WHO DESIGNED THE ILL-FATED ST. FRANCIS DAM?

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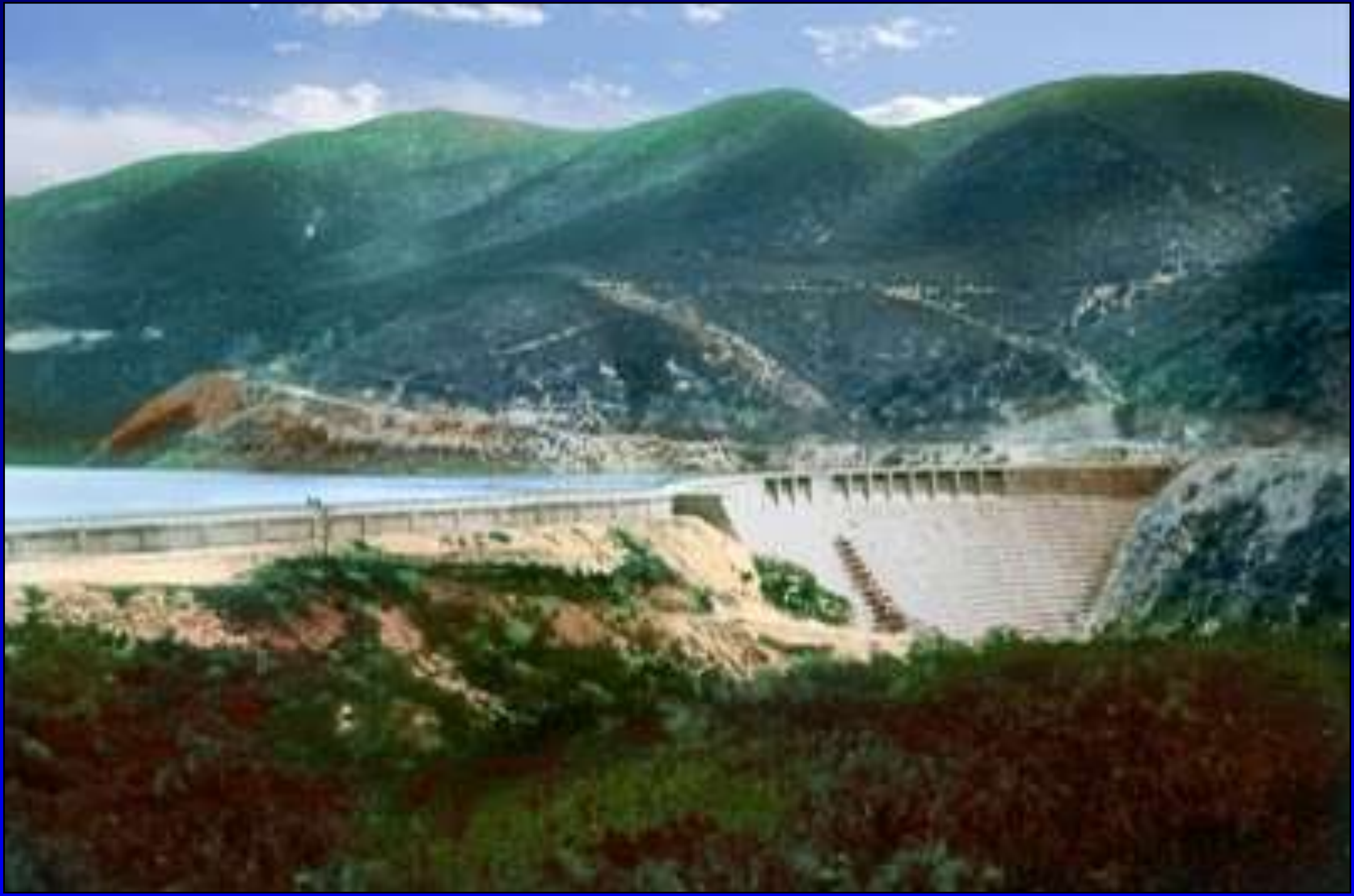


- St. Francis Dam was a 205-ft high concrete gravity-arch dam constructed by the City of Los Angeles in 1924-26
- It failed on March 12-13, 1928, killing at least 432 people, making it the worst American civil engineering failure of the 20th Century

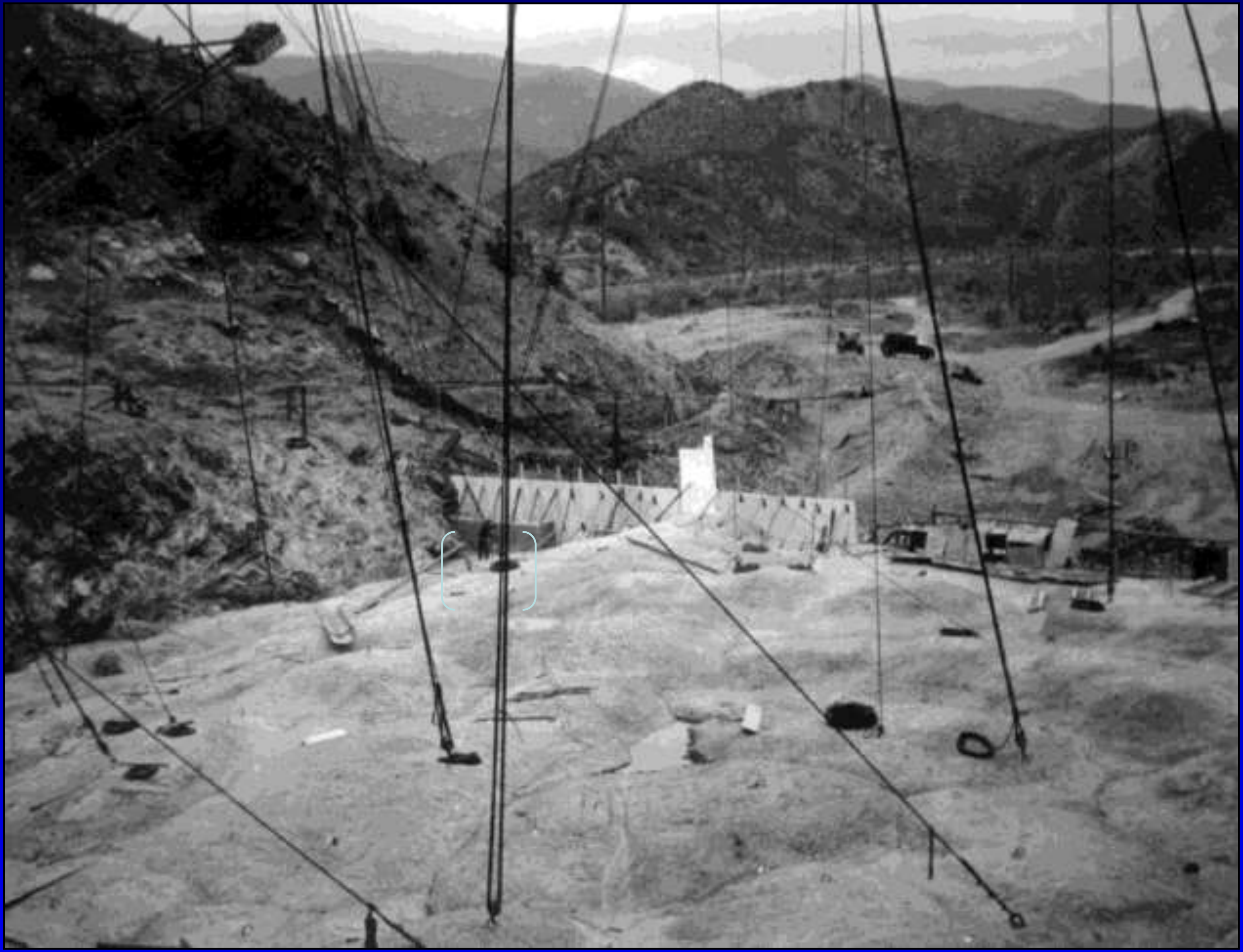
Dam Site in San Francisquito Canyon

- A construction camp was built in San Francisquito Canyon in 1911, during excavation of tunnels in the Pelona Schist between Powerhouses 1 and 2
- William Mulholland believed that the natural constriction of the canyon was an ideal location for a dam

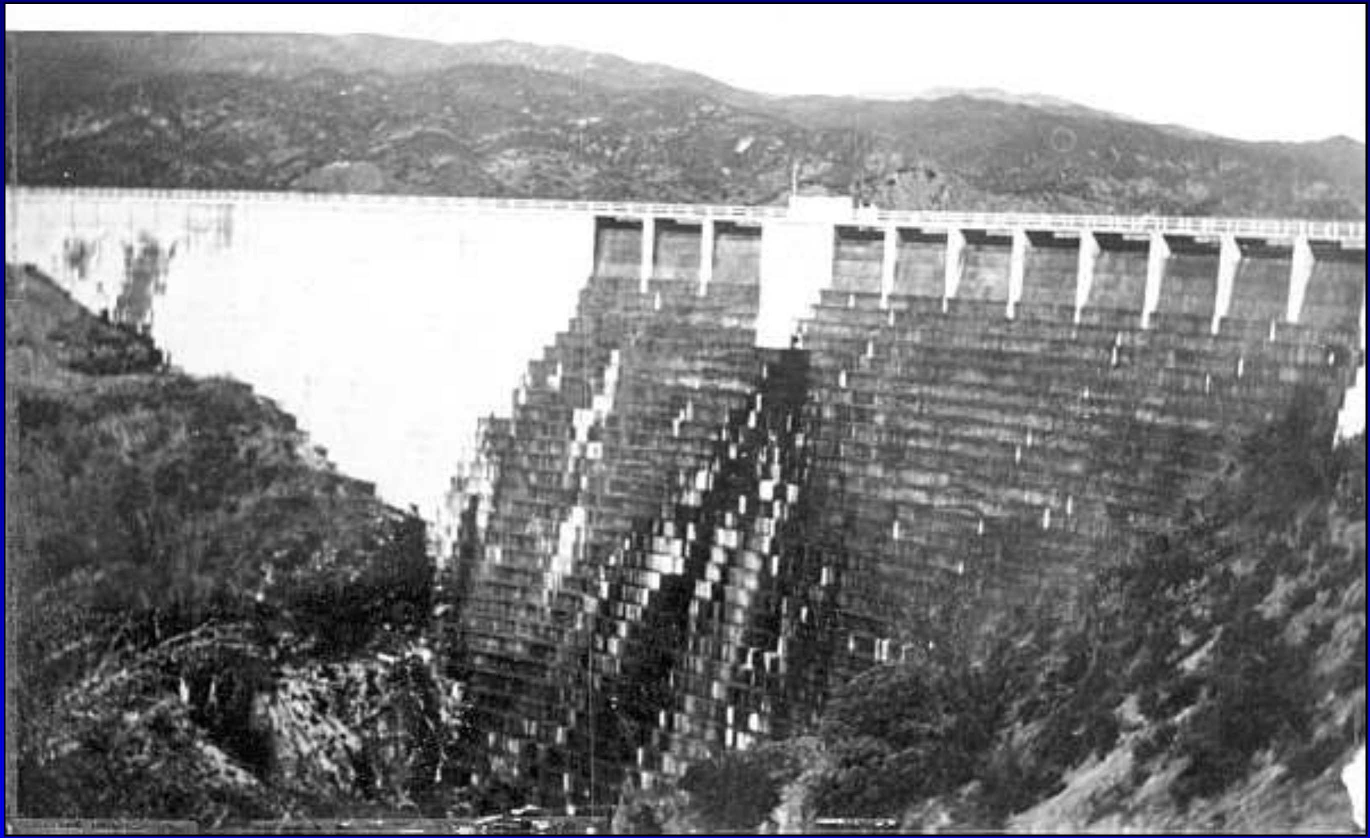
Minimal Abutment Excavation 1924-25

- Views at left show the left abutment excavation into the Pelona Schist – between 6 and 15 ft deep.
- Excavation of the schist and conglomerate on the right abutment averaged only about 4 ft deep.

- **The St. Francis Dam, looking upstream during construction. Note the upper and lower concrete batch plants, the towers and the inclined delivery troughs. This handling scheme resulted in aggregate separation during placement of mass concrete**



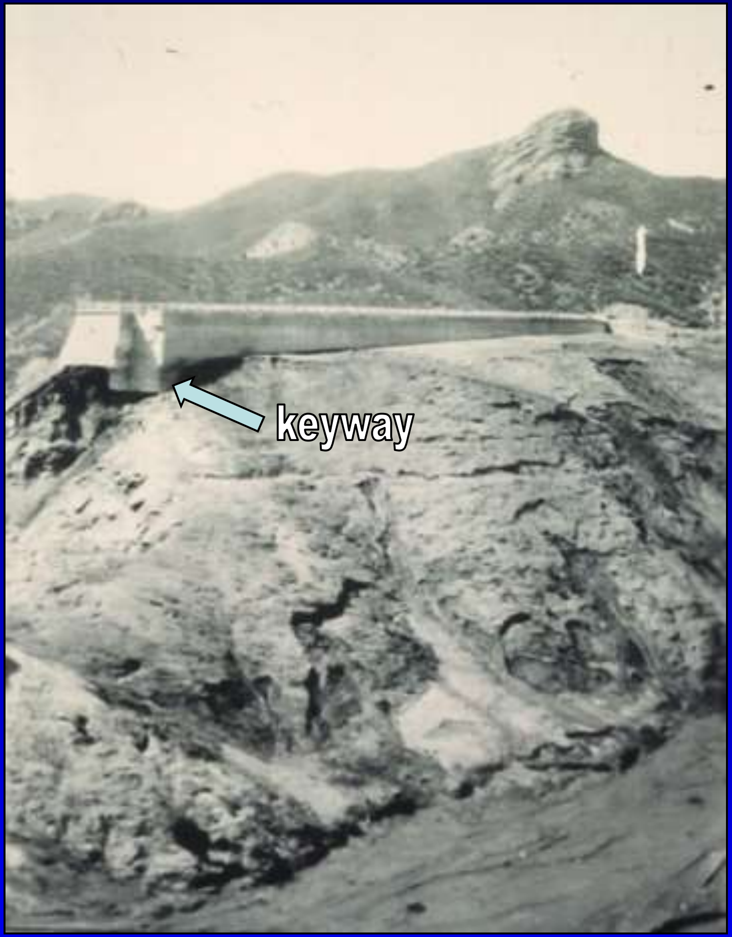
- Construction of the St. Francis Dam began in July 1924.
- This shows the first forms being placed for the upstream heel of the dam, against the 8 ft high cofferdam wall. Note “pillows” of mass concrete and absence of cold pour joints to accommodate contraction.



