The 1928 St. Francis Dam Failure and Its Impact on American Civil Engineering

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OVERVIEW

This field trip guidebook has been assembled to assist readers in understanding the events surrounding the catastrophic failure of the St. Francis Dam in March 1928 and the enormous impact this tragedy had on America, giving birth to the practice of engineering geology in California, professional registration for engineers, creation of a state agency for assessment of dam and reservoir safety, and a host of other outcomes too numerous to mention here. The flood that resulted from the dam's untimely failure killed more than 432 people, making it the worst man-caused disaster in America during the 20th Century. The forensic work on the St. Francis Dam failure illustrates the complex and interdisciplinary nature of working with earth, water, and structural systems, and conveys the frailties engineers and geologists possess, based on the limitations of their training and professional experience. All of us should read and digest the contents of this guidebook with great interest because none of us are above making many of the same mistakes, should we find ourselves in similar predicaments someday.

THE 1928 ST. FRANCIS DAM DISASTER

INTRODUCTION

The old St. Francis Dam was built in San Francisquito Canyon about 7 miles upstream of its mouth between 1924-26 by the City of Los Angeles Bureau of Waterworks and Supply (referred to herein as BWWS. The city's Department of Water & Power was created by combining BWWS with the Bureau of Power & Light [BPL] in January 1931). The structure was a concrete gravity arch type, patterned after Mulholland Dam, completed a year earlier by the City in Weid Canyon, above Hollywood and at the foot of Cahuenga Pass. The dam failed catastrophically near midnight on March 12/13, 1928, in its second year of operation. At the time of the failure, the reservoir was the largest the City owned south of the Owens Valley, storing 38,168 acre feet of water. It had been brought near its crest elevation of 1835 feet just six days prior to the failure.

The resulting flood swept down San Francisquito Canyon, with an initial depth of 140 feet above the streambed. About five minutes later, the flood destroyed the BPL Powerhouse 2, approximately 7,300 feet downstream, killing 126 of the 129 people living there. The flood wave swept on down the canyon, widening considerably at its juncture with the Santa Clara River coming out of Soledad Canyon. It then swept through Castaic Junction and on down the Santa Clara River Valley, blasting a Southern California Edison construction camp at Kemp siding (killing 84 of the 140 workers encamped there), thence inundating the migrant farm community at Camulos, before skimming the lower elevations of the established cities of

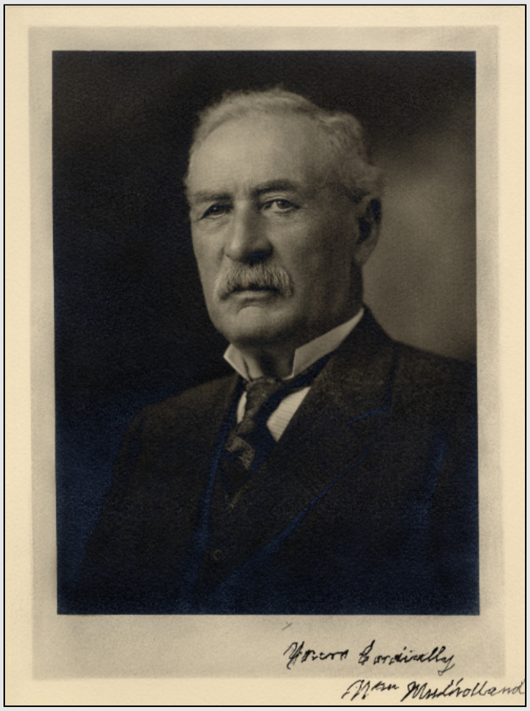
Fillmore, Santa Paula, Saticoy, and Montalvo. The flood waters reached the ocean around 5:30 AM, after travelling approximately 52 miles. The official death toll was 432 persons, making it the greatest engineering tragedy recorded in America in the 20th Century. But those official statistics did not include Mexican migrant farm workers, of which, an unknown number also perished. 179 of the listed victim's bodies were never recovered, including those of the damkeeper Tony Harnesfaeger and his 6 year old son.

At the time the dam failed most critics pointed to the presence of the San Francisquito fault beneath then dam's right abutment, and the propensity of the Vasquez sandstone comprising the upper right abutment to slake under submersion because of gypsum in its matrix. Engineering geologic studies of the dam site and various potential failure mechanisms of the dam have been carried out by the author over the past 30 years. These have revealed that the dam was unknowingly situated against and upon a series of Pleistocene-age landslides developed within the Pelona Schist. The dam also incorporated a great number of design deficiencies, though many of these were endemic of the early 1920s, when the major theories that have since governed dam design were being formulated, tested, and established. The failure of St. Francis brought to light a great deal of appreciation for the inclusion of solid geologic input and external review of large structures such as dams, whose failure can adversely impact great numbers of people.

As the years went by and the author made repeated visits to the canyon, he continued to be surprised at the number of large ancient landslides he kept discovering. It would appear that the old St. Francis dam site had favorable topographic relief because it had once been the site of a much larger landslide dam. Fluvial gravels and lacustrine silts deposited within the lake thereby created formed the anomalously broad upland glen that typifies San Francisquito Canyon upstream of the old dam site. Within this same zone, the southeast side of the canyon is littered with deep-seated rotational slumps developed within the inclined foliation of the Pelona Schist.

CONSTRUCTION OF THE ST. FRANCIS DAM

The St. Francis Dam was sited by William Mulholland, Chief Engineer and General Manager of the City of Los Angeles Bureau of Waterworks & Supply between its original inception in 1904, and his retirement in the fall of 1929, at age 74. Mulholland had achieved considerable fame by conceiving and supervising construction of the longest water supply system ever built up until that time, the 243-mile long Los Angeles-Owens River Aqueduct, completed between 1906-13. Mulholland's ability to overcome enormous engineering, financial and political obstacles and his uncanny ability to improvise brought the aqueduct in on time and on budget. But, Mulholland also had a penchant for saving money by a variety of means, including force account labor practices by city employees and having his own staff perform all their own engineering calculations, without any manner of external review. These shortcomings proved to be fatal in the case of St. Francis Dam, which had a multitude of design deficiencies, as we shall see. Its untimely and high-visibility failure had an enormous impact of dam engineering, raising consciousness about the need for engineering geologic input and appreciation of uplift forces in siting, design, and construction of dams.



William Mulholland (1855-1935) was a native of Belfast, Ireland. He went to sea at age 15 for four years, and after trying his hand in several land ventures, arrived in Los Angeles overland from the San Francisco Bay area. He arrived in 1877 on the heels of the worst drought southern California had ever experienced. Finding employment with the private Los Angeles Water Company, he succeeded Fred Eaton as Chief Engineer of that entity in 1886. In 1902 the City purchased the private water supply companies and Mulholland was retained as Chief Engineer and General Manager, a role in which he remained until retiring in December 1928, 8-1/2 months after the St. Francis disaster. Self-taught through prodigious reading, his vision for exploiting water resources help fashion the city with the largest land area in America (Los Angeles eventually incorporated an area of 464 square miles). The water also brought unprecedented growth and prosperity from 1914 through the late 1960s. The greater Los Angeles area succeeded Berlin as the world's most expansive metropolitan area after 1945, in large measure due to the Owens, Mono and Colorado River aqueducts envisioned by Mulholland. Photo from author's collection, courtesy of Catherine Mulholland.

What he, nor anyone else, foresaw was the unprecedented growth of Los Angeles in the years following the First World War, which grew by 100,000 people per year, far exceeding the most optimistic projections. In 1921 the city surpassed San Francisco as the state's most populous. 1923 witnessed more building permits than any other of the city's history (prior to 1946), with $200 million in construction. That year the city's population topped 900,000. But, the early 1920s were also years of below-normal rainfall, not just for Los Angeles, but in the famed Sierras, which fed the Owens River, which had become the city's lifeline after completion of the Los Angeles Aqueduct in 1913. Agricultural interests in the San Fernando Valley who had enjoyed unlimited amount of water just a few years previous, now found themselves struggling to survive the drought.

For a water resources engineer like Mulholland, the water crisis simply exposed the need for increased water storage during the wet years. He was one of the first engineers to recognize that the Mediterranean climate of Los Angeles experienced below-normal rainfall two out of every three years; and he cited this statistic often while promoting bond measures for water development. Mulholland proposed an ambitious plan to triple the reservoir capacity around Los Angeles, near the aqueduct's terminus. This expansion called for an increased storage of 67,000 acre-feet between 1922-26 by raising the lower San Fernando Dam seven feet and constructing seven entirely new dams. The largest of these (which became St. Francis) would store 30,000 acre-feet of water, the amount consumed by city residents in 1922.

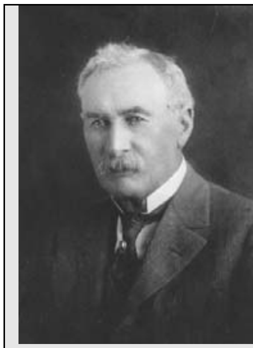
Back in 1910, during construction of the first aqueduct, Mulholland had built a construction camp in the broad wooded glen upstream of what later became the St. Francis Dam site. He had contemplated building the aqueduct up on top the ridge in the Pelona Schist, lying about 500 feet above the valley, but opted instead to build a 7-mile long tunnel, because he thought the schist too slippery for a side-hill viaduct. This tunnel, between Powerhouse 1 (completed in 1917) and Powerhouse 2 (completed in 1920) remains operational today. It was built in a series of multiple face headings, advanced from four access adits excavated into the schist.

Recognizing the potential for a dam at the narrows lying below the glen in San Francisquito Canyon, Mulholland directed some cursory exploration of the bedrock narrows. He had his workers excavate some exploratory adits into the Vasquez Sandstone, to see if it would hold water. Mulholland later testified (before the L.A. County Coroner's Inquest in 1928) that he had brought Stanford [University] geology professor John Branner (see sidebar) out to this site to gain his opinion of it, which was said to be "favorable."

John Casper Branner (1850-1922) graduated from Cornell in 1882 and received his Ph.D. in geology from Indiana University in 1885. He taught at the University of Arkansas before transferring to Stanford in 1891. He served as vice-president at Stanford from 1898 to 1913, whereupon he became that university's second president, retiring in 1915 at age 65. In 1916 he was called upon by President Woodrow Wilson to investigate the enormous landslides affecting the Panama Canal. Mulholland provided him with a tour of the Los Angeles Aqueduct while it was under construction, between 1907-13. Branner died in March 1922, so Mulholland must have been referring to Branner's having visited the future dam site sometime between 1910-12, when the San Francisquito tunnels were being bored.

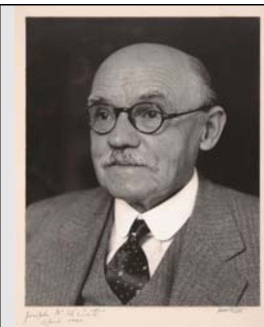
The percolation pits retained water insofar that the water lost to the annulus of the small pits calved into the pits, because of slaking caused by the gypsum. Slaking was a phenomenon that hadn't yet been explored or explained in 1910, the workers simply measured the drop in water levels with time to extract crude values of hydraulic conductivity.

When the water crisis arrived in the early 1920s Mulholland sought several avenues of relief. The first was to install additional wells along the southern side of the San Fernando Valley, to "draft groundwater." His second recourse was to construct a new series of water supply reservoirs down in the Los Angeles area. Of these, St. Francis was clearly the largest, Mulholland telling the Board of Water Supply Commissioners in his annual report of 1922 that he desired to build a reservoir above the San Fernando Valley that would store one year's water supply for the City, in case the San Andreas Fault should sever the 5-mile long Lake Elizabeth Tunnel. This was a remarkable insight, given the era in which it occurred, a half century before other civil engineers recognized the threat posed by active faults to water supply systems. The third method of increasing water supply was to acquire additional farm lands in the Owens Valley which had riparian rights to draft from the river upstream of the City's intake structure above Lone Pine.



William Mulholland (1855-1935)

Mulholland appreciated geology. William Mulholland was fascinated by the study of geology. This interest appears to have been piqued while drilling one of his first deep wells for the Los Angeles Water Company, when he encountered a tree trunk at a depth of 600 feet in the Compton area, around 1882. He was so intrigued by this discovery he visited the city library and read a copy of Professor Joseph LeConte's *Elements of Geology; a textbook for colleges and the general reader*, which appeared in 1882. His personal library included: *Treatise on Rivers and Torrents* (1861) by Paul Frisi, and John Branner's *Geology in its relations to topography* (1898) and *Syllabus of lectures on economic geology* (1895).



Professor Joseph LeConte (1823-1901)

Recognition of seismic hazards. Mulholland addressed the threat posed by the San Andreas fault in a speech he gave to the American Institute of Mining Engineers in Los Angeles on January 7, 1918 entitled *Earthquakes and their relation to the Los Angeles Aqueduct*. He provided his observations of the fault during excavation of the Elizabeth Lake Tunnel for the Los Angeles Aqueduct. He described the morphology of the fault zone in considerable detail, in what was likely the first description of an active fault trace at considerable depth (400 feet). Mulholland's eloquent lecture was promptly published in the *Bulletin of the Seismological Society of America* in March 1918. Mulholland concluded by stating that he was unable to secure "sufficient funds" to hire a "qualified geologist" to make a geologic map of the tunnel during construction. The city's recognition of the fault and the threat posed to its new aqueduct had been noted previously (Lawson, 1914).

The Elizabeth Lake Tunnel traversed the San Andreas fault at a depth of 400 feet in 1910. Mulholland recognized the threat posed by the fault to the city's aqueduct.

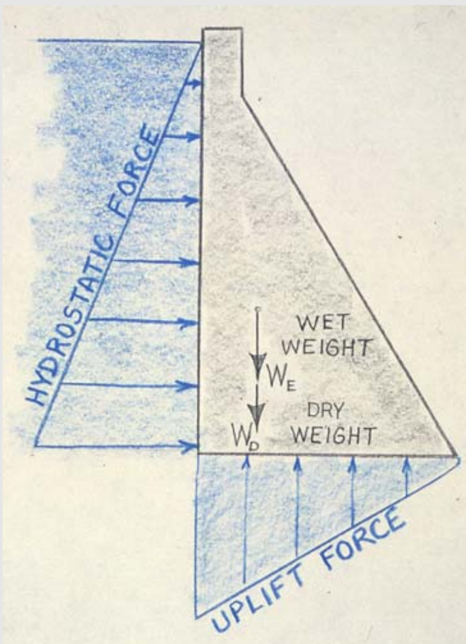
Mulholland's first choice for the big dam south of the San Andreas Fault was in Big Tijunga Canyon, above what is now Sunland. When City surveyors began mapping the site, local ranchers began clamouring for inflated values of their properties, a problem that seemed to plague the water department throughout Mulholland's lifetime, a facet of humanity that he found particularly insidious and objectionable. At that time (1921-22) the Owens Valley water wars were just beginning and ranchers clamoured for the City to buy their properties for high prices, and occasionally dynamiting the aqueduct or taking control of it, preventing the passage of Owens River water to Los Angeles. At this juncture (late summer 1922), Mulholland appears to have recalled his explorations of the San Francisquito Canyon site. Though further from the City, the site nonetheless possessed ideal topography for a large storage reservoir.

James Dix Schuyler (1849-1912), second from left above, was affectionately known as “Uncle Jimmy” to those who worked with him, like Bill Mulholland. Born in Ithaca, New York, he grew up in Connecticut, where his father was a respected civil engineer. He attended Friend’s College between 1863-68, and began working as a civil engineer for western railroads in 1869, arriving in California in 1873. In 1877 he joined the State Engineer’s Office, where that he began working on water resources projects until starting his own consultancy in 1882. In the late 1800s he designed several precedent-setting projects, including Sweetwater Dam and the original Lake Arrowhead Dam. When constructed in 1891-95 Hemet Dam was the highest masonry dam in the western hemisphere. Schuyler published “Reservoirs for Irrigation, Water Power, and Domestic Water Supply” in 1901, with a second edition in 1908. His association with Mulholland began in 1906 when he was appointed to the Board of Consulting Engineers to study the feasibility of the Los Angeles-Owens River Aqueduct (pictured above). Later he was appointed by President Theodore Roosevelt to the Commission of Consulting Engineers on the Panama Canal, in which he involved Mulholland as a consultant on the Gatun Dam. In 1907 his article for the American Society of Civil Engineers titled *Recent Practice in Hydraulic Fill Dam Construction* won the society’s coveted Thomas Fitch Rowland Prize. This image shows the independent Board of Engineers appointed to review Mulholland’s scheme for the Los Angeles Aqueduct in the Owens Valley in 1906. The members are, from left: John R. Freeman, James D. Schuyler, Joseph P. Lippincott, Frederick P. Stearns, and William Mulholland.

Up until this time (1922) Mulholland's experience had been with hydraulic fill and puddled fill earth dam embankments, of which he and James D. Schulyer (see sidebar), were more or less the founding fathers. The hydraulic fills at South Haiwee, Lower San Fernando and Fairmont, built between 1910-17, had volumes between 500,000 and 700,000 cubic yards, making them some of the largest embankments in the world at that time. However, in contemplating dams in Weid Canyon above Hollywood and in San Francisquito Canyon, there was insufficient water or natural sources of clay with which to build puddled fill earth embankments. As a consequence, Mulholland appears to have chosen mass concrete for the last two of the 22 dams he built during his career.

Design of St. Francis Dam

According to William Mulholland’s testimony before the LA County Coroner’s Inquest after St. Francis Dam failed, Edgar A. Bayley (see sidebar) was the BWWS engineer who “drew the plans and specifications” for Hollywood (Mulholland) Dam and St. Francis Dam, which were very similar. Bayley was then called to the stand and he testified that he was directed by Mulholland and assisted by another office engineer named William Wilkinson. The design for Weid Canyon (subsequently christened Mulholland Dam, which retains Hollywood Reservoir) was basic in scope, and appears to have been entrusted to office engineer Edgar A. Bayley, under the supervision of chief office engineer W.W. Hurlbut. Hurlbut testified that he had supervised the transfer of the design for Mulholland Dam in Weid Canyon and the site in San Francisquito Canyon, where St. Francis was built a year later.



Uplift refers to the hydrostatic pressure that develops beneath a structure, which reduces its dead weight through buoyancy. Uplift theory was one of the most contentious issues in American civil engineering for more than 60 years, not being resolved until the early 1950s (ASCE, 1952).

The failure to incorporate considerations of **hydraulic uplift** in the design calculations forms the central criticism of the dam's design. However, this ignorance was by no means unique to the early 1920s. The earliest murmurings about hydraulic uplift negating the dead weight of dams was first proposed by James B. Francis in 1888, who suggested applying full hydrostatic pressure at the upstream heel of a dam, diminishing to zero pressure at the downstream toe. Scant discussion ensued, with exception of John R. Freeman after the 1911 failure of Austin Dam in Pennsylvania. The first article on uplift appeared in 1916 by J.B.T. Coleman in the ASCE Transactions. Before the St. Francis failure in 1928 most engineers assumed that uplift was intrinsically tied to the permeability of the foundation rock and that of the dam material. Until 1945 those same individuals assumed that concrete was impervious and incapable of transmitting pore pressures. The books cited by BWWS engineers as their benchmark references included: Turneaure and Russell (1908), Morrison and Brodie (1910), Creager (1917), and Wegmann (1918). Turneaure and Russell (1908, p. 387) suggested that the uplift pressure could be altogether neglected. Morrison and Brodie suggested that an uplift pressure diagram in the shape of a trapezoid be employed, assuming development of two-thirds the theoretical uplift, varying lineally to zero at the toe, unless uplift relief wells were employed. Creager was of the same general opinion as regards the amount and distribution of uplift. Wegmann asserted that it was impossible to accurately estimate the amount of uplift that might develop beneath a dam and that engineers should, therefore, rely on their own judgment.

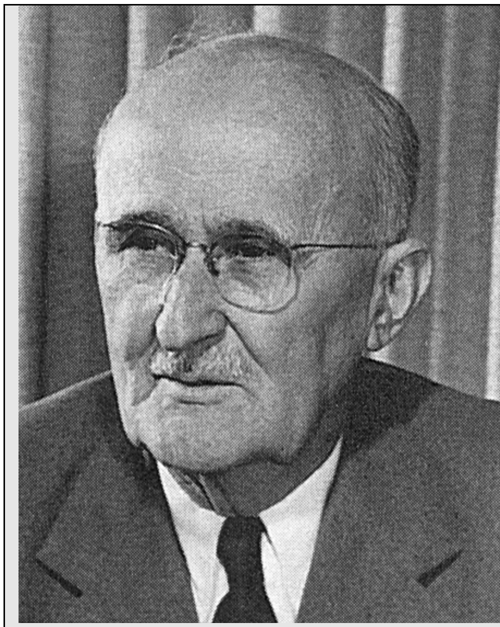
In his testimony, Bayley stated that he had reviewed the designs by the U.S. Bureau of Reclamation for Arrowrock Dam in Idaho and Elephant Butte Dam in New Mexico (completed in 1915 and 1916, respectively). The technical sources he reviewed were Edward Wegmann's *Design and Construction of Dams* (likely the 6th Edition, published in 1918) and *High Masonry Dam Design* by Charles Morrison and Orrin Brodie (published in 1910). Subsequent testimony also mentions BWWS office engineers having reviewed the texts *Engineering of Masonry Dams* by William P. Creager (1st Edition, 1917) and *Public Water-Supplies* by F.E. Turneaure and H. L. Russell (2nd Edition, 1908).

Edgar Alcander Bayley was born in Petaluma, California, but grew up in Los Angeles. He attended Throop Polytechnic Institute in Pasadena (the forerunner of Cal Tech) for two years before transferring to USC, where he was graduated with a bachelor of laws degree around 1899. Like so many others, he went to work for BWWS on the aqueduct between 1905-10, where he began as a locating engineer (surveying), then given succeeding greater responsibilities, until he was named one of five division engineers. From 1911-23 he was assistant engineer for BWWS, in charge of field surveys, siting of facilities, hydraulic design, and topographic mapping carried out in connection with the water storage and distribution systems. This work included the design of the concrete gravity arch dams in Weid and San Francisquito Canyons between 1921-23. From 1923-30 he was primarily engaged in route mapping, water rights and hydrology studies for the Colorado River Aqueduct, work that was subsequently completed by MWD. From 1930-37 he worked on the Mono Basin Project, extending the Los Angeles Aqueduct ~100 miles northward. He is most remembered for being the architect of the DWP employee pension plan, one of the first retirement programs to make use of long-term investments in the stock market (not a popular concept in 1933, but which became the model for other agencies thereafter). He died while working for DWP during World War II, having shunned retirement so younger men could join the military.

Edgar A. Bayley
(1877-1943)

All of these were accepted references on the design of masonry gravity dams in the early 1920s, but they were also largely outdated insofar as they failed to mention uplift theory, grout curtains, or uplift relief wells, design of contraction joints, water stops, grouting of contraction joints after concrete curing, and cement heat of hydration problems; details that were beginning to be employed on the Bureau of Reclamation's larger mass concrete dams, beginning with Elephant Butte Dam in 1916 (Arrowrock was of cyclopean masonry construction). The BWWS designs for Hollywood and St. Francis Dam were bereft of these kinds of details, although they did incorporate uplift relief wells beneath the main portions of both structures, but not the sloping abutments. Such deficiencies were fairly typical of non-federal masonry dams of the 1920s, before St. Francis failed.

The St. Francis site was surveyed by BWWS in December 1922, and the engineering plans appear to have been completed in May or June of 1923, whereupon Bayley and Mulholland became increasingly involved in the proposed Colorado River Aqueduct. As mentioned previously, Mulholland had gone before his governing board in 1922 stating that it was his desire to construct one large dam, capable of storing sufficient water to provide the City with an entire year's supply. This statement was politically charged because the City was then experiencing an unprecedented rate of growth. The population of Los Angeles more than doubled during the 1920s, rising from 576,673 inhabitants in 1920 to 1,238,048 by 1930. The original dam design called for a concrete monolith with a chopped downstream toe (Fig.3), 175 feet high, which would accommodate a reservoir of approximately 30,000 acre feet. In April 1924, the City filed a condemnation petition with the federal government for the reservoir area in San Francisquito Canyon. In July, the lake's capacity was enlarged to 32,000 acre feet (ac-ft) by raising the dam 10 feet. This increase appears to have been coincident with the compilation of BWWS statistics for water usage the previous year, which was 32,000 ac-ft for all city residents.



Julien Hinds (1881-1975) was a pioneer in recognizing the importance of hydraulic uplift beneath dams. Mulholland hired away from the Bureau of Reclamation in 1928. He went on to design the Colorado River Aqueduct built by MWD in the 1930s, and eventually became Chief Engineer and General Manager of MWD between 1941-51.

A precedent-setting article on uplift appeared in the March 1928 issue of ASCE Proceedings, the same month St. Francis Dam failed. It was written by a new BWWS employee named **Julian Hinds**. Hinds had started his new job in January 1928, after having worked for the U.S. Bureau of Reclamation since 1910. His article, titled *Uplift Pressures Under Dams: Experiments by the United States Bureau of Reclamation* was subsequently published along with discussions in the 1929 ASCE Transactions. Hinds was hired to oversee the engineering of a new Colorado River Aqueduct, which would pump water 1617 vertical feet out of its source using five pumping plants, and convey the water 244 miles to treatment facilities in La Verne and Yorba Linda. It seems particularly ironic that the landmark article on uplift theory would be penned by a BWWS employee and published the same month as the St. Francis disaster!

In 1930 Hinds accepted the position of Chief Design Engineer of the newly-formed Metropolitan Water District of Southern California, the agency that actually constructed the massive Colorado River Aqueduct envisioned by Mulholland in the early 1920s. Hinds went onto to become Assistant Chief Engineer in 1933, and assumed the position of Chief Engineer and General Manager of MWD in 1941. In 1945 he co-authored a three volume set of books on dam engineering with William Creager and Joel Justin, which remained in print for 20 years. After retiring on his 70th birthday in 1951 he became one of the most sought after consultants on dams in the world.

Mulholland's Distractions

Two other factors likely prevented Bill Mulholland from having as direct a role in the design of St. Francis as he appears to have exercised in earlier designs. St. Francis was fundamentally a re-work of Hollywood (Mulholland) Dam, which his office staff had designed a year earlier. The only differences were architectural decoration of the downstream face and Hollywood employed a glory hole spillway instead of crest overflow. One can more-or-less read between the lines of the Coroner's Inquest that Mulholland didn't exercise his normal penchant for day-to-day details while the St. Francis design was being pulled together, which was basically an adjustment of the Hollywood Dam design to fit the site in San Francisquito Canyon.

Mulholland also became increasingly distracted with a new concept he formulated for a Colorado River Aqueduct, beginning in late 1922. The colossal Boulder Canyon Act was introduced in Congress by Congressman Bill Swing of the Imperial Valley in November 1922, shortly after the Colorado River Compact had been successfully negotiated by Commerce Secretary Herbert Hoover between the seven basin states. The act sought to create a dam of unprecedented dimensions in Boulder Canyon near Las Vegas, which could store two entire years of the Colorado River's flow. Downstream diversions would be made near Yuma that would convey stored water to the Imperial and Coachella valleys, as well as providing summer irrigation water for the Polo Verde Valley, along the river south of Parker, Arizona. It wasn't long before Bill Mulholland began possible routes for a Colorado River Aqueduct, which was being envisioned as an expected benefit of the proposed Boulder Canyon Project, as the Colorado River's erratic flow would be harnessed by a gargantuan reservoir. The Boulder Canyon Project envisioned a reservoir 740 feet high that would store 500 times as much water as the largest reservoir in California at that time.

These activities began to heat up considerably in the late summer of 1923, when Mulholland went on the campaign trail to promote a City-wide bond measure to pay for all the surveying and feasibility studies in connection with his proposed Colorado River Aqueduct (Mulholland, 2002). In October 1923 Los Angeles citizens approved his bond measure to pay for the aqueduct feasibility studies, and Edgar Bayley was promptly dispatched to the Mojave Desert to head up these surveys. Mulholland led a small corps of engineers and friends on a tour of the Colorado River, chartering a pair of boats that take them through Boulder and Black Canyons, downstream to Parker, Arizona, which he already envisioned as one of the most likely points of diversion for conveying the river's waters west, to Los Angeles.

In December 1923 Mulholland personally supervised the launching of river surveys along 150 miles of Colorado River channel. From 1923-28 the City would send 16 survey parties to study 60,000 square miles of Mojave Desert and five possible aqueduct routes. These surveys were supervised by Edgar A. Bayley. As St. Francis was under construction in July 1924, the City of Los Angeles filed for 1500 cubic feet per second (970 mgd) of Colorado River water, a little over 1,000,000 acre-feet and about 1/8th of what the lower basin states were allowed through the Colorado River Compact.

The other Colorado basin states objected to the water rights being proposed by Los Angeles, hastening further negotiations, which involved Mulholland and Mathews. In February 1925 an amended six-state Colorado River Compact was submitted to the upper basin state legislatures. California added an amendment asking Congress to authorize a 20 million acre foot reservoir at or below Boulder Canyon. This amendment prevented the other states from ratifying the agreement. In April 1925 Mulholland announced that a 268-mile long Colorado River Aqueduct is feasible, but with a net lift of 1,416 feet. The line would divert water from near Blyth and include 75 miles of bored tunnels. The citizens of Los Angeles subsequently approved a $2 million bond issue to construct a Colorado River pipeline.

Construction of the St. Francis Dam begins in April 1924

Actual construction at the dam site began in April 1924, under the direction of superintendent Stanley Dunham. The dam's final configuration incorporated a curved plan, laid out on a constant radius of 500 feet, with a series of 5 foot high vertical steps on the downstream face of the main dam (Fig. 2). The width of each step was unique to its elevation. This style of formwork provided a simple method to control the flare and complex curvature involved with the downstream face.

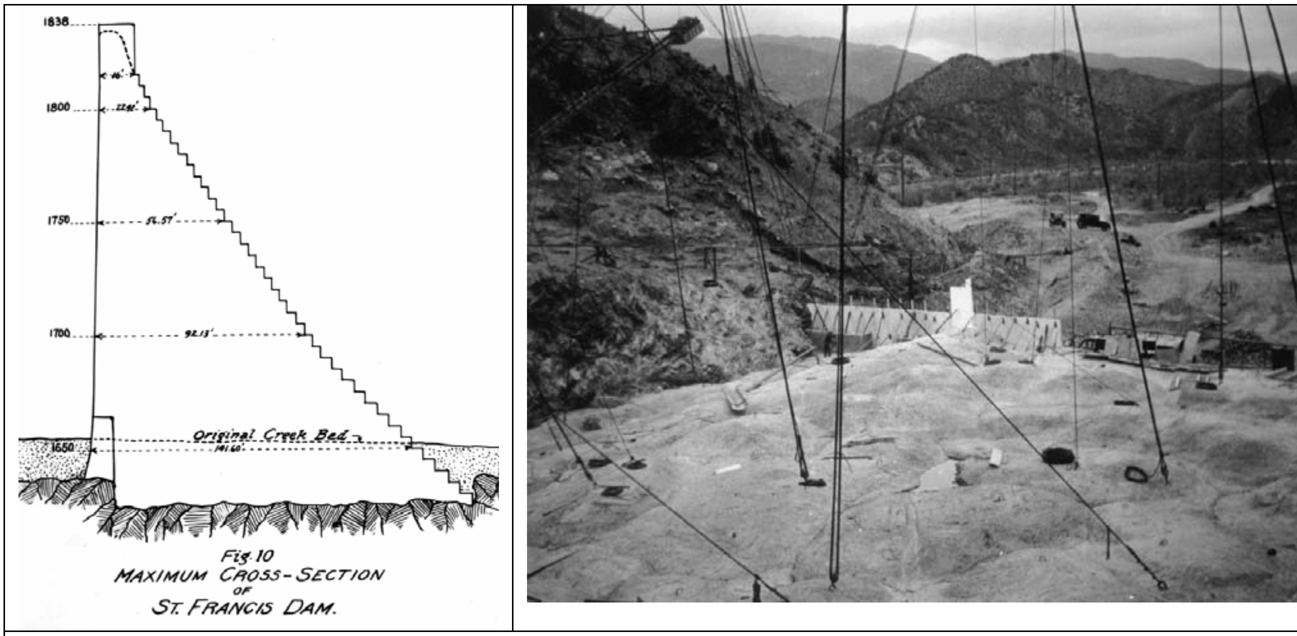


Figure 1 – The cofferdam across San Francisquito Creek is clearly seen in the photo at right, as well as the sketch at left, made by Carl Grunsky. Note the undulating “pillows” of concrete. No attempt was made to construct a through-going system of groutable contraction joints, nor was the concrete vibrated or the laitance layers jetted off the wet concrete while it set. As a consequence, the dam was constructed with an undulating series of semi-horizontal partings with low tensile strength. Both images from the Grunsky file in the St. Francis Dam Disaster Collection of the Huntington Library.

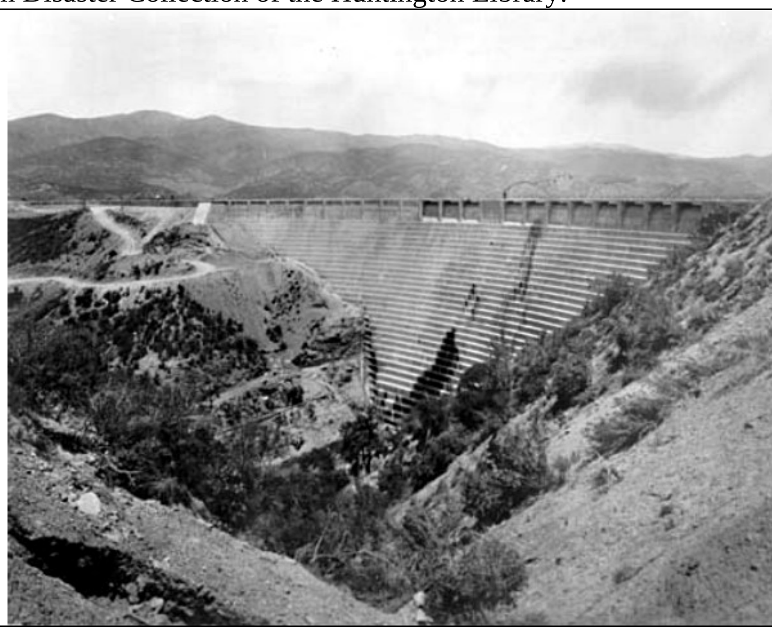


Figure 2 – St. Francis Dam as viewed from the old road, from the left abutment. The old access road with the 18% grade can be seen climbing the right abutment, below the dike. This was where the ‘muddy water’ was observed by damkeeper Harnishfaeger on the morning of the failure. Also note how it would be difficult to notice people with flashlights at the base of the dam’s left abutment, which cannot be seen from the old road.

