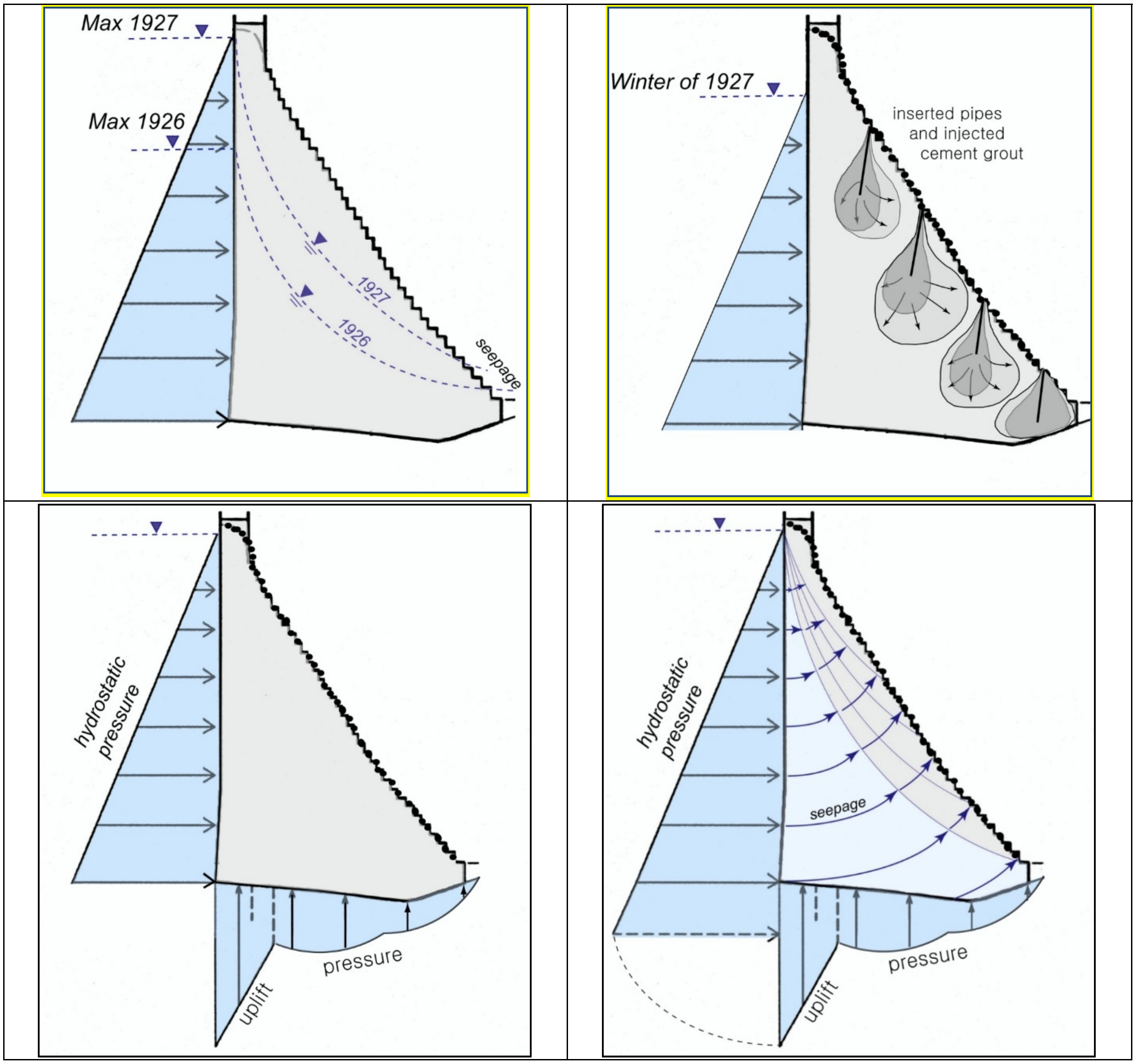

Figure 7. Plugging of the dam's contraction joints on the downstream face could have had disastrous consequences by creating full reservoir pressure against the interior faces of the main dam, especially if the grouting behind the face was anything less than a 100% seal. This was a detail apparently missed by all of the post-failure reviews in 1928.