- **The reservoir was brought to within 3 inches of spillway crest for the first time on Wednesady March 7, 1928. All city reservoirs were full by the following Sunday, March 11th.**
- **Damkeeper Tony Harnischfeger called Mulholland on the morning of the 12th to report spillage of "*dirty water*" from the right abutment area.**
- **That morning about 2 cfs spillage was coming over the spillway panels from wind-whipped waves, shown here around noon on March 12th.**

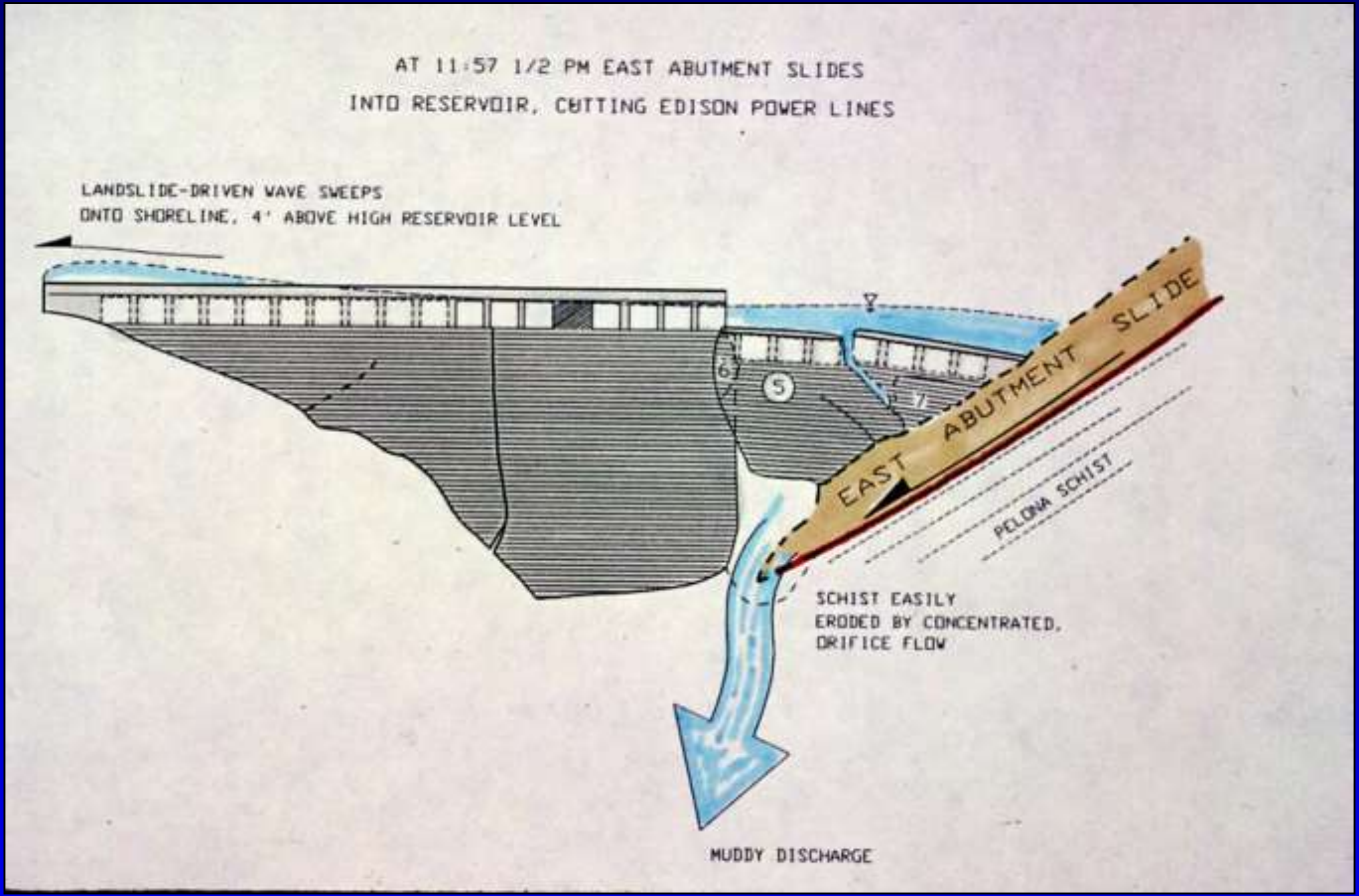
Before and After

Mulholland an Harvey Van Norman inspecting the crest of the dam 12 hours before it failed

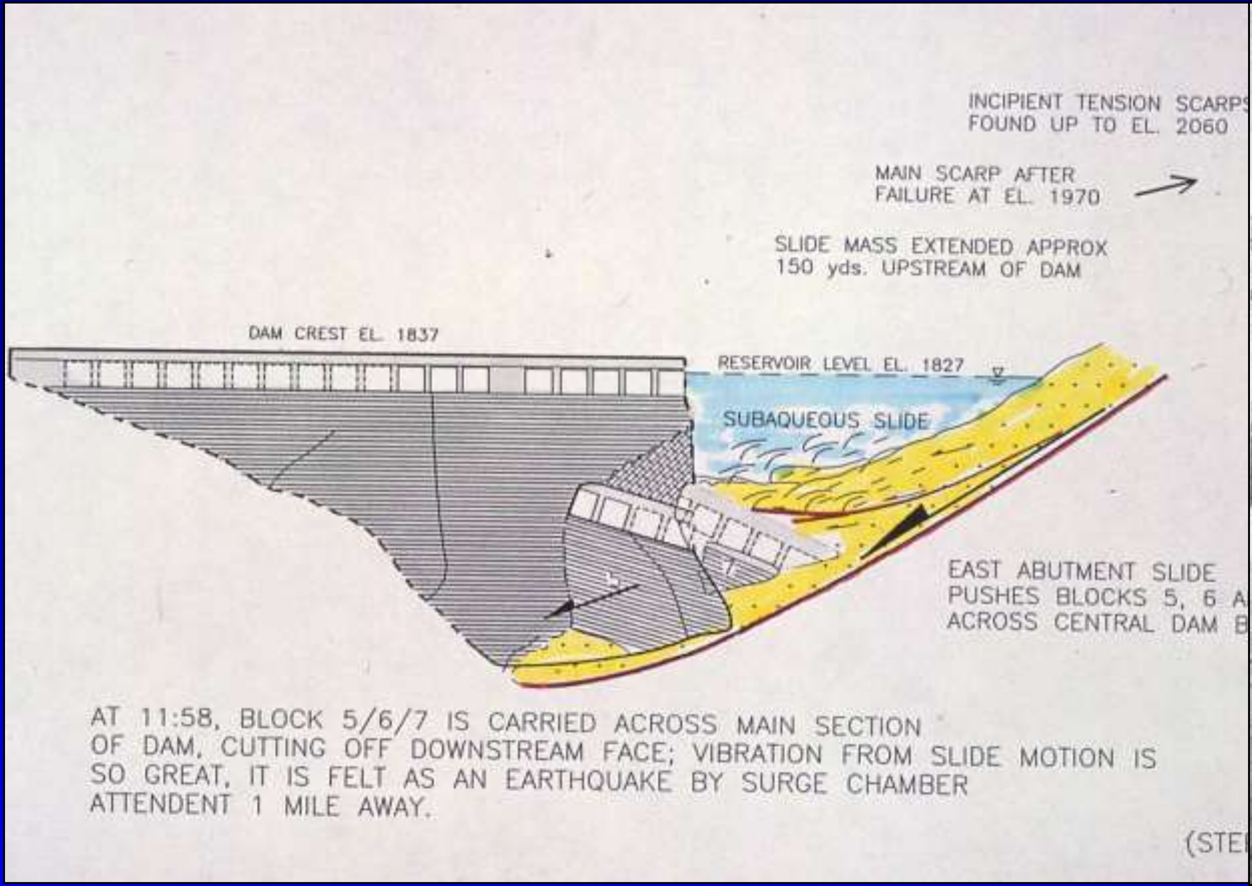


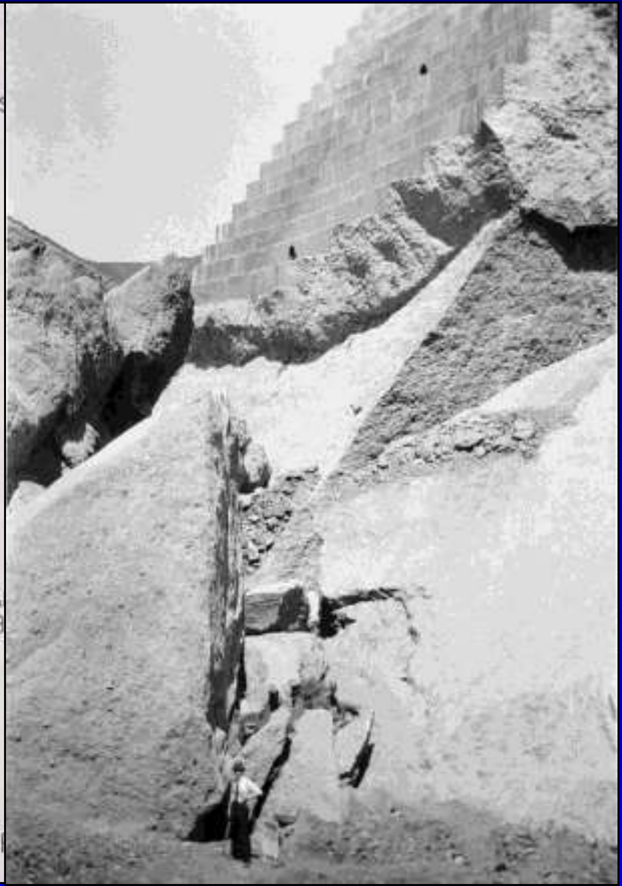
- Comparative views taken of the dam's upstream face and right abutment 12 hours before the failure (at left) and the day after (right)
- Note exposed keyway beneath right abutment dike

Landslide-induced seich

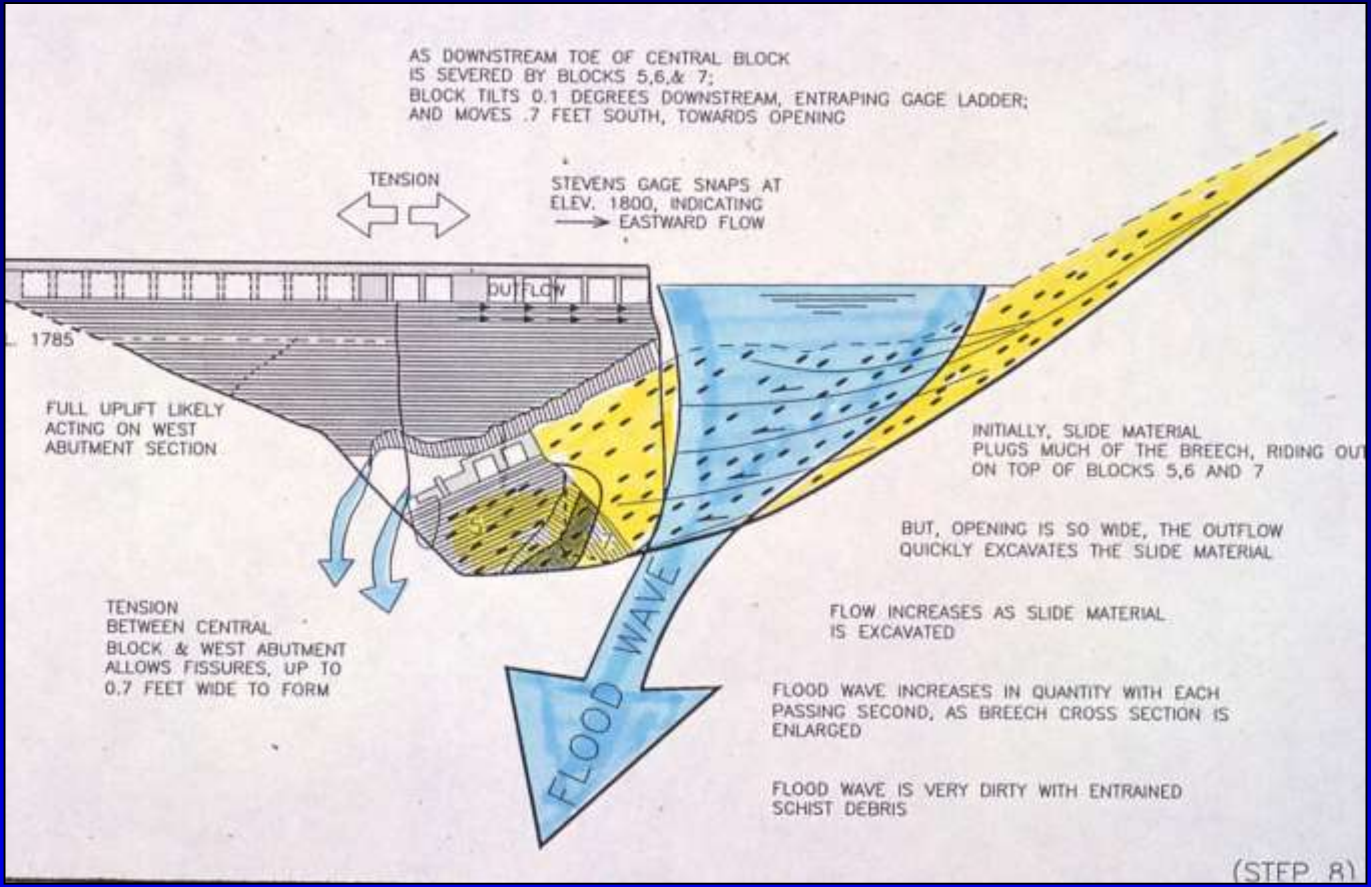


- Around 11:57-1/2 PM a massive landslide of the dam's eastern abutment initiated, severing the SCE 70 Kv Lancaster power lines.
- The entirety of the dam's left abutment was carried across the downstream face of the main dam.
- A landslide-driven displacement wave washed flotsam 4 ft above the reservoir high water line, 3/4 mile to the north