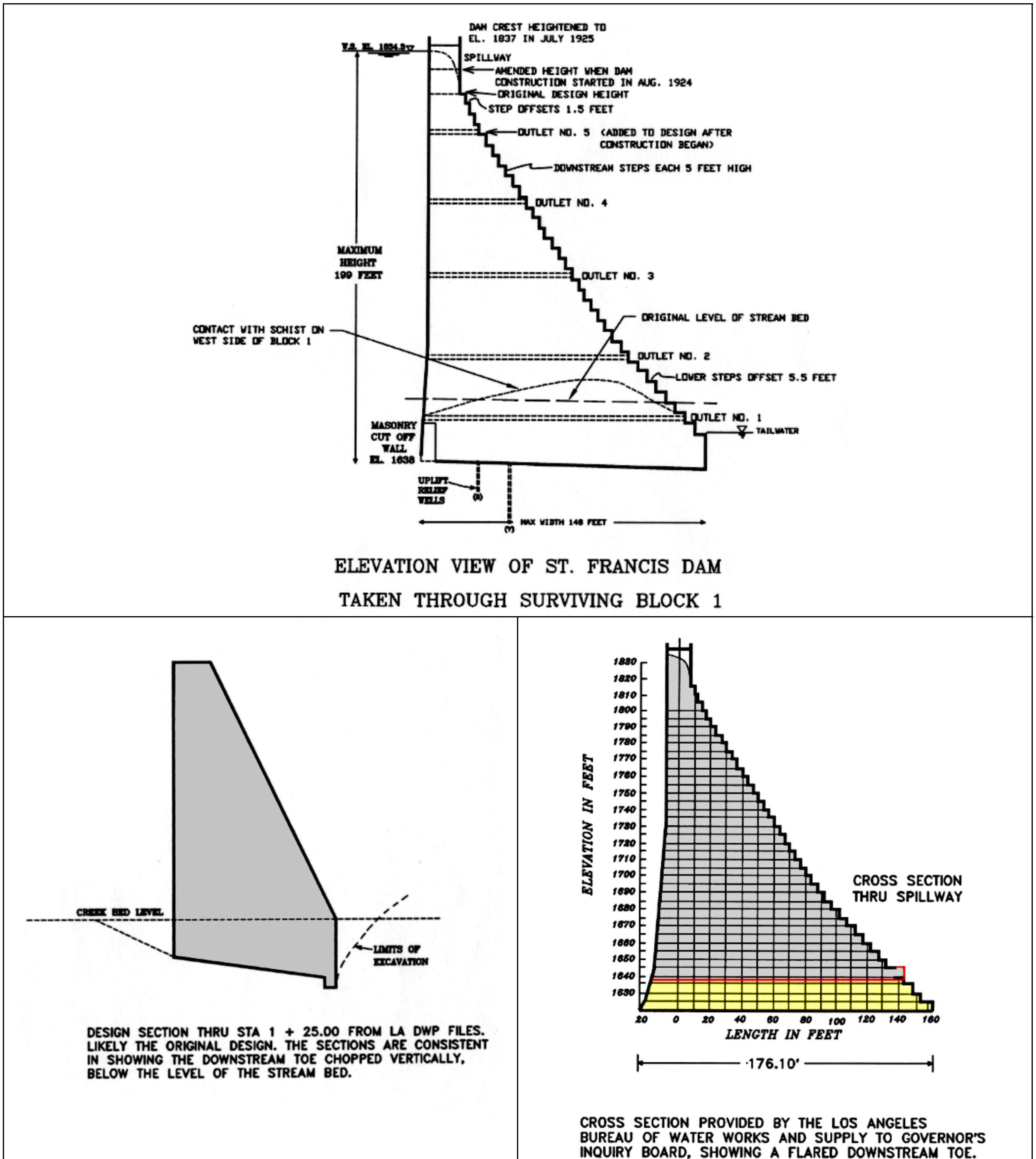


Figure 3. Comparisons between maximum cross sections of the St. Francis Dam. The upper section is what is believed to be fairly representative of the actual as-built conditions for the maximum cross section. The section at lower left is taken from the city's design files, showing the chopped base assumed in the 1923 design. The section at lower right was given to the Governor's Board of Inquiry by the city after the failure. Site photos suggest that that portion highlighted in yellow was never built, and that the maximum base width did not exceed 140 ft.

A concrete batch plant was built in the canyon at the downstream toe of the dam (Fig.4) and local aggregate was incorporated with 1.12 barrels of Portland cement per cubic yard of concrete. The aggregate source was from the bed of San Francisquito Creek, between one-quarter and two miles downstream. The aggregate was neither washed nor graded, with the exception that cobbles greater than 6 inches were excluded, to permit the method of concrete delivery, seen in Figs. 4 thru 8. The decision not to wash the aggregate was a critical one, but was likely fostered by the relative paucity of water available at the site within San Francisquito Creek, which is dry much of the year. This same omission was made a year previous while constructing Hollywood (Mulholland) Dam.

Since the perennial flow of the creek was so low, only a token cofferdam was afforded at the site, thus being incorporated into the heel of the main dam structure, at elevation 1638 (see Fig. 1). The alluvial materials (gravel and sand) were stripped from the channel and the bed of the exposed channel was excavated "about 8 feet," according to Grunsky (1928). No record survives recording any attempt to explore the depth of channel fill ahead of actual construction, nor have any official as-built records ever been recovered. Contrary to many criticisms offered after its demise, the main dam section was afforded with uplift relief, in the form of 10 relief wells, shown in the upper portion of Fig.3. These were 15 to 30 feet deep. Like many non-federal masonry dams of that era (prior to 1928), it was not designed with a proper appreciation of uplift. The dam's designers later testified that it was their belief the concrete was sufficiently impervious so as to remain essentially dry during its service life.

Figure 4 (upper). Upstream view of St. Francis Dam under construction, in the fall of 1924. The contractor's concrete batch plant lies in front of the dam. The large shed in front of this structure was where aggregate collected down-canyon was end dumped into the plant. Photo from the Lippincott collection, U.C. Water Resources Center Archives.

Figure 4 (Lower) - Same view as above, but about a year later, when the dam was nearing completion. Each of the steps were five feet high and forms can be seen along the upper three tiers. Note the dump trucks parked in the shed in front of the batch plant. Photo LA Dept of Water & Power.

Excavation of keyways on either of the abutments was also minimal, but, again, not untypical of the early 1920s, before large mobile excavation equipment became available. Keyway excavation of the Vaqueros sandstone on the right abutment was made by a track-mounted steam shovel (Fig. 5) and only extended about 10 feet into the conglomerate along the path of the concrete dike (Fig. 6). In water resources engineering, the terms “right” and “left abutment” refer to relative positions when viewed travelling downstream (like water). In this case the right abutment would refer to the northwest side of the channel while the left abutment would be referring to the southeast side.

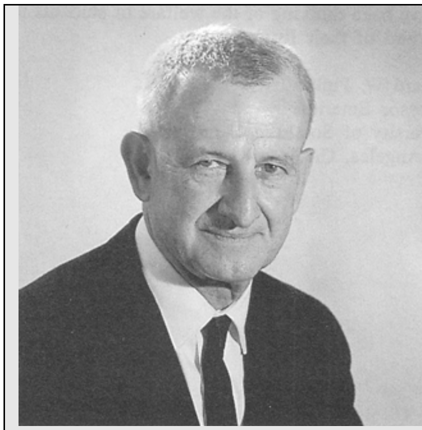
Excavation into the schist on the left abutment was of similar scale, but appears to have extended about 15 to 20 feet, as suggested in Fig. 7. A cutoff trench (or shear key) about 3 by 3 feet was noted underneath some of the dam’s blocks displaced downstream after the failure (Fig. 32). With exception of the 10 uplift relief wells under the dam’s main section, the structure was bereft of any further seepage cutoff or control, such as deep cutoff walls, internal inspection galleries, seepage grout curtain beneath the dam, or uplift relief provided beneath the dam’s steeply sloping abutments. Many of these details of foundation preparation would gain industry-wide acceptance a decade later, after St. Francis failed.

One of the great shortcomings of the dam’s monolith was the absence of any transverse or longitudinal contraction joints. Some shear key baffles were incorporated into the dam monolith towards either abutment, as viewed in Figs. 5 and 8. In Fig. 8, the staggered nature of the shear keys every five vertical feet can be easily appreciated. When the dam was designed in 1923, there was little widespread appreciation of the enormous heat created by the hydration of the mass Portland cement. Part of this ignorance arose from earlier experience being primarily with cyclopean masonry dams (like Arrowrock, Roosevelt, and Cheesman Dams), which used quarried rock with cement mortar. Cyclopean masonry dams didn’t develop significant heat during curing of the cement. The heat generated by curing of the cement fraction can foment significant thermal stresses and shrinkage of the mass concrete. 130,446 cubic yards of concrete were placed at St. Francis in just 16 months, without any attempt at cooling the concrete. As a consequence, some rather large contraction cracks formed in the monolith, which were plugged with oakum (dry wedges of oak wood, pounded into the cracks) in 1926-27 (those positions on the downstream face are portrayed in Fig. 49).

As had occurred the previous July, in July 1925 the dam was heightened another 10 feet, increasing reservoir capacity to 38,168 acre feet, which coincided with Los Angeles' water consumption in 1924. This second raising of the dam structure, viewed in Fig. 9, necessitated extension of the wing dike some 600 feet northwest of the main dam's crest, requiring another 3,826 cubic yards of concrete. The contractor was forced to set up another lattice tower and wood derrick from which to suspend long troughs to direct concrete from the batch plant in the canyon bottom (Fig. 9). An auxiliary spillway was built across a natural saddle several hundred feet beyond this (Fig. 10). This saddle has since been excavated to accommodate the new alignment of San Francisquito Canyon Road north of the dam site. This second heightening would appear to have been most critical to the dam's subsequent structural stability, as discussed later.

The completed dam was opened with little fanfare in May 1926, shown in Fig. 12. The main structure incorporated eleven 20-feet wide spillway slits, only 18 inches high, and five 30-inch diameter piped outlets, seen to good effect in Fig. 12. Head gate controls for the outlet pipes and a Steven's Reservoir Stage Gage were accessed from a central control station, which can be discerned as the solid section in the fourth bay from the right abutment. These devices were situated on that portion of the dam which withstood the ensuing failure in March 1928. A concrete-lined trapezoidal channel (seen in Fig. 12) with a maximum flow capacity of 1580 cubic feet per second (cfs) was constructed between the dam and Powerhouse 2, 1.4 miles downstream, to convey outlet water from the dam to a flow gate) where discharge could be directed back into the aqueduct, or allowed to flow down San Francisquito Creek.

Water from the Owens River aqueduct was initially diverted into the new reservoir on March 1, 1926, several months before the dam was topped off. Between March 1st and June 1st, the reservoir filled at a rate averaging about 1.8 feet per day. A year later (May 10, 1927) the reservoir pool reached elevation 1,832 feet, just 3 feet below spillway sill, before being drawn down by consumptive needs, which were highest during the dry summer months. The following winter (1927-28) the reservoir was allowed to fill to capacity, rising this time to within 4 inches of spillway crest (elevation 1834.75) by Wednesday March 7, 1928, whereupon no additional aqueduct water was diverted into the lake. On Monday morning March 12th, all the City's reservoirs were filled to capacity and BWWS began spilling aqueduct water into San Francisquito Creek at the Drinkwater Canyon bypass outlet for the first time (the flows of San Francisquito Creek had been blocked by the dam since mid summer 1924). This unusual release the day preceding the failure led several witnesses to allege this as overt evidence the dam was leaky profusely the day of the failure, which is not true.



Thomas Clements (1898-1996)
The unexpected release of discharge from the Drinkwater Canyon bypass on Monday March 12th saved the life of a young geologist named Tom Clements, who was mapping the area for his master's thesis in geology at Cal Tech. When Clements went to camp in his favorite spot several miles downstream of the dam, his car became stuck in the wet streambed. After considerable effort to free the vehicle in the gathering dark, he found himself uncomfortably covered with mud and shivering, so with much disgust, decided to drive back to Pasadena and his life was thereby sparred (described in Clements, 1966). A native of Los Angeles, Tom Clements joined the geology faculty at USC the following year (1929) and went onto to complete his Ph.D. at Cal Tech in 1932. From 1937 until his retirement in 1963 he chaired the geology, geography, and petroleum engineering departments at USC. Among his notable achievements was ushering in formalized courses in engineering geology at the undergraduate and graduate levels. Six months after retiring he was asked to serve on the Board of Inquiry to investigate the Baldwin Hills Reservoir failure. In his retirement years he served as a consultant on wide variety of southern California projects and he and his wife of 70 years, Lydia, wrote books about the geology and history of Death Valley. Lydia passed away in 1993 and Tom died on May 13, 1996, three weeks shy of his 98th birthday. When I interviewed him in 1992 I was impressed by his trim field geologist physique, a disciplined demeanour reminiscent a Marine Corps colonel, and his sharp recall of details. His only failing was his hearing. He described himself as "a lucky fellow, because I got to do what I loved doing my entire life." We should all be so lucky.

The building of the dam had necessitated construction of a new road between Powerhouses 1 and 2, about nine miles apart. This road was cut into the schist a point about 4,000 feet downstream of the dam, crossing the dam's left abutment about 13 feet above the dam's crest (Fig. 10**)**. A foot path led down to the dam, which was 16 feet wide along its crest. In order to access the dam by vehicle, it was necessary to remain on a gravel road running along the canyon bottom, pass the damkeeper's residence about a quarter mile downstream of the dam, and ascend an old construction road with an 18% grade, climbing the ravine just below the right abutment. This old road led to the auxiliary spillway. From here, vehicles could be parked on a cut pad situated between the dike section and the auxiliary spillway (Fig. 10). This road became impassable during inclement weather and the decision had been made to grade a new road with more acceptable grades on the opposite side of the ravine, leading to the same location. This road was under construction when the dam failed, and traces of it can still be seen today.

BWWS damkeeper Tony Harnischfeger became concerned on Monday morning March 12th when he noticed dirty water cascading down the slope below the dam's right abutment. New leaks and increased seepage had been noted over the past five days, since the reservoir had been elevated to maximum pool level. Mulholland was summoned, and hearing the report of "dirty water," he rushed to the scene, along with his assistant chief engineer, Harvey Van Norman. The two men arrived at the dam around 11 AM and were relieved to find that the leak emanated from the dike section atop the Vasquez Sandstone (Fig.13) was actually clear where it bubbled up, becoming turbid where it cascaded over loose side-cast fill for the old construction road. The trio spent about 1-1/2 hours walking the dam making inspection of its condition and detected no overt problems. They then returned to Los Angeles around 12:30 PM, less than 12 hours before the failure.

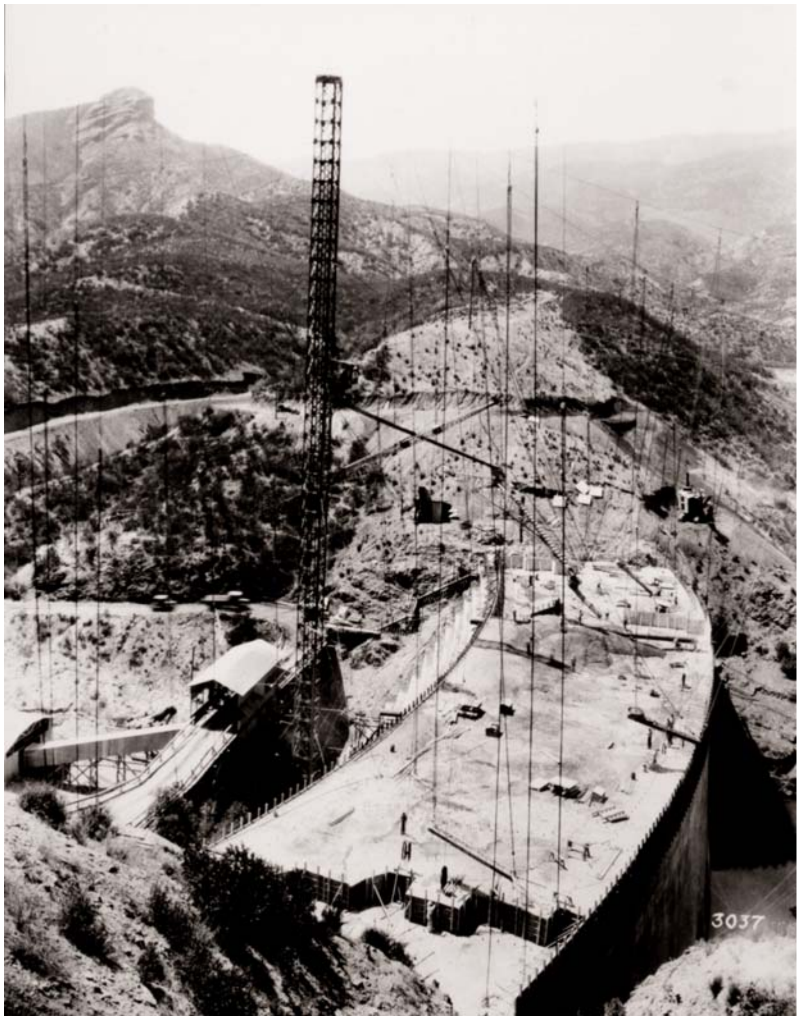


Figure 5. View looking northwest towards the left abutment, during the dam's construction, around March 1925. Shear key baffles are being placed within the dam, about 50 and 100 feet from either abutment. Note the steam shovel working on the right abutment and the contractor's tower, used to deliver concrete to the central dam area via a system of cables.

Figure 6. Keyway excavation in the Vasquez conglomerate cut by steam shovel for the dam's dike section, which extended about 600 feet northwest of the right abutment crest. Photo taken from Lippincott collection, U.C. Water Resources Center Archives.

Figure 7. View looking west southwest towards the left abutment, in the Pelona Schist. Excavation of about 20 feet of schist can be seen, as well as the planar nature of the foliation surface, paralleling the abutment. Note the standing ponds of laitance moisture sitting upon the concrete pillows in foreground. Photo from L.A. Dept. of Water and Power.

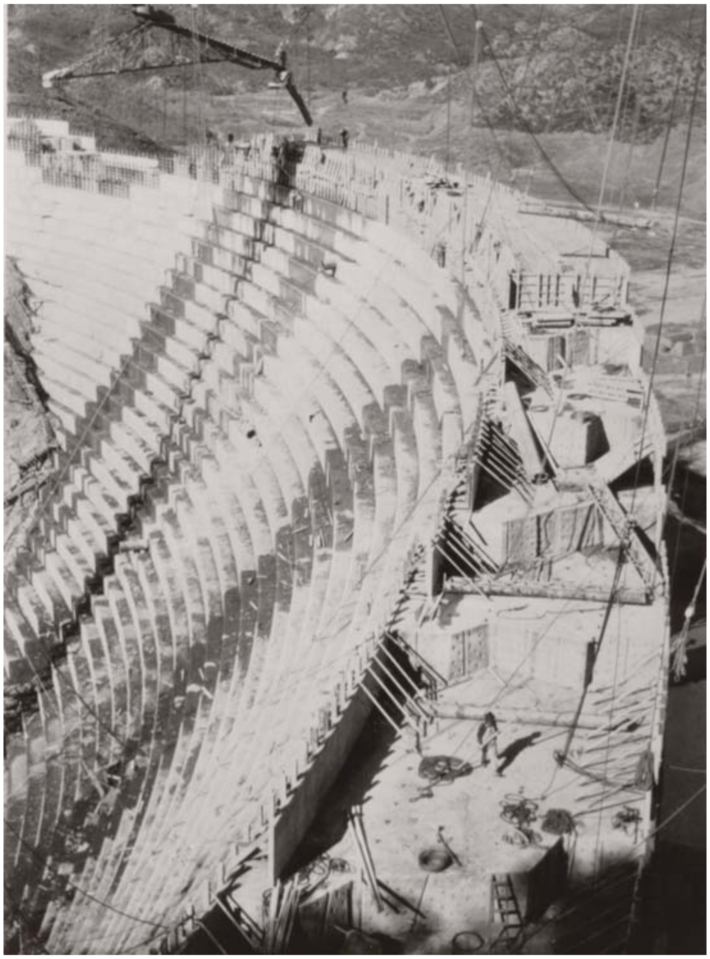


Figure 8. View of the main dam crest under construction, as seen from the left abutment crest. In this zone the shear key baffles were placed more frequently. Note how each step on the downstream face has a unique width, decreasing with upward elevation. Photo Lippincott Collection of U.C. Water Resources Center Archives.

Figure 9. The dam design was amended to increase the overall height by 20 feet, taken in 10-feet increases on two occasions, a year apart. This view shows the dam topping out, sometime in 1926. The finished crest width was 16 feet. By this time the contractor was forced to install additional towers to aid in concrete placement along the dike section in the background. Photo from Lippincott Collection of U.C. Water Resources Center Archives.

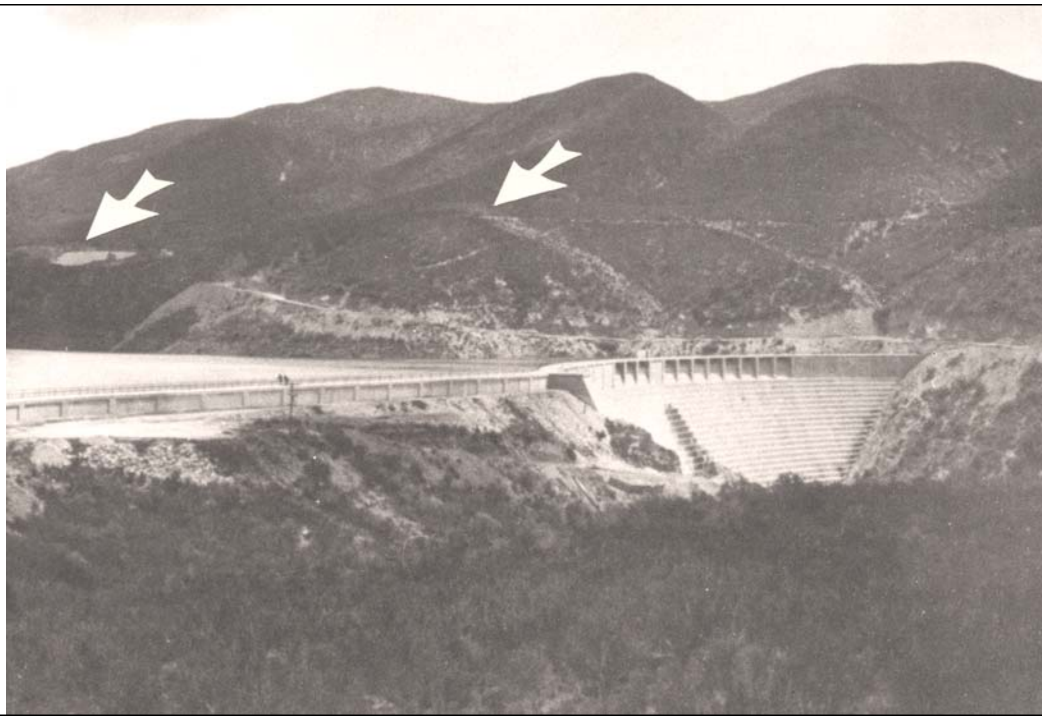


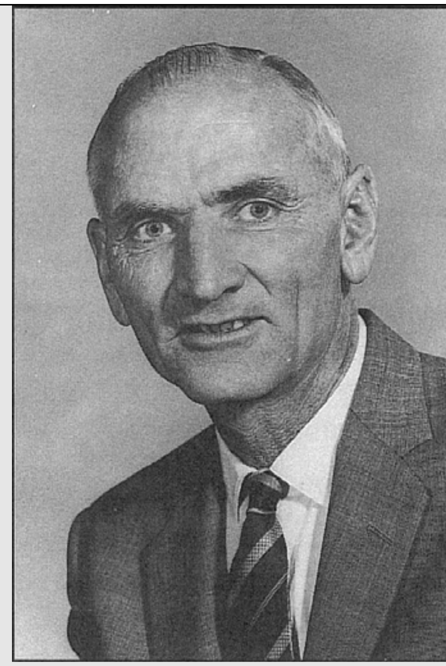
Figure 10 (upper). Part of a three photo panorama, believed to have been imaged in the spring of 1927, when the reservoir was about 20 feet below the spillway slits. Note the position of San Francisquito Canyon Road, cutting across the dam's left abutment, about 13 feet above crest. Also note the prominent terrace platforms exposed in the Pelona schist. Photo L.A. Dept. of Water & Power.

Figure 10 (lower). Same view taken after the failure. Note the prominent topographic bench in the Sierra Pelona escarpment, caused by massive landslippage. The east abutment slide is at right center. Another slump is obvious at left center, which dropped the old San Francisquito Cyn. Rd. about 50 feet (profiled in Fig. 45). From La Rue Collection at the Huntington Library.

FAILURE OF THE DAM

What occurred at the dam during the evening hours of March 12-13, 1928 has been the subject of considerable conjecture since the dam's untimely failure. The most complete discussion of the events is summarized in Charles Outland's book *Man-Made Disaster*, published in 1963 and 1977 (reprinted in 2003). Outland did a magnificent job of collating the various personal accounts, but was unable to gain access to the records maintained by the Los Angeles Department of Water and Power.

Charles Outland (1910-1985) was a native of Santa Paula. He was a senior in high school when the flood waters from St. Francis swept through the lower elevations of his home town, killing entire families. The following year he attended Whittier College, and followed by Boston College, before returning to Ventura County in 1933. A successful rancher, he became interested in local history and remained active in the County Historical Society throughout the 1950s, when he began researching Man-Made Disaster: the story of the St. Francis Dam, which first appeared in 1963. A second edition with 45 pages of additional information was released in 1977. Outland developed an excellent slide-illustrated lecture on the St. Francis disaster, videotapes of which are available from the Santa Clarita Valley Historical Society at William S. Hart State Park. His research files are archived at the Ventura County Museum of History and Art. He wrote four other books before passing away in 1985. An excellent description of his work on St. Francis was written by historian Abraham Hoffman in The St. Francis Dam Disaster Revisited (1995, 2003).



The eyewitness accounts

Of great import are several facts, only briefly related here. There were several employees of Powerhouse 1 (upstream of the dam) who passed by the dam's left abutment (actually, slightly above the abutment, as seen in Fig. 10) within a few hours of the failure. One of these was the Ray Silvey family, who crossed by the dam between 8:30 and 9 PM on March 12th. Silvey was the Powerhouse 1 operator who went on shift at 11 PM, along with a Mr. Tate. Silvey later recalled crossing a crack about 12 inches high extending across the road, just upstream of the dam (see Outland, 1977, p. 234). Insofar as the road was completely upon cut in the Pelona schist (Fig. 11), this observation can only suggest incipient motion of a large bedrock landslide in close proximity of the dam's left abutment.

Dean Keagy, a warehouseman at Powerhouse 1, had driven by the dam around 11:30 PM, about 25 minutes or so prior to the failure. He testified that he saw lights at the bottom of the canyon, which he described as "a sort of a camp." This could be taken to describe the damkeeper's cottage, which was the nearest structure with electricity, although it was located a quarter mile downstream. There were no lights on the dam.

Fig. 11 - En-echelon tension cracks in San Francisquito Canyon Road several hundred feet upstream and about 20 feet above the dam's left abutment. The Ray Silvey family noted that one of these scarps was 12 inches high when they passed the dam between 8:30 and 9 PM, forcing them to stop their car and excavate ramps for their tires. These scarps were developed in the Pelona Schist. Photo by Bailey Willis, from the St. Francis Dam Disaster Collection at the Huntington Library.

Two other Powerhouse 1 employees, Helmer Steen and Katherine Spann, drove past the dam between 11:35 and 11:40 PM. They later testified that they did not see anything unusual, and that the dam was completely dark. The last person to see the dam was Powerhouse 1 carpenter Ace Hopewell, riding a motorcycle with sidecar. He appears to have passed the dam's crest around 11:50 PM, about 7-1/2 minutes prior to the collapse. Although he recalled seeing the headlights of two cars up ahead (Keagy and Steen/Spann), he did not notice anything unusual, until stopping for a cigarette about a mile above the dam, at which time he heard strange crashing sounds.

After the dam's failure the fully clothed body of Lenoa Johnson, damkeeper Harnischfeger's common law wife, was found wedged between two blocks of the dam, a quarter mile upstream of their demolished home. The fact that Johnson's body was found by the dam, that she was fully clothed, and that Keagy noticed lights near the base of the dam when he drove by, has lead to speculation that she and Harnischfeger were up at the dam carry flashlights or lanterns looking at something unusual or out-of-place (it was near midnight) when the dam suddenly collapsed, trapping them. Neither Harnischfeger nor his son's bodies were ever identified. If they were exploring the base of the dam's left abutment, any hand-held lights they had might not have been visible from the road, due to the steep slope (60 degrees at the base of the left abutment).

Figure 12. Frontal elevation view of St. Francis Dam, believed to be taken the day of dedication, in May 1926. Note the eleven crest spillway bays, each only 18 inches high, and the concrete-lined trapezoidal channel in foreground, which ran 7,300 feet downstream, to Powerhouse 2. Image colorized by Pony Horton.

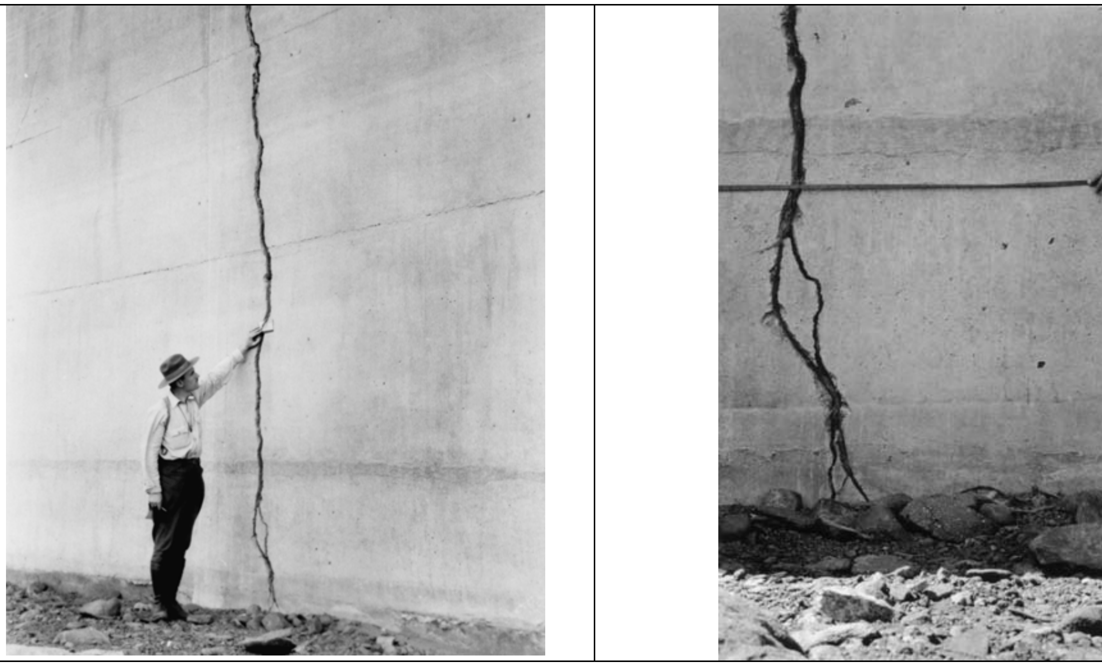


Figure 13. This was the crack discharging about 2 cubic feet per second of clear water the morning of March 12, 1928, as seen from the reservoir side, after the failure. Mulholland had come out to inspect the leak, on the opposing side of this photo, around 11 AM. Post-failure surveys indicated that the dike lifted 0.13 feet at the location, as compared to its as-built elevation. Left image from Huber Collection of U. C. Water Resources Center Archives. Right image from LaRue Collection at Huntington Library.

Precise timing of the dam's collapse

Figure 14. Downstream view of the dam site after the failure, showing location of the SCE 70 Kv Borel Power Line poles, about 60 feet above the high water mark on the right abutment, about 650 feet downstream of the dam. Photo from Ventura County Museum of History and Art.

The Southern California Edison Company's 70-Kv Borel Power Line traversed the mountain range through San Francisquito Canyon, extending eastward to Palmdale. The line was situated upon tandem sets of timber poles, and crossed the canyon about 600 feet downstream of the dam, at an elevation about 200 feet above the channel, in order to ascend the dam's left abutment (Fig.14). The line continued to rise to a position about 90 feet above the crest of the left abutment (Fig. 15). At 11:57-1/2 PM the operators at Powerhouse 1 (Silvey and Tate) noted a heavy bump, bus voltage spiking to 90, which corresponded to Southern California Edison Company's loss of power on the Borel Line. The Borel Power Lines were severed by massive landslippage of the dam's east abutment, shown in Fig.15. This suggests that the dam's catastrophic demise was ushered by a massive landslide enveloping the dam's entire left abutment, at the beginning of the failure sequence.

Figure 15. View looking upstream at the base of the left abutment landslide. Note the planar surface of Block 2, which broke along a cold pour joint. The three downed power lines clearly seen entering the slide area in this view had been clipped before the Governor's Board made their site inspection on March 22nd. Note tandem SCE poles in distance, upstream of the east abutment landslide. Photo by H. Wildey, author's collection.

The Stevens Reservoir Stage Record and cantilever (bending) forces

As shown in Fig. 16-upper, a mass concrete gravity dam cannot theoretically sustain tension in its heel, or it becomes unstable in overturning. The resultant thrust (R_T) is the vector sum of the dam's dead weight (pushing downward) and the pressure of the reservoir water (pushing horizontally, against the dam). The inclination of the resultant thrust must remain within the middle third of the dam's base to prevent the heel from separating from the underlying foundation. For this reason, masonry dams over 200 feet high are generally battered on their upstream face, to widen their footprints and, thereby, keep their upstream heels out-of-tension.