SUPERVISION OF THE DAM'S DESIGN

At the Coroner's Inquest BWWS Senior Office Engineer William W. Hurlbut stated that he was responsible for overseeing "*all of the drawings, computations, in connection with that,*" [for the St. Francis Dam] were "*done under his supervision*." He then added that "*the dam was designed on the basis of studies which were made on the Hollywood Dam. The studies for Hollywood Dam were for a gravity type of dam, two hundred and ten feet in height, and the design on that dam corresponds to the same general conditions as on the St. Francis. One of them is 203 and the other 208 feet, and the studies were on the gravity type dam of 208 feet.*"

When asked who made the stability computations for St. Francis Dam, Hurlbut replied that the computations were actually made for the Hollywood Dam, and then applied to the St. Francis Dam. He then added "*Those computations were made under Mr. Bayley's instructions in the design of that dam, that the same general design that was used on the Hollywood Dam was used on the St. Francis, under the Chief Engineer's directions*" (referring to William Mulholland). Bayley acknowledged that Mulholland had only built two [concrete] gravity dams during his lengthy career, most of his experience being in embankment dams.

Hurlbut said that his office engineers designed the entire project in-house, without any advice or review from external sources. He then went onto describe the physical similarities between Hollywood and St. Francis Dams: St. Francis having a crest length of 668 feet, while Hollywood's was 890 feet; St Francis was designed with a constant radius of 500 feet, while Hollywood employed 550 feet. These figures are at considerable variance with those cited by Edgar Bayley, who stated that St. Francis was set out on an arched radius about 50 feet longer than the Hollywood Dam, with a crest of 492 feet, as opposed to 542 feet for Hollywood Dam. The same bearing pressures were used on both dams: 10 tons per square foot (tsf) on the toe of the dam, and 12 tsf on the dam's upstream heel.

When pressed if he were the engineer-of-record responsible for the St. Francis design, Hurlbut replied "*I did not, as I stated, make the design on that dam. The design of the Hollywood Dam was made by Mr. Bayley, as I said, and I said that the same section was ordered to be used, with minor modifications, by the Chief Engineer. I did not make the computations on that*." Hurlbut then added that "*there were no changes in the design to fit the different conditions,*" and that he considered the respective factors of safety employed in both dams to "*have been identical*." There was, therefore, no site-specific design input, other than the site's natural topography.

In his initial testimony Edgar A. Bayley asserted that the St. Francis Dam was designed by Mr. William Wilkinson. Bayley said he only performed the "*cross sectional transfer of the Hollywood Dam.*"

During his testimony Hurlbut was questioned about the differences in geology at the Hollywood and St. Francis Dam sites. He said schist was the dominant material at St. Francis and sandstone at Hollywood. He added that at Hollywood Dam the rock was "not so broken up." Hurlbut related that had visited the St. Francis Dam site "*probably a dozen times*" during its construction.

In the initial round of questions posed to W.W. Hurlbut included queries about the structural stability of vertical strips of the dam, to ascertain its safety with respect to overturning or sliding, because of the prominent shrinkage cracks noted after the failure (three of the jurors, Blaine Noice, Oliver Bowen, and Chester Waltz, became founding members of the Structural Engineers Association of California in 1932). Hurlbut didn't appear to understand what was being asked of him.

In his second appearance on the witness stand Edgar Bayley stated that he verified a Factor of Safety of 2 against overturning with the resultant thrust in the middle third of the Hollywood Dam's base. Bayley then summarized rough estimates of gravity dam dimensions needed for overturning stability: height divided by square root of the dam material's specific gravity (Gs). The Gs was usually assumed to be > 2.0 for concrete.

Bayley felt that "*arching should add between 6% and 10% to the safety factor*," but this was ignored in the original calculations (the Trial Load Method of analyzing arch dams was not formally introduced until 1929, after the dam's collapse). When Bayley was on the witness stand

Deputy District Attorney Dennison asked him "*Do you understand that Mr. Mulholland and you designed the Hollywood Dam?* Bayley answered "*Well, in effect, yes. Mr. Mulholland, the detail, and myself the stress diagrams.*" Sample design calculations were reproduced in the few available textbooks of the era, and Bayley stated that he had used Morrison & Brodie's Design of Masonry Dams. An example "stress diagram" from Morrison & Brodie's 1916 text is presented in Fig. 8.