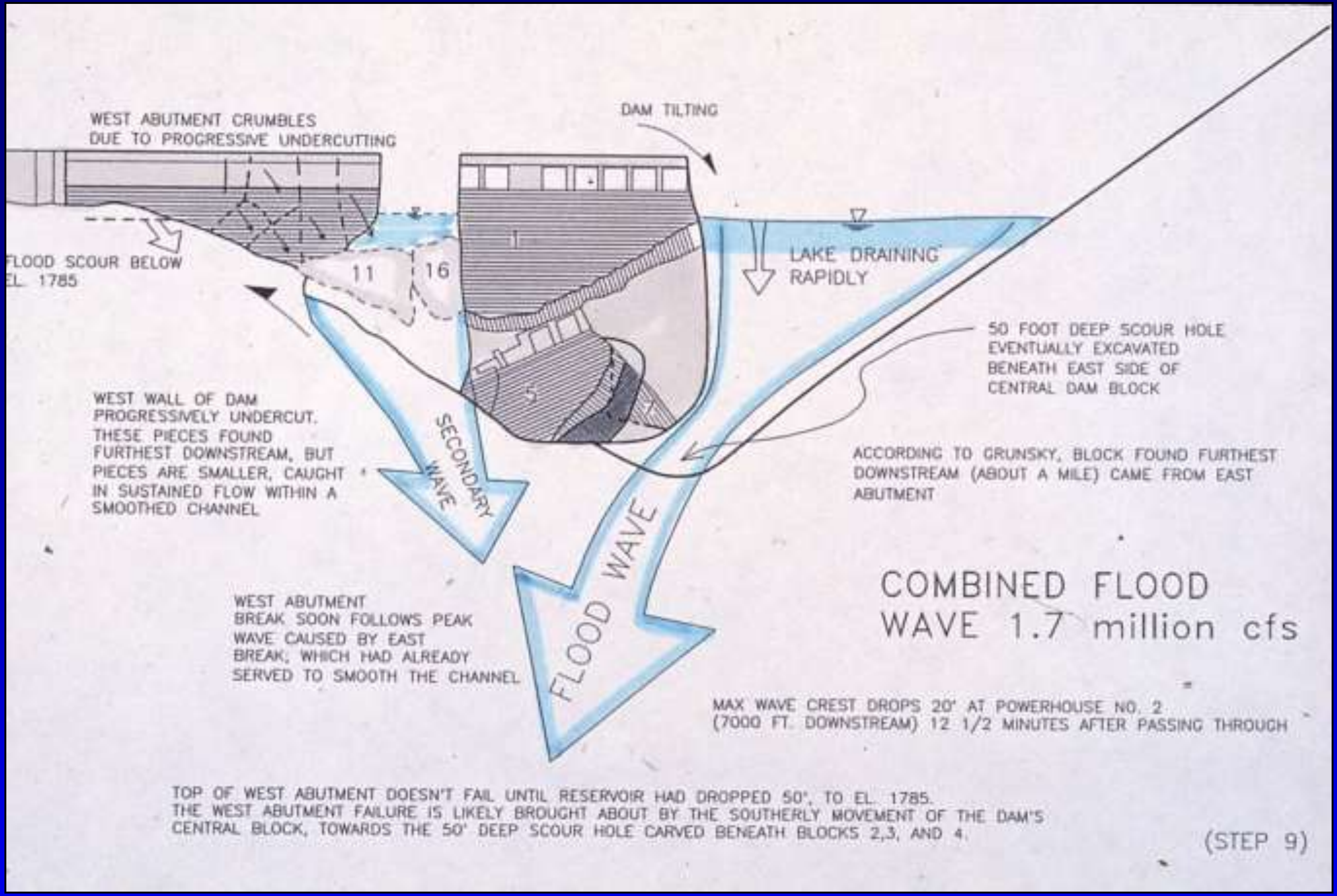




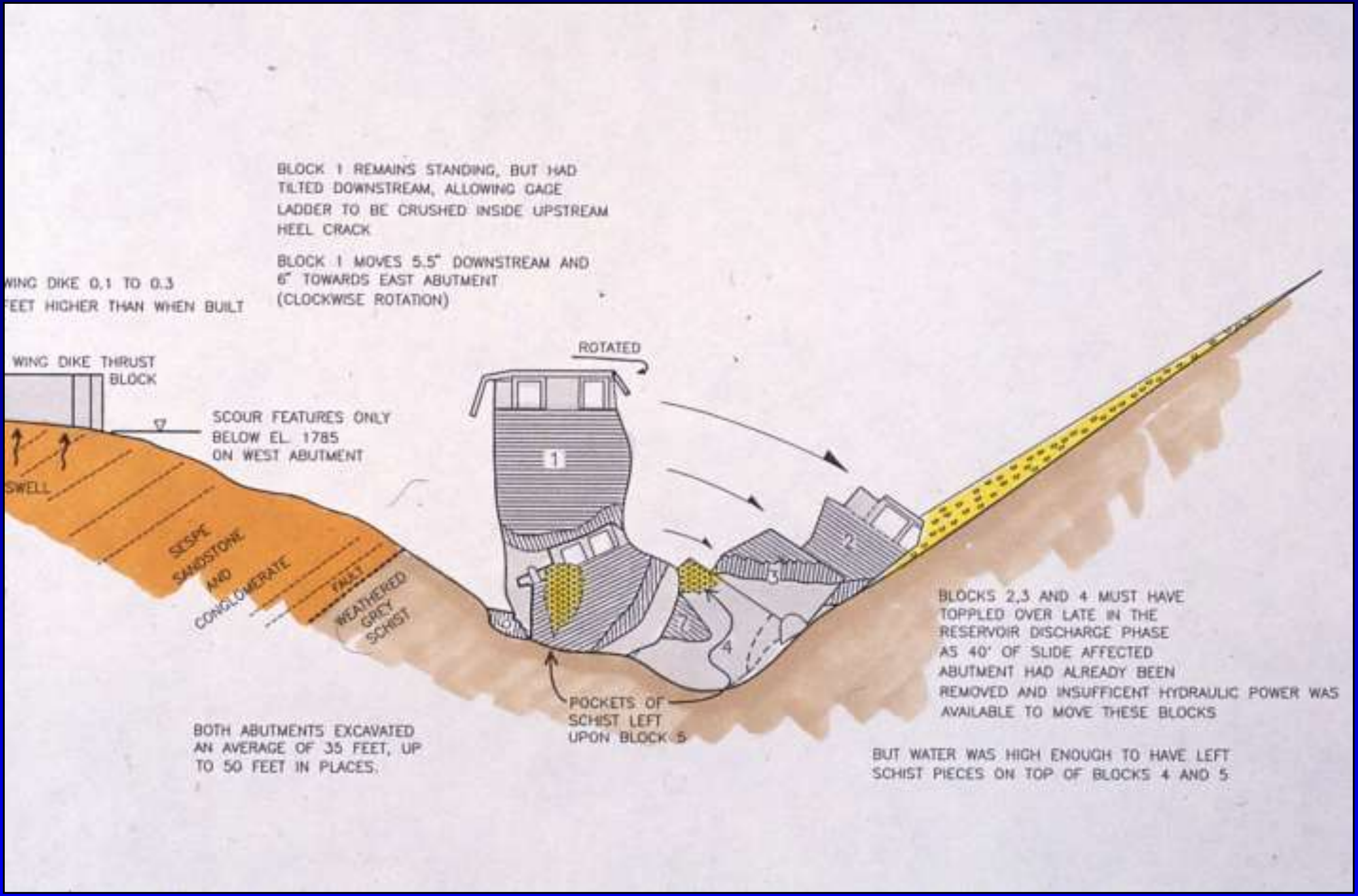
- **The mobilized landslide debris (shown in yellow) carried the dam's left abutment section across the canyon, these heavy blocks sheared off 10 to 20 feet of the dam's stepped concrete face (seen at right).**



- The landslide debris dam was rapidly eroded by the outpouring water, in five to seven minutes
- The out-rushing flow bent the cylindrical stilling well of the Stevens Gage towards the left abutment
- Block 5 originally turned upward, against the right abutment

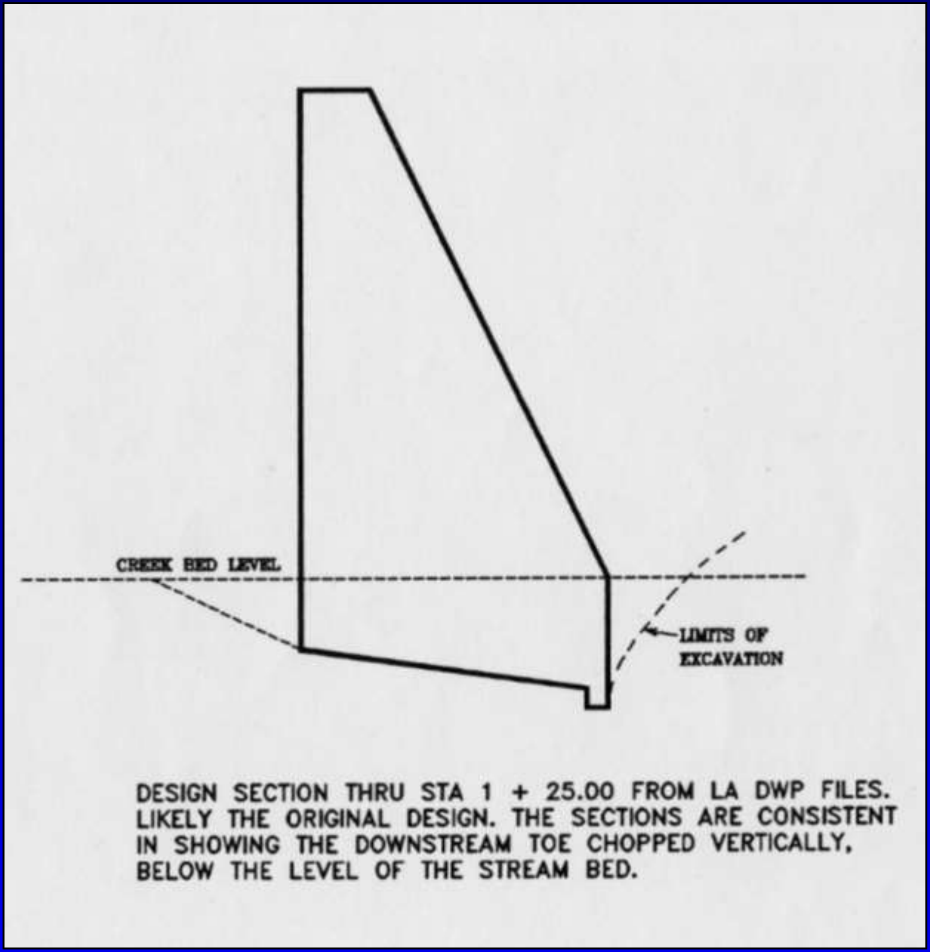


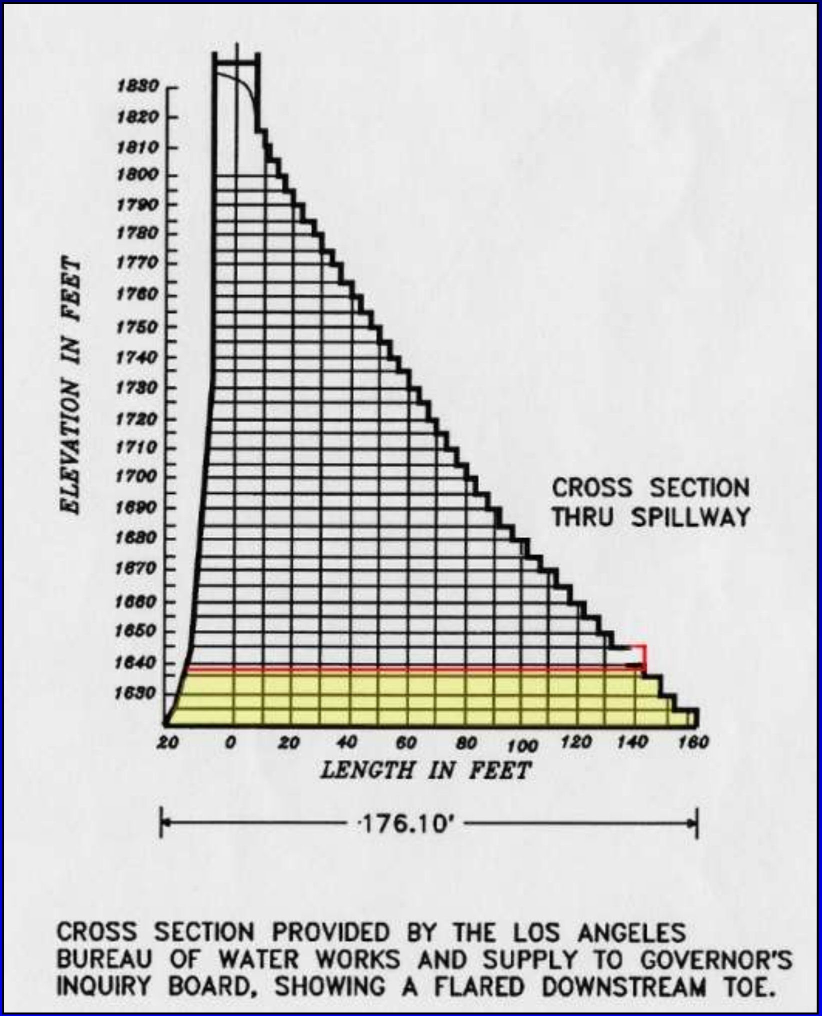
- **As the left side of the main dam was undercut, the middle monolith tilted slightly and rotated, allowing water to enter the shrinkage crack along the west side of Block 1**
- **This triggered a chain-reaction failure of the right abutment, after the reservoir level had dropped 70 to 80 feet.**



- **When the reservoir was about 16 feet deep, the left half of the main dam topped backward at an angle of 54 degrees, after being undercut by the outbreak flood.**
- **The depth of this down cutting was about 35 vertical feet!**
- **Patches of schist detritus were left upon Blocks 5 and 7 (shown in yellow)**