The author carried out several forensic back-analyses of the dam in the 1990s. One of these examined the likely cantilever (bending) forces that could have been expected to develop given what was known about the actual geometry of the dam, at its highest point, through Block 1. Fig. 16–lower left shows how the cantilever loads were summed and compared, while Fig. 16

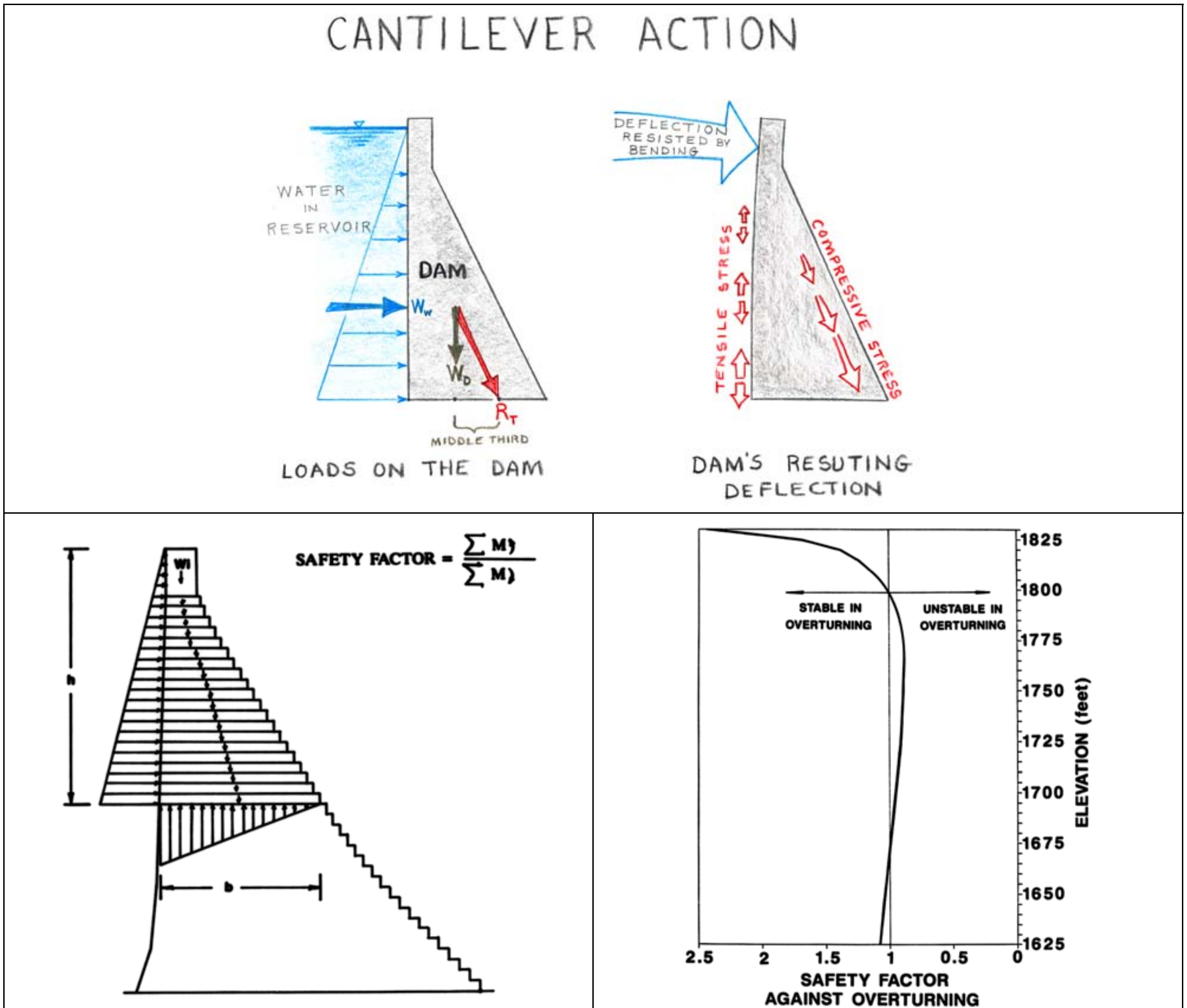
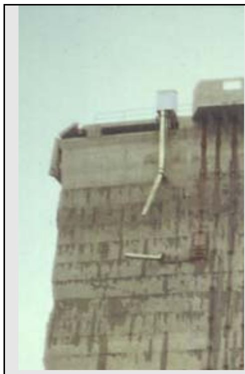
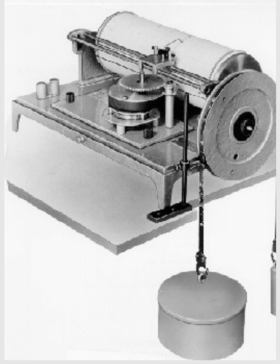
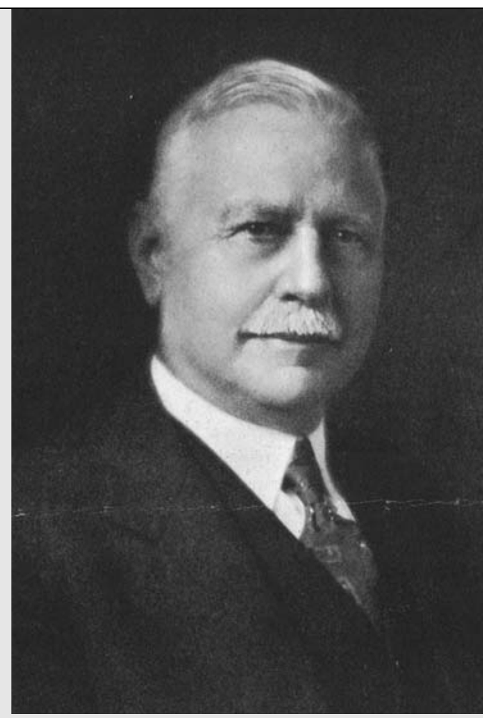


Figure 16. Upper – Cantilever action of the dam resists load through simple bending through fixity of its base. Note how tensile stresses can form at the base of the upstream face if the resultant thrust falls outside the middle third of the base. This would be considered unsafe. Lower – These frames show how the cantilever forces were calculated (lower left), assuming full uplift, and how the dam becomes unstable with respect to overturning when the reservoir rose to 1830 feet, five feet below the spillway sill (the dam crest was at 1837 feet). Taken from Rogers and McMahon (1993).

-lower right shows the results of these summations. These back-analyses revealed that the structure becomes unstable in overturning when the reservoir pool was raised to within five feet of the spillway lip (elevation 1830 feet), a condition that occurred five days previous to the failure (Rogers and McMahon, 1993). The reservoir pool had been brought up to within 3 feet of spillway sill the previous year for just one day (May 10th), then maintained at 4 feet below crest for another two weeks, until May 25th, when it was drawn down to 1812 to 1820 ft through the balance of the year. The reservoir pool was then brought through elevation 1830 on February 5th, and maintained above this level for the next 36-1/2 days, until the failure. This would have allowed time for increased percolation beneath and around the dam, into its abutments.

		A **Stevens Water Stage Recorder** was attached to a 12-inch diameter #16 gage galvanized steel pipe 75 feet long (deep), affixed to the upstream face of the dam, slightly southeast of the outlet pipe head gates. It contained a 1-inch diameter hole at its bottom to allow reservoir water to enter and rise to a level commensurate with the actual hydrostatic pressure against the upstream face of the dam. Invented by water resources engineer **John C. Stevens** (1876-1970) in 1911, the device allowed for accurate recording of reservoir level without interference of wave action in the reservoir. Many of these mechanical stage gages remain in use today throughout the Third World because they do not require electrical power.

After the dam failed, half the central core remained standing, shown in Fig. 16 left. The pencil record of reservoir stage was recovered from the mechanical drum of the Steven's Reservoir Stage Gage sitting on top the remaining section, which was re-set by winding the device's counterweight every seven days (see sidebar description). The gage had been rewound on Sunday March 11th, the day preceding the failure. The Stevens Gage showed a peculiar drop (Fig. 19) in the reservoir, beginning about 40 minutes prior to the dam's collapse, at 11:57-1/2 PM.

Carl Ewald Grunsky (1855-1934) was the most lauded civil engineer in California between 1900 and the time of his death in 1934. The same age as Mulholland, he was a native of Stockton. There being no established engineering schools in California he elected to attend Stuttgart Polytechnica in Wurttemberg, Germany, graduating in 1876. He returned to California and worked for the State Engineer's office between 1878-88. After this he entered private practice, consulting on sewerage, flood control, and water resources projects. He designed San Francisco's sewerage system at the turn of the 20th Century, was appointed by President Roosevelt to the first board of consultants for the Panama Canal in 1905, designed the Sacramento River's system of flood control bypass structures (completed in 1913), and received just about every award imaginable from his profession, culminating with his tenure as President of the American Society of Civil Engineers in 1924. His review of the St. Francis Dam was orchestrated by the disgruntled ranchers of the Santa Clara River Valley in 1925, at which time he proved the city's collection of surface waters within San Francisquito Canyon reduced recharge of the river gravels, which the ranchers depended upon. He returned to the dam site with retired Stanford geology Professor Bailey Willis shortly after the dam failed, and wrote some of the most insightful articles about the dam's untimely demise. He was to northern California what Mulholland was to southern California, but with more polished pedigree and international reputation.	 **Carl E. Grunsky was the visionary force behind many prominent water supply and flood control projects in northern California and a national figure in American civil engineering.**

One of the most interesting aspects of the post-mortem analyses of St. Francis Dam concerns the massive tension crack exposed in the upstream heel of Block 1, discovered by San Francisco engineer C. E. Grunsky (see sidebar discussion) about two weeks after the failure, when the ground around the upstream face of Block 1 had drained sufficiently to see more details. The wooden ladder (Fig. 18) came from a position about 50 feet southeast and 100 feet below where it was affixed to the dam's upstream face, between the Stevens Stage Gage stilling pipe and the pull-rod for Outlet Sluice Gate No. 2 (see left side of Fig. 17 left, below).

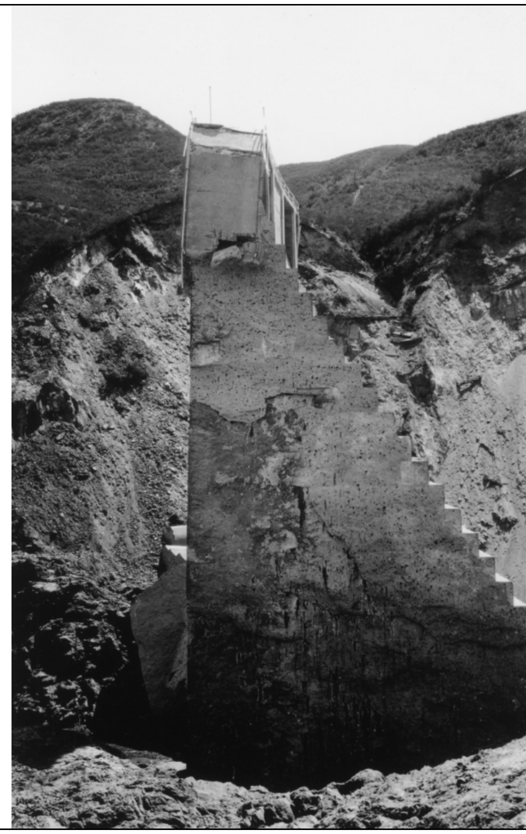


Figure 17. Left - Carl Grunsky discovered the gage attendant's wooden ladder wedged inside an enormous tension crack in the right upstream heel of Block 1 (from Ventura County Museum of History & Art; colorized by Pony Horton). Right – Profile view of the Block 1 monolith. No discernable upstream batter can be seen near elevation 1730, about half the height of the block (from La Rue Collection of the Huntington Library).

The existence of such a large tension crack in this portion of the dam was mute testimony of a seriously overstressed structure. Subsequent structural analysis by the author revealed that the presence of a crack in the heel of Block 1 would have shifted the dam's resultant thrust some 240 feet downstream of the dam, when it would need to be within the middle third of the dam's base to maintain stability (Figs. 16 and 20). No dam could withstand such imbalance, as the reservoir's full hydrostatic pressure would have entered such a fracture and greatly reduce the effective weight of the dam's concrete. These findings suggest that the progressive drop in reservoir level recorded by the Stevens Stage Gage during the hours preceding the failure appear to correspond with tilting of the dam's central core, due to its being overstressed (Fig. 20). So, it would appear that the Stevens Stage Gage faithfully recorded dangerous tilting of an overstressed dam, not an actual drop in the reservoir stage level, as most presumed at the time.

Figure 18. Detail view of the wooden gage attendant's ladder found in a large tension crack in the right upstream heel of Block 1. This testifies to significant deformation of Block 1, tilting downstream under active hydrostatic pressure. Some of this may have occurred after Block 2/3/4 fell away, removing lateral restraint on the left side of Block 1. Photo taken from Outland (1963).

ST. FRANCIS RESERVOIR
WATER STAGE RECORD
MARCH 12-13, 1928

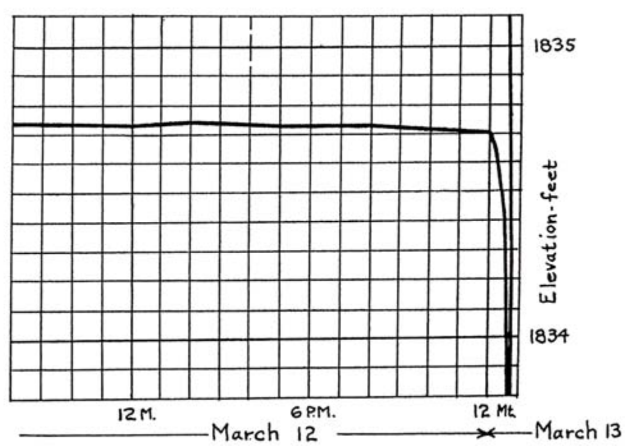


Figure 19. Charles Lee's reconstruction of the Steven's Gage record recovered from the crest of Block 1 after the failure. Note the increasing drop in reservoir stage that began about 40 minutes prior to the 11:57-1/2 PM failure. Lee (1928) recognized that this deformation might have come from the left abutment pushing against the dam and "lifting it slightly." The gage appears to have recorded cantilever deformation of the main dam, deflecting almost two degrees from vertical when the dam collapsed.

After St. Francis failed, BWWS presented the State Board of Inquiry with a standard cross section, reproduced in Fig. 3 - lower right. This section shows a battered upstream face commencing at elevation 1730, and increasing markedly, below elevation 1645, which would be considered good practice. From the photographs of Block 1 that survive, however, it is difficult to discern any hint of an upstream batter of the dam's maximum section, in Block 1 (see Fig. 16 right).

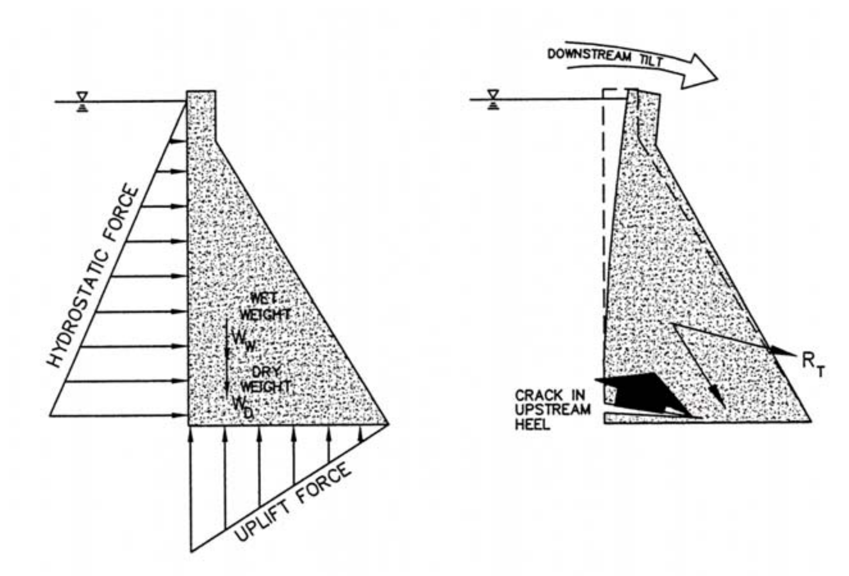


Figure 20. Left - The resultant thrust within a gravity dam is the vector sum of the horizontally-inclined hydrostatic force and the vertically-inclined dead weight of the dam. Stability in overturning requires that the resultant thrust R_T be within the middle third of the dam's base. BWWS engineers ignored uplift forces in their analyses because they installed 10 uplift relief wells under this portion of the dam, which did not fail. Right - The Steven's Gage attached to Block 1 faithfully recorded a drop of 12 inches in 40 minutes, which would equate to a 2 degree tilt about an axis of rotation at the deepest point of Block 1, about 106 feet downstream of the dam's upstream heel.

Arch stresses

Although the dam incorporated a rather tight constant radius arch, arch stresses were ignored in the original design, a conservative assumption. The trial load method of arch dam analysis was developed by the Engineering Foundation Committee on Arch Dam Investigation, which initially convened in 1923 to study the problem of how loads are carried in concrete dams via arching. This study was accomplished through the fabrication of the thoroughly instrumented Stevenson Creek Test Dam in California in 1926. The first progress report of the committee appeared in the May 1928 ASCE Proceedings, and the trial load method of arch dam analysis was initially summarized by Howell and Jaquith (1929) the following year, although the Arch Dam Committee didn't issue their final report until 1933 (Civil Engineering, 1933). So, these methods for analyzing arch stresses were not available to BWWS engineers in 1922-23, when they designed the dam.

Arch stresses typically increase upward in a constant radius arch dam, because of diminishing dam mass (Fig. 21-left). Rogers and McMahon (1993) performed modern structural assessment of arch loads on the main section of the St. Francis Dam. The results were as perplexing as those accomplished on cantilever stresses (Fig. 21-right). Arching stresses towards either abutment exceeded 10,000 pounds per square foot (5 tsf) when the reservoir pool was raised to within three feet of the spillway. The decision to raise the dam 20 feet without widening the dam's base was one of the more significant design flaws that can easily be appreciated today.

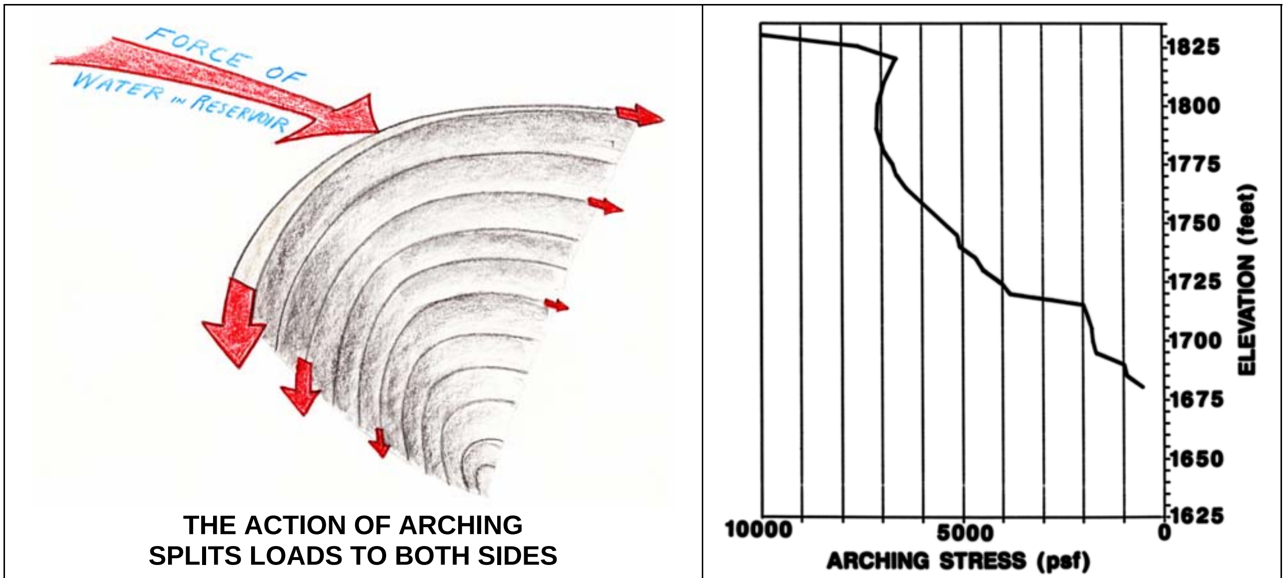


Figure 21. Left – Arching transfers loads horizontally as thrust onto both abutments of a curved dam. These loads typically increase upward in the dam, because the structure has diminishing cross sectional area upwards toward the crest (a given load divided by a smaller and smaller bearing area at the abutments, yields progressively greater force per unit area). The tighter the arch radius, the greater the percentage of the imposed load that can be transferred to the abutments. Right – Plot of arch stress versus elevation from Rogers and McMahon (1993). This suggests that the arching stress began to elevate significantly when the reservoir rose to within 10 feet of spillway sill, around elevation 1823 ft.

Concrete quality and cold pour joints

The dam's concrete was of fairly poor quality; in terms of porosity (13% average), bulk density (143 pcf average) and, most important, splitting tensile strength, which averaged less than 95 pounds per square inch (psi), and as low as 35 psi along cold pour joints. Post failure tests in 1928 only evaluated the compressive strength of the concrete, and varied between 2000 and 2800 psi, which was considered adequate for mass concrete. Most mass concrete has splitting tensile strength of about 11% of the compressive strength (Raphael, 1984). Petrographic analysis of the dam concrete reveals that most of the aggregate was somewhat dirty, having a selvage of clay, silt or gypsum surrounding much of the aggregate surface, which prevents desired bonding with the cement paste in the matrix.

The other problem with St. Francis relates to the method of concrete placement in the era in which it was constructed. At that time the preferred method of bringing concrete from the on-site batch plant to the dam was via a tower with cables that could support long troughs, through which the concrete was poured (Fig. 4). The flow distances were therefore considerable, and aggregate segregation inevitably occurred, causing pockets of highly porous open work concrete. In addition, at that time, few engineers appreciated the need to strip off the high water content laitance layer of cement paste, which developed upon the surface of a newly poured lift of concrete (seen as little ponds on the undulating concrete surface in Figs. 1 right and 7). This high water-cement ratio paste has high porosity and low tensile strength. It should be of little surprise, therefore, that all of the dam's displaced blocks broke apart along near-horizontal pour joints. These joints appear to have very low tensile strength. The horizontal segregation of the concrete placement is easily observed and appreciated when walking about on the premises of Block 1 at the dam site.

Rock mechanics analyses of the left abutment

In the late 1980s methods of analysis became available to enable assessment of block kinematics of the rock mass comprising the dam's foundation. The process began by collecting attitudes of controlling discontinuities at the dam site, climbing the abutment scars to obtain measurements of strike and dip of the foliation, bedding, and other discontinuities, mostly joints (some of these are shown in Fig. 23). The existing ground surface lies 30 to 40 feet below that excavated for the left abutment, because of the left abutment landslide and erosional scour by the outpouring water of the reservoir. The right abutment has been excavated to accommodate the old San Francisquito Canyon Road, used between 1930 and 2004. Suites of fractures were identified, the schist being pervaded by an impressive array of joints. The left abutment is essentially a dip slope of about 35°, locally steepened to as much as 63° (see images in Fig. 27). These data on the left abutment were processed by several methods, including key block analysis (Goodman and Shi, 1985; Rogers, 1992) and discontinuous deformation analysis (Shi, 1993; Rogers and McMahon, 1993). The keyblock analysis was intended to evaluate a block uplift mode of failure, similar, but likely much smaller than, that which caused the Malpasset arch dam in France to fail catastrophically upon its initial filling in 1959 (Londe, 1987; Leonards, 1987).

Figure 22. Upstream view of the dam site, taken within five days of the failure, when the downed power lines were still visible, leading into the left abutment landslide. Note position of the intact power poles high above the reservoir water line in background. Photo from C.H. Lee Collection, U.C. Water Resources Center Archives, colorized by Pony Horton.

The results of the keyblock analysis of the dam's left abutment are shown in Fig. 24. Three keyblocks with potentially deleterious geometry were identified within the Pelona Schist.

Of these, keyblock B had most unfavorable geometry with respect to hydraulic uplift. A free body diagram of the forces likely acting upon such a keyblock is presented in Fig. 25. The most critical area for such a keyblock would have been at the base of the dam's left abutment, where a 60 degree cut was excavated (Fig. 26). The keyblock analysis suggests that block uplift failure could have occurred at the base of the left abutment. This was a similar failure mechanism as that which caused the untimely failure of Malpasset Dam in 1959 (which was also bereft of uplift relief wells on the steeply sloping abutments).

Left abutment landslide

An enormous landslide occurred on the dam's left abutment, involving something close to 550,000 cubic yards of schist (Figs. 26 thru 29). As appreciated in Fig. 23, only about a quarter of this material was subject to saturation by the rising reservoir pool. The slide extended up to elevation 2000, more than 170 feet above the maximum reservoir level. The landslide mass was probably experiencing incipient motion the evening of the failure, as evidenced by the 12-inch high tension crack described by Ray Silvey (Fig. 11). Percolation of the reservoir water into the schist must have been fairly rapid because the dam failed only 5-1/2 days after reaching maximum pool level the previous Wednesday. The timing constrains estimates of transmissivity through the left abutment to with an order of magnitude, as water must have penetrated beneath the left abutment to have destabilized it.

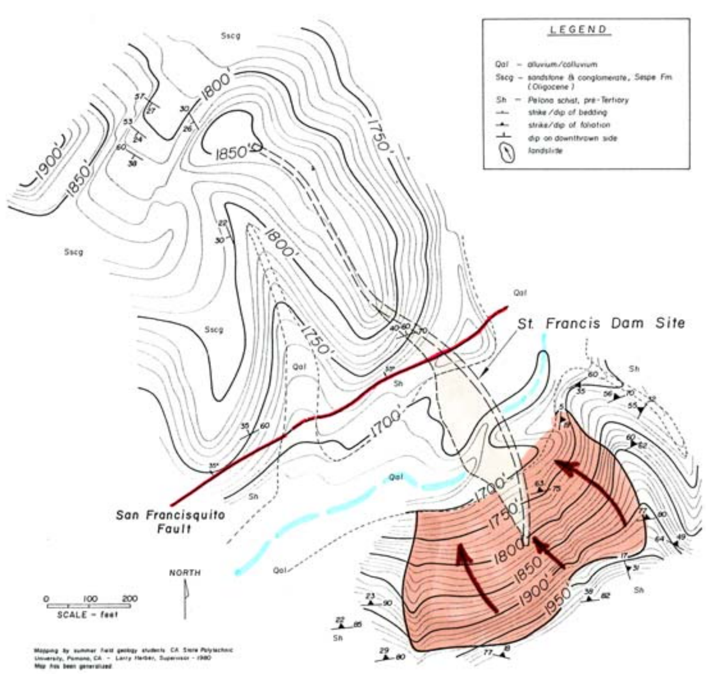


Figure 23. Plane table topographic map of the existing dam site made by students at Cal Poly Pomona in 1980. The original position of the dam is shown in its former position, using survey data provided by LADWP. Note position of the dam crest with respect to the left abutment landslide, right in its center.

In 1993 a more sophisticated method became available to assess rock block kinematics, modeling elasto-plastic behavior in discrete strain iterations, termed Discontinuous Deformation

Analysis, or DDA (Shi, 1993). By modelling discrete movements, the prototype behavior which typifies progressive rock slope failures can be more accurately predicted, including inter-block crushing with increasing block rotation and strain. The DDA analysis was applied to the left abutment landslide in order to gain insight as to how the failure may have progressed so far upslope, above the level infused with reservoir water. The results of these DDA analyses are presented in Fig. 30. They show that significant pore pressures were likely developed via entrapment within foliation (shistocity) planes near the toe of the slope. As the mountain side began to move, the rock mass dilates, but there was nowhere for water trapped within the lowermost area, along the plane of slippage, to escape. As a consequence, pore pressures became sufficiently elevated to cause this portion of the slip zone to become near-frictionless. This is a problem particularly acute to schist because the material is platy and highly anisotropic. In addition to be very weak in the plane parallel to foliation, preferentially aligned mica plates prevent easy migration of water normal to the foliation.

Channel hydraulics of the outbreak flood

When St. Francis Dam failed techniques of channel hydraulics appreciating turbulent and supercritical flow had yet been developed. The senior author modelled the outwash flood using modern forensic techniques. Although the dam site had been surveyed by plane table following the failure, this location could not be used in a back-analysis of outflow because the cross sectional flow area would have been enlarging itself during the outbreak flood, as portions of the dam and its abutments were progressively removed and washed downstream.

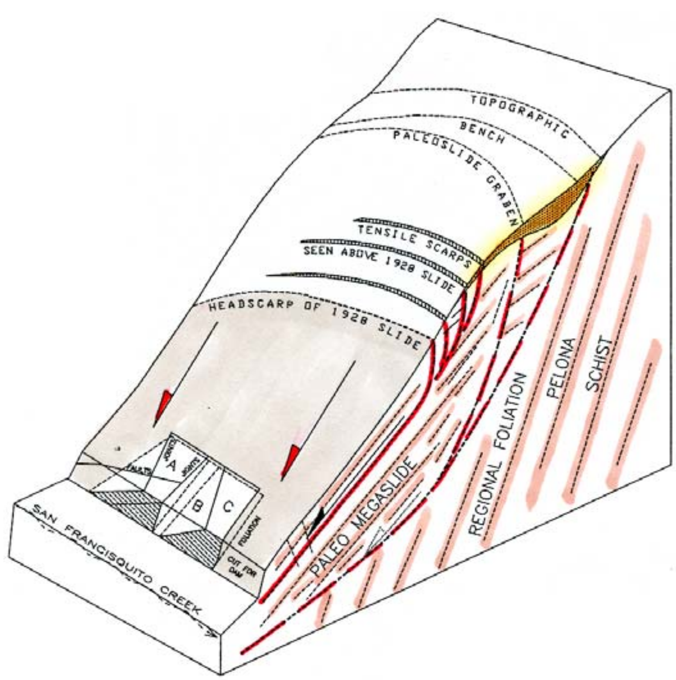


Figure 24. Schematic block diagram of the base of the dam's east abutment, showing rock wedges A, B and C in the Pelona schist predicted by the keyblock analysis. A 60° cut at the base of the left abutment created an unstable situation with respect to this family of keyblocks, based upon measurement of discontinuity suites recently measured in the left abutment scar.

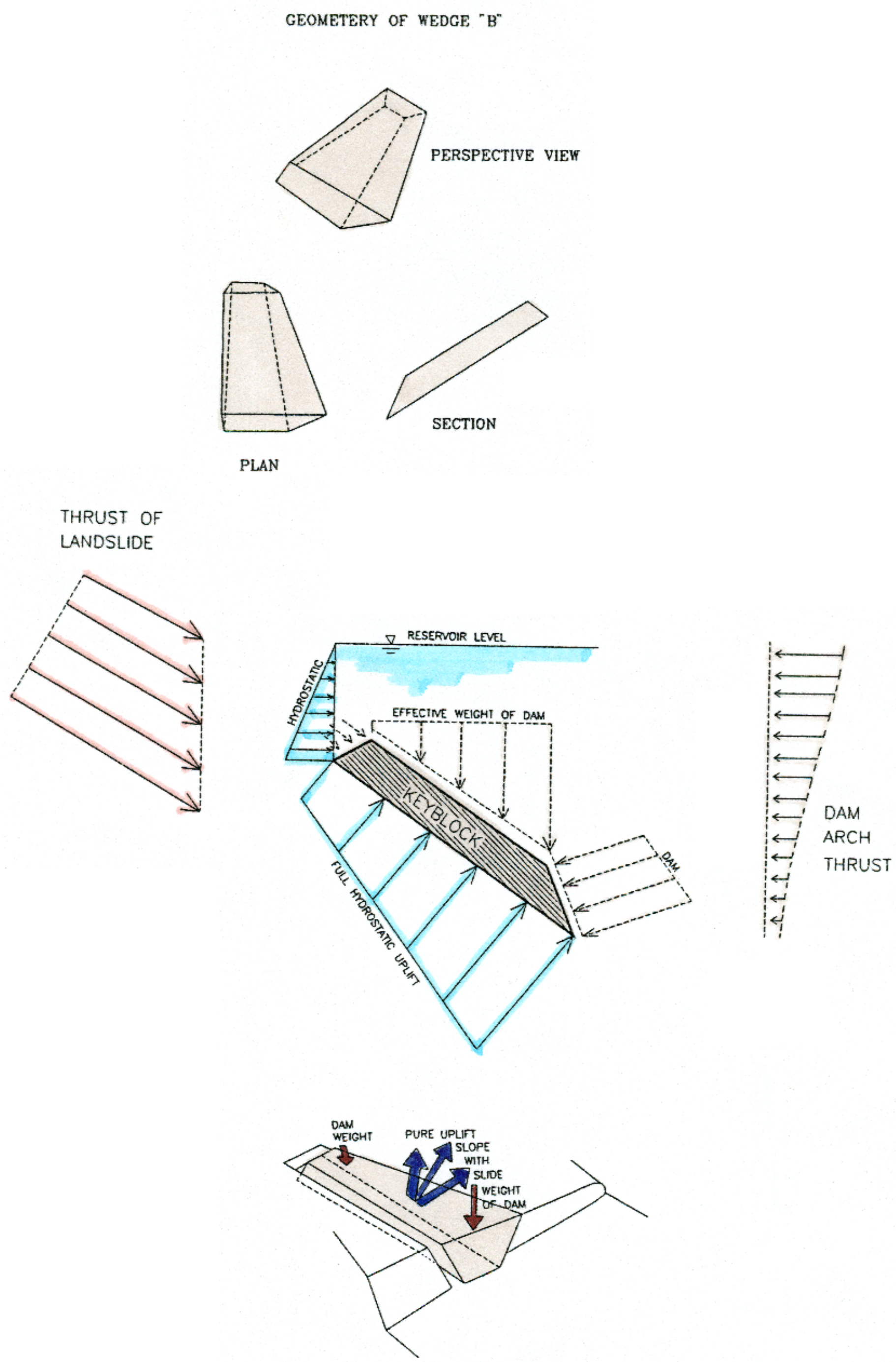


Figure 25. Plan, elevation and perspective views of keyblock B, shown in the previous figure. The elevation view (middle) parallels the foliation of the schist, normal to the dam's abutment. The forces acting upon this block are sketched in. Full hydrostatic uplift would be acting upon the block because the sloping abutments were without any manner of seepage cutoff, grout curtain, or uplift relief wells. The lower figure shows the predicted uplift of keyblock B, in vicinity of Block 35 (Fig. 40).

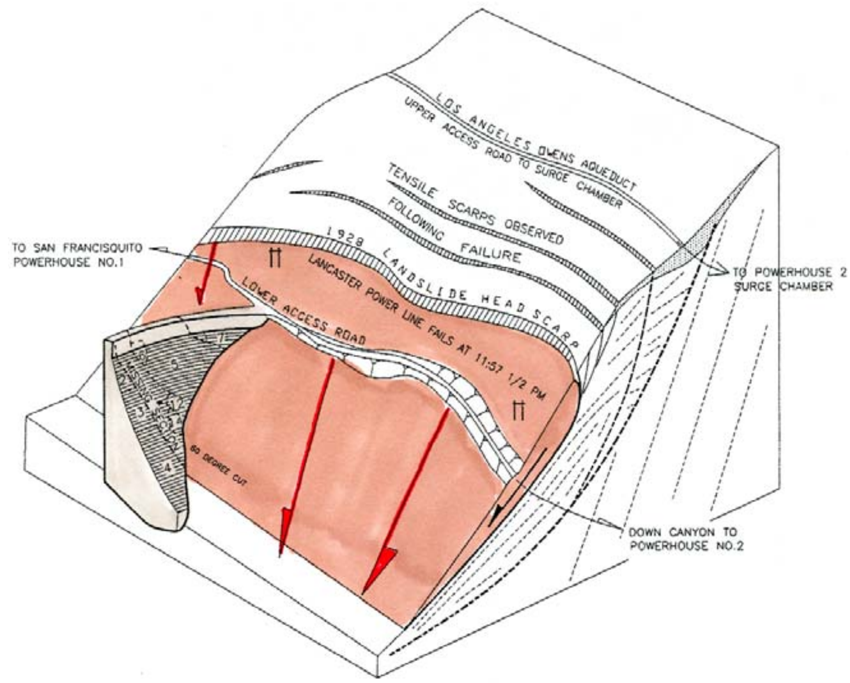


Figure 26. Schematic block diagram of the left abutment area, showing the approximate areal limits of the 1928 east abutment landslide. Bailey Willis (1928) was the only person who recognized that the east abutment slide was only a small portion of a much larger prehistoric landslide developed within the schist.