After the jurors had completed their inquiries of W.W. Hurlbut, the examination was passed onto Deputy District Attorney A.J. Dennison. He asked Hurlbut about the blueprints brought to the Inquiry, specifically, if they were "*for the St. Francis Dam?*" He replied that these are the "*original drawings*" used in the construction of the dam, but that their supporting computations were in the files at their office.

Dennison got Hurlbut to admit that St. Francis Dam not "designed" per se, but constructed according to the layout and general dimensions previously developed for the Hollywood Dam in Weid Canyon. When pressed for the "computations," Hurlbut answered "*The original records which have been submitted here by various other witnesses who have been called, and the computation books on the design of the Hollywood Dam on which the basis of the design of the St. Francis Dam was used.*"

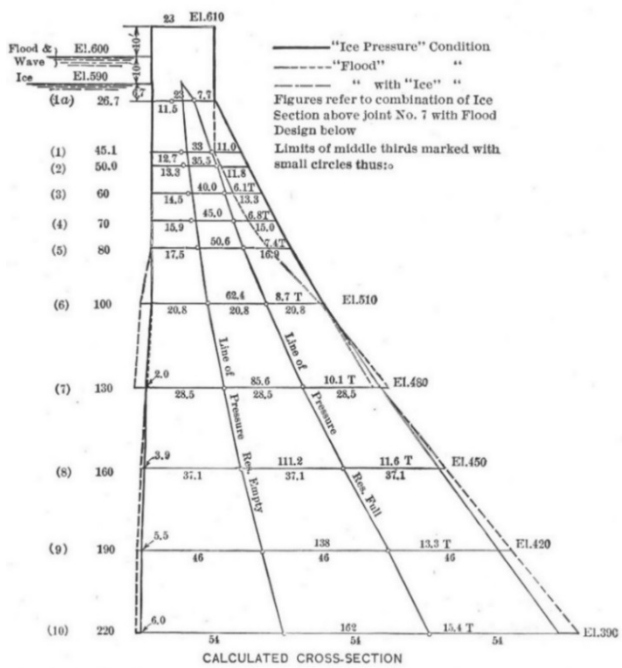

Figure 8. Example of the "stress diagrams" described by Edgar Bayley, taken from *Masonry Dam Design, 2nd Edition* by Morrison & Brodie (1916). This shows a maximum compressive stress of 20 tons per square foot (tsf) along the 'Line of Pressure-Reservoir Full.' These were the same values used by Bayley in the design of Hollywood Dam, which were then applied to St. Francis Dam.

Deputy DA Dennison followed with a series of questions that sought to identify ultimate responsibility for constructing a dam without any site-specific input, other than the constraints of the natural topography:

Q: *I want to know if I have this thing straight now. The Coroner asked you this question and I don't think it has been answered definitely; who designed the St. Francis Dam?*
A: *The St. Francis Dam was designed under the instructions of the Chief Engineer and based on studies which were made for a gravity type dam, which was the Hollywood Dam, that is, the main study is,- as I explained - that was made on the basis of a dam two hundred and ten feet high and it was applied to both of the studies in connection with that and were applied to both of these dams.*

Q: *Now, who designed the St. Francis Dam? Did you design it?*
A: *I did not.*

Q: *Did Mr. Mulholland design it?*
A: *It was designed under his instructions.*

Q: *Then, am I to understand that Mr. Mulholland designed the St. Francis Dam?*
A: *It was designed under his instructions.*

Q: *Did you design the Hollywood Dam?*
A: *No sir.*

Q: *Who did design it?*
A: *It was designed under Mr. Mulholland's instructions, and Mr. Bayley was detailed on that work, and other men made the details under his instructions.*

Q: "*Did I get this correct? Is this information you are trying to give the Coroner: that Mr. Mulholland designed the Hollywood Dam, that is, he said that he wanted a dam over there?*"
A: "*He gave instructions for a dam to be designed with a gravity type section, according to the best engineering practice and it was assigned to Mr. Bayley to do that.*"