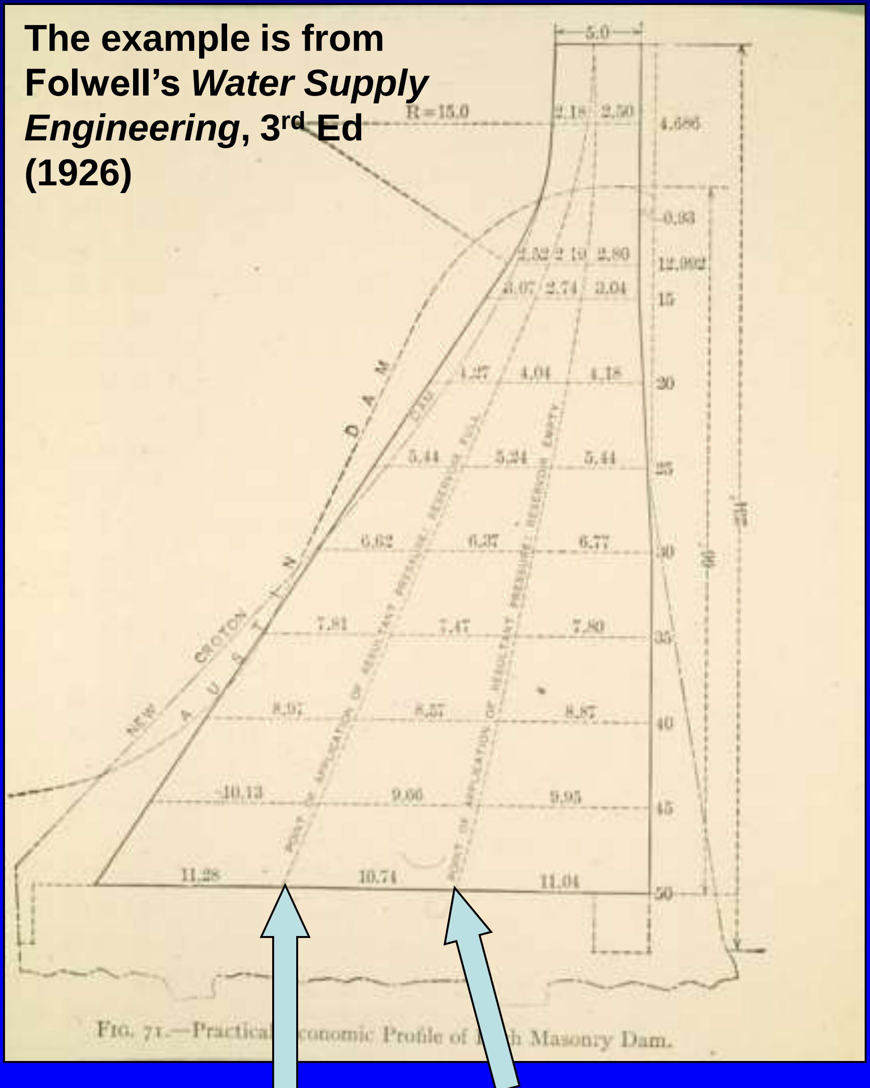
- How the dam site appeared the following morning.
- Note the high water line was noticeably lower downstream of the right abutment (arrow)



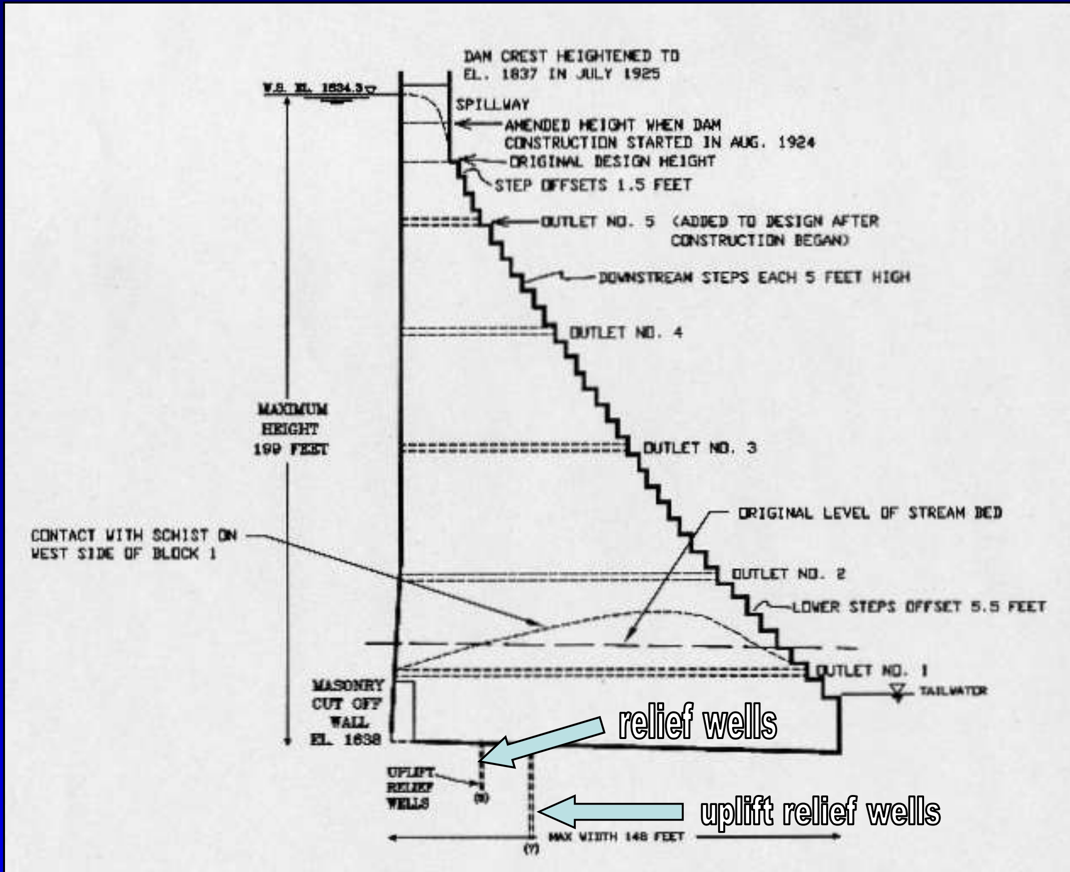


- **Original (1923) design concept for the St. Francis Dam from the LA BWWS files, shown at left**
- **The cross section given to the Governor's Commission by BWWS is shown at right. It extends down to Elevation 1620. The red line approximates the actual limits of the dam.**

Design Methodology in early 1920s



- **Prior to 1928, the example designs published in textbooks summed the gravity forces as a line-of-thrust without reservoir pressure, and another line-of-thrust with full reservoir pressure.**
- **Until 1945, most engineers assumed that concrete was sufficiently impervious to resist saturation, and that dams founded on crystalline rock, such as granite or gneiss, would not be subject to hydraulic uplift.**

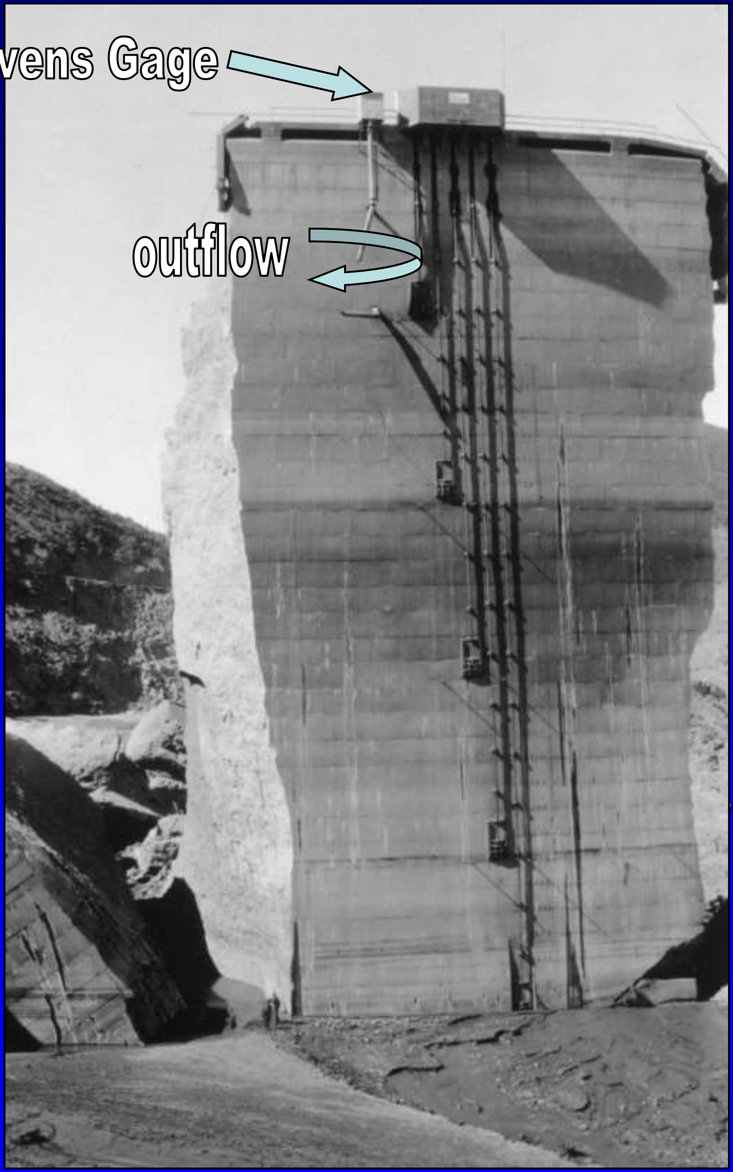


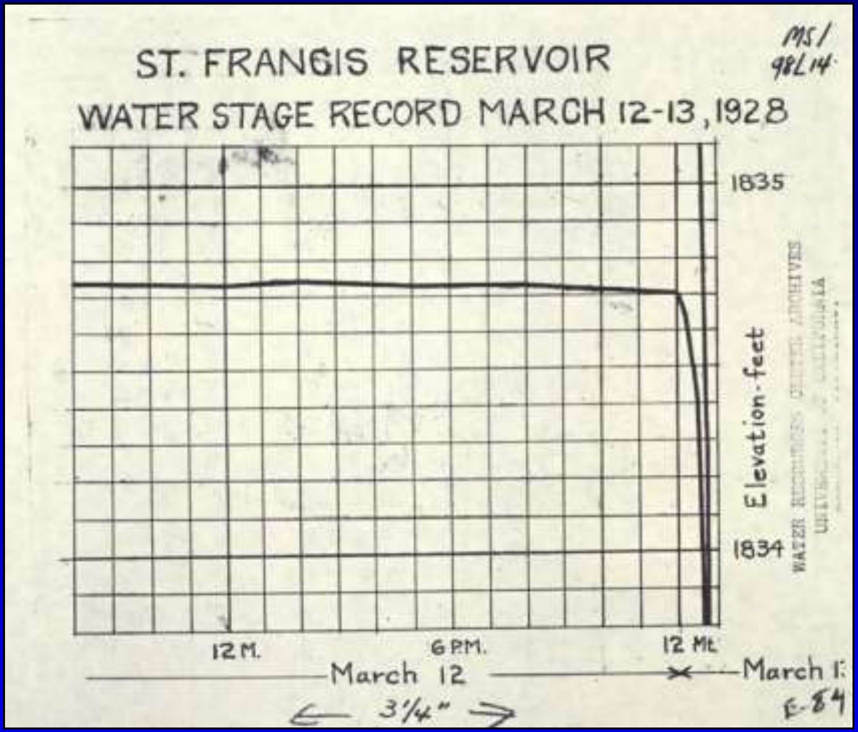
ELEVATION VIEW OF ST. FRANCIS DAM
TAKEN THROUGH SURVIVING BLOCK 1

- **In most of the masonry dams designed before 1928, subdrainage was limited to the maximum sections, and often ignored on the sloping abutments.**
- **The 1959 failure of the Malpasset arch dam in France pointed to the vulnerability of concrete arch dams to uplift, especially, on steeply-sloping abutments.**

- **The main section of the St. Francis Dam was constructed with 10 uplift relief wells, set in two rows, as shown here. Both of the sloping abutments (without uplift relief) failed, on two different rock types.**