Fortunately, many photographs were taken of the canyon bottom, between the dam site and the remains of Powerhouse 2, about 7,300 feet downstream. Fig. 31 shows a downstream view of the silt banks deposited by the flood about 4,500 feet downstream of the dam. A number of cross sections were surveyed in the canyon, and presented in the Report of the Governor's Commission to Investigate the Failure (California, 1928). The silt seen in Fig. 31 can still be accessed, and comparative photos were taken at these same locations, then offset photos, in order to develop strereopairs, from which terrestrial photogrammetry methods could be employed to survey the elevations of the outbreak flood high water lines along the canyon walls. As one progresses upstream, the flood detritus, almost wholly comprised of Pelona Schist from the left abutment landslide, becomes increasingly coarse. This can be appreciated in Fig. 32, which shows Blocks 44, 27 and 43 sitting atop schist detritus of average 12-inch size. Sieve analyses of the flood detritus show it to be well sorted (all the same relative grain size) within any given stratum. As the flood flow diminished, progressively smaller size detritus was deposited upon the more coarse fractions. This stratigraphic sequence is typical of short-lived outbreak floods with diminishing flow volumes.

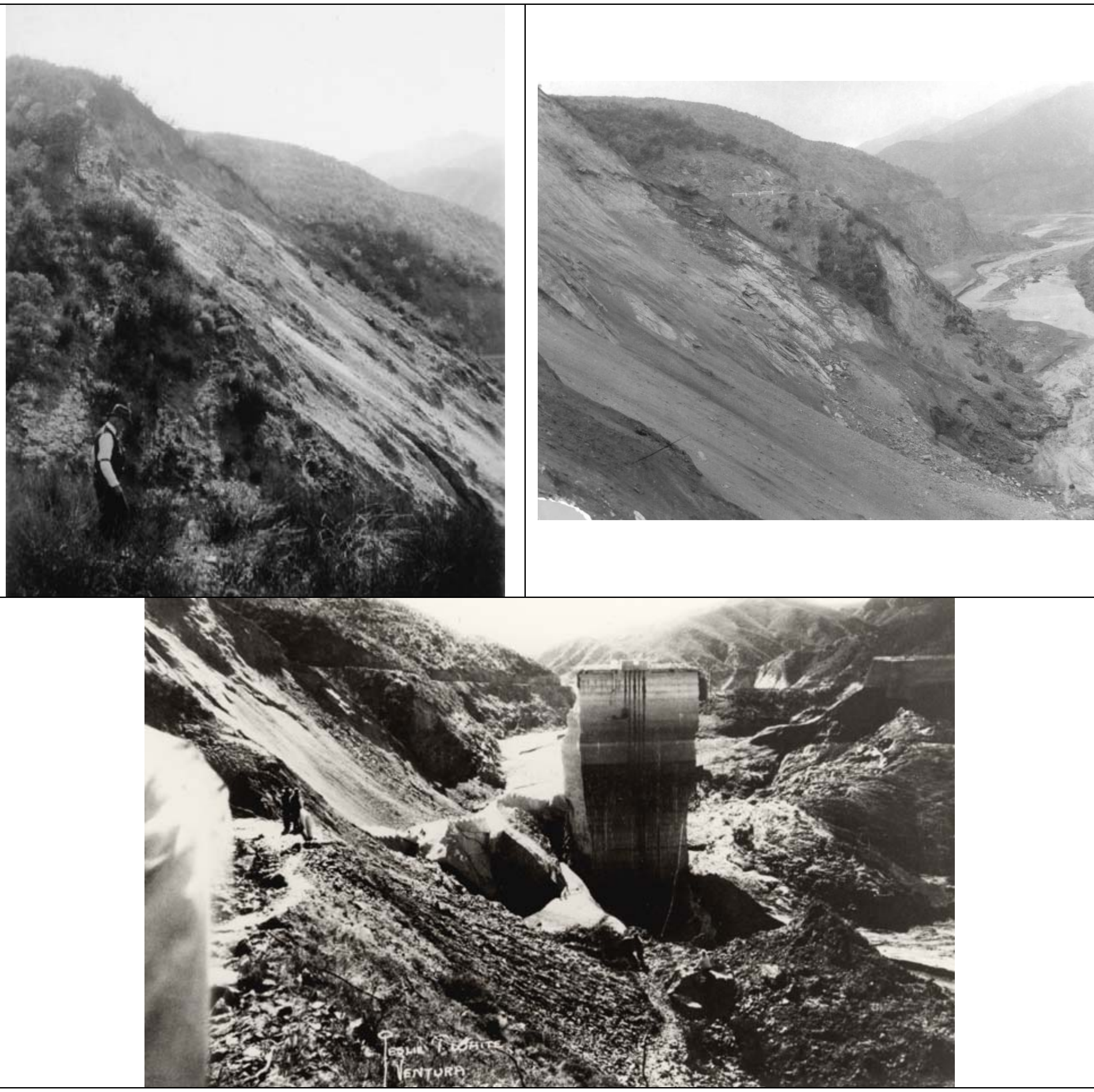


Figure 27. Upper - Downstream views of the planar foliation surface exposed in the east abutment landslide. Note the near vertical headscarp, about 40 feet high (from Grunsky report in St. Francis Dam Disaster Collection at the Huntington Library). Lower – A similar view, but taken from behind the dam. The left abutment slide carried the dam's sloping abutment section across the downstream face of the main structure, from left to right (Ventura County Museum of History and Art).

Figure 28. Aerial oblique view of the dam site by Spence Aerial Surveys the morning after the failure. Note the position of the east abutment landslide and old San Francisquito Canyon Road with respect to the dam (from the UCLA Spence Photo Collection).

Figure 29. Aerial oblique view looking upstream at the dam area the morning after the failure. Note how high the east abutment landslide extended above the reservoir. Also, note the massive slump block upstream of the dam, caused by rapid drawdown (UCLA Spence Photo Collection).

The greatest obstacle in ascertaining the paleoflood hydrograph was to gain accurate check points on the peak flow, the rate of drawdown, and the likely cessation of flow. The peak scour level was easily attained, and the total lost volume known (38,168 acre-feet). The one location where amplifying data was recorded was at Powerhouse 2 (Fig. 33). The power went off-line at Powerhouse 2 at precisely 12:02 AM, due to grounding of the lines, which short circuited in the water. So, we can deduce that the initial flood wave arrived at Powerhouse 2 around 12:02-1/2 AM, about five minutes after the Borel Power Line went down at the dam site.

Above Powerhouse 2 lived a man named E.H. Thomas with his mother. Thomas was the surge chamber attendant for the aqueduct tunnel where it fed into the Powerhouse 2 penstocks. Thomas heard the dam crash and spill down canyon, believing the rumble to be an earthquake. He hurriedly dressed and rushed out to the canyon precipice overlooking where Powerhouse 2 had existed just minutes before, only to view a throbbing, gnashing pool of water and debris. Even though it was dark, he walked down the inclined tramway tracks (to the left of the two steel penstocks in Fig. 33) and reached the high water line (110 feet above channel elevation), where he stopped and looked at his watch. He noted that the time was 12:15 AM. He also noticed that the flood waters had already receded 20 vertical feet, his estimate being based on the number of timber ties for the tram's tracks, which formed natural steps (Fig. 33).

A series of flow cross sections can be constructed from the 6-minute (1:24,000 scale) topographic maps specially prepared by the U.S. Geological Survey for Los Angeles County between 1923-41. These maps were among the first USGS maps ever prepared by orthophoto aerial imagery, and were prepared with contour intervals of 5 and 25 feet. The relevant portion of the Red Mountain 6-minute quadrangle (completed in 1936) is presented in Fig. 36. Because of the available flow data, a channel cross section was chosen at Powerhouse 2, which resulted in a believable outbreak flood hydrograph, shown in Fig. 34. This hydrograph suggests that a peak flow of 1.3 million cfs was likely realized shortly after 12:02-1/2 AM, akin to a giant debris flow. Hydrographs could then be calculated for successive positions, upstream to the damsite. These analyses suggested that a maximum outflow of 1.7 million cfs likely occurred at the damsite. This estimated peak flow is much higher than any of the assessments made in 1928, which were between 440,000 and 1,000,000 cfs for maximum outflow at the dam.

Displaced positions of the dam's identifiable blocks

The most alluring puzzle left by the St. Francis Dam failure were the enormous blocks of the dam's concrete that were left scattered about the canyon, upwards of 1-1/2 miles downstream (Fig. 36). The largest of these was Block 16/44 (Fig. 38), which came from the right abutment, immediately above the San Francisquito fault. It weighed an estimated 10,000 tons! Two differing numbering systems were implemented after the failure; one by the Governor's Board of Inquiry (which convened for 6 days, beginning on March 19th, and issued their report on March 27th) and that of the City's Bureau of Waterworks and Supply (BWWS), who painstakingly sorted out the pieces over a three-month period. The State's representation was contained in the panel's final report (California, 1928), which included a frontal elevation view of the main dam section and a plane table survey of several pieces, of which, only a few had been positively identified as to their source positions in the dam (Fig. 37).

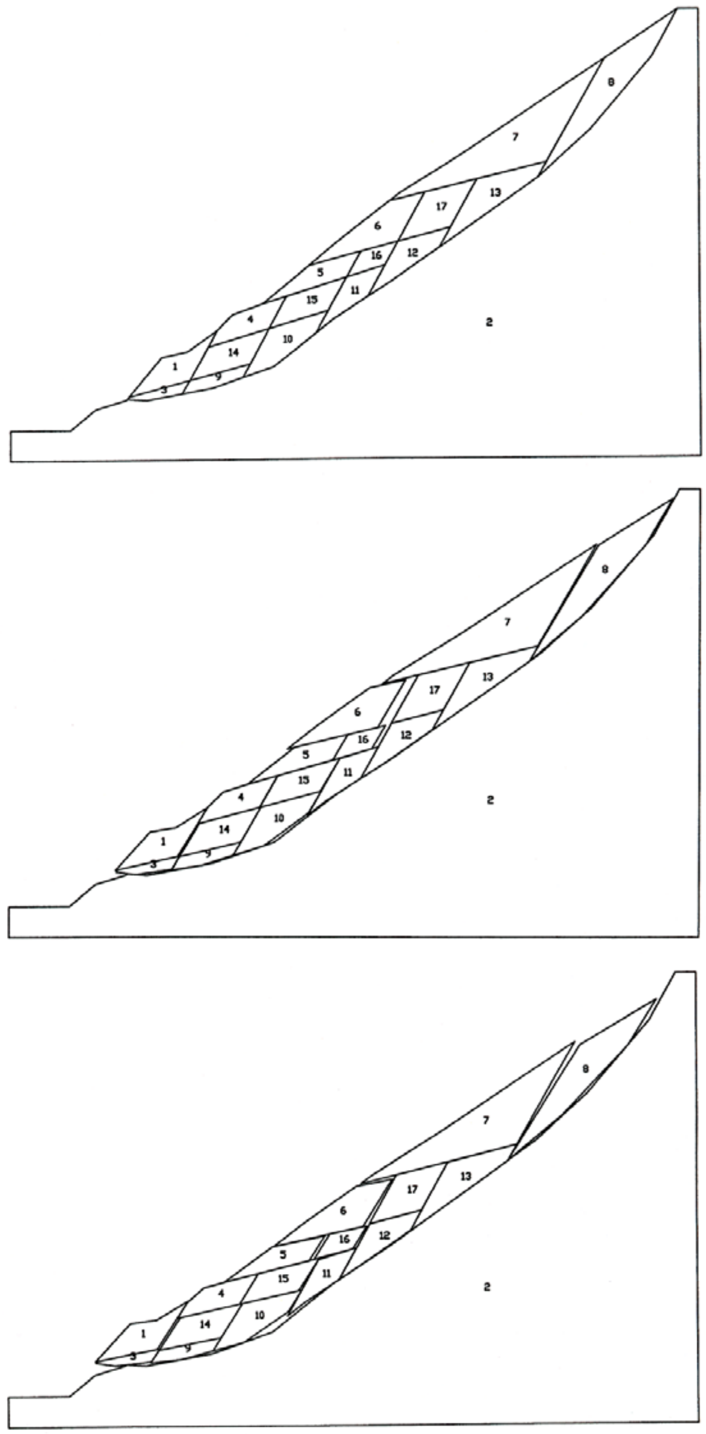


Figure 30. Discontinuous Deformation Analysis of the east abutment landslide, performed by Max Ma. These sections show the destabilizing effects of lateral loss of restraint that triggered upslope migration of the slide mass. Pore pressure entrapment likely developed at the base of the slide, beneath wedges 3, 9, 10 and 11, reducing the friction along the planes of schistocity.

Figure 31. Downstream view of the silt blanket deposited by the flood, just above the first hairpin turn of San Francisquito Creek, about 1,000 feet upstream of Powerhouse 2 (taken from the 'C' in Canyon on Fig. 36). The flood detritus is predominately Pelona Schist, and the grain size distribution is quite uniform. At the peak of the outbreak flood, water spilled over the saddle at middle right (from the Huber Collection, U.C. Water Resources Archives).

Figure 32. Ground view of Blocks 44, 27 and 43 resting upon a flood outwash terrace of schist detritus, with an average grain size of 10 inches. These blocks were likely freighted upon this extensive blanket of detritus, which emanated from the east abutment landslide. The token cut-off trench beneath the dam's right abutment is seen running diagonally across Block 43 (at right). Photo from the Lee Collection, U.C. Water Resources Center Archives.

Figure 33. Rebuilding activities at Powerhouse 2 a few weeks after the failure. Surge chamber attendant E. H. Thomas descended the slope along the tramway tracks at left, reaching the high water mark at 12:15 AM, and noting that the flood waters had already dropped 20 feet. The maximum depth of flow here was about 110 feet above the channel (Huber Collection, U.C. Water Resources Center Archives).

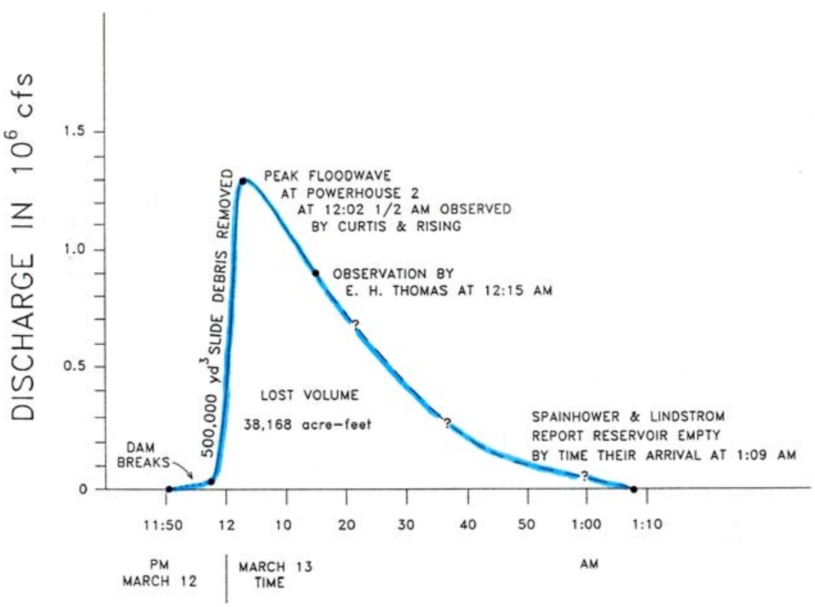
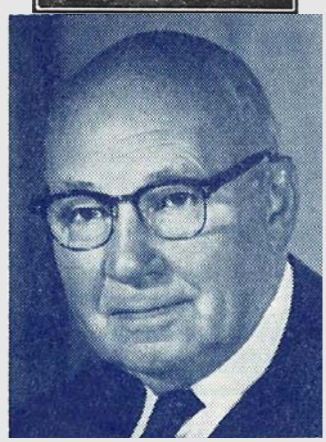


Figure 34. Reconstructed hydrograph for the outbreak flood at Powerhouse 2, approximately 7,300 feet downstream of the dam. Observations and times of events at this location, allowed for the reconstruction using modern methods of channel hydraulics.

The City's surveys were supervised by BWWS field engineer Ralph R. Proctor (see sidebar in Aftermath of Dam Failure). Proctor's efforts were more fruitful than the hurried efforts undertaken for the Governor's Board of Inquiry (which were assembled by a State Highways Surveyor on plane table). Proctor worked with the City's expert witness civil engineer, Charles H. Lee of Berkeley to unravel where the blocks had come from. The pair used the telltale widths of the dam's downstream face steps to estimate source elevation, and pieces of the country rock adhered to abutment pieces to fix which side of the dam the piece came from (the upper right side was against orange colored Vasquez sandstone, the left abutment against grey schist). The relative dip of the schist foliation (to the north) was used to delineate lower right abutment pieces (oblique angle between concrete and schistocity) as opposed to planar parallel contact, typical of the left-most abutment pieces (as seen in background of Fig.7).

Charles Hamilton Lee (1883-1967) graduated from U.C. Berkeley in 1905 and went to work for the U.S. Geological Survey as a hydrologist He made the first credible studies of groundwater resources of San Diego County. In 1906 he was hired by Mulholland to assess the water resources of the Owens River watershed, writing a comprehensive report that was published as U.S.G.S. Water Supply Paper 294 and included as an appendix to the final report on the Los Angeles Aqueduct (Board of Public Service Commissioners, 1916). While working on the aqueduct in 1912 he began a life-long association with Karl Terzaghi (1883-1963), an Austrian engineer who visited the aqueduct to view its construction. Terzaghi went on to become the father of soil mechanics and foundation engineering. Lee left the City's employment after completing construction of the earthen dams associated with the aqueduct in 1916. In 1919 he opened up a consulting office in Los Angeles to compliment another he had in San Francisco, consulting mostly in the field of hydrology and water resources. He was regularly engaged by the City as their expert witness in the many lawsuits involving matters of hydrology in the Owens Valley and the St. Francis Dam failure. In 1926 he established the Pacific Hydrologic Laboratory, the first soils engineering laboratory on the West Coast. Lee was also the first engineer in California to make consultations in the emerging field of soil mechanics, building on the increasing notoriety of Terzaghi, who taught at MIT in 1925-29, and then, at Harvard between 1938-56. Lee's files on the St Francis failure are among the best resources available, maintained by the University of California Water Resources Center Archives in Berkeley. Lee's pioneering work on predicting long term settlement and risk from earthquakes to the hydraulic fill comprising Treasure Island in San Francisco Bay proved remarkably accurate and prophetic. He continued working for the City of Los Angeles and the Metropolitan Water District into the 1950s. Increasingly cantankerous with age (he refused to pay employees for vacation or sick time), he died in his Berkeley home at the age of 84 on May 4, 1967.

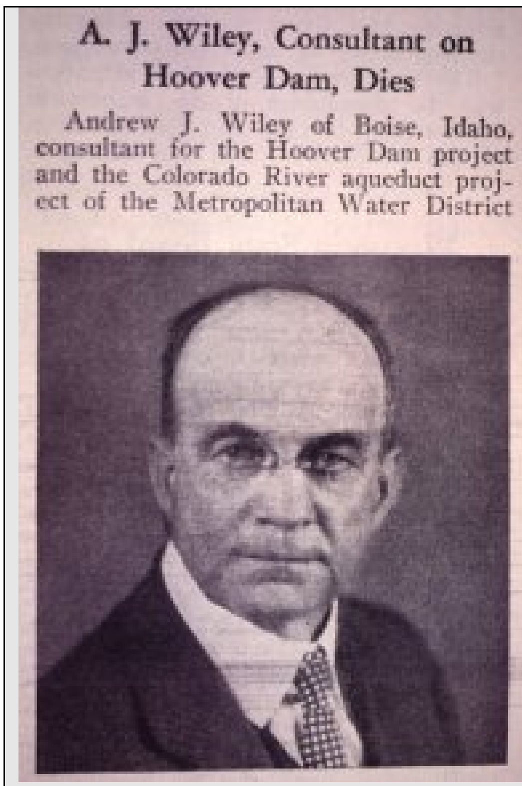


Upper image shows Charles H. Lee in 1915 while that below was taken in 1963.

Lee and Proctor delineated the identified blocks in a manner similar to the State Inquiry Board (Fig. 39) and worked up a plan view (Fig. 40) by overlaying aerial photograph enlargements taken by Fairchild Aerial Surveys. The respective block designations of the State (Fig. 38) and BWWS are different, and are listed in Figs. 38 and 39. BWWS's survey efforts were published in *Western Construction News* in late June 1928 (Lee, 1928). The BWWS surveys indicated that the identifiable pieces found furthest downstream were actually from the so-called 'missing section', between the dam's central core (which remained in-place) and that portion of the left abutment which slid across the downstream face of the dam (see Fig. 37). Block 35, at the base of the missing section, was the identified piece found furthest downstream (Fig. 40), and remains visible today.

The Governor's blue ribbon Board of Inquiry

The State appointed a six person Board of Inquiry (California, 1928) chaired by A.J. Wiley, consulting engineer of Boise, Idaho. The panel was somewhat unusual insofar as it included two geologists: Professors Leslie Ransome of Cal Tech and George Louderback of U.C. Berkeley (see sidebars). The other members were Frank E. Bonner (Chief of Geography, District No. 1, U.S. Forest Service, San Francisco), H.T. Corey (consulting engineer from Los Angeles), and Frederick H. Fowler (consulting engineer from San Francisco, who went on to become president of the American Society of Civil Engineers in 1941). The panel convened a week after the failure, on March 19th, made one site visit on March 22nd, and submitted their report to the Governor on Tuesday March 27th in Los Angeles, amid considerable press coverage. Their visit came after the downed SCE Edison lines had been clipped (see Fig. 15).



A. J. Wiley, Consultant on Hoover Dam, Dies

Andrew J. Wiley of Boise, Idaho, consultant for the Hoover Dam project and the Colorado River aqueduct project of the Metropolitan Water District

Andrew Jackson Wiley (1862-1931) was a native of Delaware and life-long bachelor. He graduated as valedictorian from Delaware College in 1882. After working a year for the B&O Railroad, he headed west in 1883, where he spent the balance of his professional career working on railroad, mining and irrigation projects. His career attained notoriety in the early 1900s from his close association with famed water resources engineer Arthur Dewitt Foote on early Bureau of Reclamation projects such as Arrowrock Dam and the New York Canal in Idaho, as well as numerous projects in Oregon and California (Foote's pioneering career is profiled through his wife's eyes in Wallace Stegner's book *Angle of Repose*). He eventually became the pre-eminent engineering consultant on dams in the west during the 1920s. In August 1927 he was one of three engineers named to a permanent consulting board to the U.S. Bureau of Reclamation, from which he made input on a series of record-breaking projects, including Owyhee Dam, 60 miles from his home in Boise, and the prototype mass concrete dam of the post-1930s. After chairing then St. Francis inquiry, he was retained by the City to review the remaining 32 dams in their charge. His own comments on the St. Francis disaster were contained in an article for Journal of the American Water Works Association in September 1928 (v. 20, n. 3, pp. 338-342). Wiley was the first engineer selected for the Hoover Dam Consulting Board in 1929, and was undertaking work for the Los Angeles County Flood Control District in San Gabriel Canyon (above Azusa) when stricken with his fatal illness in May 1931.

Professor Louderback was particularly critical of the dam's placement directly across the San Francisquito fault (see California, 1928, pp. 10-13; and Louderback, 1928). The stark nature of the faulted contact between the Vasquez formation conglomerate and the Pelona Schist scoured clean by the outpouring waters of the reservoir can be appreciated in Fig. 41. Ransome appears to have been more critical of the Vasquez formation's (then called the Sespe formation) tendency to swell and to slake upon submersion, due to some of its beds containing gypsum. In the aftermath of the dam's failure a favorite ploy of prosecuting attorneys attacking Mulholland and the city was to drop a piece of this arkosic sandstone into a glass of water and watch it disintegrate (in the wrongful death suits brought against the city by BWWS Powerhouse 2 survivor Ray Rising, who lost his wife and children; see Davis, 1993, p. 251). The formal recognition of slaking and development of a standard to test for it were not developed until the late 1930s, during work on the MWD Colorado River Aqueduct.

Frederick Leslie Ransome (1868-1935) was born in Greenwich, England of Quaker stock. When he was two years old the family immigrated to San Francisco, where his father Ernest Leslie Ransome established the Ransome Concrete Machinery Co., from which he constructed the first reinforced concrete buildings and bridges in America. Leslie graduated in geology from U.C. Berkeley in 1893, remaining to work on the first geologic maps of Marin County with Professor Andrew Lawson (who had come to Berkeley in 1890). After finishing his doctorate Ransome joined the U.S. Geological Survey in 1896 as one of the first four civil service professionals hired by the survey (the others were A. C. Spencer, G. O. Smith and W. C. Mendenhall). He then spent a year at Harvard's museum, before re-joining the USGS in Washington, D.C. His first survey assignment was in the mother Lode of California's Sierra Nevada range, thence projects in Colorado, Arizona, Idaho and Nevada, producing a series of reports on mining geology in those regions. Ransome became the USGS Chief of Metalliferous Studies in 1912, and was named to the National Academy of Sciences in 1916. In 1922 he accepted a position at the University of Arizona as Professor of Economic Geology and became dean of the graduate college in 1925. He joined the geology faculty at Cal Tech in Pasadena in 1927. He was particularly critical of BWWS's ability to appreciate geologic hazards at the St. Francis Dam site, and these thoughts were published in *Economic Geology* in 1928

and in the *Transactions of ASCE* in 1931. He spent the balance of his career preparing comprehensive studies on the geology of the Boulder Canyon (Hoover Dam) Project and geologic siting of MWD's Colorado River Aqueduct. Though Ransome's professional title remained "applied geologist" until his death, he was one of the pioneering engineering geologists of the west.

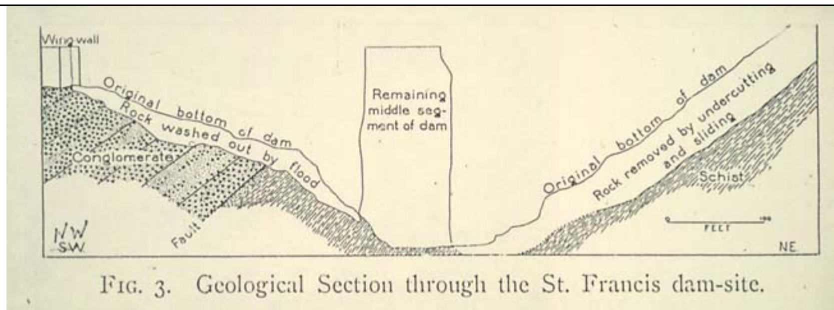
Mulholland's crude 'percolation test pits' excavated in the Vasquez sandstone succeeded in 'holding water' because, as the pit walls caved inwards, there was progressive volumetric displacement of the water to compensate for that absorbed in the pit walls. That the water thereby introduced would have become very turbid was never mentioned or addressed because the work was likely carried out by labourers, and not under the direct observation of Mulholland or any of his senior engineers.

The Governor's Board opined that the dam's right abutment, over the San Francisquito fault, likely failed first, through hydraulic piping. This assertion appears to have been based upon the errant recognition that Block 16 (which had straddled the fault, on the right abutment), was found further downstream than Blocks 12 and 14 (from the base of the left abutment), as presented in Fig. 38. Of course, at this early date (late March 1928) the whereabouts of an entire section, between Blocks 2, 3, 4 and 5, 6, 12, and 14 remained unknown (the so-called 'missing section,' shown in yellow on Fig. 39). The other complication in the board's reasoning about relative positions of the blocks was that Blocks 12 and 14 were actually situated 26 feet *higher* in elevation than Block 16, and much further askance the main channel (see Fig. 36).

George Davis Louderback (1874-1957) was a native of San Francisco, where he father was a lawyer and judge. He graduated from U.C. Berkeley in 1896 with majors in chemistry and geology, and stayed on for his Ph.D., which he received in 1899, working with Andrew Lawson. In 1900 he joined the faculty in the newly forming Mackey School of Mines in Reno, leaving to work at the Carnegie Institute in Pasadena (the forerunner of Cal Tech) in 1903, then back to Mackey in 1905, before returning to Berkeley as an assistant professor in geology in 1906. He remained an active member of the geology faculty at Berkeley until 1944. In 1913 he formulated the recognition of the upper middle Miocene-age Monterey formation in coastal California He led a geological expedition into northern China in 1914, thence into Szechuan in 1915, for the Standard Oil Company of New York. From 1928 onward, he became increasingly involved in consultations on large dam projects, principally in California. Louderback had perhaps one of the most long lived and varied careers of any California geologist. He was the first geologist to research the seismic history of California and compile an earthquake catalog and a comprehensive history of seismic recording stations in California. Louderback spent the later years of his career attempting to unravel the geologic structure beneath San Francisco Bay. Louderback was the only geologist to serve on both the St. Francis Inquiry Board and the State Consulting Board on the Safety of Dams, which convened in 1929 and revoked the permit for the Forks dam being built for the Los Angeles County Flood Control District in San Gabriel Canyon.

The Governor's Board also opined that it was their belief that the left abutment landslide (Figs. 27-29) was initiated by toe excavation of a large eddy, just downstream of a right abutment breach, due to flow expansion leftward (which is a plausible scenario, considered by itself). But, the physical data suggests that the left abutment landslide actually triggered the failure sequence. The evidence for this is compelling. Consider: 1) The only position where SCE's 70 Kv Borel Power Line was severed was *within* the east abutment landslide, and that power grounded out at 11:57-1/2 PM; 2) the entire left abutment of the dam was carried across the central portion of the dam, up onto the right abutment (Figs. 5 and 48 thru 56) the dam's largest displaced blocks were found lying on an enormous volume of schist detritus (Fig. 32), which must have emanated from the left abutment landslide.

The Governor's Board violated several fundamental precepts of forensic science. These included: a failure to collect their own data, perform their own measurements, supervise their own tests, and perform careful independent analyses of the collected data. In addition, some critical clean-up work had already been accomplished *prior* to their arrival, such as: the clipping of the downed 70 Kv power lines (leading into the landslide); insufficient time to collect and digest all of the eye witness accounts and time-line data that eventually came to light. They also accepted the as-built drawings given to them by BWWS without independent verification from photographs (e.g. the cross section presented in Fig. 3, lower right, was clearly in error if just compared with the remains of the prototype structure in the field). The board only made one visit to the dam site, and that was a rather cursory inspection, without making any measurements.



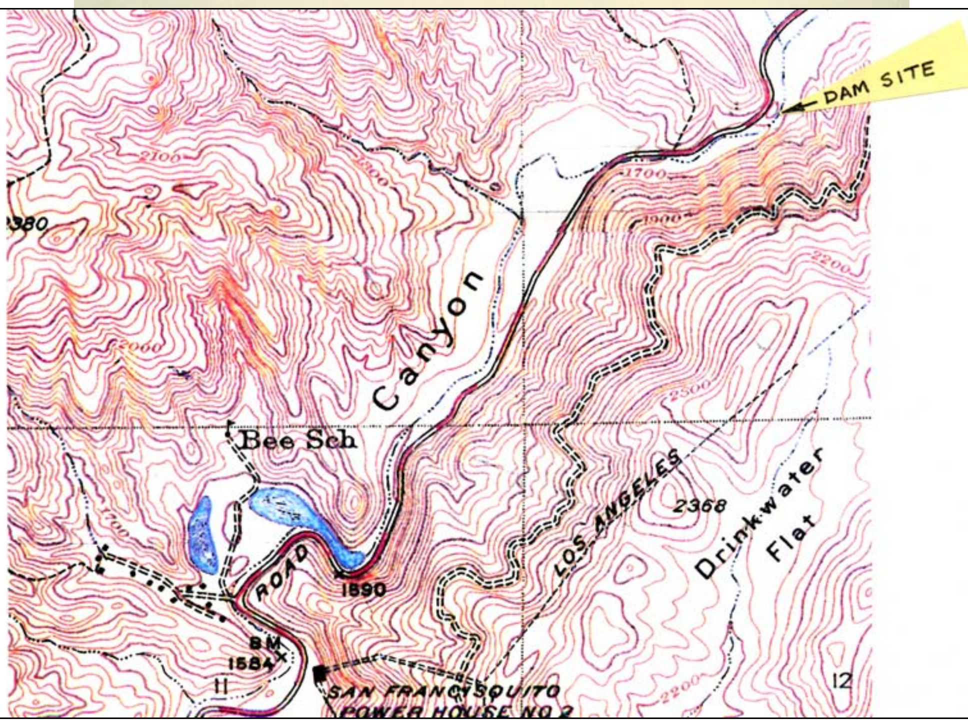


Figure 35. Upper – An outbreak flood hydrograph could not be estimated for the dam site initially, because the cross sectional area of flow would have been changing each second that side slope debris and portions of the dam were removed by the outpouring reservoir water (from Ransome, 1928). Lower - Portion of the Red Mountain 6-minute quadrangle released in 1936 which includes the St. Francis Dam site and DWP Powerhouse 2. This map was used in the forensic reconstructions of the outbreak flood hydrograph. The two lakes upstream of the powerhouse were filled by the city in 1952.

The Governor's Board reached some quick decisions and released their report before any others. A sad fact of post-failure reconnaissance reports is that the first one to be released usually garners the lion's share of publicity and is the most oft-quoted thereafter, even if it is incomplete and contains errors. At least dozen separate forensic reports were compiled and released after the report of the Governor's Board, but none of those are cited in the engineering literature.

Figure 36. Displaced blocks of the dam, as viewed from a position about 1,000 feet downstream of the dam site. The block numbers written on the photo are those of the State Board of Inquiry (Fig. 38). Although Blocks 12 and 14 came from the base of the left abutment, they were situated between 22 and 26 feet higher than Block 16, seen further downstream and within the low flow channel.

Figure 37. Close-up view of Block 16 (State designation) or 44 (BWWS designation), at 10,000 tons, the largest of the dam's displaced blocks. It was found about 1,500 feet downstream of the dam. The only plausible mechanism by which such a large block could be hydraulically transported would be by saltation in a dense slurry, akin to a massive debris flow. Photo from the Lee Collection, U.C. Water Resources Center Archives.