Q: *And Mr. Bayley had prepared the blueprints in accordance with Mr. Mulholland's request for a dam?*
A: *He prepared studies in connection with that, and, as a result, the drawings were made.*

Q: *And then, when they wanted the St. Francis Dam, they got out the old drawings of the Hollywood and revamped them under your instructions and sent them up there?*
A: *They got out the computations and the studies on the Hollywood Dam, and the matter was gone into with Mr. Mulholland and others at that time.*

CONCLUSIONS

The maximum cross section of St. Francis Dam provided by BWWS after the failure was not entirely factual, suggesting a higher base-to-height ratio than actually existed. This oversight appears to have been missed by the various investigative panels, who did not perform independent verifications of the dam's dimensions.

The testimony suggests that the only engineering design work was carried out for the maximum cross section of the Hollywood Dam; and that this design was subsequently applied to the topography of the St. Francis site in San Francisquito Canyon. Bayley's calculations appear to have been limited to a static analysis of the dam's highest section, estimating the factors of safety against 1) cantilever bending/overturning; and, 2) basal sliding.

The dam collapsed 10 days after the reservoir's initial filling, to within three inches of the spillway sill. This condition would have represented the maximum pore water pressure being applied to the dam mass and its foundations.

The coefficients of friction assumed for the foundation materials were inappropriately low for planes of foliation in mica schist, and for gypsiferous horizons in the arkosic conglomerate, which was subject to slaking upon submersion.

Foundation exploration was minimal, consisting of 10 shot borings in the stream channel and one exploratory adit 30 to 40 feet long into the Pelona Schist on the left abutment, just downstream of the dam. Keyway excavations into the sloping abutments were also minimal, the deepest being between 3.6 and 4.3 m.

No accommodation for uplift relief was installed beneath the sloping abutments, which were comprised of contrasting materials (mica schist and arkosic conglomerate, separated by a fault). The fault could also have served as a significant aquitard, restricting downward percolation of seepage from the reservoir through the right abutment.

The dam was unknowingly constructed against an ancient bedrock landslide complex developed in the Pelona Schist. This was identified by Prof. Bailey Willis of Stanford University after the failure (Willis, 1928), and evaluated in some detail by Rogers (1992, 1993, 1995, and 1997). Elevated pore water pressure in the old landslide likely served to reactivate a small portion of this mass, about six times greater mass than the dam.

William Mulholland's decision to caulk and grout the transverse shrinkage cracks in January and February 1928 (Fig. 7) likely triggered the dam's untimely demise a few weeks later. Mulholland's goal was to save precious water being lost through the cracks, but caulking the fissures with oakum on the downstream face served to trap reservoir water pressure within the dam itself, a potentially catastrophic situation because it would have hastened internal instability. This condition is born out to a noticeable degree in the downstream tilt of about one degree, recorded by the Steven's Gage on Block 1 of the dam, beginning around 8:30 PM on March 12th, 3-1/2 hours before the failure (Rogers 1995; 2007). Few people at the time understood the destabilizing impacts of pore water pressure beneath concrete arch dams, which were altered radically by the failure of Malpasset Dam in France in 1959.

Import of Peer Review. Without any site-specific design input other than the site topography, it must have been an awful embarrassment for William Mulholland and the City's Bureau of Waterworks & Supply to have the St. Francis Dam fail catastrophically, and for the first 62 victims to have been City employees and their dependents living by the dam and San Francisquito Powerhouse No. 2.

In his testimony before the Coroner's Inquest a sorrowful Mulholland said that he "*only envied those who were killed.*" He went on to say *Don't blame anyone else, you just fasten it on me. If there was an error in human judgment, I was the human."* No truer words were ever spoken.

After considering the 840 pages of testimony, the Coroner's Jury concluded:
"A sound policy of public safety and business and engineering judgment demands that the construction and operation of a great dam should never be left to the sole judgment of one man, no matter how eminent, without check by independent authority, for no one is free from error, and checking by independent experts will eliminate the effect of human error and insure safety."

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