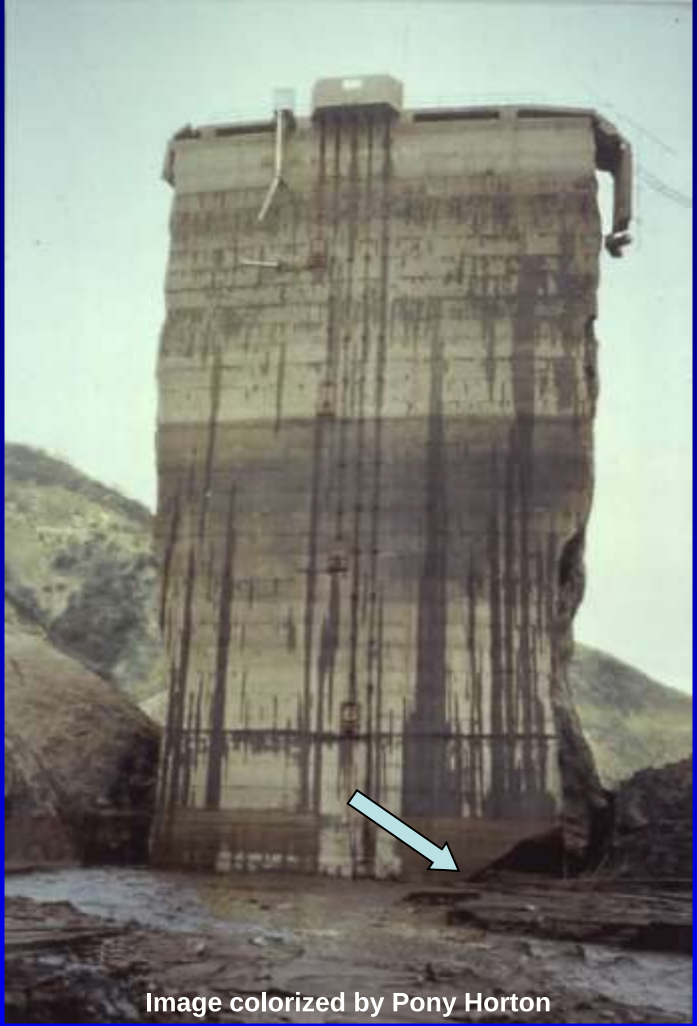
The Stevens Stage Record



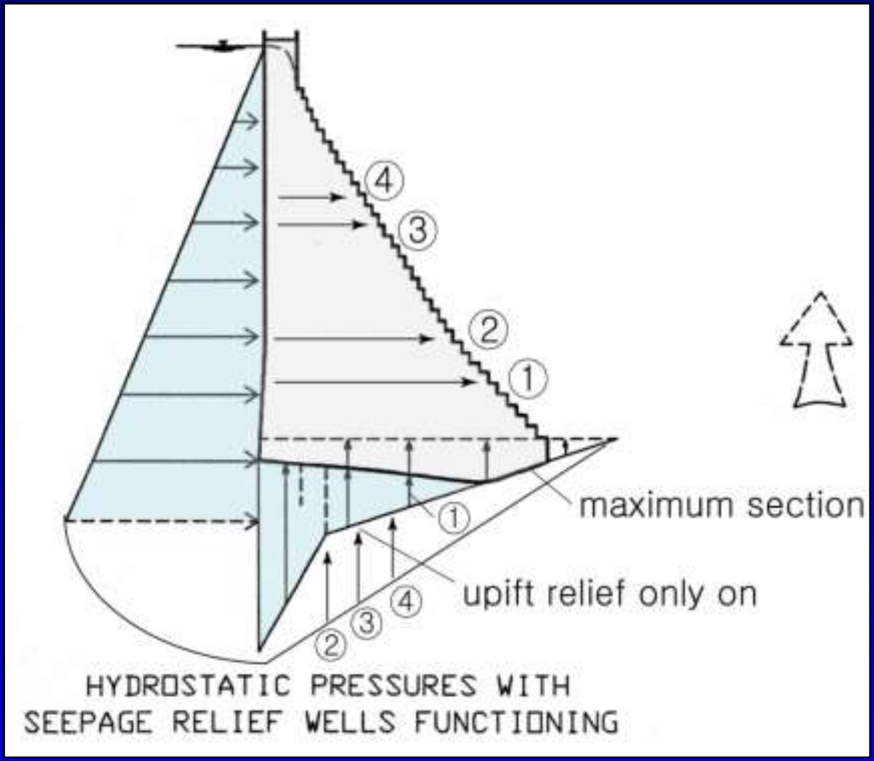


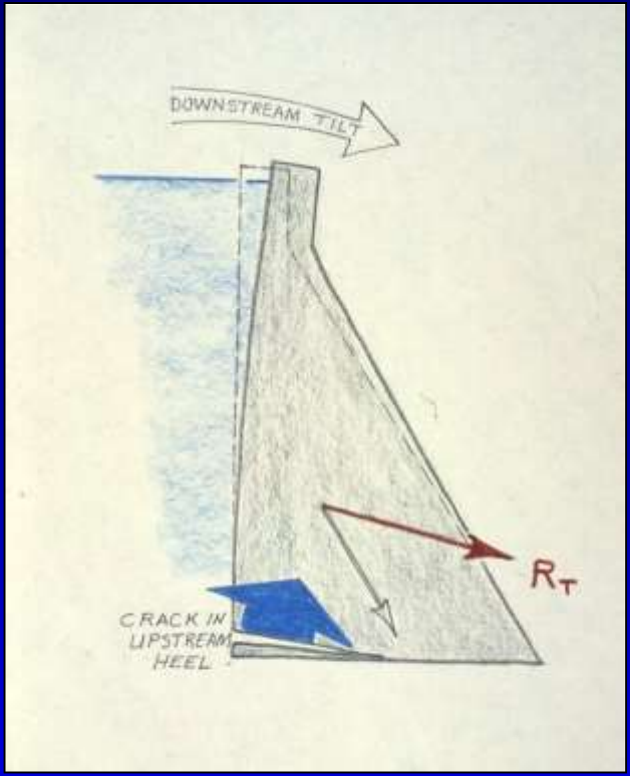
A Stevens reservoir level recorder was mounted on the crest of Block 1 (left view). It recorded a slight drop of the reservoir, beginning around 8 PM, then an increasingly sharp drop beginning around 12 Midnight. The timing mechanism may have been slightly ahead of schedule.

Grunsky's Ladder

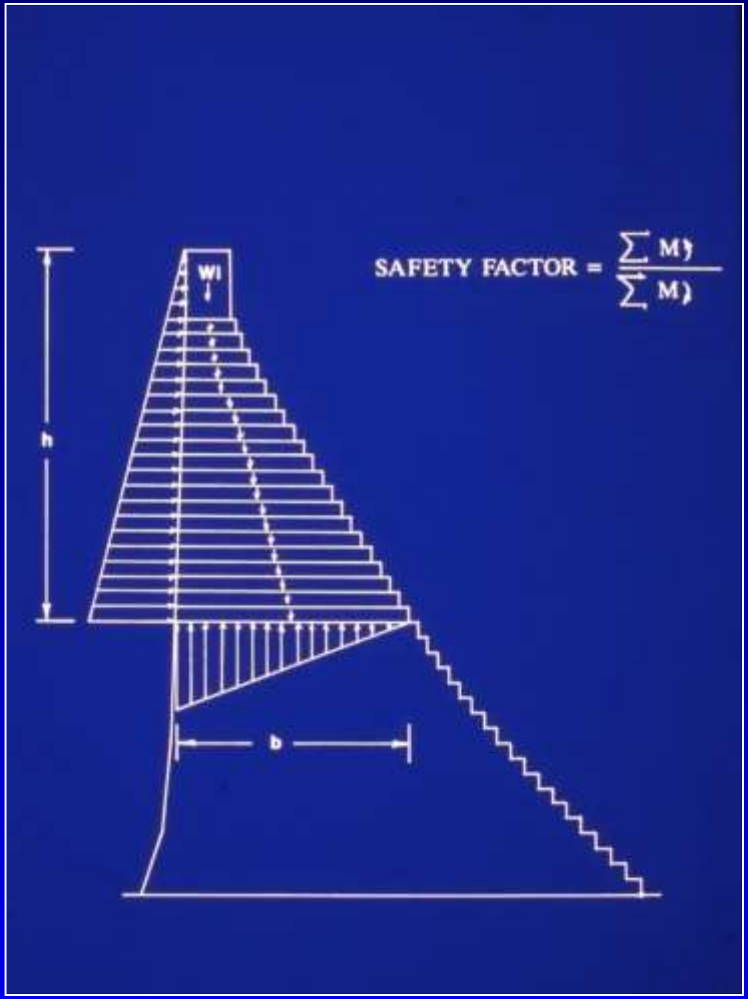


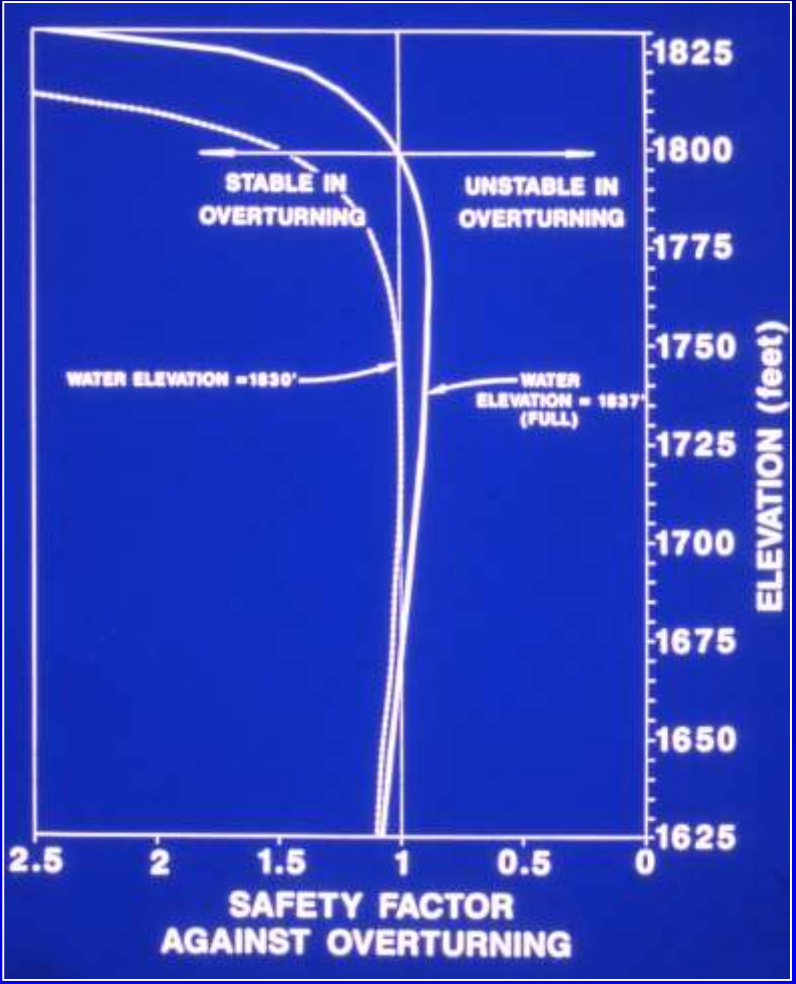
- San Francisco consulting engineer Carl Grunsky discovered the crushed remains of the wooden ladder attached to the dam's upstream face, wedged in a tension crack at the dam's upstream heel. The dam's heel was in tension, which would cause cantilever instability.



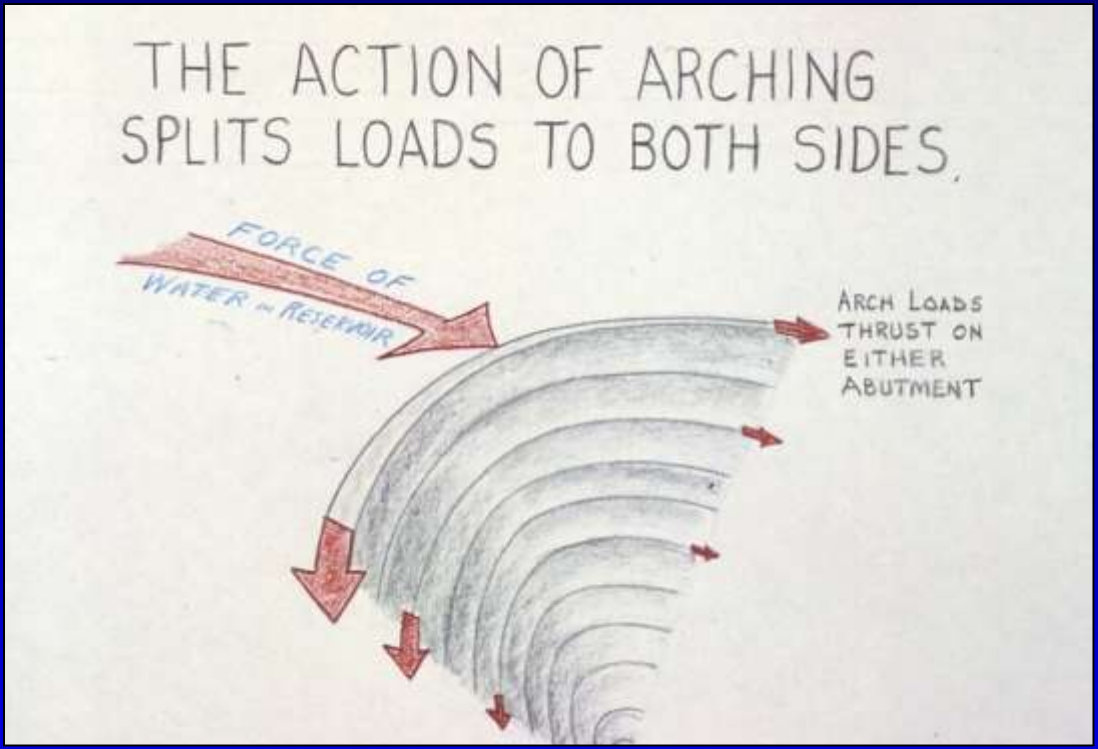


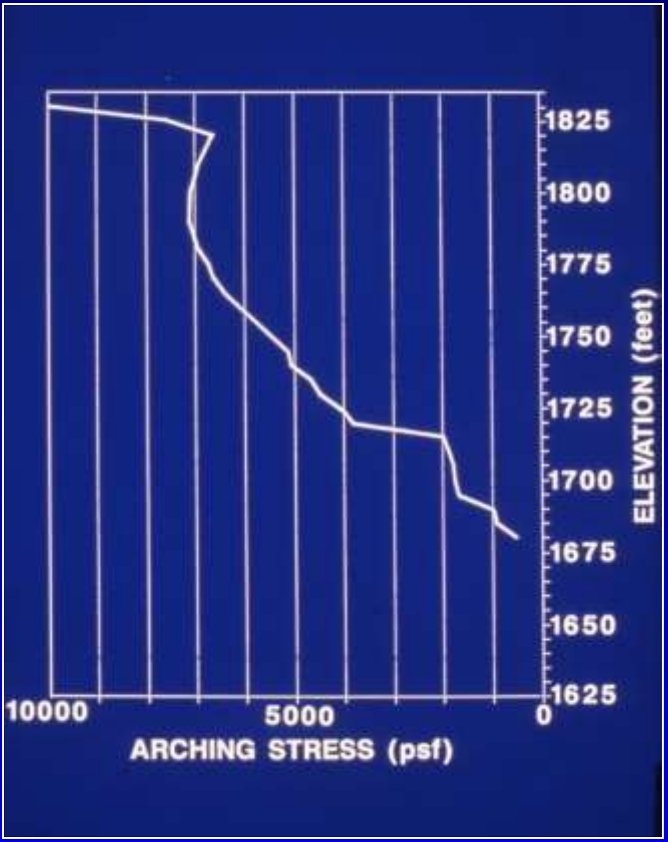
- **Hydrostatic, or uplift forces, act equally in all directions and serve to reduce the effective weight of the dam, and may cause it to become unstable.**
- **If the dam tilted forward ½ degree, this would explain the 3.67 inch drop of the reservoir, recorded 40 minutes before the failure.**
- **When the dam separated at its upstream toe, the resultant thrust would have been shifted 240 feet downstream, indicative of overturning instability.**