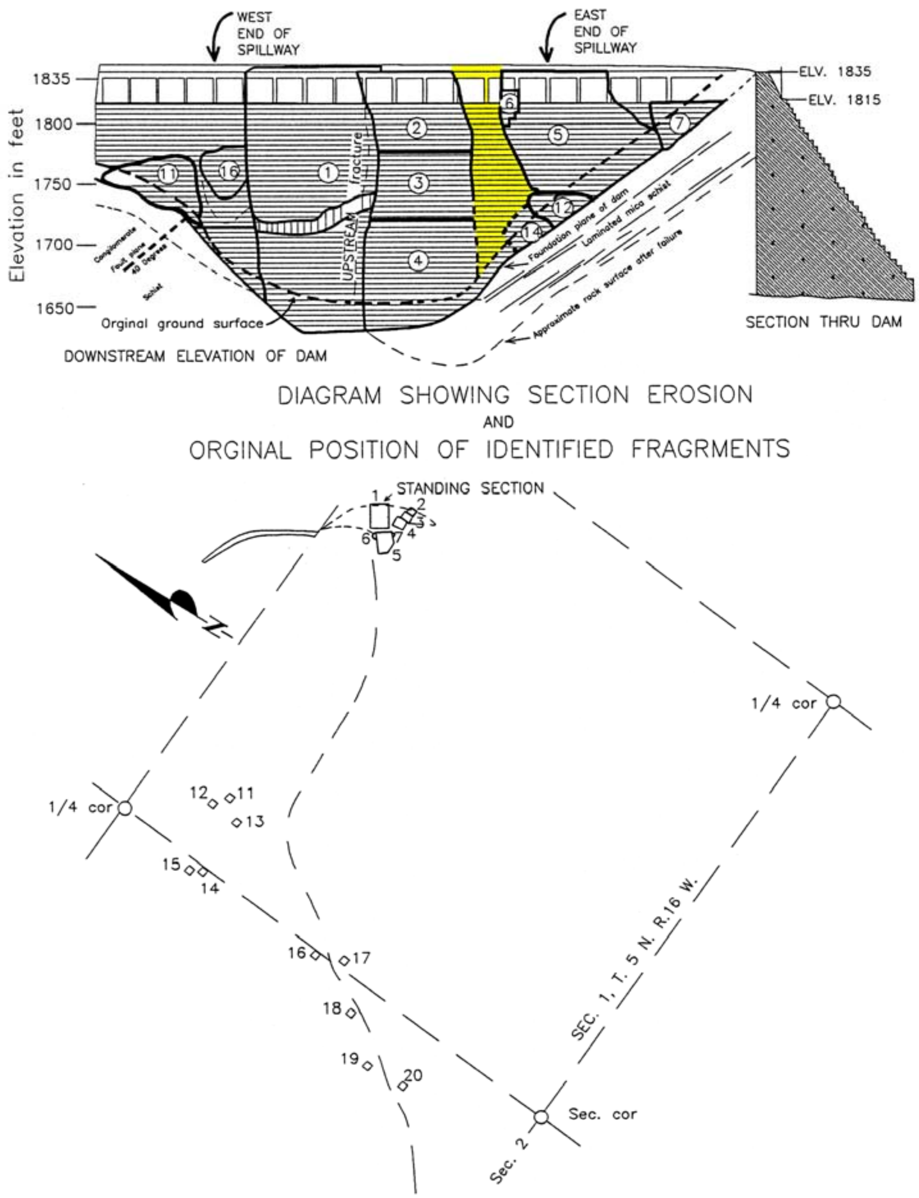


Figure 38. Upstream elevation view and plane table survey of the St. Francis Dam site made by state highway surveyor Horace Wildey (1880-1973) and presented in the Governor's Board of Inquiry report (Plate 8). At the time this was prepared (between March 20-25, 1928) the source locations of many of the dam's blocks had not been determined. Note missing section, between Blocks 2, 3, 4 and 6, 5, 12, 14, which is highlighted in yellow. Several of these pieces were subsequently identified by Charles Lee and Ralph Proctor, as described in the text.

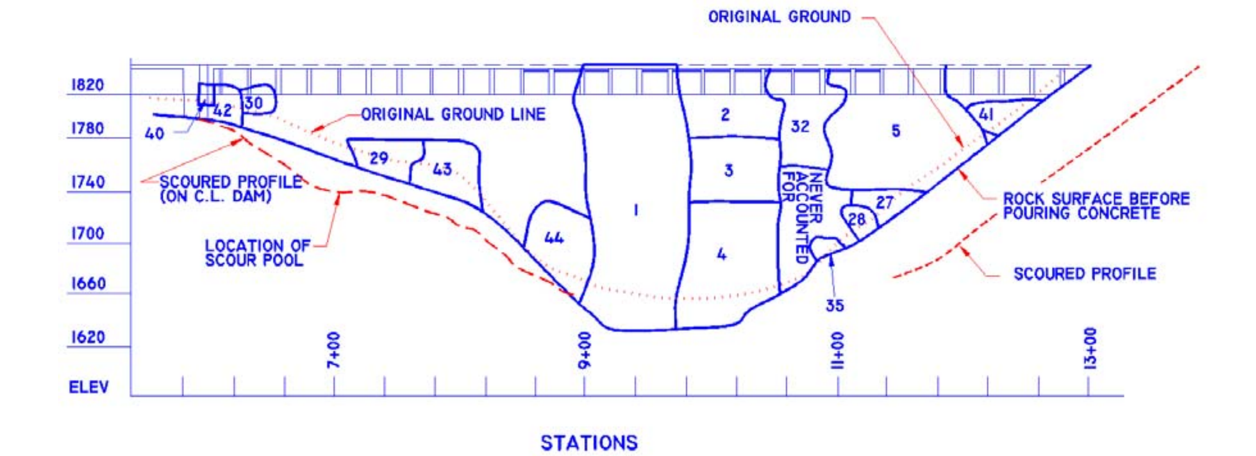


Figure 39. Upstream elevation view of the St. Francis Dam showing blocks positively identified by Charles Lee and Ralph Proctor, during surveys performed in March, April and May 1928. Note that many of the block designations differ from those presented in the State report, shown in the previous figure.

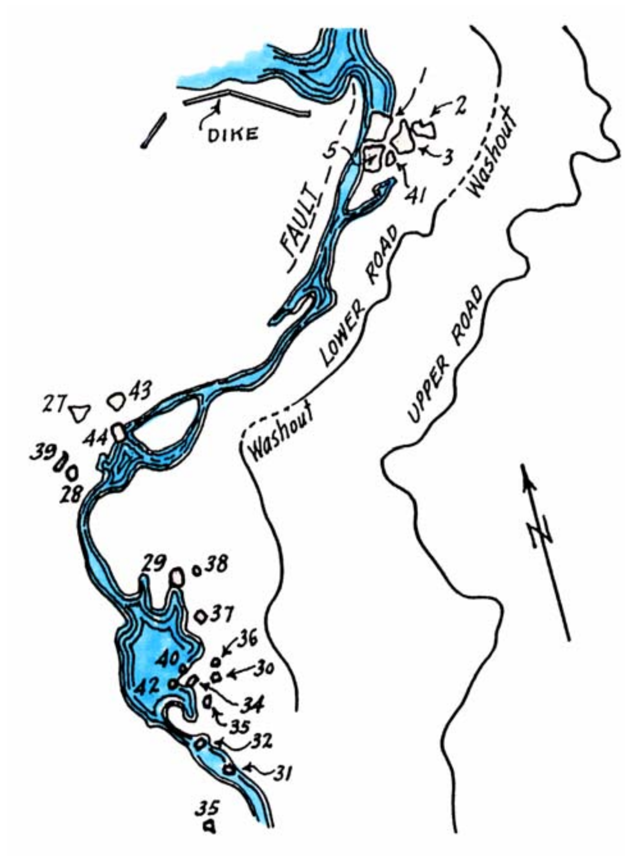
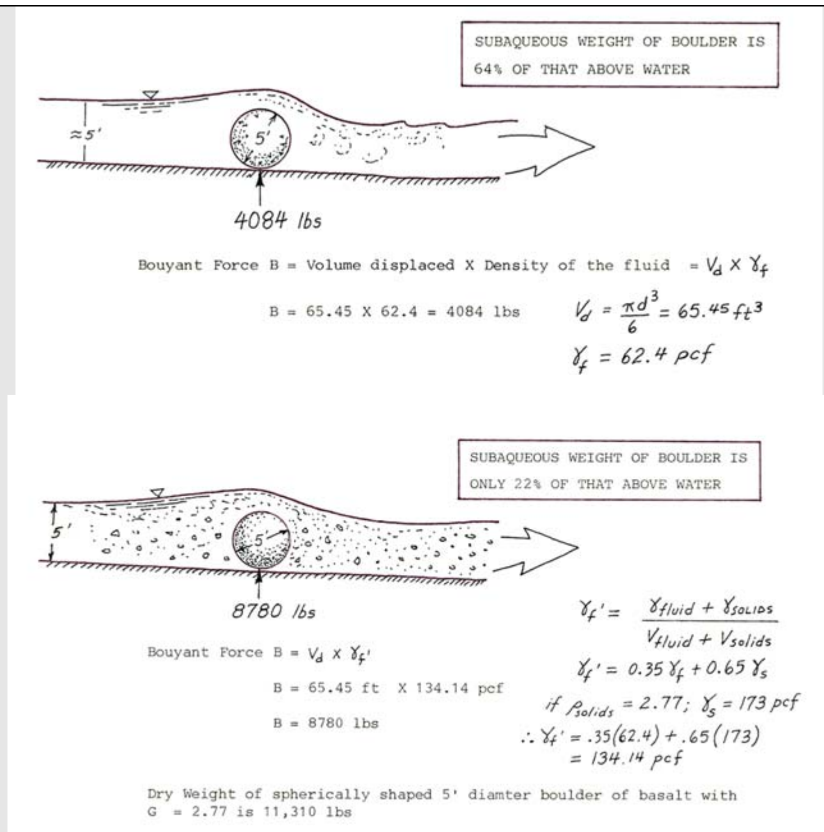


Figure 40. Plan view of the dam's displaced blocks determined by Lee and Proctor. This figure is an overlay of an annotated aerial photographed, and is not spatially corrected for parallax distortion on the photo. Of interest are the positions of Blocks 32 and 35, from the missing section on the left abutment, found furthest downstream.

Hydromechanics of block movement

If we now consider the 1.7 to 1.3 million cfs outflow from the ruptured dam, are such flows sufficient to freight 10,000 ton blocks of concrete 5,000 feet downstream? The answer is 'no.' A 10,000 ton block of concrete is a pretty big piece of rip-rap, and it should not move any appreciable distance, even in a short-lived peak flow event of over 1 million cfs. How then, were such enormous pieces moved?

The answer lies in realizing the density of the outflow was extremely turbid because of two unique factors: 1) the introduction of 550,000 cubic yards of disaggregated schist available for hydraulic transport from the left abutment landslide; and 2) the propensity of the schist to remain in suspension when contained in a slurry, such as a debris flow (Rodine and Johnson, 1976). If 38,000 acre feet of water eroded between 600,000 and 800,000 cubic yards of debris at the dam site, that would only represent between 1 to 1.3% entrained sediment, overall. But, the initial flood surge, cutting through an enormous gap formed by the east abutment landslide, must have been supercharged with sediment, because over half a million cubic yards of material was swept away in about five minutes.



Archimedes Principle and the transport of heavy objects in dense fluids. The *subaqueous weight* of the dam's concrete blocks would have been reduced in proportion to the *bulk density* of the outbreak flood slurry surrounding them. In the upper diagram the uplift force engendered by clear water reduces the weight of the block to 64% of its dry weight. The lower diagram shows that a fluid with 65% entrained solids would further reduce the block's submerged weight, to just 22% of its dry weight. Debris flows slurries containing significant mica tend to entrain higher proportions of solids because the platy mica particles remain in suspension.

Destructive debris flows in Wrightwood, California periodically occur along Sheep Creek and Heath Creek, channels which emanate from the Pelona Schist, on the same (southwest) side of the San Andreas fault, about 50 miles southeast of San Francisquito Canyon. Work on these debris flows (Sharp and Nobles, 1953; Morton and Campbell, 1974; Morton, Campbell, et al, 1979) has shown that slurries containing between 65% and 85% entrained solids have been documented (Rogers, 1984; Johnson, 1996). These unusually high values are ascribable to the mica content of the slurries (Johnson, 1970), which promotes dispersion. When the dam's concrete blocks were submerged in clean water, their effective weight would be diminished through simple buoyancy: their weight would be reduced by the amount of their dry weight minus the weight of fluid displaced. This would correspond to a decrease from 143 pcf to 80.6 pcf, as shown in Fig. 42. If we consider the turbidity of the outbreak flood, the block's effective submerged weight would be progressively diminished, described in the sidebar below and in Fig. 42. This is how debris flow slurries fright such enormous volumes of coarse clastic debris.

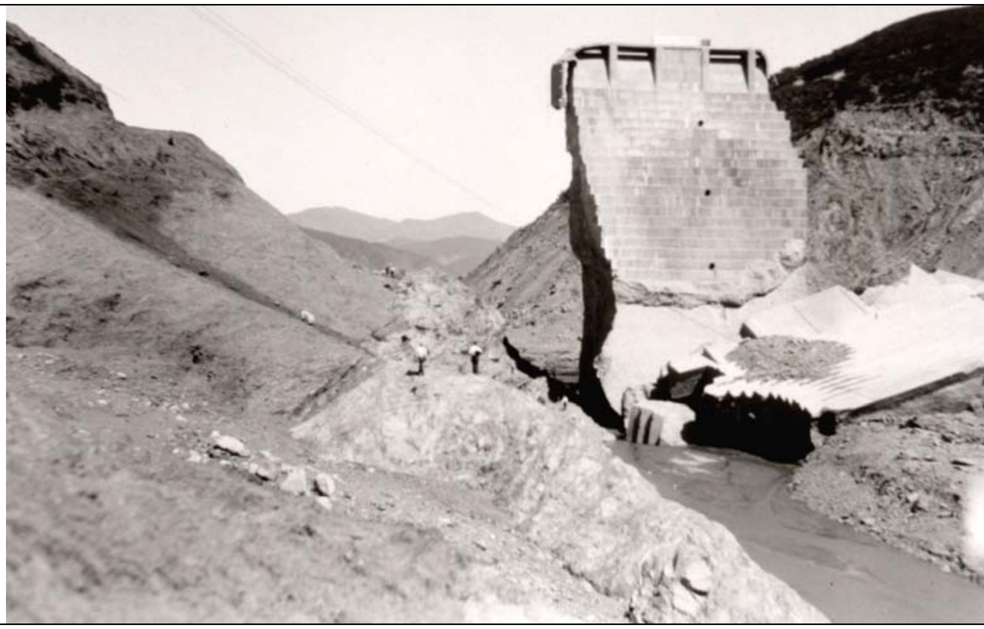


Figure 41. View of San Francisquito fault contact, between the Vasquez sandstone (at left) and Pelona schist (center of image), as viewed looking upstream at the dam's right abutment. Note the graphic nature of the contact, planed off by the outpouring water. Also, note the downed SCE power lines, trending towards the east abutment slide, out of view to the right. These lines were clipped before the Governor's Board of Inquiry visited the dam site (from Lippincott Collection of the U.C. Water Resources Center Archives).

If the initial flood wave emanating from a landslide breach of the left abutment did occur, it is conceivable that the percent entrained solids would have been something between 20% and 65%, possibly even higher at the flow snout, which tends to form as the trailing debris has less flow friction to overcome about it's wetted perimeter. As a consequence, the trailing slurry moves faster, building up a steep-faced flow snout (see sidebar discussion**)**. A slurry with 65% entrained solids would reduce the weight of the 10,000 ton block to just 2,000 tons, as shown in Fig. 42. It is likely that these large blocks were freighted downstream via saltation, within dense, fast-moving debris slurry.

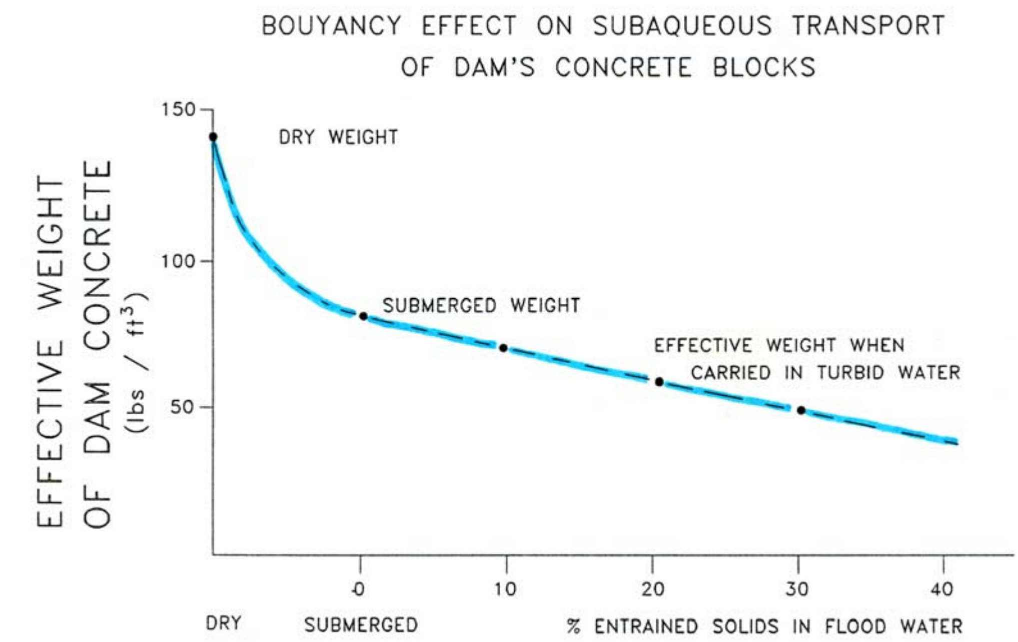


Figure 42. Relationship between effective weight of the dam's concrete blocks and the turbidity of outflow. Slurries developed in debris flows emanating from the Pelona Schist have been documented with between 65% and 85% entrained solids.

Geologic setting of the dam site

One of the most intriguing aspects of these studies has been the appreciation of solid training in geomorphology. This is nothing really new, the tools have been established for well over a century. That San Francisquito Canyon is blanketed with dozens of bedrock landslides never occurred to me until I read Charles Outland's book, where Outland quotes the work of then-retired Stanford geology professor Bailey Willis, who published an obscure article on the geology of the dam site in *Western Construction News* (Willis, 1928). Bailey Willis was probably the first formally trained engineering geologist in America. He was also one of the most long-lived and controversial figures in the annals of American geology (Geschwind, 2001).

As an outspoken pioneer in the fields of paleoseismicity and seismic risk, his comments drew the ire of the entire Los Angeles business community (Geschwind, 2001; Hill, 1928). Right about the time St. Francis failed, he was embroiled in a public controversy with R.T. Hill of the U.S. Geological Survey, over his comments about seismic hazards posed for the Los Angeles area (one destructive earthquake every 25 years, though he was speaking for the entire state, not just Los Angeles). A few years later he would be embroiled again in a long-standing controversy with Berkeley geology professor Andrew Lawson, in regards to the stability of the southern pier for the Golden Gate Bridge, which was founded on serpentine.

Bailey Willis (1857-1949) was born in Idlewild, New York. He attended Columbia School of Mines, where he was granted diplomas as Engineer of Mines in 1878 and Civil Engineering in 1879. His scholastic training in mining geology and civil engineering probably made him the first formally trained engineering geologist in America. After working as a special agent to the 10th U.S. Census (1879-1881), he was given charge of the Pacific Division of the Northern Transcontinental Survey of the U.S. Geological Survey between 1884-89; from which he became geologist in charge of the Appalachian Division, USGS, between 1889-91; thence editor of geologic maps for folios of the Geologic Atlas of the United States (1891-93). In 1895-97 he was in charge of USGS studies in the Cascade Range and Puget Sound Basin, then back to duties on the Geologic Atlas of the U.S. in 1897-1902. He thereupon embarked on an overseas career, travelling to China under the auspices of the Carnegie Institution of Washington between 1903-04. He was a lecturer at Johns Hopkins (1895-1902), the University of Chicago (1909) and detached himself to the Ministry of Public Works of Argentina in 1911-15. He succeeded John Branner as Head of the Department of Geology and Mining at Stanford from 1915-22, from whence he retained his residence and position as professor emeritus until his death 27 years later. During his remarkable retirement Willis continued to work all over the world, and published extensively on the structure of east Africa and Patagonia.

In 1923 Willis authored a series of articles on *Earthquake Risk in California* in the Bulletin of the Seismological Society of America. In these Willis asserted that the underwriters of insurance in California should estimate a severe earthquake coming somewhere in the State, causing more or less loss, every 25 years. Additional articles followed, mostly within the insurance underwriting literature, over the next few years. Willis' assertions before underwriters caused earthquake insurance rates to skyrocket between 100% and 2,200% in a single year (1927-28). Angelino businessmen responded with a vengeance, right about the time St. Francis Dam failed. They asked the USGS to prepare a formal response to Willis' doomsday assertions, and USGS geologist R.T. Hill was given the job of picking apart Willis' reasoning in his book titled *Southern California Geology and Los Angeles earthquakes*, published by the Southern California Academy of Sciences just two weeks after St. Francis Dam failed. It was within such a context that Willis's insightful assertions about ancient bedrock landslides in San Francisquito Canyon were revealed to an angry Los Angeles populace in the summer of 1928, when his professional reputation was under fiery attack. Willis' insights as the geomorphic evolution of San Francisquito Canyon are impressive, and demonstrate the value of field experience having been gained across the length and breadth of four continents and the Philippine archipelago before venturing forth to view a notorious dam failure in the Sierra Pelona.

In the June 25, 1928 issue of *Western Construction News*, Willis authored *Report on the Geology of the St. Francis Damsite, Los Angeles County, California.* Willis was working on the St. Francis failure with civil engineer C. E. Grunsky, and both were employed by the Santa Clara River Protective Association (the ranchers downstream). This article is a classic piece of geomorpology in the vain of William Morris Davis or Kirk Bryan, in which Willis lays forth his theory that the entirety of the dam's left abutment, and most of the southeast side of the reservoir area, was underlain by enormous paleolandslides (Fig. 43).

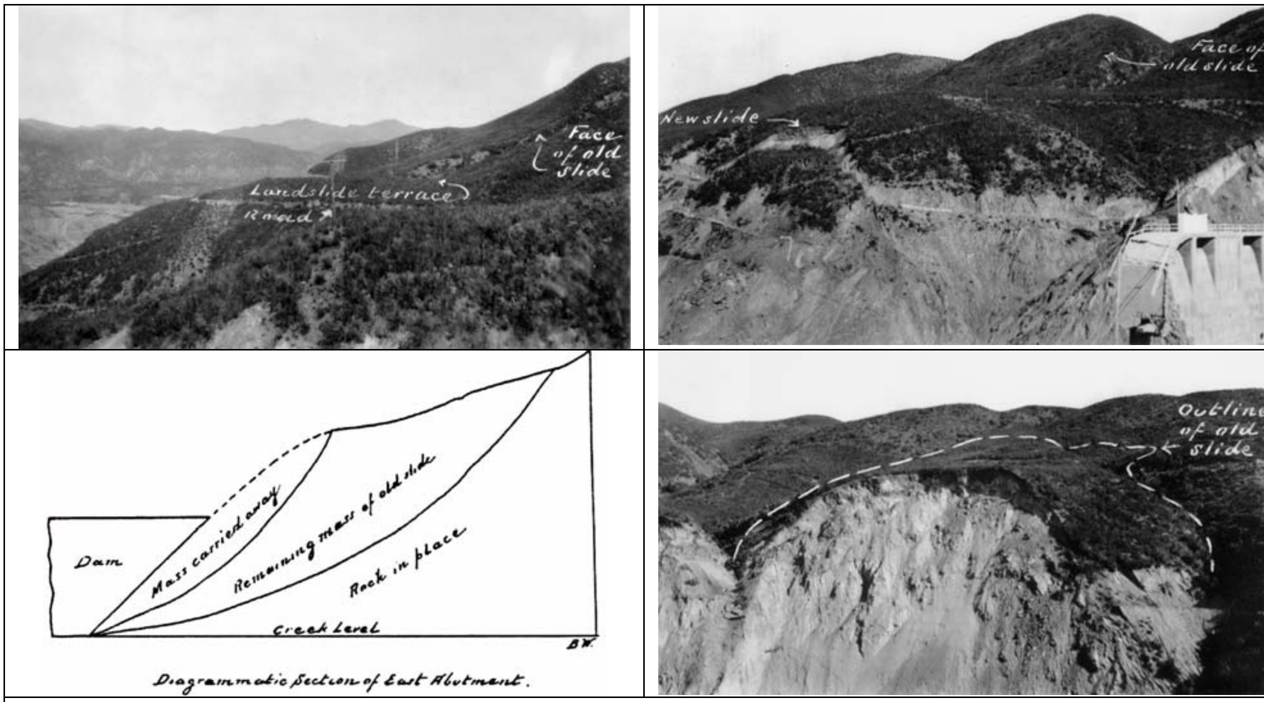


Figure 43. Some of the key figures from Willis June 1925 article in Western Construction News. The upper left image shows the old landslide terrace developed in the Pelona Schist above the reservoir area. The image at upper right shows one of the landslides that slipped into the reservoir due to rapid drawdown. The lower images show a hypothesized cross section through the east abutment landslide (left), suggesting that most of the pre-existing bedrock slide forming the dam's left abutment was not mobilized in the failure (photos courtesy of the Grunsky family).

Willis' assertions came from employing classical theorems about terraces; asking which mechanisms were responsible for creating the many prominent terraces exhibited within the Pelona schist along a strike-controlled dip slope. Several of Willis' key figures are reproduced in Fig. 43. He asserted that the east abutment slide was simply the partial reactivation of a much larger paleolandslide developed in the schist sometime during the Pleistocene epoch. Some of these slumps slid a short distance into the reservoir area, likely triggered by rapid drawdown of the reservoir as it drain, as sketched in Fig. 44. Note how the greater volume of these dormant landslide features were not reactivated in 1928, just as Willis alleged.

There is a good deal of physical evidence to support Willis' assertions. DWP's Bee Canyon power line road ran parallel to the reservoir's southeastern shoreline, about 300 feet above the valley floor (Figs. 28, 29, 44, and 45). Inspection of this road after the failure revealed large tension cracks at either end of a broad depression, about 300 feet above the dam's left abutment, as shown in Fig. 45 right. The entire slope appears to have dropped two to nine feet, well above the ragged heasdscarp of the east abutment slide.

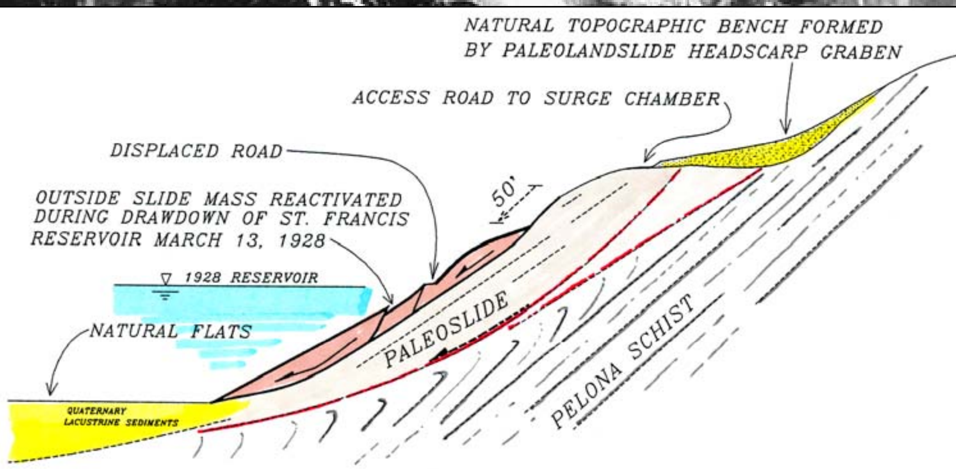


Figure 44. Upper image shows the large slump block that dropped into the reservoir upstream of the dam, due to rapid drawdown of the reservoir (from UCLA Spence Collection). Lower figure from Rogers (1992) shows a cross section through this slump block based on field reconnaissance. It appears to be a retrogressive translational block glide that moved about 50 feet. Note how only a small fraction of the parent slide mass was involved.

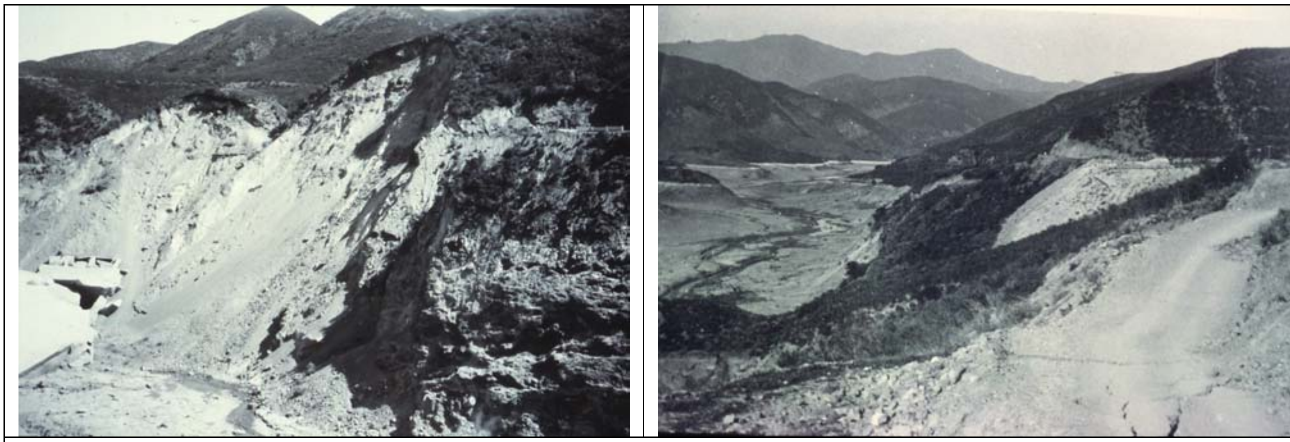


Figure 45. Left photo shows exposed scarp of the east abutment landslide extending well above old San Francisquito Cyn. Rd. Image at right shows gross ground deformations along the Bee Highline Road, about 300 feet above the dam's left abutment. The slope dropped two to nine feet above the east abutment slide. Both photos from Ventura County Museum of History & Art.

The many prominent terraces developed upon the Pelona escarpment (Fig. 10) can still be appreciated today (Figs. 42 and 43). As Willis deduced, these are not erosional terraces capped by terrace deposits, but colluvial-infilled headscarp grabens of enormous slump blocks, which slid upon the schist's micaceous foliation planes; just like the 1928 east abutment slide, but much larger. A landslide map created by the author and the late Perry Ehlig (see sidebar) is presented as Fig. 46.

Born on a ranch in the San Gabriel Valley, **Perry L. Ehlig** (1927-1999) received his B.A. (1952) and Ph.D. (1958) in geology from UCLA, doing his thesis for John C. Crowell on the Pelona Schist, Vincent thrust, and basement terrane of the central San Gabriel Mountains. He began teaching at Cal State Los Angeles in 1956, where he remained active until his death in 1999. Perry assuaged that, based on his reconnaissance mapping, the Pelona Schist contained more landslides than any other crystalline rock unit in southern California. Most of these slides were so large and so aged, they were usually overlooked. Perry was actively sought as a engineering geologic consultant on a broad array of projects between 1954 and his death. He achieved considerable notoriety as the geologist who developed the Plan- of-Control for the Abalone Cove Landslide in the Palos Verdes Peninsula, the first Geologic Hazard Abatement District (GHAD) in California. In 1981 Perry wrote a memorable article titled *Origin and tectonic history of basement terrane of the San Gabriel Mountains, central Transverse Ranges*, which appeared in The Geotectionic development of California, edited by Gary Ernst. This article has been cited by all subsequent workers in the Transverse Ranges, including Thomas W. Dibblee, Jr. Perry was the quintessential field geologist, never afraid to ascend any slope, and always able to hike his students or colleagues into the ground. It was one of the great thrills of any geologist's career to have worked out in the field with him.

Paleolandslides along the flanks of San Francisquito Canyon

The reason Bill Mulholland found the St. Francis site so topographically enticing for a reservoir was that it had previously been the scene of a paleolandslide dam-caused reservoir, much larger than St. Francis, at some time in the distant geologic past. A map showing recognized landslides developed within the Pelona Schist in vicinity of St. Francis Dam and reservoir is presented in Fig. 46. The dam site could be filled with a modest dam of just 130,000 cubic yards of concrete for a reservoir storing 38,000 ac-ft (see sidebar discussion, below). The reason the site possessed such favorable geometry for a dam was because it had repeatedly been the scene of a much larger dams and reservoirs, created by bedrock landslides that slumped into the canyon, blocking it. These occurred thousands of years previous to its exploration in the early 1900s. There is no mistaking the anomalous character of the flat alluvial-filled glens that typify the canyon just upstream of the dam site. The veneer of alluvium is likely underlain by clastic lacustrine sediments, overlain by low energy sediments, such as silt and clay.

Favorable topography for a dam. To understand just how favorable the topography was for the St. Francis Dam site in San Francisquito Canyon, consider that the sister structure of the same height, Mulholland Dam, only retained 7,437 acre-feet of water; as compared to the 38,168 acre-feet retained by St. Francis. Both dams were ~200 feet high, but the exceedingly flat reservoir area in San Francisquito Canyon was created by the hydraulic choke afforded by the paleolandslides developed in the Pelona Schist and the structural control of the ancient San Francisquito fault. Topographically, it was a great place to put a dam.

Mulholland Dam was the sister structure and prototype for St. Francis Dam, completed a year earlier, in mid-1925. It retains Hollywood Reservoir.

Mulholland wasn't the only engineer to ever construct a high dam unknowingly against an ancient bedrock landslide(s). Recently, former USGS chief engineering geologist Robert Schuster has identified 254 dams world-wide, greater than 35 ft (10 m) and as high as 570 ft., have been built on pre-existing landslides, usually, without the landslides having been recognized beforehand (Schuster, 2006). Some of these are as high as 560 ft 153 of these dams are located in the United States, principally, in the states west of the Rocky Mountains. The State of Colorado has 56 dams built against landslides (Schuster, 2003), followed by California with 21, Oregon with 18, Utah with 16, and Washington with 14. These sobering statistics point to the fact that engineering geologic site characterization has often been overlooked in favour of simple topographic relationships in expensive structures such as dams.