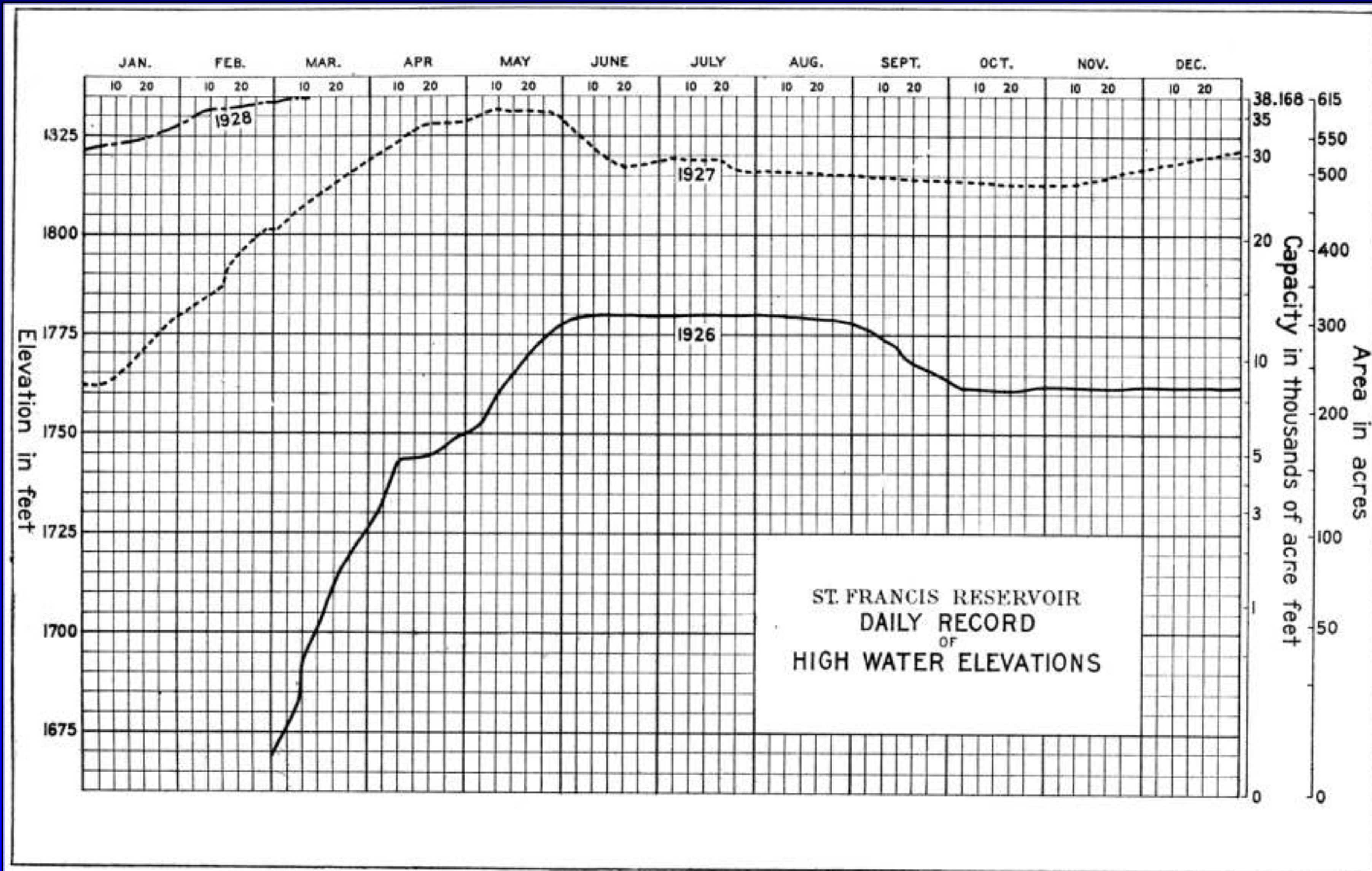


- In 1945 Karl Terzaghi published an article which demonstrated that water pressure could infiltrate mass concrete, saturating it.
- A conventional analysis of cantilever stresses in St. Francis Dam assuming full uplift reveals that the dam becomes unstable in overturning when the reservoir rose to within 7 feet of its crest! Full uplift may have developed beneath the sloping abutments, which were not afforded uplift relief wells.

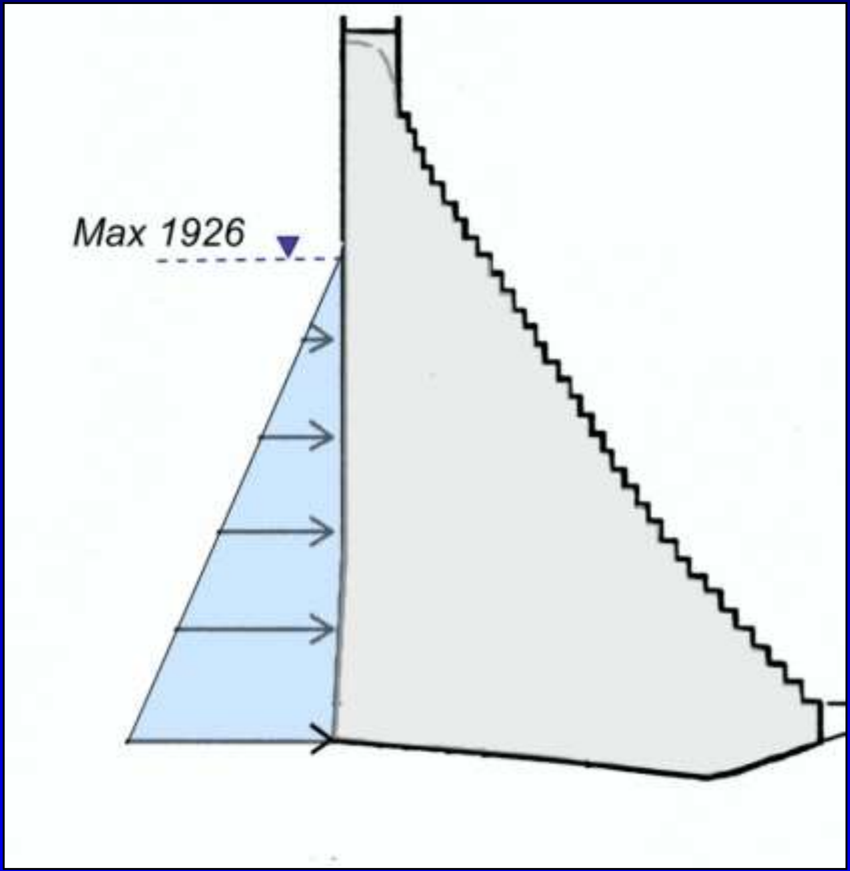




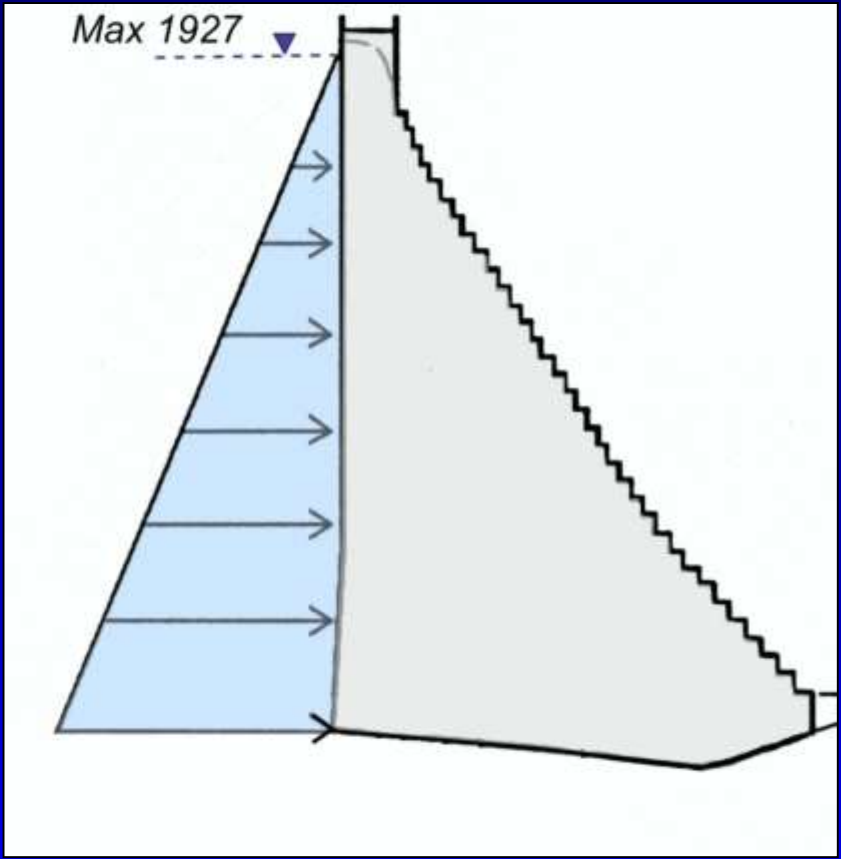
- **The arch stresses on the St. Francis Dam increase markedly when the reservoir rose to within 11 feet of the spillway crest.**
- **The dam was designed before the Trial Load Theory of Arch Stress Distribution was developed, so the contribution of arching to its stability was only assumed.**

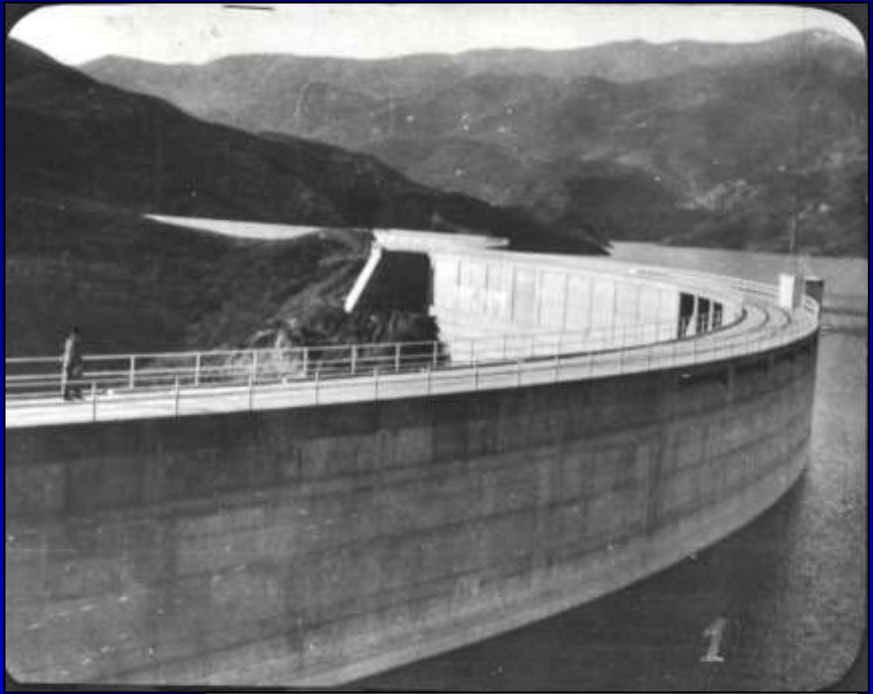


- **Reservoir Stage Curves for St. Francis Reservoir between March 1, 1926 and March 13, 1928**

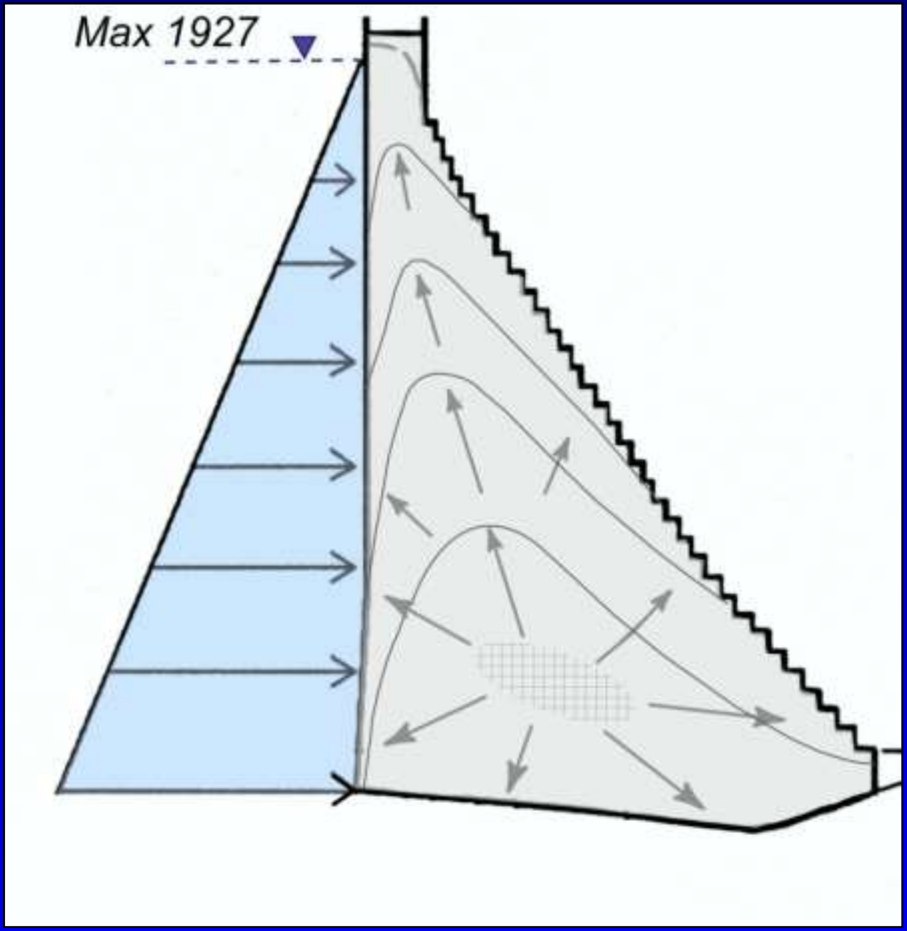


In 1926 the reservoir was filled 110 feet, up to elevation 1780 feet, between June 1st and September 1st; then drawn down about 20 feet through the fall and winter months, when municipal and agricultural demand was lowest.