That the senior author spent so many years hiking around San Francisquito Canyon without recognizing the enormous paleolandslides is a good lesson in basic geology. Geologists operate on two fundamental axioms: 1) we are all prejudiced by our unique pedigree of experience education and experience; and 2) *We will not see those structures we are not looking for*. The landslides became obvious once had had read Willis' old article and went back to San

Francisquito Canyon searching for evidence of massive paleolandslippage. So, published works, maps, and even collegial hearsay each have the ability to influence our thinking and interpretations. The most dangerous aspect of site assessment is making one's own self aware of any preconceived notions we may or may not have about the geomorphic evolution and any given site. We should probably carry a check list of fundamental questions that should be asked and answered when we begin working in a new area, beginning with a thorough knowledge of

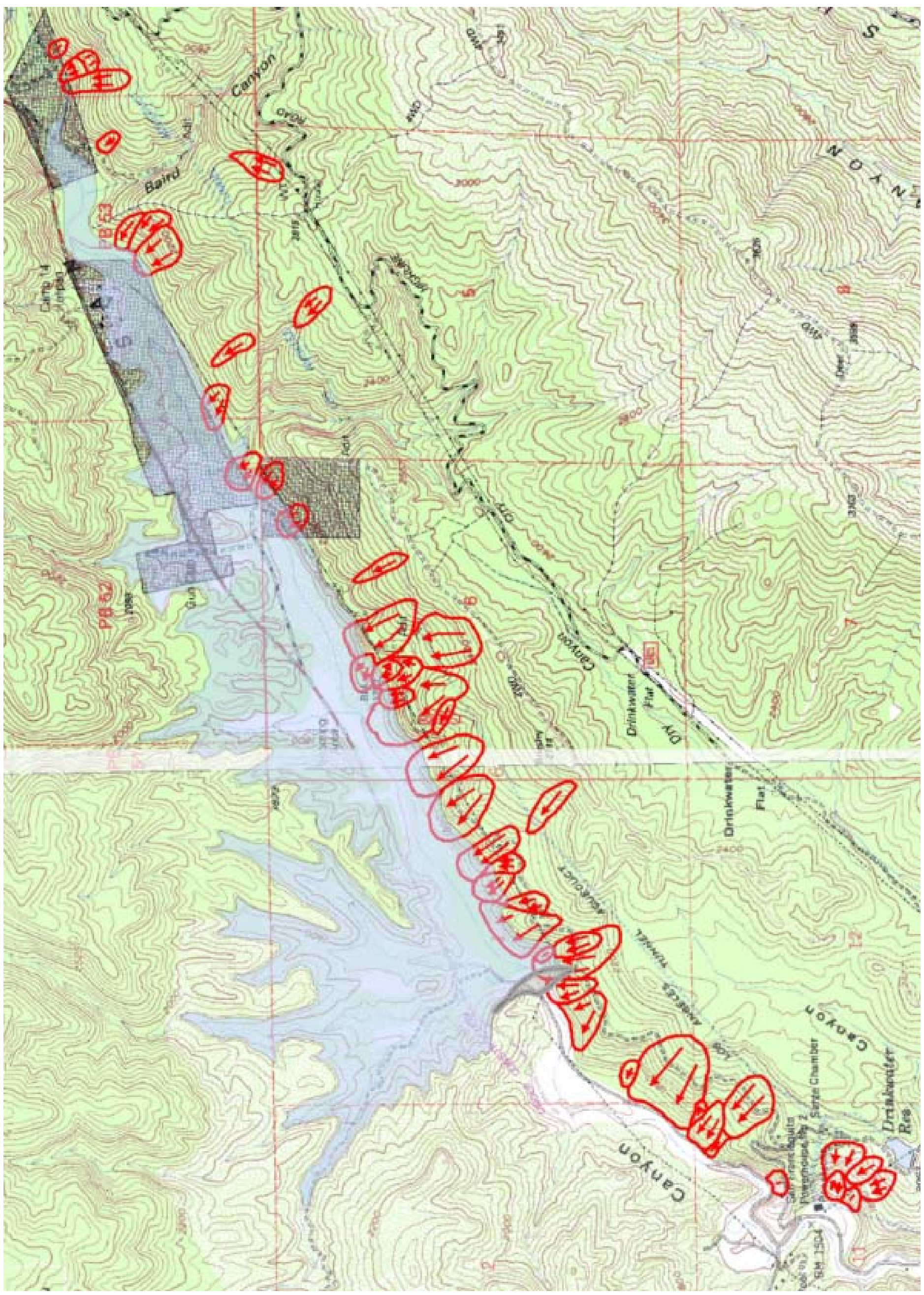


Figure 46. Landslide map of the St. Francis Dam and Reservoir area, overlain on the current USGS 24K quadrangles. The slides are developed in the Pelona Schist along inclined foliation, which averages about 35 degrees northwest. The ancient slides in the narrow, fault-controlled canyon blocked the channel and trapped sediment, creating the anomalous sediment filled glen that appeared topographically favourable for a storage reservoir. The age of the landslide dam is unknown, but there are some paleoflood outwash terrace deposits downstream of these slides, testifying to periodic floods of immense magnitude.

everything one's predecessors have carried out in the same area, even in the distant past. When we begin believing that we know more than all our predecessors combined, we might be riding too high in our saddles, and any overconfidence we harbour will inevitably be our undoing, which is what happened to Bill Mulholland.

Our best insurance against errors, omissions, and overconfidence is thoughtful peer review by other members of our profession, with seasoned experience. A fresh look by someone else with contrasting experience and expertise can offer fresh insights or alternative explanations that might otherwise, be overlooked. Peer review also helps us to tighten up our hypotheses and put them into a concise and coherent story that others can read and, hopefully, understand. Had Mulholland employed peer review from any number of seasoned individuals, like Jack Savage, C.E. Grunsky, Leslie Ransome, Bailey Willis, or E.C. La Rue, he might have made the necessary adjustments that could have staved off disaster.

Likely genesis of the dam failure

It would appear that the St. Francis Dam failed catastrophically near midnight on March 12/13, 1928 via a massive landslide of the left abutment. The physical evidence for this failure sequence is compelling, and is presented sequentially in a series of frontal elevation sketches presented in Figs**.** 48-56. A massive landslide is the only mechanism by which the dam's left abutment section could have been carried across the downstream face of the dam. The chatter marks on the downstream face of Block 1 actually rose upward, 30 feet above the final resting position of Block 5 (Fig. 58). A seiche wave carried flotsam 4 feet above the reservoir pool level on the northwest shore as well (Fig. 51), attesting to the suddenness of the slide, likely when the pool was near its maximum elevation.

Other evidence (discussed earlier) also suggests that the dam was experiencing stress redistributions and excessive tilting, which began increasing rapidly 40 minutes preceding the collapse. The fact that Blocks 35 and 32 (Figs. 38 and 39**)** were found the furthest downstream (of those blocks identifiable) suggests that the maximum outflow emanated from the left abutment. When engineers viewed the carnage the morning after (Fig. 59) only Block 1 remained standing. However, the left half of the dam’s main monolith (Blocks 2, 3 and 4) was not swept away, it simply rotated backward, into a 50-feet deep scour hole carved around the left side of the structure (Fig. 56), and broke apart, along low tensile strength horizontal cold pour joints (Figs. 53 and Fig. 60). Scour marks left upon Blocks 2 and 3 suggest that the reservoir was only 17 to 20 feet deep by the time these blocks fell backward, into the scour hole (Fig. 61). The dam’s main section was too large to be carried away, but Block 1 was rotated 0.70 feet, in a clockwise motion, downstream, which fits with the large tension crack observed in the right upstream heel after the failure.

The reservoir was about two-thirds empty by the time the right abutment gave way, as evidenced by the low scour line on the right abutment (Fig.62). This section likely gave way as Block 1 moved towards the gap on the left abutment side, the motion increasing as the flood volume diminished, lessening the lateral restraint. That Blocks 16/44 and 11/43 were transported so far is likely ascribable to their having been carried on a bed of fluidized debris, which had been deposited by the left abutment landslide and protected where it had piled up on the upstream face of the right abutment (this is why the chatter marks on Blocks 1 and 16 were so far above the final position of Block 5). So, the right abutment blocks were carried away in a debris slurry which represented a secondary mobilization of what remained of the left abutment slide debris (Fig. 55).

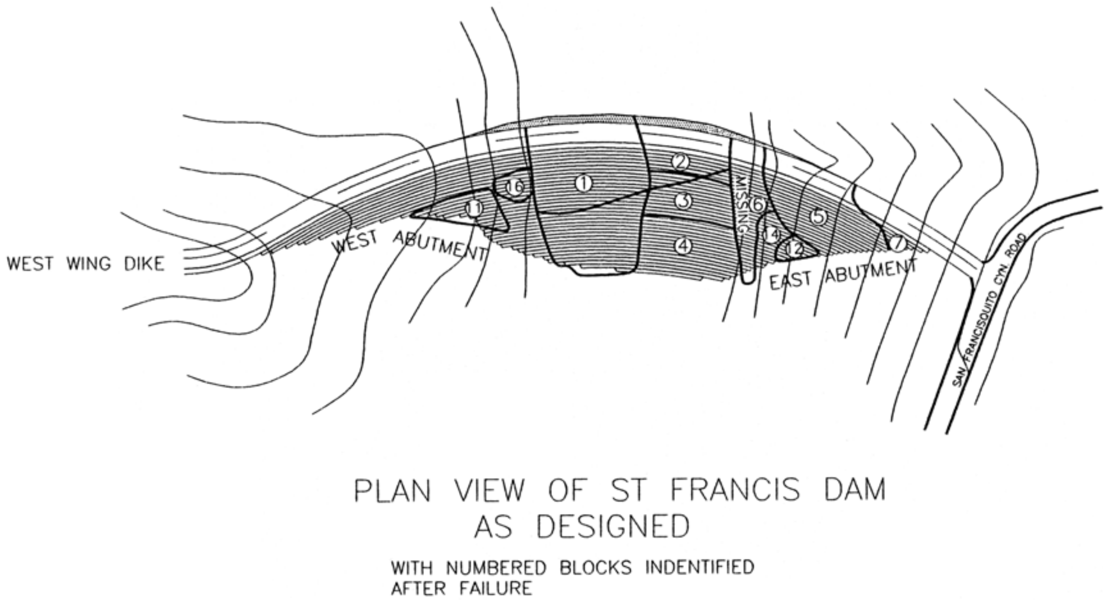


Figure 47. Plan view of the main dam, as originally designed. Diagonal lines and numbers delineate dam blocks with the State's nomenclature (as presented in Fig. 38). The dam's vertical steps were each 5 feet high, but the horizontal distances varied from 5.5 feet at the bottom to 1.5 feet near the top.

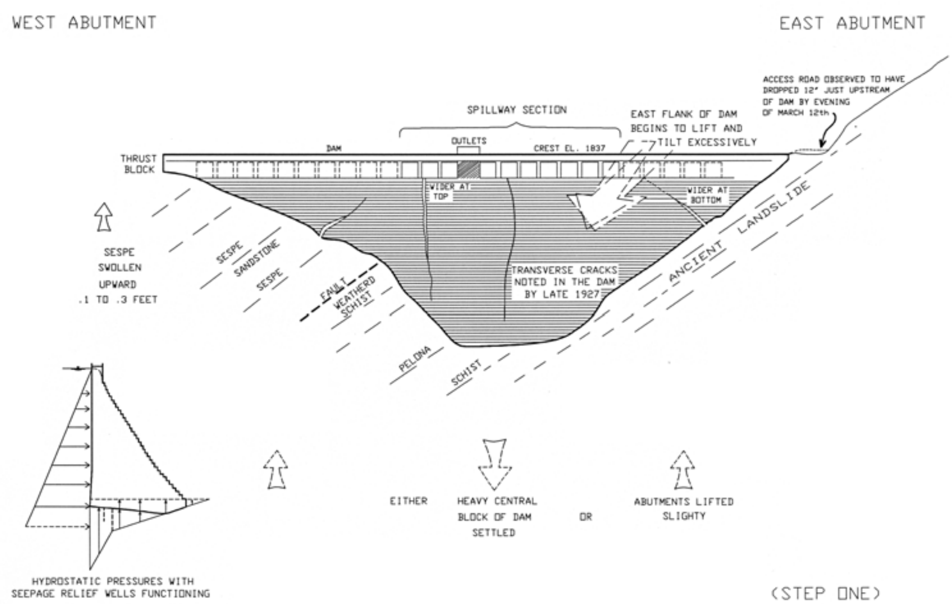


Figure 48. Schematic elevation view of the dam with transverse cracks which appeared on the downstream face of the dam a year previous to the failure. The dam was built without contraction joints. Some hydrostatic pressure relief was afforded the central core of the dam, as shown at lower left. This portion of the dam did not fail, only the sloping abutments failed.

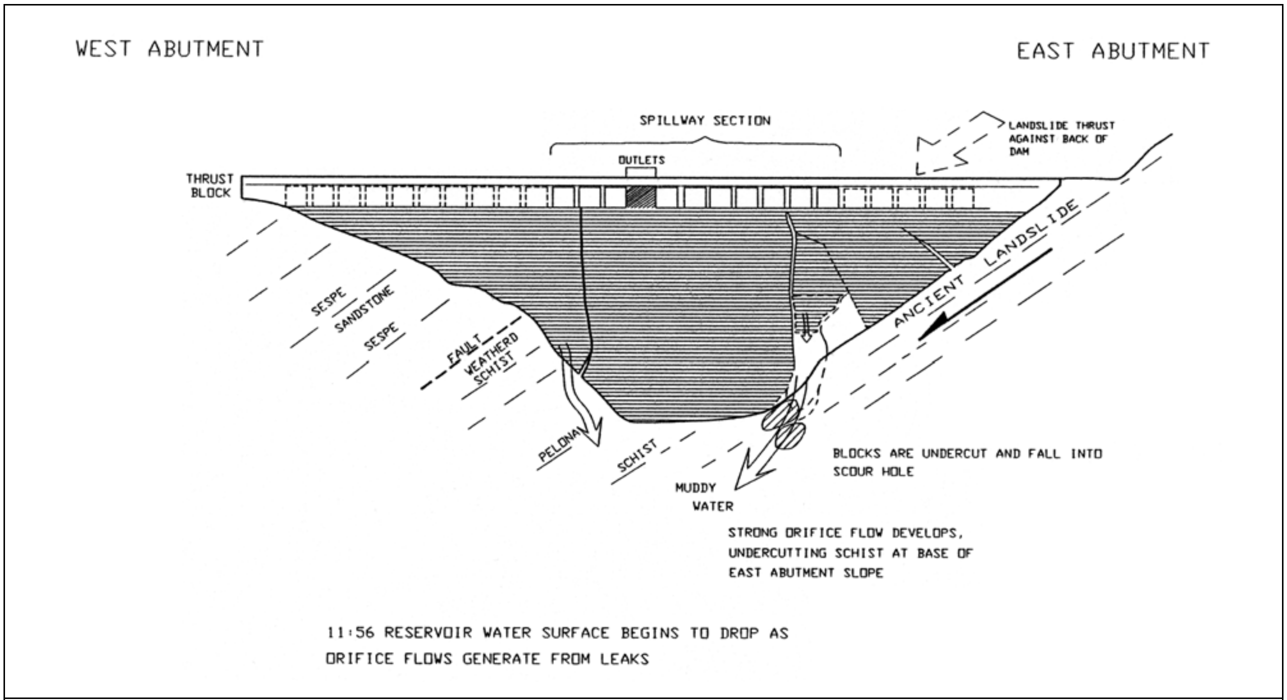


Figure 49. Schematic elevation view hypothesizing a precursory leakage at the base of the dam's left abutment. The body of the damkeeper's wife was later found at the base of the structure, and pieces of the dam from this area were carried furthest downstream.

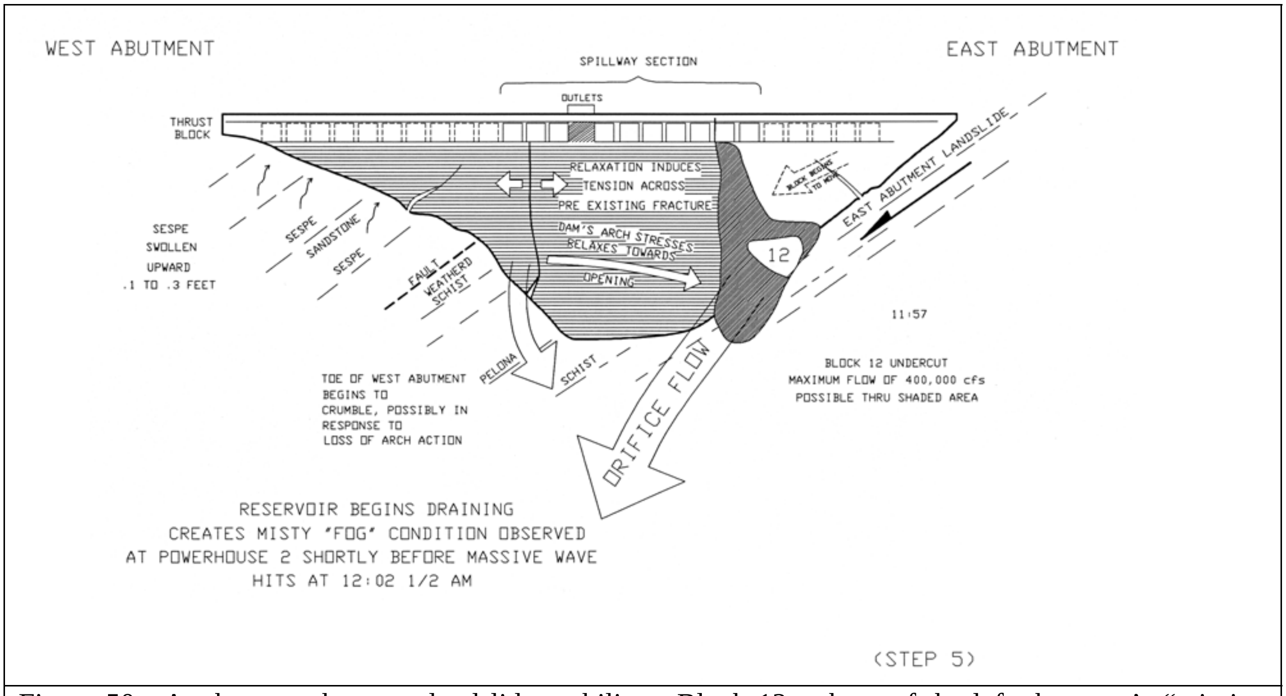


Figure 50. As the east abutment landslide mobilizes, Block 12 at base of the left abutment's "missing section" is separated from the dam. Orifice flow at base of the left abutment slide may have created misty fog condition described by one of the Powerhouse 2 survivors.

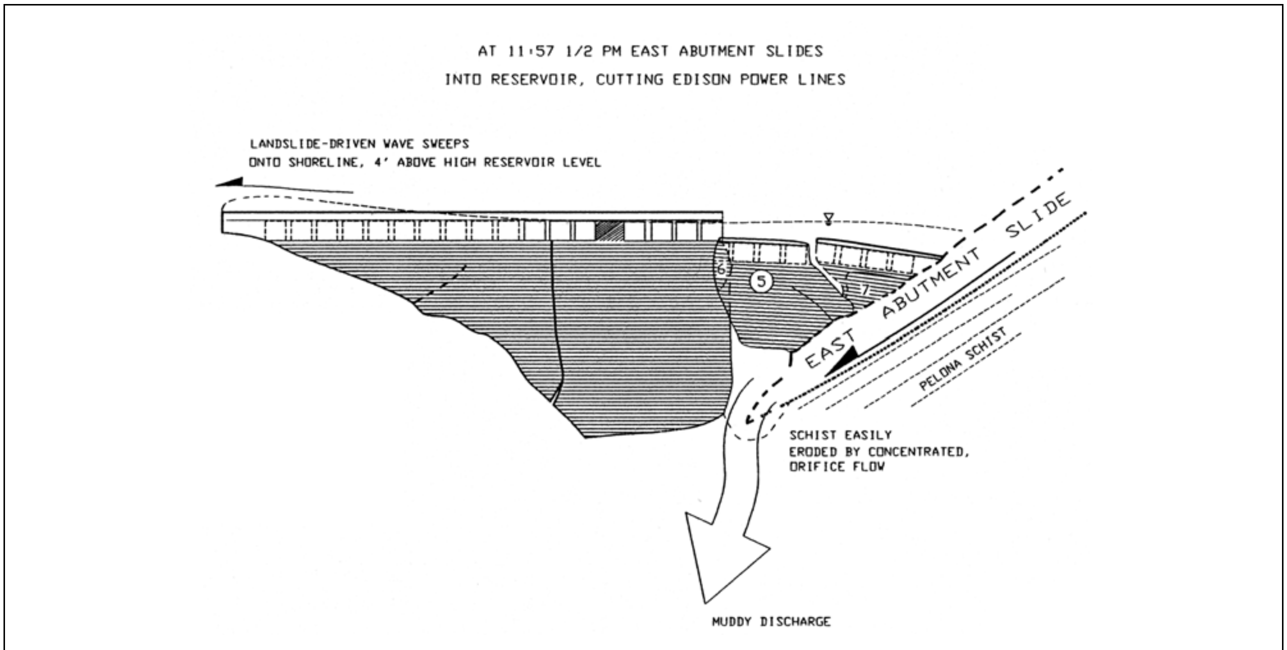


Figure 51. Schematic portrayal of the initial mobilization of the east abutment landslide, which severed power lines 90 feet above the dam crest on this abutment at 11:57-1/2 PM. A pile of flotsam was discovered the day after the failure washed 4 feet above the maximum pool level on the northwest shore of the former reservoir.

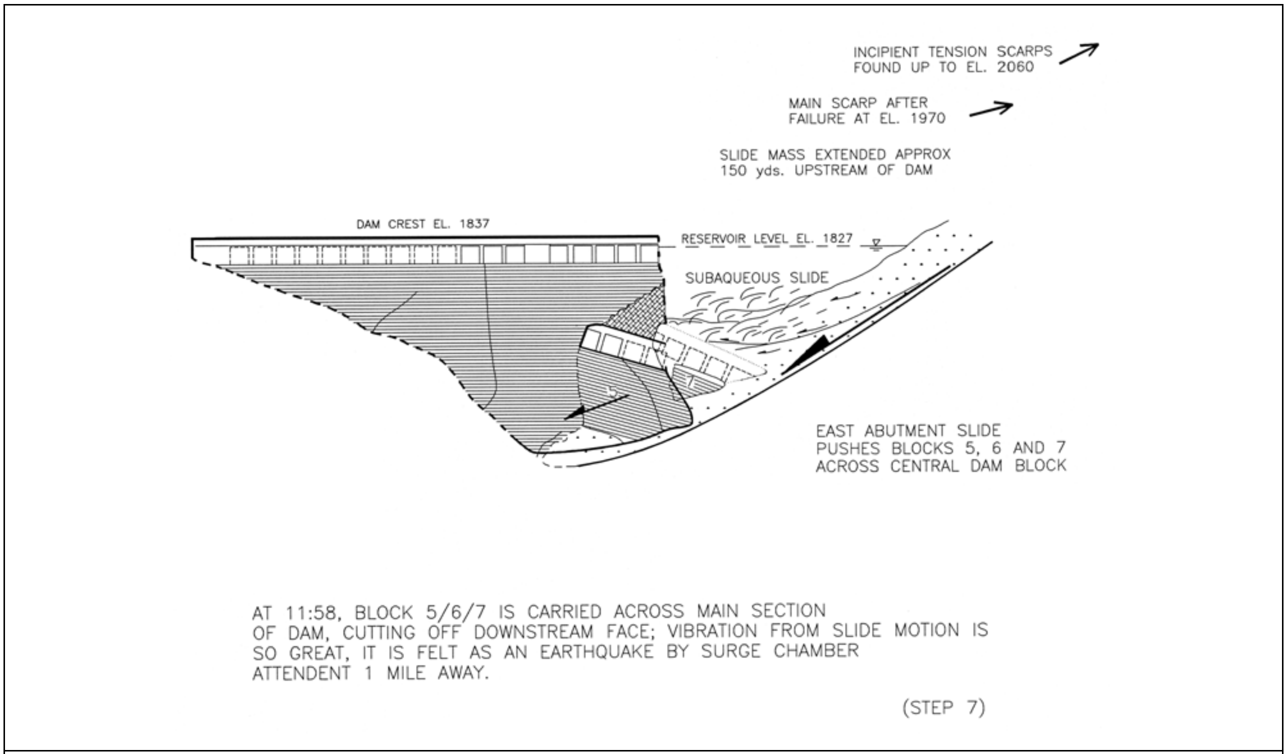


Figure 52. Schematic portrayal of the east abutment slide carrying Blocks 5/6/7 across the downstream face of the central dam core, shearing off about 10 feet of the dam's concrete on the stepped downstream face.

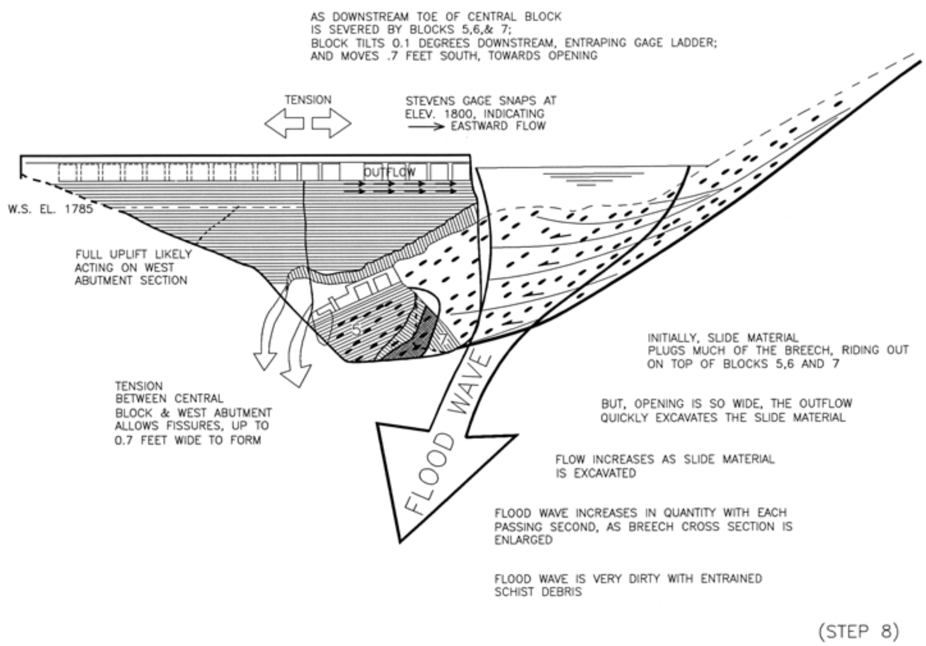


Figure 53. Schematic portrayal of the removal of the landslide debris dam created by the sudden mass movement of the east abutment slide, as a sort of quasi-subaqueous flow. The debris was a short-lived impedance to the outpouring waters. Note that Block 5 originally came to rest at a higher elevation, as noted by the chatter marks on Blocks 1 and 16.

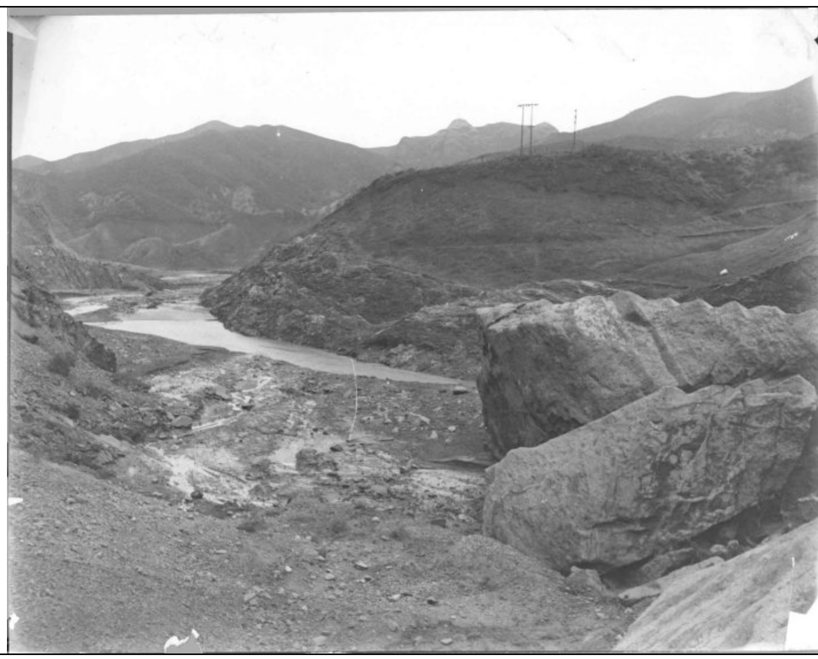


Figure 54. View from left abutment looking downstream at Block 7 wedged in behind Block 5. Note the accumulation of talus shed off the east abutment landslide scarp, which was 450 ft high. Photo by H. Wildey, from the author’s collection.

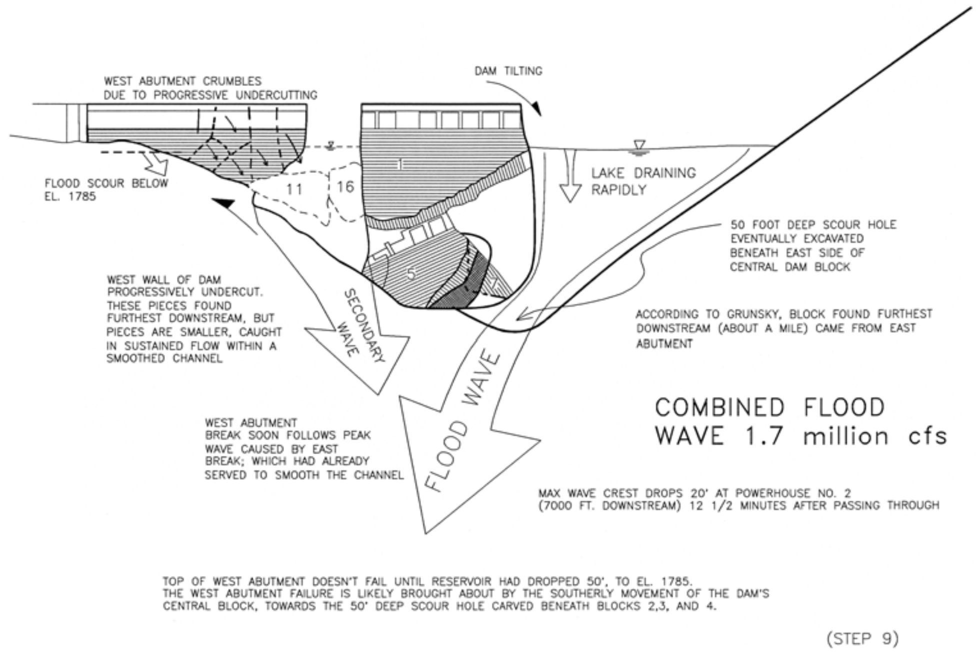


Figure 55. As the outpouring water removed more and more of the slide debris from the left side of the central core (Blocks 1 thru 4), the flow area increased (though hydraulic head was decreasing). This outpouring soon scoured beneath the core's left side, causing the core to tilt towards the expanding void. When this tilt occurred, there was a loss of arch stress transfer towards the right abutment, and this area began to break up along the pre-existing shrinkage crack bordering Block 1.

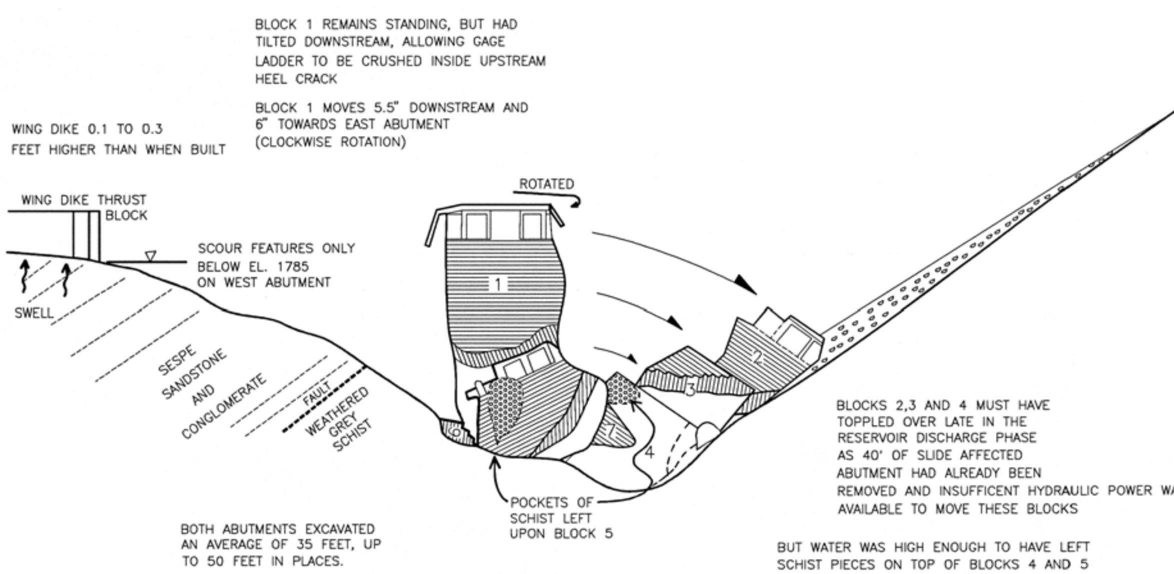


Figure 56. Schematic portrayal of the final stages of the St. Francis failure, when Block 2/3/4 fell backward, into the enormous hole scoured about the core block's left side. The left half of the dam's central core broke into three pieces as it rotated ~58^{o} backward. All the dam's major pieces appear to have split along low strength horizontal pour joints because of low tensile strength of those horizons.

Figure 57. Upstream view of Block 5 sitting in front of Block 1 after the failure. Note the quantity of schist detritus sitting atop Block 5, testifying to its having been carried down slope in a slurry of disaggregated schist. Note the chatter marks on Block 1 cut by Block 5 and the latter's final resting position, about 30 feet lower. The material originally supporting Block 5 was likely swept away when the right abutment subsequently failed. Photo from the Lee collection, U.C. water Resources Center Archives.

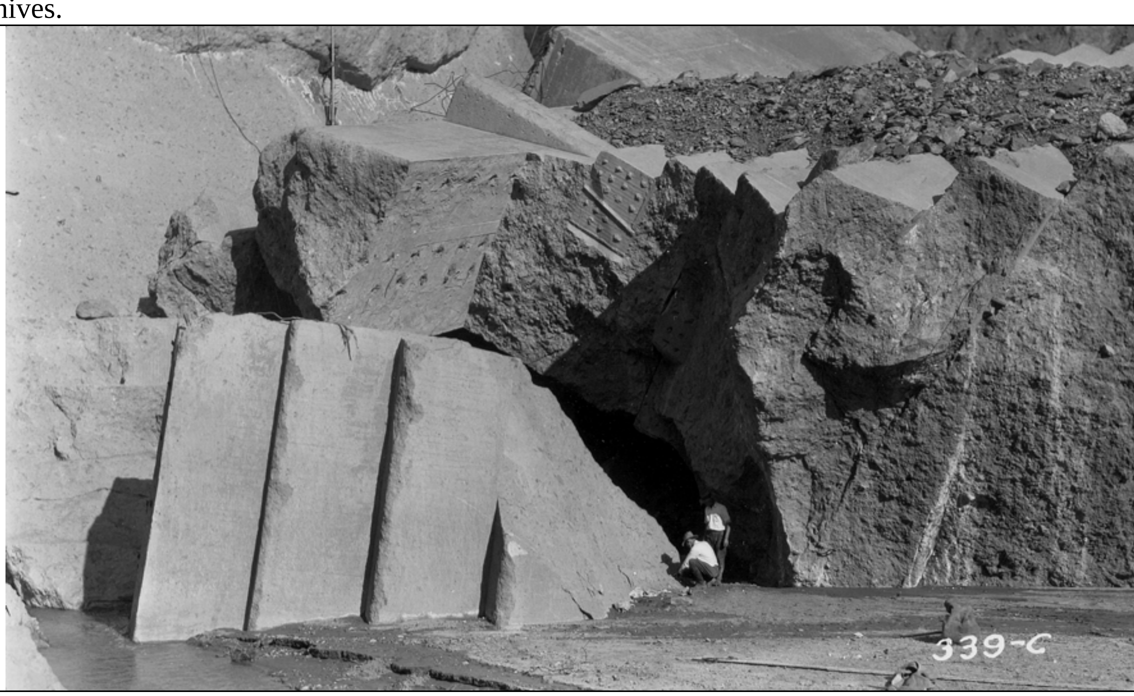


Figure 58. State survey party examining Block 6, which fell off of Block 5. Note the schist detritus infilling the 5 foot high steps of Block 5, 25 to 30 feet above the channel in foreground. Photo by H. Wildey, from author's collection.

Figure 59. View looking upstream at the imposing monolith of Block 1. As in the previous photos, the gap between Block 5 and the chatter mark cut into Block 1 is noticeable, as is the clean character of the right abutment, swept clean of all debris in the later stages of the failure. Photo from the W.L. Huber Collection of the U.C. Water Resources Center Archives.

Figure 60. Upstream view of Blocks 1, 5 and 6 and those of Block 2, 3, 4, which rotated backward into a deep scour hole cut around the core's left side. Note the broken surface of Block 2 and most of Block 3, where the dam's downstream steps have been sheared off. Historian Charles Outland unravelled this puzzle while he was writing *Man Made Disaster* in the early 1960s. Photo from L.A. Dept. of Water & Power.

Figure 61. Ground view of Block 2 and a portion of 3, taken after the failure from upstream of Block 1. The horizontal scour marks across the inclined block testify to the reservoir stage when Block 2/3/4 toppled over. The reservoir was only about 17.5 feet deep, or nearly drained, when the left half of then dam's central core fell over. Photo from then W.L. Huber Collection of the U.C. Water Resources Center Archives.

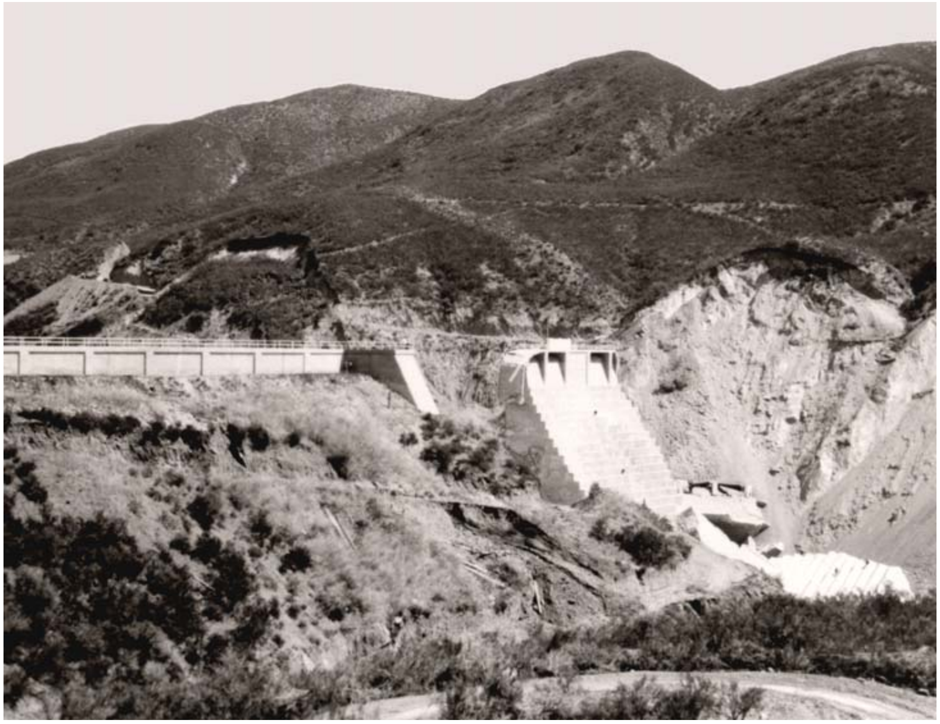


Figure 62. Ground view of the right abutment, just downstream of the dam following the failure. The intact nature of all vegetation on the dam's right abutment to an elevation at least 75 feet below the dam's crest suggests that the reservoir was 2/3 drained before the right abutment of the dam gave way (also see Fig. 29).

CONCLUSIONS

It would appear that the St. Francis Dam failure was precipitated by a number of siting and design deficiencies, many of which were not unique to the early 1920s. By modern standards, the dam had a great many shortcomings, listed in Table 1. However, the author cautions readers about blaming any particular shortcoming as being the most serious, insofar as we have evaluated seven different modes of failure, and the dam's imminent failure is predicted on each occasion!

TABLE 1
DESIGN DEFICIENCIES IDENTIFIED IN ST. FRANCIS DAM

1. Lack of hydraulic uplift theory being incorporated into the dam's design, especially on the sloping abutments. The dam was afforded 10 uplift relief wells beneath its central core, which did not fail

2. Failing to recognize that the dam concrete would eventually become saturated (not universally appreciated until after 1945, when Karl Terzaghi published a landmark article on development of pre water pressures in mass concrete, reversing his previous opinions on this subject).

3. Lack of any meaningful seepage cutoff, preferably situated near the upstream heel. The cutoff trench employed by BWWS was only 3 feet square, of inconsequential scale for a structure 205 feet high, even in 1924.

4. Lack of uplift relief wells on the sloping abutment sections of the dam. This shortcoming was not universally appreciated until the late 1960s, after the 1959 Malpasset Dam failure had been unraveled (Londe, 1985).

5. Failure to analyze the arch stresses of the main dam, which were overstressed in the upper 11 feet of the structure. Trial load analysis of arch stresses in mass concrete dams did not come about until 1931.

6. Failure to account for the mass concrete heat-of-hydration. This phenomenon was being explored by the U.S. Bureau of Reclamation in the late 1920s, as they began designing various schemes for Hoover Dam. After 1934, low alkali cement was employed in mass concrete dams to solve this problem.

7. Failure to remove high water content cement paste (laitence layer) between concrete lifts. This issue didn't gain widespread exposure until after 1930 (McMillan, 1930), after St. Francis failed. Jetting of the laitance layer was initially employed in mass concrete dams during the construction of Owyhee Dam by the Bureau of Reclamation between 1929-31.

8. Failure to wash concrete aggregate before incorporation in the dam's concrete. This was a common problem in remote sites bereft of ample water, and plagued countless military projects constructed in the Pacific Basin during the Second World War (1941-45)

9. Failure to batter the upstream face of the dam to reduce tensile forces via cantilever action. This mistake was a direct consequence of assuming no significant uplift forces would develop under the dam's maximum section because of the uplift relief wells placed beneath that area. These were fairly common assumptions until the late 1940s-early 1950s, when laboratory and field measurements confirmed that concrete was capable of near-instantaneous pore pressure conductance (Terzaghi, 1945, ASCE, 1952, Simonds, 1953).

10. Failure to provide the dam with grouted contraction joints. This practice was evolving throughout the 1920s (Hays, 1933). The Bureau of Reclamation had demonstrated the need for grouted contraction joints at Elephant Butte Dam, completed in 1916, but the subject is largely missing from any of the reference texts on dam design and construction prior to 1927, several years after St. Francis was designed.

11. Failure to adequately account for changes in cantilever and arch loads caused by raising the dam 11% of its original design height (from 185 to 205 feet). This was a major oversight, occasioned by fact that uplift forces were completely ignored because uplift relief wells had been employed beneath the dam's central core.

12. Failure to recognize tendency of some of the arkosic sand beds in the Vasquez Formation to slake upon submersion, due to presence of gypsum. Slaking was not recognized until the mid-1930s, during construction of MWD's Colorado River Aqueduct. There was no accepted test methodology for its evaluation developed until 1972 (Franklin and Chandra, 1972).

13. Failure to recognize paleo-megalandslide structure of the Pelona Schist comprising the dam's left abutment. This was a common problem in the early years of dam engineering, as evidenced by the 153 other dams unknowingly constructed against landslides in other parts of California and the United States (Schuster, 2006). Never-the-less, it might have been discovered and mitigated had BWWS employed the services of a seasoned geologic consultant to evaluate the site. The world's largest dam, San Gabriel Dam at the Forks Site, was cancelled by the State Engineer in November 1929 after a massive landslide occurred on the dam's right abutment the previous August.

14. Failure to install a cement grout curtain beneath the upstream face of the dam and the dike. Grout curtains installed using small diameter boreholes pumping sand-cement mixtures into the foundations near the upstream face were initially employed by the U.S. Bureau of Reclamation at Elephant Butte Dam in 1914-15. By the early 1930s grout curtains were been injected under pressures of up to 600 psi (Hays, 1933). Despite these efforts, by the early 1940s many engineers began to appreciate that grout curtains could never be made 100% effective (Goodman, 1999), but their employment is always considered beneficial and of sound practice to avoid development of excessive uplift pressures developing beneath a dam (ASCE, 1952; Simonds, 1953; and Casagrande, 1961).

TABLE 2
LESSONS WE SHOULD LEARN FROM THE ST FRANCIS DAM FAILURE

- "For every complex problem, there is a solution that is simple, neat, and wrong" – H. L. Menken

- A calculated Factor of Safety less than 1.0 does not, in of itself, mean that a structure failed via the precise mechanism analyzed. All manner of failure mechanisms should be evaluated without prejudice. This is difficult to do, for we are all prejudiced by our life's experiences. – Ralph B. Peck

- We will not identify those geologic features or structures for which we are not specifically looking for. We have to have in mind what we are seeking, realizing that we will seldom be able to recognize those features with which we've had little prior experience.

- Engineering geology, by its nature, is a very subjective science, built upon each person's unique pedigree of experience. The simple inclusion of a geologist on a project, will not, in of itself, insulate such projects from disaster. There are over 153 existing dams in the United States are currently founded upon or against ancient landslides (Schuster, 2006).

The weight of any forensic assessment must necessarily lie within a careful and complete sifting of the physical evidence. St. Francis had so many shortcomings, it may be impossible to unravel precisely which factors were most important, in some descending order. Given the fact that so many other dams of that era were also built without a proper appreciation of uplift, and that more than 254 dams world-wide have now been identified as having been built against paleolandslides (Schuster, 2006), these factors, in of themselves, cannot strictly account for the dam's untimely demise.

As in the case for so many failures, it is the aggregate combination of shortcomings, that most often lead to unanticipated tragedy. Structures that place the public at risk, must be treated with greater care, ensuring redundant systems that cannot trigger catastrophic failure if one or more of their components fail to perform as assumed. This is how aircraft are designed, because the consequences of system failure are so grave. Critical structures protecting people or situated in a position to harm people, should be subject to regular independent peer review.

Probably the greatest single factor that could be pointed to was the Board of Waterworks and Supply's decision to heighten the dam a *second time*, long after a commensurate extension of the base width could have been accomplished (more than a year after construction began). Aside from the geologic shortcomings, all of the structural analyses predicted overstressed conditions when the reservoir pool rose with 7 to 11 feet of crest. Had the dam not been heightened that last 10 feet, it *might* have survived and its inherent deficiencies revealed at some later date, such as occurred with Mulholland Dam a few years later (though these assessments were triggered by the St. Francis failure). High-visibility failures have an enormous impact on public opinion and policing of professional standards.

William Mulholland (1855-1935)

REQUIEM FOR MULHOLLAND

Like any person, Bill Mulholland had weak points in his character. His thirst for thriftiness was one of these flaws, but that same trait allowed Los Angeles to build its municipal infrastructure ahead of its burgeoning population, at rock bottom prices. He had an enormous capacity for innovation; getting difficult projects completed on-time and on-budget

He also had the depth of character to accept responsibility for shortcomings in the dam's design and construction which he, nor anyone else at the time, fully comprehended. He told the Coroner's Inquest: "*don't blame anyone else, you just fasten it on me. If there was an error in human judgment, I was the human.*"

After hearing all of the evidence, the Los Angeles County Coroner's Inquest 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 ….checking by independent experts.*" None of us should forget this advice.

BENEFITS TO SOCIETY THAT CAME FROM THE ST. FRANCIS TRAGEDY

The civil engineering profession gained much from the public outcry and notoriety accompanying the St. Francis Dam disaster. Sound engineering geologic input on dams became commonplace in the 1930s (it had been all but absent in the 1920s). Some of the more positive aspects that came about as a direct result of the St. Francis Dam failure are briefly profiled below.

Review of federal dams

Two days after St. Francis failed (March 15, 1928), public concerns about dam safety hastened the U.S. Bureau of Reclamation to order that all their dams be promptly examined by a competent engineer and reported on as to their safety. This was no small task, and required the bureau to hire numerous consultants to make independent assessments. A. J. Wiley, who headed up the Governor's Board of Inquiry, was tasked by the Bureau of Reclamation with reviewing 20 of their largest dams over the following six months. The City of Los Angeles asked him to review all 32 of their dams over the remained of 1928, and issue written reports as to his findings.

Dam safety legislation

In 1915 the California legislature passed its first dam safety legislation, which required all plans for dams and reservoirs to be submitted to the State Engineer for approval, but the act provided no penalty for failure to comply. In August 1916 the State Reclamation Board issued a report recommending that the State Engineer regulate all storage reservoirs. No further action was taken by the legislature until after January 1916 floods in Southern California. In 1917 a new dam safety act was enacted in the wake of public outcry following the failures of the Lower Otay and Sweetwater Dams in San Diego County during the floods of January 1916. The 1917 act granted the State Engineer authority over all dams > 10 feet high or which impound > 9 acre acre-ft (3 million gallons), with exception of: 1) dams for mining debris constructed by the California Debris Commission; 2) dams constructed by municipal corporations maintaining their own engineering departments (such as Los Angeles BWWS); and 3) dams and reservoirs that are part of water systems regulated by the State's new Public Utilities Act.

That same year (1917) the State Railroad Commission was given authority over all dams owned by public utilities. The railroad commission exercised some oversight on 46 of 140 dams built in California between 1917-1929. Municipal water agencies, such as publicly-owned agencies and districts, were exempt from State overview (until the 1929 legislation). From 1917-29 the State Engineer was given authority to review plans for dams prepared by irrigation districts, private companies and individuals. In 1920 the Federal Power Commission began supervising dams for power projects involving the public domain.

In the wake of the St. Francis Dam failure, the state passed a much more comprehensive Dam safety Act on August 14, 1929. The Act empowered the State Engineer to review all non non-federal dams > 25 feet high or which impound > 50 acre acre-feet of water. The act also allowed the State to employ consultants, as deemed necessary. The State Engineer was given $200,000 and instructed to examine all dams in California within three years and issue recommendations. The State Engineer was given full authority to supervise the maintenance and operation of all non-federal dams (exempting those constructed by the Army Corps of Engineers and the Bureau of Reclamation)

Between August 1929 and November 1931 the State Engineer inspected 827 dams. One third were deemed to exhibit adequate safety, while another third were recommended for further examination, such as borings or subaqueous inspection, before a determination could be made. The remainder, roughly, another third, were ascertained to be in need of alterations, repairs or changes; frequently involving spillway capacity.

After this there followed a six-year program of dam safety inspection, which were concluded in July 1936. During this period 950 dams were inspected; with 588 of these dams being under the State's jurisdiction. One third of these dams were found in need of repairs. New dam construction was also placed under state observance from August 1929 forward.

Professional engineering registration

The State also mandated professional registration for engineers early the following year (1929). A registration act had been passed by the State Assembly and Senate in Sacramento in 1925, but failed to gain the governor's approval. Those promoting registration eventually formed the California Engineers Registration Association (CERA) on March 10, 1928, just two days before St. Francis Dam failed. As it turned out, their timing was fortuitous, as the public clamoured for "something to be done" to better ensure public welfare and safety. CERA's rolls swelled to 600 members by November and politicians were eager to demonstrate to the public that they were making sweeping changes to the status quo.

The Civil Engineers Registration bill sailed through the state legislature in early July 1929 and became law on August 14th. Right up to its adoption, the act was vigorously opposed by a number of professional organizations, such as the American Institute of Mining Engineers and the American Society of Mechanical Engineers. The new act defined civil engineering as: "that branch of professional engineering which deals with the economics of, the use and design of materials of construction and the determination of their physical qualities; the supervision of the construction of engineering structures; and the investigation of the laws, phenomena and forces of nature; in connection with fixed works for: irrigation, drainage, water power, water supply, flood control, inland waterways, harbors, municipal improvements, railroads, highways, tunnels, airports and airways, purification of water, sewerage, refuse disposal, foundations, framed and homogeneous structures, bridges, and buildings. Furthermore, it included city and regional planning, valuations and appraisals, and surveying, other than land surveying as already defined in Statutes adopted by the legislature in 1891 (the first engineering registration act in the United States) and amended in 1907. It mandated that any person who practices or offers to practice civil engineering in any of its branches must be registered, and created The Board of Registration for Civil Engineers.

The act also directed that civil engineers in state service must be duly registered if they served in a capacity of 'Assistant Engineer" or higher. The California Supreme Court quickly issued rulings that a contract for engineering services was invalid if the party undertaking to furnish engineering services was not registered and the State's Appellate Courts ruled that engineers offering expert testimony should be registered, although it left the ultimate decision to the discretion of individual judges because some individuals had previously been qualified as experts, before passage of the registration law.

The act allowed the three-person board to develop standards for applicants over a two year period and to survey registration standards being employed by other states, for purposes of comparison. California made a comprehensive study of procedures practiced in 25 other states and seven Canadian provinces which had laws regulating engineering practice. The standard California adopted required that applicants be at least 25 years old, a legal resident of the state for at least one year prior to the date of application (which was waived for those willing to sit for the examination), and demonstrate no less than six years of professional practice, including at least one year of being in "responsible charge." Their application must be supported by at least four engineers unrelated to them by family or marriage, who could vouch for their character, experience, and technical competence, before they would be eligible to sit for the written examination. The board allowed a college degree in engineering to be the equivalent of four years experience, while graduate work in engineering could be credited for up to one year of experience (California did not offer doctorate degrees in civil engineering until sometime later, but this discrepancy has never been amended). The cost was set at $15 to apply, an additional $10 when applicants successfully passed the examination (to pay for their certificate), and an annual renewal fee of $5.

5,700 individuals applied for civil engineering registration during the first year applications were accepted, more than double what the state board had expected. Grandfathering was only allowed for the first 10 months, until June 30, 1930, after which time, applicants would be required to take a written examination. Many of those who applied for grandfathering were asked to appear before the three man board (appointed by the governor) for oral interviews. The basic determinant for "gray area" cases was whether applicants had entered the profession from the labor ranks of construction, this experience was not deemed to be 'engineering experience."

Of those who applied the first year, 5,035 were accepted, providing the State of California with about one registered engineer for every thousand people then living in the state! State Engineer Edward Hyatt was named Registered Civil Engineer (RCE) No. 7; Carl Grunsky received RCE 15; and William Mulholland was assigned RCE 2779. It took California another 25 years to register the next 5,000 civil engineers. Many other states followed the examples demonstrated by New York and California. By 1932, 28 of the nation's 48 states had enacted professional registration for civil engineers.

In September 1932 the California board begin granting the special title "structural engineer," which required applicants to demonstrate 3 to 5 years of responsible charge of structural engineering projects as eligibility to sit for a special examination. But, those individuals who could document more than 5 years of experience in "responsible charge" were duly grandfathered into using the title. In March 1933 the Long Beach earthquake killed 115 people and caused $50 million in damage, mostly to unreinforced masonry structures, such as public school buildings. Within a month of the quake, the California Legislature passed the Field Act, which empowered the Office of the State Architect to undertake whatever measures it deemed appropriate to ensure safe design and construction of public school buildings, which included requirements for plans prepared by a certified architect or structural engineer and set requirements for lateral earthquake loads, which depended on location. The Field Act left a lasting imprint on how structural engineers would be qualified in California; requiring them to demonstrate an understanding of analyses, designs, and consultations involving structural engineering principles associated with the application of seismic loads. A companion legislation called the Riley Act was also enacted in 1933, which required local agencies in California to establish their own building and inspection departments (the first Uniform Building Code had appeared in 1927, but only a handful of the state's largest cities had adopted it). The Riley Act also required all new construction to be designed to withstand an earthquake acceleration of at least 0.02g, but also allowing municipalities the discretion to employ even higher values, as they deemed appropriate.

In October 1932 a National Council of State Boards of Engineering Examiners (NCSBEE) was endorsed at a meeting in New York of the National Bureau of Engineering Registration (NBER), headquartered in Columbia, South Carolina. NCSBEE sought to create standardized civil engineering registration examinations and requirements so reciprocity of licenses between the 28 states mandating professional registration could be undertaken more efficiently. NCSBEE changed its name to the National Council of Engineering Examiners (NCEE) in 1967. NCEE developed standardized tests which were gradually adopted by most states, beginning in the 1960s. NCEE broadened its scope to include establishment of a *Model Rule for Professional Conduct* in 1979, which many courts have considered as national standards for professional engineering conduct. In 1989 NCEE became the National Council of Examiners for Engineering & Surveying (NCEES). Its headquarters remains in South Carolina (at Clemson). Curiously, California remained unaligned with the national examination concept until 1975, when they finally acquiesced to the standardized NCEE examination, which they have since employed. The reason the California board gave for this reticence was the "eastern bias" they perceived in the NCSBEE/NCEE exams, which had less emphasis on transportation engineering problems, as compared to California's own tests.

State-mandated arbitration hearings for victims of natural disasters

In the wake of thousands of wrongful death lawsuits against the City of Los Angeles following the St. Francis tragedy, the State enacted special legislation to adjudicate financial compensation of the victim's surviving next-of-kin, omitting compensation to attorneys (described in Teague, 1944). A council of 14 arbitrators was selected from Los Angeles and Ventura Counties, who used established methods of estimating remaining life worth and made compensatory awards to the legitimate survivors. This legislation was used by the State Attorney General's Office to effect a reasonable process for compensating victims of natural disasters who have brought suits against the state seeking damages for personal injuries, wrongful death suits, pain and suffering actions, etc., from failures of state-owned facilities, such as bridges, highways, levees, injuries sustained while engaged in hazardous duty with the National Guard, collisions with emergency vehicles, alleged mistakes made by emergency responders, etc., etc. Binding arbitration procedures were employed by the Attorney General's Office following the 1955 and 1964 floods in northern California, and the 1989 Loma Prieta earthquake.

Impact on passage of the Boulder Canyon Project Act and the design of Hoover Dam

Perhaps the biggest casualty of the St. Francis failure was the negative publicity it caused to Los Angeles politicians, who were actively engaged in promoting passage of the Boulder Canyon Project. The Boulder Canyon Project Act had been introduced in Congress back in 1922, and Mulholland had vociferously applauded and promoted it s passage over the previous five and a half years. It had become his absorbing concern since the summer of 1923, hastening frequent trips with city attorney W. B. Mathews to Washington, D.C. to lobby for the act's passage (at least twice each year). The Act sought $150 million to build the tallest dam ever conceived (740 feet) in Boulder Canyon.

After years of debate, the Boulder Canyon Project Act finally received approval of the US House of Representatives on May 15, 1928. But, the act died in the Senate after a successful filibuster by Arizona and Utah senators a few days later, who pointed to the St. Francis Dam tragedy and assuaged that Boulder Dam was being promoted by the "same Los Angeles interests who brought us the St. Francis Dam catastrophe." In late May a compromise was reached in Congress. In order to placate fears about a colossal dam that might fail catastrophically, like St. Francis, Congress passed a joint resolution that created a Colorado River Board to review the plans of the proposed Boulder Canyon Project. The board was to be chaired by retired Major General William L. Sibert; with two engineers and two geologists. The geologists were Columbia University Geology Professor Charles P. Berkey and Professor Warren J. Mead of the University of Wisconsin (Fig. 63). The engineers were Professor Daniel W. Mead and New York consulting engineer Robert Ridgway (both of whom subsequently served as ASCE Presidents). They were charged with reviewing existing documents and making a recommendation on where to site the great dam along the Colorado River. This unprecedented action came about as a direct result of the St. Francis Dam failure; and it was a most positive and fortuitous development, for all concerned.

Figure 63. Members of the Colorado River Board, created by Congress in May 1928 to review the plans for the proposed dam in Boulder Canyon (which became Hoover Dam) in the wake of the St. Francis Dam tragedy. From left: W. L. Siebert, Bureau of Reclamation commissioner Elwood Mead, Warren Mead, Charles Berkey, Dan Mead, and Robert Ridgway. The three Meads were not related to one another, just a coincidence. Siebert had achieved distinction working for the Army Corps of Engineers on the Panama Canal. Image from U.S. Bureau of Reclamation.

The Colorado River Board made an exhaustive review of the plans and design assumptions being used by the Bureau of Reclamation. The board issued its report to Congress in November 1928, recommending that an alternative dam site in upper Black Canyon be utilized in lieu of the sites in Boulder Canyon. The reasons it gave were: 1) Superior geology; 2) Narrower canyon, steeper walls; 3) Site more accessible from existing rail lines and highways near Las Vegas; 4) River channel not as deep, less excavation to competent rock; 5) Dam of equal height would cost less and store greater volume of water than at Boulder Canyon; 6) rock less jointed; 7) few open fractures; 8) rock appears less pervious than at Boulder Canyon site; 9) rock easier to drill and excavate than at Boulder Canyon (one deep hole was advanced to a depth of 557 feet below the low water surface at the Black Canyon dam site and encountered same formation all the way down).

The board also recommended that the Bureau of Reclamation use a concrete gravity arch dam 550 feet tall, with radius of 760 feet and a crest elevation of 1200 feet (above sea level), with opposing powerhouses, on either side of the channel. The hydroelectric powerplant was now an integral part of the proposed project. No bureau dams had previously been equipped to generate electrical power because this was opposed by private utilities. The board also suggested five major design changes: 1) reduce the contact pressure against the foundation rock from 40 tons per square foot (tsf) to 30 tsf; 2) increase the capacity of the river bypass diversion tunnels from 100,000 cfs to at least 200,000 cfs (to convey a 25 yr flood); 3) increase spillway capacity to some figure greater than 11,000 cfs; and 4) increase the volume of active flood storage (the proposed dam was raised 25 feet). They also determined that an All-American Canal could be constructed north of the Mexican border and that all of the hydropower electricity could be absorbed by the expanding market of greater Los Angeles. They placed the cost of the entire project at $165 million.

The Boulder Canyon Project name was retained because Congressman Phil Swing and Senator Hiram Johnson had been trying to push the bill through Congress every year since 1922, finally succeeding with their 4th version during the second session of the 1928 Congress in December 1928. On December 14, 1928 Congress authorized the Boulder Canyon Project Act by a vote of 63-11 in the Senate. The House approves it with Utah amendments on December 18th, and the bill is signed by lame-duck President Calvin Coolidge on December 21st. This is the first time such a large appropriation has been made to the Bureau of Reclamation from the general funds of the United States. The authorization came only after a hard fought debate about the pros and cons of publicly-owned versus privately-owned electrical power.

Earlier in 1928 the Metropolitan Water District of Southern California was incorporated in Los Angeles with the expressed intent of taking over construction of the 240 mile long aqueduct between Los Angeles and the Colorado River that had been envisioned by Mulholland. MWD was comprised of all the major southern California municipalities then in existence, thereby ensuring the new agency would convey waters to all of southern California, not just the City of Los Angeles.

The Boulder Canyon Project Act was declared effective June 25, 1929. The Bureau of Reclamation proceeded with preparation of plans and specifications for public bidding. It was the largest Federal contract ever let up until that time and Hoover Dam was subsequently constructed for a cost of $48.9 million (within 0.05% of the Bureau's estimate). Six Companies, Inc. built the massive dam between May 1931 and June 1935, completing it two years ahead of schedule and pocketing an enormous profit. The last concrete was poured on May 29, 1935, allowing Bill Mulholland to see his last dreams come to fruition, quietly passing away at the age of 79 at his home on St. Andrews Place in Los Angeles on Monday July 22, 1935.

State rescinds permit for San Gabriel Dam at The Forks

As mentioned previously, California enacted legislation creating a model dam safety authority for the United States, which eventually became the Division of Safety of Dams (DSOD) of the State Department of Water Resources. A few months after the legislation went into effect (August 1929) they exercised their new authority to cancel the San Gabriel Dam at The Forks, in San Gabriel Canyon above Azusa.

Figure 64. Ten times the size of St. Francis, San Gabriel Dam at The Forks site would have become the largest dam in the world if the State of California had not cancelled the project. This review authority over non-Federal dams by the state was established in the wake of the St. Francis disaster. These images show the excavation activities and landsliding that occurred on the right abutment in 1929. Photos from US Bureau of Reclamation.

The original San Gabriel Dam was intended to be a record breaker. It was laid out to be 500 feet high with a crest length of 2,300 feet and a concrete volume of 3.8 million yds^3 (even larger than Hoover Dam, completed 7 years later). The owner was the Los Angeles County Flood Control District, which had already spent \$3 million of the \$25 million contract, awarded in September 1928. During excavation of the dam's right abutment in June 1929, the contractor loaded coyote tunnels with 193,000 lbs of powder, bringing down 160,000 yds^3 of rock, but over-blasting the abutment left the rock severely fractured. On September 16th a massive landslide involving more than 200,000 yds^3 slid down into the canyon, halting further construction. The three images in upper panel of Fig. 64 show, from left, the right abutment before excavation, during the detonation in June 1929, and after the large rock slide in August 1929. The lower image in Fig. 64 is an elevation view looking at the right abutment before the blast of June 26, 1929.

The State Engineer used his new powers to review non-Federal dams and appointed a panel to review the project and render its findings. This panel was chaired by Jack Savage, chief design engineer of the U.S. Bureau of Reclamation (see sidebar on Savage, below). Savage's panel included three geologists: Professors George Louderback of U.C. Berkeley and Charles Berkey of Columbia, and Ira A. Williams, a consulting geologist from Portland. On November 26, 1929 the panel released their findings, concluding that the proposed dam "cannot be constructed without creating a menace to life and property." They suggested that as an alternative, "a earth and rockfill dam of conservative design" might be successfully employed at a site about one mile downstream.

The flood control district sued to recover \$2.7 million from the contractor, but ended up settling out of court for only \$738,000 because one of the County's elected supervisors was convicted of bribery for influencing award of the contract, and sentenced to prison time. The Los Angeles County Flood Control District reshuffled their management structure and a new San Gabriel Dam was completed in 1937, as the world's highest rockfill dam (355 ft high).

Jack Savage was a native of Wisconsin, receiving his bachelor's degree in civil engineering from the University of Wisconsin in 1903. He joined the newly formed U.S. Reclamation Service in 1904, and rose through the ranks to become the agency's Chief Design Engineer twenty years later, in 1924. He held this position for two decades, until retiring in 1945. He was responsible for the design of most of the Bureau's record breaking projects of that era, including Owyhee, Hoover, Grand Coulee, Friant, and Shasta Dams. He chaired the state's independent review panels for the San Gabriel Dam in 1929 and Mulholland Dam in 1930, convened after California passed new dam safety laws in the wake of the St. Francis disaster. The San Gabriel panel found the design for the massive concrete dam in San Gabriel Canyon to be inadequate, shutting down the project. The 1930 panel stated that Mulholland Dam was "safe," but it was rumoured that Savage requested a private audience with Harvey van Norman, where he apprised him of the shortcomings of the Mulholland and St. Francis Dam designs, which hastened Van Norman's decision to retrofit of Mulholland Dam and permanently draw down Hollywood Reservoir. Savage was pioneer in concrete dam design theory and one of the first the appreciate the importance of hydraulic uplift on dam stability.

John Lucien "Jack" Savage (1879-1967) was probably the greatest single personage in American dam engineering of the 20th Century.

Retrofit of Mulholland Dam

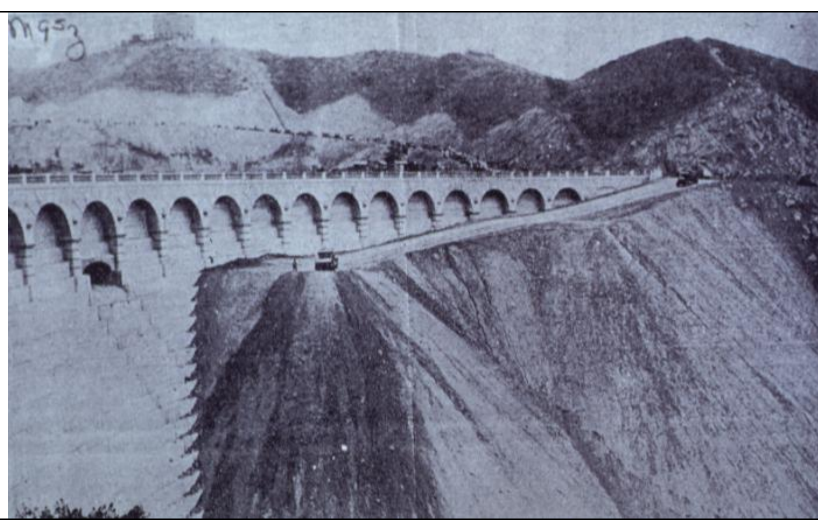
Since March 1925 Mulholland Dam had retained Hollywood Reservoir in Weid Canyon above populous Hollywood. Virtually identical in every detail to St. Francis, the city lowered its reservoir pool by 50% in the late spring of 1929, bowing to public pressure fomented by continuing concern of city residents that lived in its shadow. Though not favoured by BWWS, this turned out to be a wise precaution. The dam was initially given a "clean bill of health" by several internal and external review boards convened in the wake of the St. Francis failure to make a review of all city-owned structures. Concerned residents of Hollywood continued clamouring for a 'wholly independent review' by a panel of experts above influence of the City of Los Angeles, or the BWWS. In January 1930 such an external review panel was convened by the State of California, under the auspices of the new dam safety act enacted in August 1929. This state panel was chaired by John L. Savage, chief design engineer of the U.S. Bureau of Reclamation (see sidebar discussion, above). This independent panel included geology Professors George D. Louderback and Charles P. Berkey.

Worried about the political fallout of any negative findings by the external panel, the city 'responded' with their own 'board of review' in March 1930, which included BWWS chief engineer and general manager Harvey Van Norman (see sidebar, below). The independent panel issued their report in June 1930, and it was overtly critical of Mulholland Dam, causing the city considerable embarrassment.

Harvey Van Norman succeeded Mulholland as chief engineer and general manager in December 1928.

Harvey Arthur Van Norman (1878-1954) grew up in Los Angeles. Self educated, he was hired by Mulholland to build the small hydroelectric plants at the base of the eastern Sierras for the Owens River aqueduct in 1907. He soon rose to positions of succeeding responsibility, directing aqueduct construction in the Lone Pine, Owens Valley and Mohave Divisions of that project until 1913, whereupon he supervised the aqueduct's maintenance until 1923. He took leave of BWWS to supervise the design and construction of Los Angeles' first sewer collection and outfall system between 1923-25, whereupon he became Assistant Chief Engineer of BWWS until December 1928, when he succeeded Mulholland as Chief Engineer and General Manager. In this position he oversaw the melding of the Water and Power divisions in early 1931, retiring as the City's second "chief" in November 1944. Known to his intimates simply as "Van," he was like a son to Mulholland. The upper and lower San Fernando Reservoirs were renamed the Van Norman Reservoirs when he retired in 1944. The lower reservoir embankment experienced a liquefaction failure during the February 1971 Sylmar earthquake. Photo courtesy of the Los Angeles Department of Water & Power.

It is an old political axiom that "if you don't like the conclusions of an external panel, you can lobby to appoint another panel," a process that can be repeated until one hears the answer they are searching for. All sarcasm aside, a third independent panel to evaluate Mulholland Dam was assembled in 1931, comprised of B.F. Jakobsen, Charles T. Leeds, and USC geology professor Allen Sedgwick. Jakobsen was a consulting engineer in Los Angeles, but he was also under investigation for his role in reviewing and approving the plans of the San Gabriel Dam at The Forks site (described earlier) and he was subsequently expelled from the American Society of Civil Engineers. A few months later Jacobsen and Sedgwick issued a majority report that faulted the dam's base width as being insufficient to withstand uplift and that the spillway sill should be lowered 35 feet. The third time was the charmer. This time the City bowed to the external pressures being brought to bear upon them and they acquiesced to making permanent alterations to Mulholland Dam and Hollywood Reservoir, which were carried out with as little fanfare and publicity as possible over the next two and a half years.