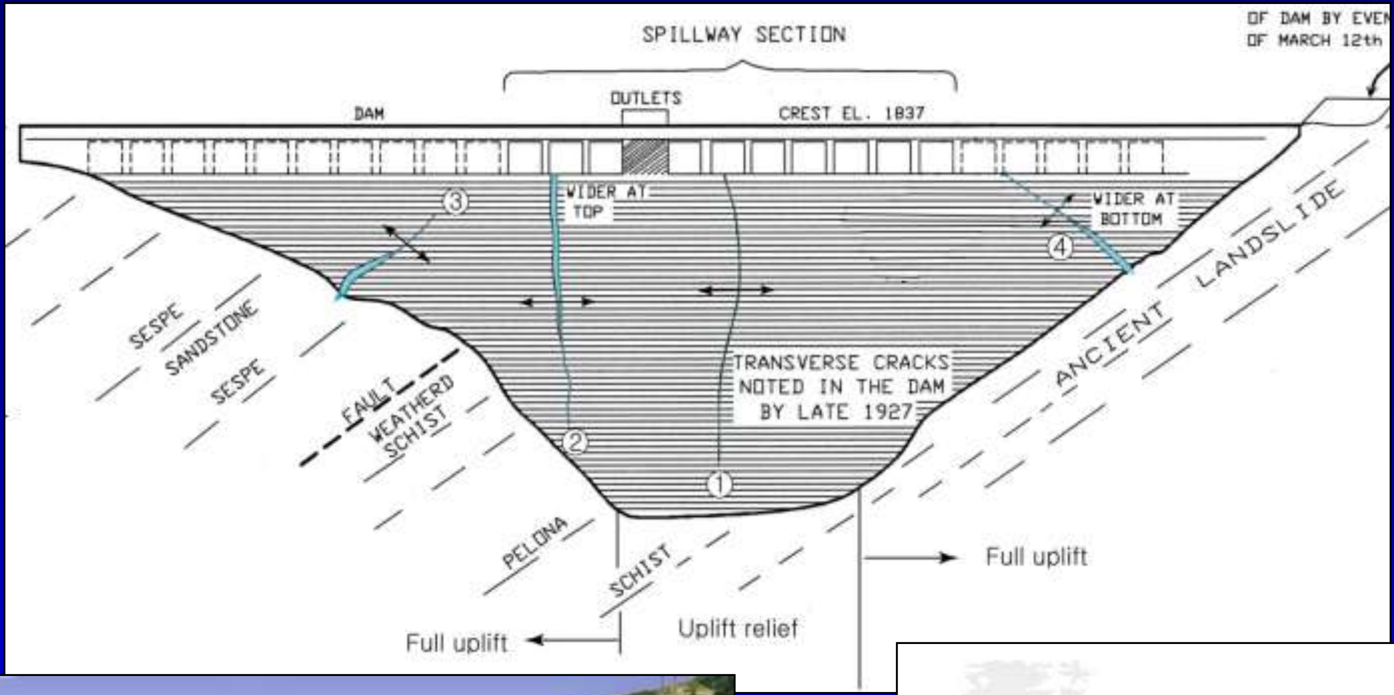


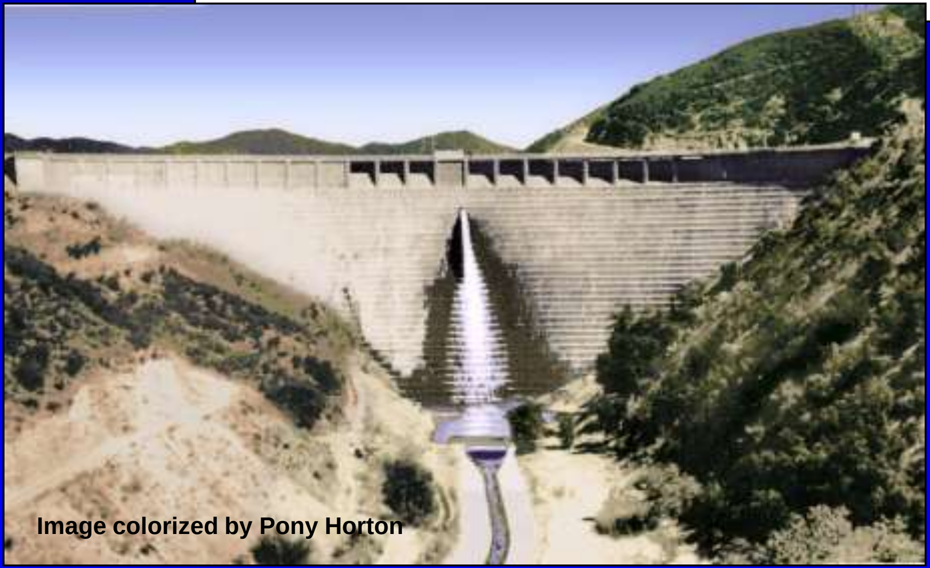


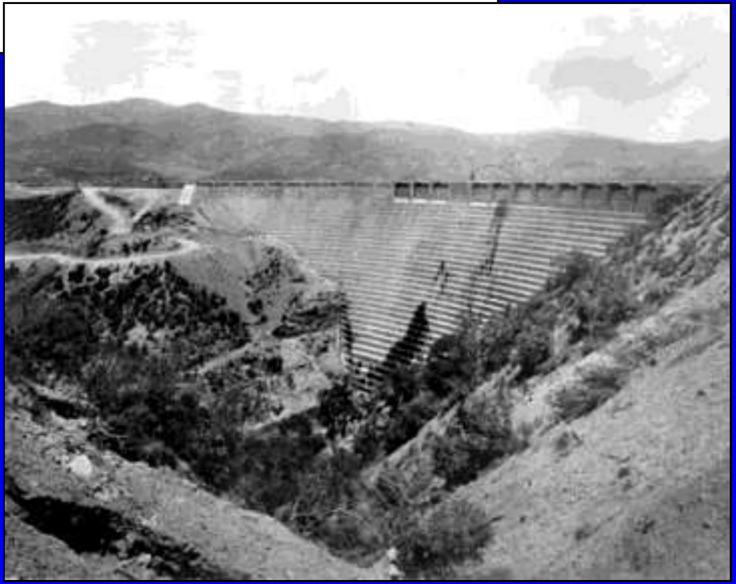
From January 5 to May 8,1927 the reservoir was raised another 52 feet, to elevation 1832, within three feet of the spillway sills, and held there for 3 weeks; then drawn down to elevations 1813 to 1819 ft, until November 10th.



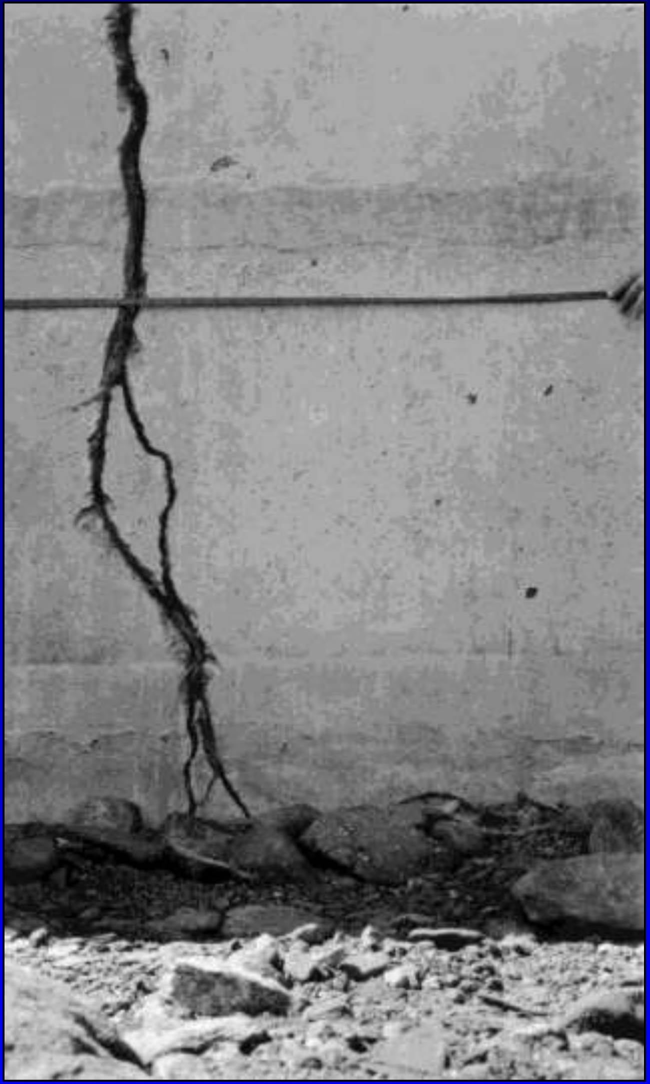
During the first year of operation several large tension cracks formed transverse to the dam's axis. These were likely in response to the cement heat of hydration, which would have been considerable for 130,000 yds^3 of mass concrete.



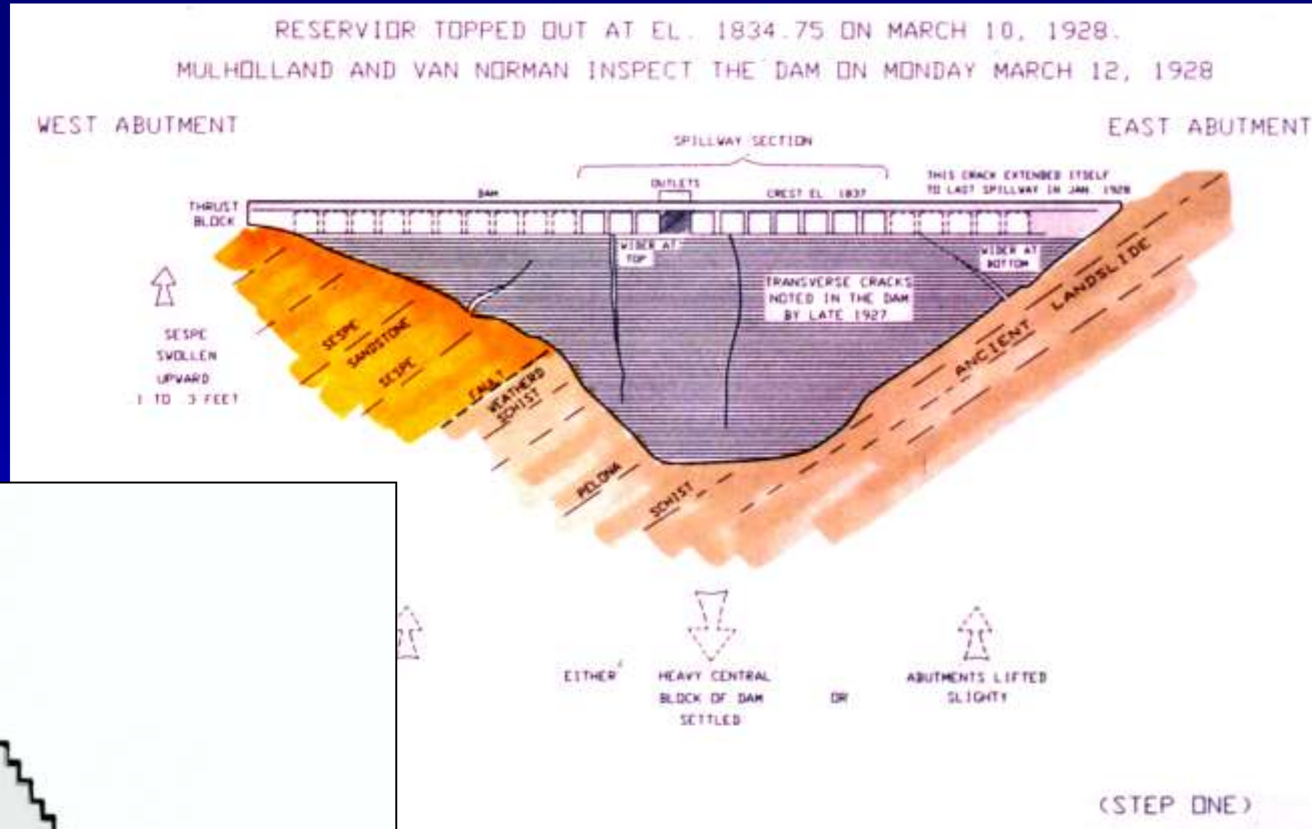


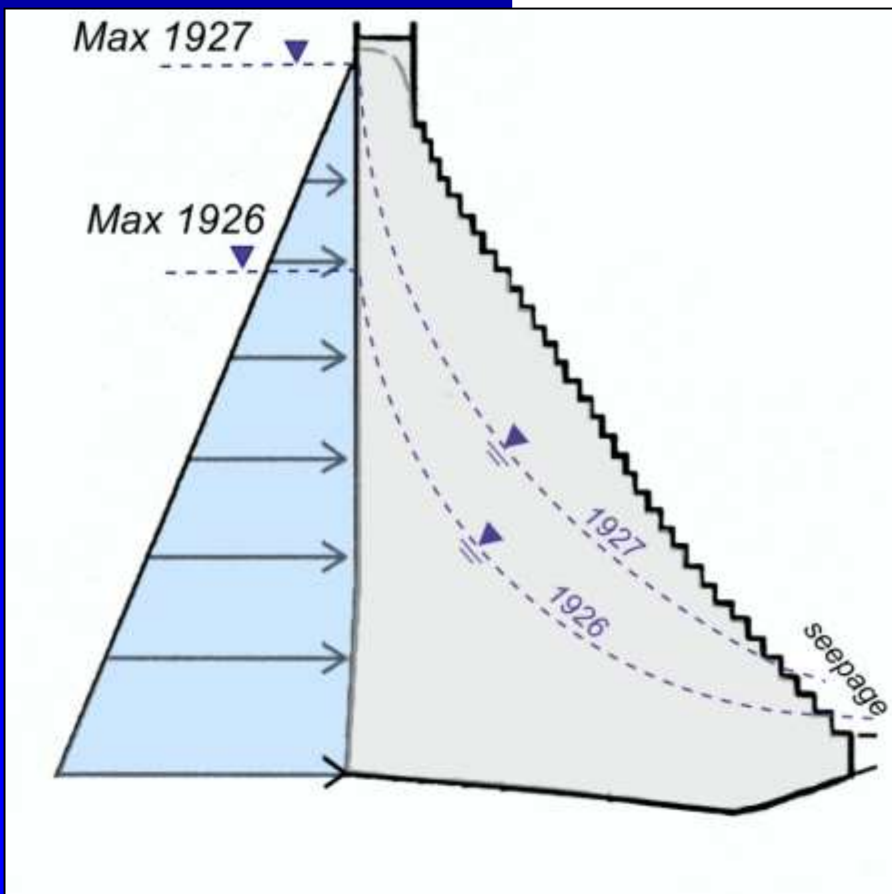


Four prominent contraction joints leaked noticeable volumes of water in the main dam as the lake level rose.

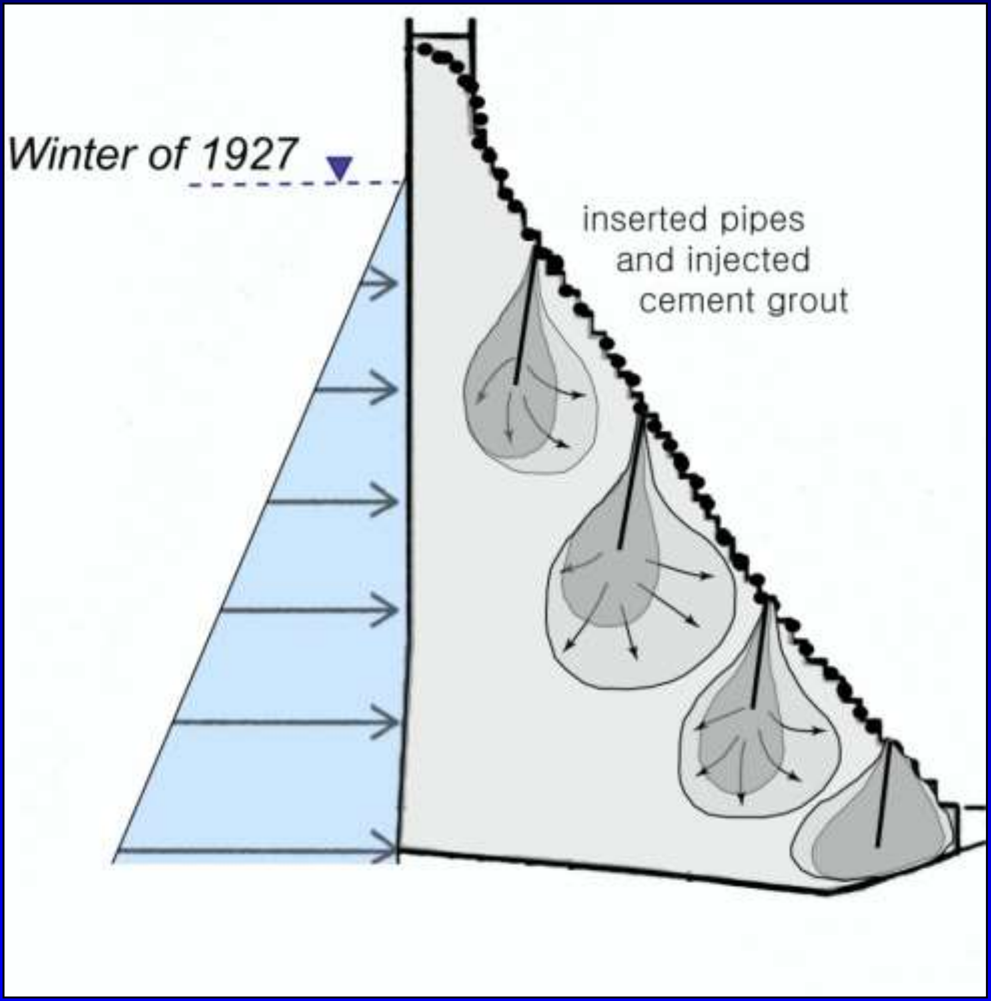


Several tension cracks also formed in the concrete dike section during the second year of operation, in 1927-28. These began leaking noticeably in early March 1928.