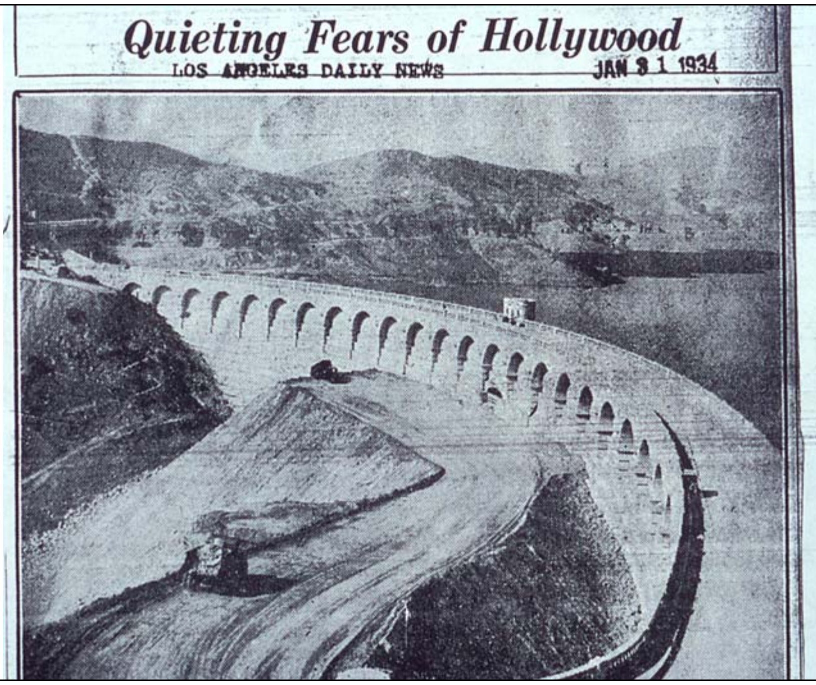


Figure 65. The sister structure to St. Francis, Mulholland Dam underwent a massive refit in early 1934, which saw the placement of 300,000 cubic yards of earthfill against its downstream face. In addition, the reservoir storage was curtailed 54%, from 7,437 to just 4,029 ac-ft of water. This reduced level was considered safe by the external review board. Images from the Municipal Reference Department at the Los Angeles City Library.

All of the review panels, even that chaired by BWWS's own Harvey Van Norman in 1930, concluded that Mulholland Dam had insufficient control of hydraulic uplift and underseepage to be stable in overturning under full reservoir pressure, more especially so, during an earthquake. They recommended drawing the reservoir down to elevation 715 feet, 36 feet below the dam crest, to bring the resultant thrust inside the middle third of the structure. The reservoir pool had been drawn down 50% in 1929 as a precaution to placate concerned Hollywood residents while the dam was analyzed. The Van Norman panel recommended placing an enormous earthen buttress against the dam's downstream face to heighten its safety factor against possible failure in the event of a major earthquake and placate public concerns.

After considering the increased stability engendered by the downstream embankment fill, the city concluded that the reservoir pool could be maintained no higher than 54% of the maximum level (4,028.7 ac-ft), and this is where is has remained since 1931. The reservoir is normally operated at a pool level between 715 and 721 feet, which is a conspicuous 35+ feet below the dam's crest elevation of 756 feet. In January and February of 1934 the City quietly supervised the placement of over 300,000 cubic yards of earth against the downstream face of Mulholland Dam to provide a massive buttress (Fig. 65). Today this slope is covered with eucalyptus trees, obscuring the concrete parapets of a once famous concrete dam that still bears the name of the City's famed waterworks engineer. Mulholland Dam retains Hollywood Reservoir, which local residents refer to as "Lake Hollywood."

External Peer Review and the Proctor Compaction Test

In the aftermath of the St. Francis Dam tragedy, the Los Angeles Department of Water & Power (DWP) developed a sensitive curiosity about the potentially deleterious effects of hydraulic uplift beneath dams. Under intense public scrutiny, the city opted to construct the sorely needed replacement for St. Francis using an earth dam. The location chosen was in Bouquet Canyon, east of upper San Francisquito Canyon, at an elevation of 3000 ft (1165 ft above the level of St. Francis Reservoir). The Bouquet Canyon site was located about 3.6 miles east of the aqueduct, so a 94 inch diameter steel siphon with a vertical drop of 870 feet was employed, which was 18,000 ft long. This steel pipe connected to a 1000 ft long concrete lined tunnel that served the new reservoir. The reservoir was intended to store 33,000 acre-feet, about the same volume as St. Francis (its storage is presently listed as 30,000 ac-ft).

The Bouquet Canyon project required two embankments: a main dam 221 ft high, involving 2,125,000 yds^3; and a saddle embankment near one corner of the reservoir, about 42 feet high, which required 136,000 yds^3 and another 40,000 yds^3 of stripping. Unlike the old days of the 1920s, the Department of Water & Power now went to great lengths to have the project subjected to external peer review and approval. The Bouquet Canyon plans were received external review from engineers Charles T. Leeds, Louis C. Hill, and J. B. Lippincott (see sidebar), as well as input from a host of additional engineers and geologists external to DWP, including: geologists Charles P. Berkey, Allen E. Sedgwick, Robert T. Hill, F. Leslie Ransome, and Rush T. Sill. Other engineers providing input included Thaddeus Merriman, R.E. McDonnell. And, the State Engineer also reviewed the project and provided an on-site representative to inspect the construction as it progressed.

EXTERNAL PEER REVIEW APPLIED TO WATER & POWER PROJECTS

Charles T. Leeds (1879-1960) [above left] was a former Corps of Engineers officer (West Point Class of 1903 with a second BS degree from MIT in 1906). While working for the Corps' as the Los Angeles District Engineer in 1909-12, he oversaw design and construction of the enormous breakwater that created the Port of Los Angeles in San Pedro. He began private practice with Wilfred K. Barnard in 1912, interrupted by service as the Corps' Los Angeles District Engineer in 1917-19, during the First World War. His firm merged with Quinton, Code and Hill in 1930, becoming Leeds, Hill and Jewett in 1946. Their dams and tunnels group were subsequently absorbed by Woodward-Clyde in 1982. **Louis C. Hill** (1865-1938) [middle image] was arguably, the most respected Los Angeles consulting engineer at this time. A graduate of the University of Michigan in 1886, he earned a second degree in electrical engineering in 1890. He was a professor at the Colorado School of Mines from 1890-1903, at which time he was enticed to join the newly-formed Reclamation Service in Denver. He supervised a string of famous projects in the upper and lower Colorado River basins, including Roosevelt Dam (1903-11), the giant siphon under the Colorado River at Laguna Dam, and the design of Elephant Butte Dam. He entered private practice in March 1914, and availed himself as a consultant to the Bureau of Reclamation and Corps of Engineers for the balance of his life. Shortly after the First World War, he became a partner in Quinton, Code, and Hill in Los Angeles, which consulted on a wide range of water supply and flood control projects, nation-wide. He gained national recognition when the Bureau of Reclamation named him to their Board of Consulting Engineers for Hoover Dam in 1930. He went onto become President of the American Society of Civil Engineers in 1937. **Joseph B. Lippincott** (1864-1942) [right] graduated from the University of Kansas in 1887. He joined the U.S. Geological Survey in 1889 as a topographer, making some of the first maps of the San Gabriel Mountains. After two years in private practice he rejoined the USGS Water Resources Branch as a hydrographer in 1895, while maintaining his consulting practice. When the Reclamation Service was formed in 1902, Lippincott became their third employee, with the title Supervising Engineer. He was allowed to continue private consultations with *existing clients*, which included the City of Los Angeles. He oversaw the Service's early feasibility studies in the western states, including that evaluating the Owen River watershed, shortly before Los Angeles acquired water rights of the Owens River. In 1906 he was named to the Board of Consulting Engineers to review the feasibility of Mulholland's scheme for the new aqueduct. A few months later Mulholland hired him to oversee design and construction aspects of the aqueduct, which triggered conflict of interest charges by Owens Valley residents (described in Hoffman, 1981). He remained in the city's employment until the aqueduct's completion in November 1913, and remained busily engaged in private consultations until his death. Known as "J. B.," Lippincott was one of the few contemporaries who publicly defended Mulholland's character after his fall from grace.

The board of consulting engineers felt that DWP should do everything in their power to build the model dam project at Bouquet Canyon. The DWP field engineer overseeing construction activities on the project was Ralph Proctor (see sidebar, below), who had been the BWWS field engineer overseeing construction of the St. Francis Dam, as well as supervising the forensic surveys after it failed (described previously).

Proctor sought to develop some means by which DWP might prove to the world that they were doing the best possible job of compacting the massive earthen embankments required to create a storage reservoir in Bouquet Canyon. The California Division of Highways had developed a wet soil density test procedure a few years earlier. Working independently, Proctor developed his own unique procedure for assessing the bulk density and moisture content of compacted soil, using the soil's *dry density* as his standard. His approach simulated field compaction operations by varying the energy input and soil moisture content in the laboratory, so these variables could independently be evaluated. The results pleased everyone because contractors could be told how much moisture to add or subtract to make compaction operations most efficient. Proctor authored a series of four articles that appeared in Engineering News Record in August and September 1933, a few months after the Bouquet Canyon embankments were completed. Proctor's procedures were well reasoned and easy to employ. With the rapid evolution of large earth-moving equipment (like scrappers) in the early 1930s, the construction industry was in dire need of some measurable standard by which soil compaction could be judged and evaluated, especially for high risk or high value earthen structures, like dams.

Ralph Roscoe Proctor (1894-1962)

Origins of the Proctor Compaction Test. Ralph Proctor joined BWWS in 1916 after studying engineering at USC for two years. Proctor spent his entire career with LADWP as a field engineer, including all of the surveying work on St. Francis while it was under construction, as well as supervising the post-failure surveys. He gained considerable recognition for his efforts developing the soil compaction test that bears his name in 1933, while serving as the field engineer on the Bouquet Canyon Reservoir embankments, the replacement structure for St. Francis. The Proctor Compaction Test (ASTM D 698) and the modified Proctor (ASTM D 1557) have become standardized test procedures used around the world. In 1948 Proctor authored four papers for the Second International Conference on Soil Mechanics in Rotterdam, including one titled *The Elimination of Hydrostatic Uplift Pressures in New Earthfill Dams*, considered one of the pioneering papers on a subject dear to the hearts of DWP engineers who lived through the humiliation of the St. Francis disaster. His last project was the construction of the Baldwin Hills Reservoir, which failed a year after his death, in December 1963.

Proctor's compaction test soon evolved into a national standard when the Army Corps of Engineers began employing it for construction of highways and airfields. The American Association of State Highway Officials (AASHO T-99) adopted Proctor's procedure for use on highways in 1938. This procedure was also adopted by the American Society for Testing Materials (ASTM) in 1942. Proctor's original test employed an input energy of just 12,400 ft-lbs per cubic foot of soil. In 1947, shortly after the Second World War, the Corps of Engineers developed a modified Proctor compaction test procedure, which employed an input energy of 56,000 ft-lbs per cubic foot of soil. This was intended to better simulate the compactive effort engendered by the much larger construction equipment developed since 1933. Increased soil density correlated with improved bearing capacity, needed for heavier vehicles and aircraft, such as the B-36 bomber. The modified test procedure was adopted by AASHO as T1-180 in 1950, but was not published by ASTM until 1958, with a slightly different mold size.

POST FAILURE NOTES

The City undertook demolition of the dam's recognizable pieces in the late summer of 1929, following the death of an 18-year old man who fell from Block 1 when his companion threw a rattlesnake at him (the victim's father watched from below). The father of the deceased sued the City. The demolition work appears to have been carried out by City public works crews, working with the City fire department. Dynamite charges were placed in holes jack-hammered into the concrete. Keystone Newsreels filmed some of the dike section being exploded, as well as excavation work on the upstream heel of Block 1, shown in Fig. 66.

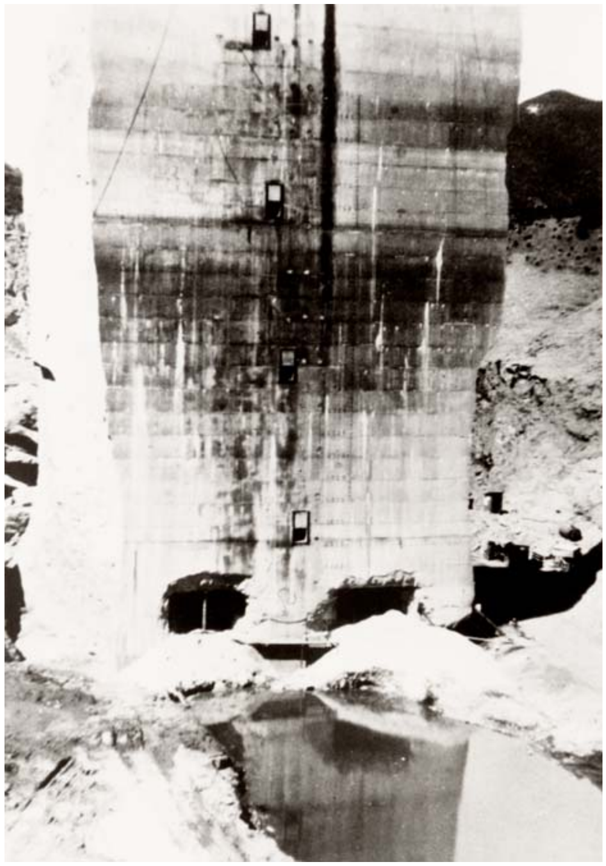


Figure 66. View looking at upstream heel of Block 1 in mid-1929, when the City was engaged in demolition work at the damsite. These adits in the upstream heel of Block 1 were loaded with dynamite and detonated, blowing the block backward, just like Blocks 2/3/4. Block 1 toppled backward and split into five discernable pieces. As in the case for Blocks 2/3/4, the concrete separated along undulatory cold pour joints, due to the weak tensile strength along these horizons, coated with a high water content laitance layer.

BWWS rebuilt Powerhouse 1, repairing the same turbines and placing them inside a new structure, which still stands. The dependent's housing at Powerhouse 2 was moved upstream of its former position, in a more protected side canyon on the northwest side of San Francisquito Creek. The City built old San Francisquito Canyon Road in the canyon bottom in 1929 to allow access between Powerhouses 1 and 2. The road was paved by Los Angeles County in 1931 and operated until massive flooding in early 2005. The County later established Road Camp No. 7 in the upper reservoir area sometime during or shortly after the Second World War. Inmates at this road camp were engaged in grading the new high speed highway alignment, which bypasses the dam site, about 1/4 mile north. The County's Road Camp work furlough program appears to have been suspended in the early 1970s, and the road remained unpaved for 30 years until it was paved in 2005-06 and opened to traffic in 2006.

Dozens of pieces of the dam can still be viewed within San Francisquito Canyon, even Block 35. City crews were ordered to the site in the summer of 1929 to break up some of the largest and most conspicuous pieces, such as Block 16/44. This was to discourage gawkers who were infiltrating San Francisquito Canyon to take pictures of Block 1 and gather souvenirs. The plunge pools excavated by the dam failure (Fig. 29) remained in the canyon bottom and were stocked with fish and used for swimming by the children living at Powerhouse 2 (Kott, 1998). The pools were partially filled with sediment brought by heavy flooding in March 1938 and again, in January 1952, after which, what remained of them was filled in by city crews. The city then built a swimming pool for the Powerhouse 2 residents, adjacent to their living quarters. The main channel of San Francisquito Creek also shifted at the dam site, and instead of running between Block 1 and the right abutment, now cuts a deep chasm between Blocks 1 and 2/3/4. This change likely occurred when the old road was graded in 1929.

Field trips to the St. Francis dam site became pilgrimages of passage for all geology students in enrolled in the colleges and universities of southern California, including the author's. Students were paraded about the site and informed what a buffoon William Mulholland and any other engineers must have been to have constructed a dam across the San Francisquito fault. Everyone should know that *faults are dangerous*, and should be avoided at all costs, etc. As far as I've been able to tell, no mention was ever made, at any time, about any pre-existing landslides in the opposite abutment, underlain by the micaeous Pelona Schist. So, the simple inclusion of a geologist may not have prevented a catastrophe form occurring at this site, unless it would have been Bailey Willis, the most hated man in Los Angeles in 1928 (described previously). So it is that truth is often stranger than fiction.

In 1973 Hollywood produced the movie *Chinatown*, staring Jack Nicholson and Faye Dunaway. The film was a drama that sought to exploit conspiracy theories about BWWS engineers discharging water at night to feign water shortages and politics playing a decisive role in reservoir siting and engineering, or lack thereof. In regards to the portrayal of the City's water resources engineers, the movie is so filled with arch stereotypes it merits no further comment. Unfortunately, for millions of people, *Chinatown* is their only exposure to William Mulholland and the politics of water resources engineering in Los Angeles. In 1974 the disaster movie *Earthquake*, starring Charlton Heston and a cast of others, portrayed the disastrous demise of Los Angeles in a major earthquake. This film plays upon Hollywood's old fears about Mulholland Dam, which is portrayed failing via a mechanism of progressive cracking of its downstream face, which subsequently inundates Hollywood. The dam failure sequence was filmed using a model.

SAN FRANCISQUITO CANYON TODAY

Over the past decade the lower reaches of San Francisquito Canyon have been subdivided. The old Harry Carey Ranch, situated about a mile above the canyon's mouth, was named for the silent western film star, who owned the ranch and spent weekends and vacations there. It survived the flood and is being turned into a local museum. DWP Powerhouses 1 and 2 continue to labor on, their first generator replacements not occurring until the mid-1980s. A number of the people living and working at the DWP Powerhouses are second and third generation employees, who've decided to work and live in the canyon they love. Frank Rock, a native of Newhall born on the 25th anniversary of the dam's failure, leads an annual walking tour of the dam site for the local Santa Clarita Historical Society every March, on the Saturday nearest the anniversary. In the late 1990s Frank led the excavation of an old 1916 Saxon touring car in the riverbed, about half a mile downstream of the dam, and is thought to have belonged to damkeeper Tony Harneschfeger. It was re-taken by the creek during record flooding of the canyon in 2005 and moved over a mile downstream, near the mouth of Drinkwater Canyon.

The Santa Clarita Historical Society maintains a nice museum displaying many artifacts of the dam failure in the old Southern Pacific Depot that has been relocated to the William S. Hart State Park on State Route 126 (San Fernando Road), about a mile west of the Antelope Freeway. It is open on the weekends. The museum also sells several videotape lectures, including one of Charles Outland's St. Francis Dam slide lecture, Frank Rock's tour of the dam site, and an interview with flood survivor Ivan Dorset. The best option for interested parties is to contact the Santa Clarita Valley Historical Society by E-mail at info@scvhistory.com or visit their website at http://scvhistory.com/scvhistory/ The website has a special link to the dam failure at http://www.scvhistory.com/scvhistory/stfrancis.htm

The historical society runs a superb field trip each year on the weekend closest to the anniversary of the failure, March 12th-13th. Try to reserve a seat early for that annual trip.

A small informal museum of sorts is also maintained at the Forest Service Fire Station at Powerhouse 2. Powerhouse 1 maintains a small, but impressive museum, with a 7-minute videotape recalling the historical significance of that facility, the City's first powerplant. Reservations are required.

The dam site lies within the Angeles National Forest. In 1997 the Forest Service began administering a program requiring "Adventure Permits" for parking along highways and roads in their jurisdiction. We suggest you inquire locally about where these permits can be purchased. Cars can be safely parked along the new highway alignment (opened in 2006), near a gated entry to the old highway, which passes through the dam site. This entry is about 3/8 mile north of the dam site, adjacent to the expansive tree-filled valley, just above a major cut in the red vaqueros Sandstone beds, where the auxiliary spillway was situated prior to grading of the new highway alignment. If you go hiking around the dam site, wear appropriate clothing and footwear. Exercise extreme caution when climbing over the jagged concrete blocks. Climbing onto Block 2/3/4 can be extremely hazardous. Rattlesnakes and scorpions are very common to the area.

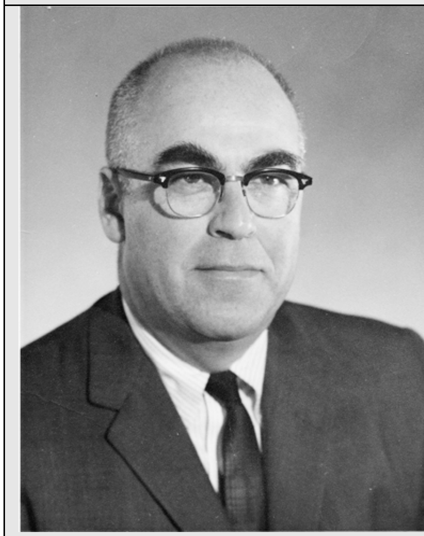
Additional trivia and background information is available in a series of posted interviews with the senior author J. David Rogers by the L.A. Grim Society, posted on their website, The Grim Archives, at: http://www.grimsociety.com/archives/rogers.html

The author also has several PowerPoint lectures on the St. Francis Dam failure posted as color pdf files for easy downloading and storage on his website, at:
http://web.umr.edu/~rogersda/st_francis_dam/
These can be posted on an FTP site as PPT files if you would like to use them for teaching. Simply send an e-mail request to rogersda@umr.edu

ACKNOWLEDGEMENTS

My interest in the St. Francis Dam was piqued by one of my Berkeley mentors, Professor Jerome M. Raphael (see sidebar), who was renown for his expertise in concrete gravity dams. I inherited his collection of materials on the dam, which came from Bureau of Reclamation engineer Jack Savage. My interest was stimulated further by my interviews with Stanford Professor Richard H. Jahns in 1980, and Los Angeles consulting geologist James E. Slosson in 1985. Like Raphael, Jahns and Slosson believed that the true causes of the failure had not been adequately evaluated at the time. Field work and background research was carried out between 1977-99, alongside Professors Lawrence J. Herber at Cal Poly and Perry Ehlig of Cal State LA, C. Michael Scullin, Patrick L. Drumm, Frank Rock, and Dan Kott.

JERRY RAPHAEL – A SPECIAL MENTOR



Jerome M. Raphael (1912-89)

The author’s interest in the St. Francis Dam was fostered by the late Jerome M. Raphael (1912-89), professor of structural engineering at the University of California, Berkeley. I got to know Raphael while working on the 1976 Teton Dam failure near Rexburg, Idaho, as part of my graduate research for Professor H. Bolton Seed at Berkeley. Professor Raphael mentored my interests in civil engineering history, dam engineering, and the importance of considering multiple failure mechanisms.

A graduate of MIT in architectural engineering (BS, 1933, MS, 1934) Raphael had been a protégée of John L. Savage, chief design engineer of the U.S. Bureau of Reclamation, before accepting a teaching position at Berkeley in 1953. He gave me many original materials about the St. Francis Dam failure and the external reviews of the San Gabriel and Mulholland Dams that had been passed onto him by Savage. Professor Raphael provided the stimulus for my work on re-assessing the St. Francis Dam failure by exploding the myths I held about the dam’s untimely demise being tied to the ancient San Francisquito fault. Raphael bluntly informed me that “*no dam could fail simultaneously on both abutments, with such differing geologic conditions. They never really figured out how it failed because it was too complicated, and the negative publicity caused by all of the human suffering threatened passage of the Boulder Canyon Project Act and Hoover Dam. It was in everyone’s interest to sweep it all under the rug and get on with life. Mulholland acquiesced, took full blame for the tragedy, and thereby concluded the public spectacle of trial for criminal negligence. It was most accommodating of him to fall on his sword like that; sparring the engineering profession further slander and embarrassment*.”

Raphael also informed me that in 1930, while Jack Savage was chairing the state panel that reviewed Mulholland Dam, he took it upon himself to discretely inform BWWS chief engineer and general manager Harvey Van Norman of the deficiencies city engineers had employed in their designs of the Mulholland and St. Francis Dams; and that Van Norman had been appreciative of his tact. Savage presumed that these details were subsequently passed onto Mulholland by Van Norman, who was like a son to the latter.

Like Bob Ballard trying to hunt down the location of the Titanic, I was irrevocably hooked, committing myself to solve the mystery. Professor Raphael guided my efforts over the succeeding decade, until he passed away in March 1989, within a few weeks of Professor Seed.

In 1991 Dick. Proctor encouraged me to publish my findings in AEG’s *Engineering Geology Practice in Southern California*, released at the annual meeting in October 1992. This article was singled out for recognition by the E. B. Burwell Award of the Geological Society of America and the Rock mechanics Award of the National Research Council, both in 1994. That notoriety led to encouragement by Doyce Nunes and Charles Johnson to prepare a historical article titled *A Man, A Dam and A Disaster*, jointly published by the Historical Society of Southern California and the Ventura County Historical Society in 1995 and re-printed in 2003. This led to my nomination as the 1996 R.H. Jahns Distinguished Lecturer in Engineering Geology by incoming AEG President Eldon Gath.

I have also been blessed with a great deal of invaluable help. Frank Stockl at LA DWP researched the engineering drawings of the St. Francis project and provided rare photographs from DWP files. His assistance was essential to my unravelling so many details of the site topography and the original design of the dam. DWP archivist Paul Soifer was of invaluable help in providing access to hard-to-find agency references. Charles Johnson at the Ventura County Museum has provided access to dozens of unpublished photos, the panorama views, Charles Outland's research materials and a sympathetic ear. Paul Atwood, Linda Vida, and Gerald Gieffer of the U.C. Water Resources Center Archives at U.C. Berkeley provided access to the collections of Charles H. Lee, J. B. Lippincott, and Walter L. Huber, as well as materials from C. E. Grunsky and John D. Galloway. Their help has continued year after year, and has been invaluable.

Over the past decade I have continued my research, answering correspondence from interested parties, including the relatives of many people associated in some way with the disaster. I have also continued hunting for documents. The Huntington Library in San Marino, CA honoured me as their 2001 Trent Dames Civil Engineering Heritage Lecturer. This association open the door to more research at the Huntington, whose archivists Bill Frank and Dan Lewis provided invaluable assistance. I began reviewing all kinds of new materials in 2003, including documents from the: Richard Courtney, Pierson M. Hall, E. C. La Rue, Charles C. Teague, and St. Francis Dam Disaster Collections, as well as several of their California Scrapbooks containing newspaper clippings from the 1920s. The Courtney Collection contains a rare copy of Mulholland's testimony at the Los Angeles County Coroner's Inquest, which was copied and reviewed for me by documentary filmmakers and Los Angeles historians Jon and Nancy Wilkman. It provided many missing details about how the dam was designed and constructed, including the salient technical references the BWWS engineers relied upon.

REFERENCES

American Society of Civil Engineers, 1952, Uplift in Masonry Dams: Final Report of the Subcommittee on Uplift in Masonry Dams of the Committee on Masonry Dams of the Power Division: Transactions of the American Society of Civil Engineers, v. 117, pp. 1218-1252.

Board of Public Service Commissioners of the City of Los Angeles, 1916, Complete Report on Construction of the Los Angeles Aqueduct: City of Los Angeles, Department of Public Service, 319 p.

California, State of, 1928, Causes Leading to the Failure of the St. Francis Dam: State printing Office, Sacramento, 77 p.

California Highways & Public Works, 1936, March Storms Took Big Toll: State of California, Division of Highways and Department of Public Works, v. 16, n. 4 (April), pp. 1-9.

Casagrande, A., 1961, Control of Seepage through Foundations and Abutments of Dams: The First Rankine Lecture, Geotechnique, v. 11:3, pp. 161-181.

Civil Engineering, 1933, Arch Dam Committee Renders Final Report: Recommendations for Designing, Construction, and Testing Arch Dams, American Society of Civil Engineering: v. 3, n. 6 (June), pp. 347-348.

Civil Engineering, 1978, Big Thompson flood damage was severe, but some could have been prevented: American Society of Civil Engineers: v. 78, n. 2 (February), pp 72-77.

Clements, Thomas, 1966, St. Francis Dam Failure of 1928: in Engineering Geology in Southern California, ed. by R. Lung and R. Proctor, Southern California Section, Association of Engineering Geologists, pp. 88-89.

Davis, Margaret L., 1993, Rivers in the Desert, Harper Collins, New York, 303 p.

Franklin, J., A. and Chandra, R. (1972). "The slake durability test". Int. J. Rock Mech. Min. Sc. Vol. 9, pp.325-341.

Geschwind, Carl-Henry, 2001, California Earthquakes: Science, Risk, & the Politics of Hazard Mitigation: The Johns Hopkins University Press, Baltimore and London, 337 p.

Goodman, R.E., 1999, Karl Terzaghi: The Engineer as Artist, ASCE Press, Reston, 340 p.

Goodman, R.E., and Shi,Gen-hua, 1985, Block Theory and Its Application to Rock Engineering: Prentice Hall, Inc., New York, 338 p.

Hays, J. B., 1933, Grouting Dam Foundations and Construction Joints, Civil Engineering, v. 3, no. 11, pp. 606-610.

Hill, R.T., 1928, Southern California Geology and Los Angeles Earthquakes: Southern California Academy of Sciences, 232 pages.

Hoffman, Abraham, 1981, Vision or Villainy: Origins of the Owens Valley-Los Angeles Water Controversy: Texas A&M University Press, College Station, 308 p.

Hoffman, Abraham, 1995, Charles Outland, Local Historian, in The St. Francis Dam Disaster Revisted, ed. D.B. Nunis, Jr., Southern California Quarterly, v. 77, n 1-2; and Ventura County Historical Society Quarterly, v. 40, nos. 3-4, pp. 165-180 (reprinted 2003).

Howell, C.H., and Jaquith, A.C., 1929, Analysis of Arch Dams by the Trial Load Method: ASCE Transactions, v.93, pp. 1139-1166.

Johnson, Arvid M., 1970, Physical Processes in Geology: Freeman, Cooper & Co., San Francisco, 577 p.

Kott, Dan, 1998, personal communication. Mr. Kott was training operator at San Francisquito Powerhouse No. 1. He grew up as a dependent at San Francisquito Powerhouse No. 2.

Lawson, Andrew, 1914, Geologic Atlas of the United States: San Francisco Folio. Tamalpais, San Francisco, Concord, San Mateo, and Haywards Quadrangles, California: U.S. Geological Survey, 19 p. oversize text, and five plates.

Lee, C. H., 1928, Theories of the Cause and Sequence of Failure of the St. Francis Dam: Western Construction News, v. 3, (June 25), pp. 403-08.

Leonards, G.A., ed, 1987, Dam Failures; Proceedings of the International Workshop on Dam

Failures, Purdue University, Aug 6-8, 1985, El Sevier Publishing, 612 p.

Londe, Pierre, 1987, The Malpasset Dam Failure: Engineering Geology, v. 24, pp. 295-329.

Louderback, G.D., 1928, Geology of the St. Francis Dam: Proceedings of the San Francisco Section, American Society of Civil Engineers, v. 24, pp. 8-12.

McMillan, F. R., 1930, Causes of Concrete Disintegration: Engineering News-Record, v. 104 (May 1, 1930), pp. 735-36.

Morton, D.M., and Campbell, R.H., 1974, Spring Mudflows at Wrightwood, Southern California: Quarterly Journal of Engineering Geology, v. 7, pp. 377-384.

Morton, D.M., Campbell, R.H., Barrows, A.G., Kahle, J.E R., and Yerkes, R.F., 1979, Wright Mountain Mudflows: Part II in Landsliding and Mudflows at Wrightwood, San Bernardino County, California: Cal Division of Mines & Geology Spec Report 136, pp. 7-21.

Mulholland, Catherine, 2002, William Mulholland and the rise of Los Angeles: University of California Press, Berkeley and London, 411 p.

Outland, C.F., 1963, Man-Made Disaster: The Story of the St. Francis Dam: Arthur H. Clark Co., Glendale, 249 p.

Outland, C.F., 1977, Man-Made Disaster: The Story of the St. Francis Dam, Second Edition: Arthur H. Clark Co., Glendale, 275 p. (reprinted 2003)

Ransome, F.L., 1928, Geology of the St. Francis Dam Site: Economic Geology, v. 23.

Ransome, F.L., 1931, High Dams: The Viewpoint of the Geologist: Transactions of the American Society of Civil Engineers, v. 95, pp. 149-58.

Raphael, J.M., 1984, Tensile Strength of Concrete: American Concrete Institute Journal, March-April , Title No. 81-17, Technical Paper, v. 81, pp. 158-165.

Rodine, J.D. and Johnson, AM, 1976, The ability of debris, gravity freighted with coarse clastic materials, to flow on gentle slopes: Sedimentology, v. 23, pp. 213-234.

Rogers, J.D., 1984, Some General Aspects of Debris Flows: Article 5.1, National Short Course on Slope Stability & Landslides, University of Wisconsin Extension, 14 p.

Rogers, J.D., 1992, Reassessment of the St. Francis Dam Failure: in Engineering Geology Practice in Southern California, ed. by R. Proctor and B. Pipkin, Association of Engineering Geologists, Special Publication No. 4, pp. 639-666.

Rogers, J. D., 1995, A Man, A Dam and A Disaster: in The St. Francis Dam Disaster Revisited, ed. D.B. Nunis, Jr., Southern California Quarterly, v. 77, n 1-2; and Ventura County Historical Society Quarterly, v. 40, nos. 3-4, pp. 1-109 (reprinted in 2003).

Rogers, J. D., 1997, Man-Made Disaster at an Old Landslide Dam Site: in Ehrenspect, H.E., and Powell, J. R., eds., A Day in the Field with Thomas Dibblee and J. David Rogers, St. Francis Dam area: Dibblee Geological Foundation, Santa Barbara, May 17, 1997, pp. 27-103.

Rogers, J.D., and McMahon, D.J., 1993, Reassessment of the St. Francis Dam Failure: Proceedings of the 10th Annual Meeting State Dam Safety Officials, Kansas City, pp. 333-339.

Schuster, R.L., 2003, Dams built on pre-0existing landslides – the Colorado experience, in Boyer, D., Rogers, W.P., and Santi, P.M., eds., Engineering Geology of Colorado: Association of Engineering Geologists, Rocky Mountain Section, Denver, 32 p. (CD-ROM).

Schuster, R.L., 2006, Interaction of Dams and Landslides – Case Studies and Mitigation: U.S. Geological Survey Professional Paper 1723, 107 p.

Sharp, R.P., Nobles, L.H., 1953, Mudflow of 1941 at Wrightwood, Southern California: Bull GSA v. 64, pp. 547-560.

Shi, Gen-hua, 1993, Block Systems Modeling by the Discontinuous Deformation Method: Topics in Engineering Vol. 11, Computational Mechanics Publications, Boston, 209 p.

Simonds, A.W., 1953, Final foundation treatment at Hoover Dam: Transactions of ASCE, v. 118, pp. 79-99.

Teague, C.C., 1944, Fifty Years a Rancher: Ward Ritchie Press, Los Angeles, 199 p.

Terzaghi, K., 1945, Stress conditions for the failure of saturated concrete and rock: Proceedings of the American Society for Testing Materials, v. 45, pp. 777-801.

Willis, Bailey, 1928, Report on the Geology of the St. Francis Damsite: Western Construction News: v. 3 (June 25), pp. 409-13.