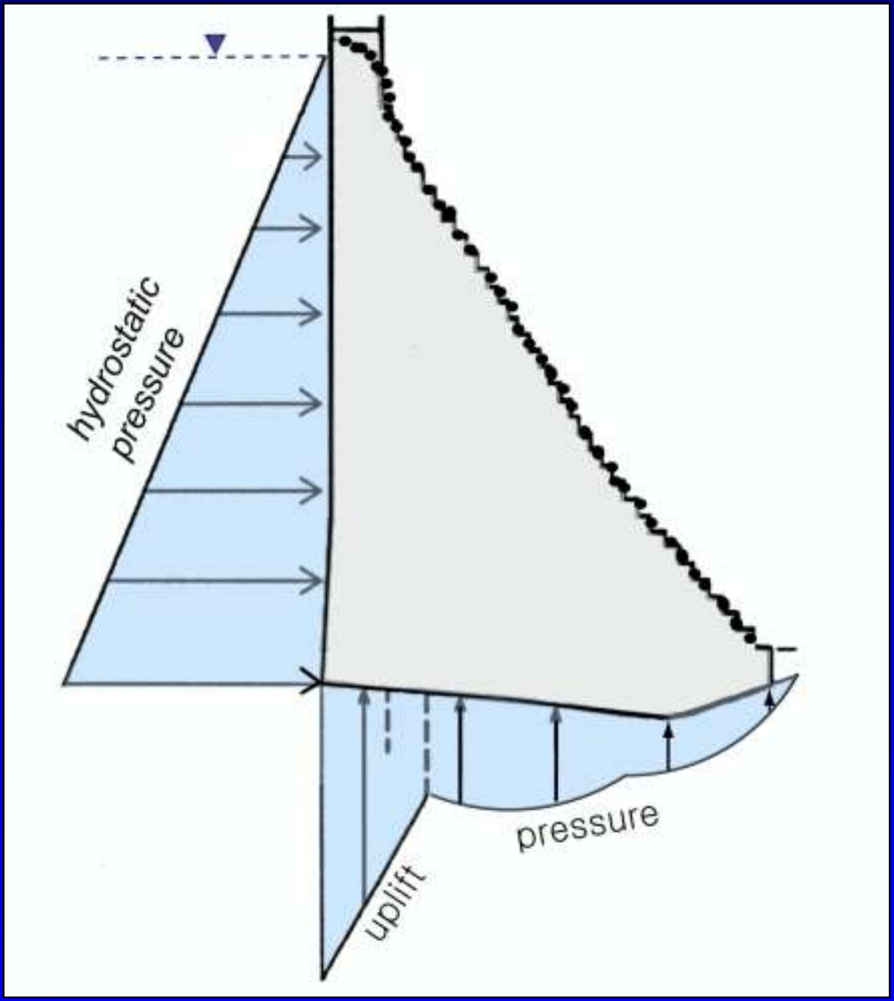


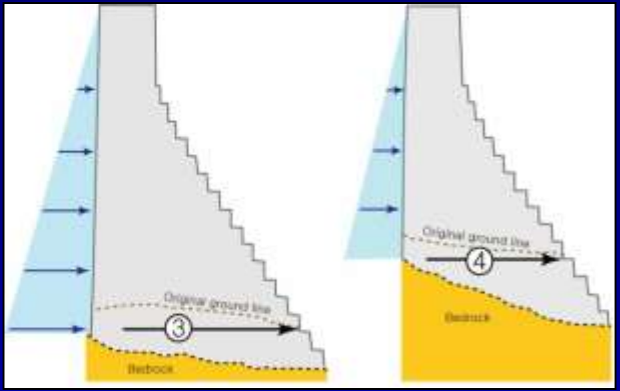


During the high water stand of 1927 seepage increased markedly through the downstream face, along four prominent shrinkage cracks in the dam.

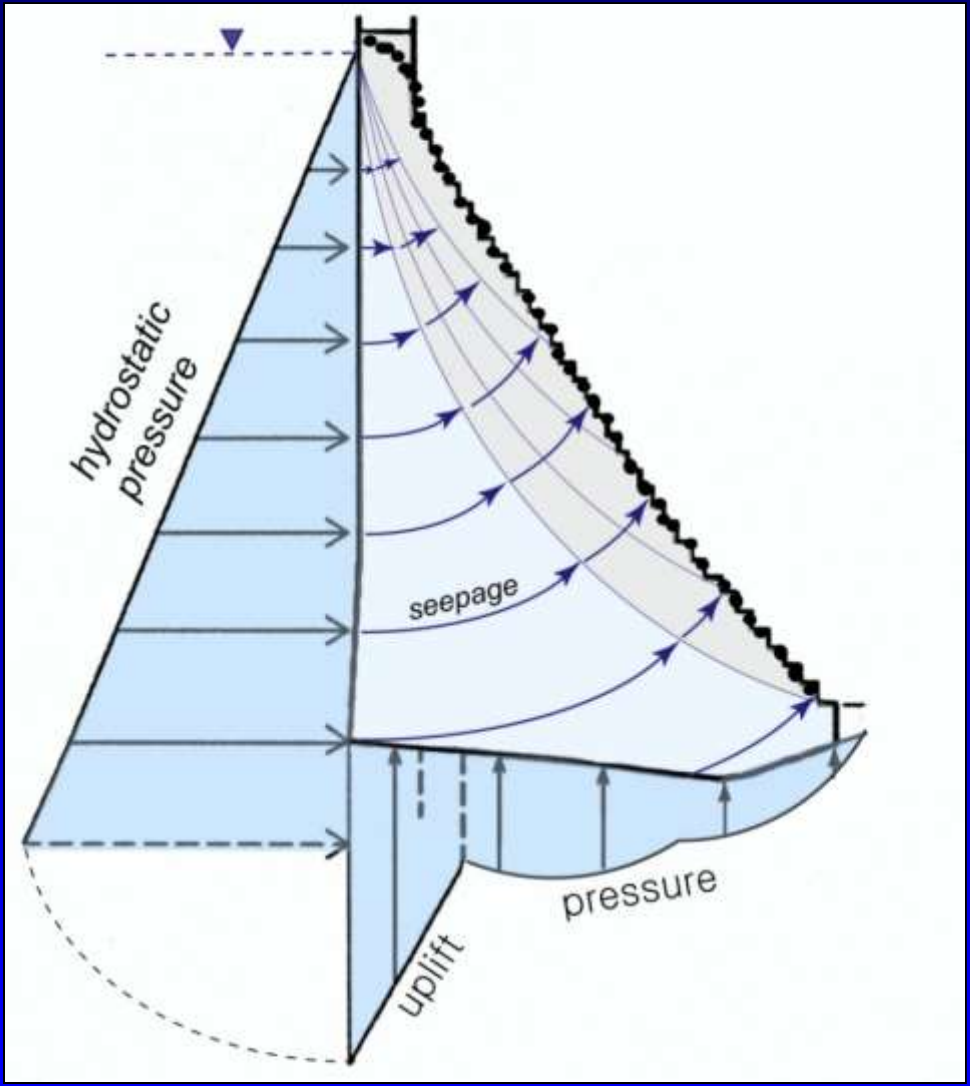


In January-February 1928 Mulholland ordered the four prominent cracks to be caulked with oakum, to prevent loss of cement grout injected into these cracks.





On March 2, 1928 the reservoir was raised to within three inches of the spillway sill elevation of 1835 feet, exerting the greatest hydrostatic forces on the dam



If the transverse shrinkage cracks were sealed at the dam's downstream face, full hydrostatic pressure would be expected to develop BETWEEN adjacent blocks of the dam.

Prominent shrinkage crack observed cutting through Block 5, observed after the failure

The oakum caulking can be discerned on the post-failure images as dark lines across the dam's downstream face

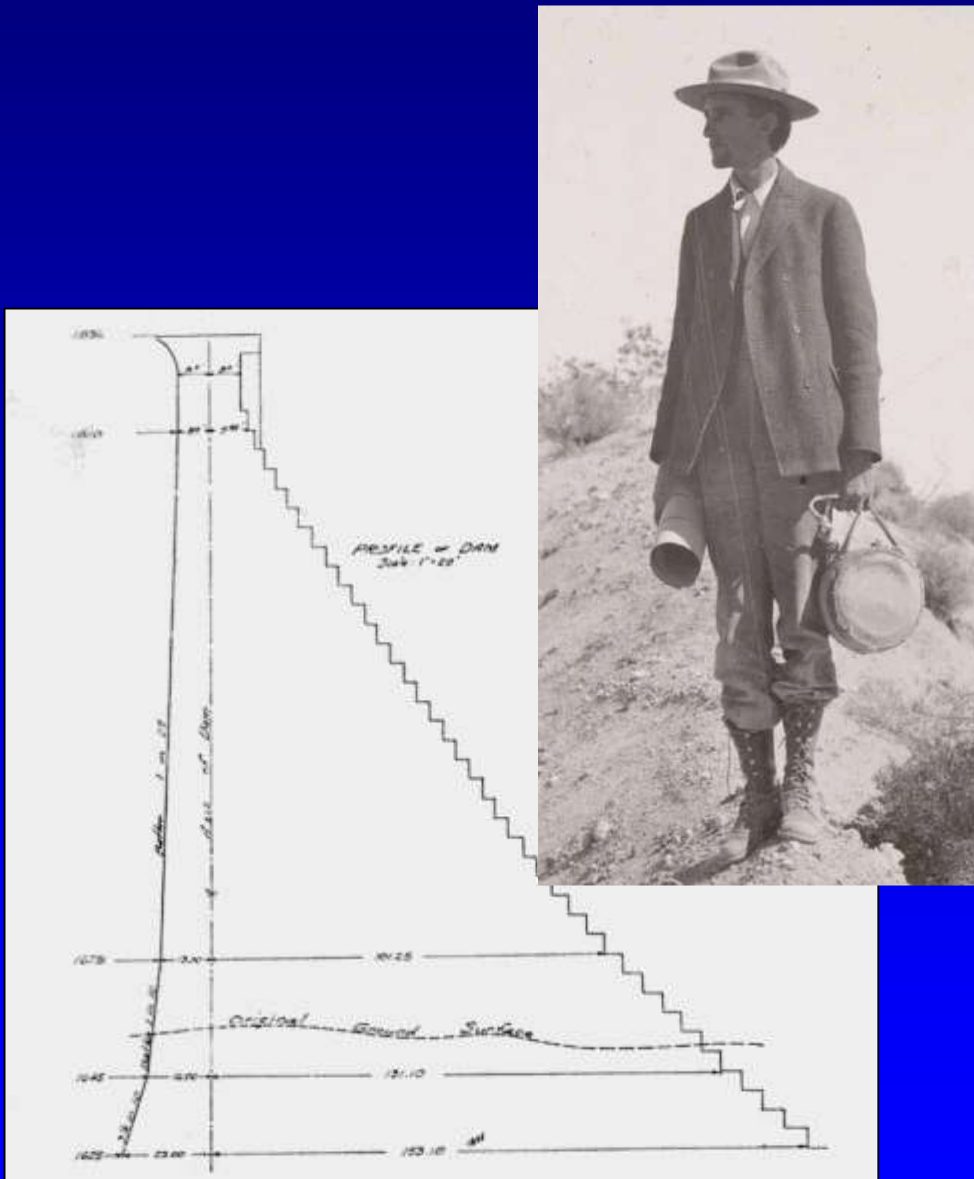
DESIGN DEFICIENCIES #1

- The dam was unknowingly built against a paleolandslide in the Pelona Schist. This is why the canyon was so narrow at the dam site
- No stability calculations were performed on the dam, so the destabilizing impacts of hydraulic uplift were not considered
- No grout curtain; shallow shear keyways
- Cement heat of hydration effects ignored, shrinkage cracks not grouted prior to filling, along with water stops

DESIGN DEFICIENCIES #2

- **Low strength laitance layers formed between successive concrete lifts**
- **Aggregate separation using trough placement, created hemi-horizontal horizons of low tensile strength**
- **Dam heightened 20 feet without increasing base width**
- **Downstream face chopped off at elev 1650 ft, giving a thinner cross section than actually required to overcome uplift of the upstream toe**
- **Plugging the dam's expansion cracks with oakum <u>on the downstream face</u> was the worst thing they could have done to destabilize the dam**

Who actually 'designed' the dam?



- **Mulholland Dam was "laid out" by BWWS office engineer Edgar A. Bayley, shown at left (1877-1943)**
- **No evidence has been found that any rock cores or tests of the foundation rock were actually made by BWWS**
- **It does not appear that any structural calculations were made by BWWS personnel**
- **The design appears to have been based upon examples presented in Smith's *Construction of Masonry Dams* (1915), Fowler's *Water Supply Engineering* (1926) and Wegmann's *The Design and Construction of Dams* (1918, 1922)**

- **Mulholland instructed his office engineering staff to take the design for the Weid Canyon/Mulholland Dam and "make it fit" the site in San Francisquito Canyon.**
- **The decision to seal transverse tension cracks extending through the main dam using oakum on the downstream face was a poor choice, and likely hastened the dam's untimely demise in March 1928**
- **Mulholland rightly accepted responsibility for the catastrophe**