# DAMS AND DISASTERS:

## a brief overview of dam building triumphs and tragedies in California's past


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# Oldest Dam and Irrigation canal in the United States (1815)

- In 1814-15 a rubble masonry dam was constructed across the upper end of Mission Gorge in San Diego. It had a maximum height of about 13 feet, was 13 feet thick at its base, and was 244 ft wide. Water was released through gates and spillways into a six-mile long tile-lined flume, down Mission Valley, and terminating near the Franciscan Mission of San Diego de Alcala, established in 1769.
- The dam gradually fell into disrepair mission after the missions were secularized in 1833.
- The lower left image shows the dam being overtopped by the Flood of 1914 or 1916.

Today the Old Mission Dam is a nationally registered historic landmark and preserved within the Mission Trails Regional Park, along Father Junipero Serra Trail and the San Diego River

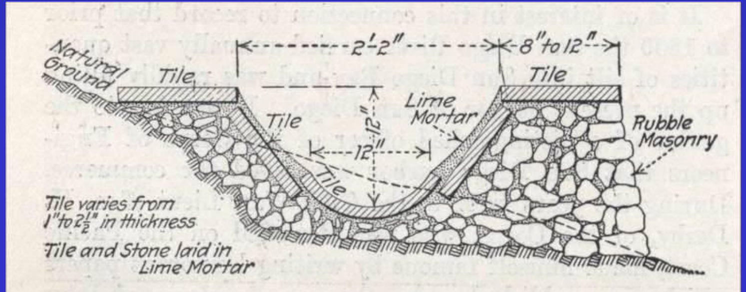
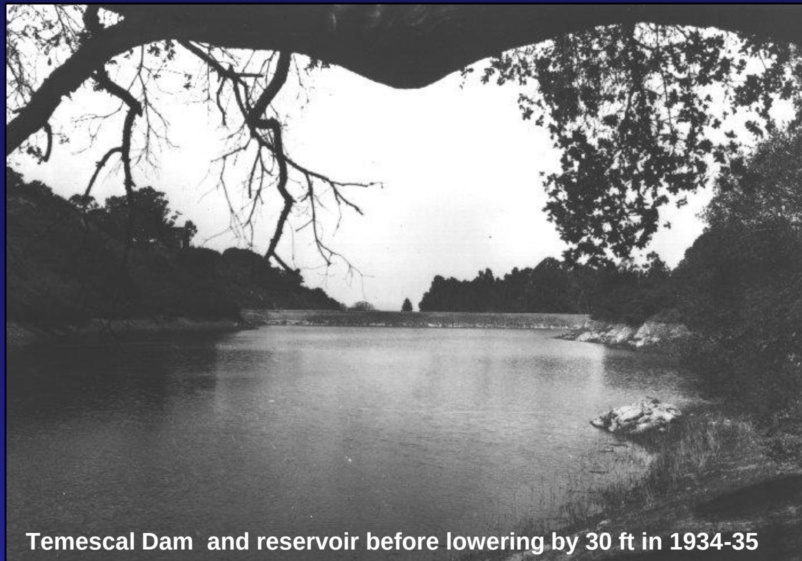



FIG. 3. TYPICAL CROSS-SECTION OF OLD MISSION CONDUIT NEAR SAN DIEGO, CALIF.

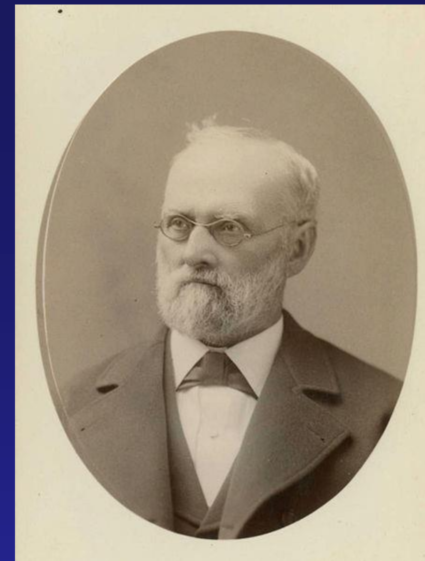
Left images are from ENR Feb 17, 1916 article on the dam and conduit. The conduit was a remarkable feat of engineering for its day

# FIRST RESERVOIR IN LOS ANGELES

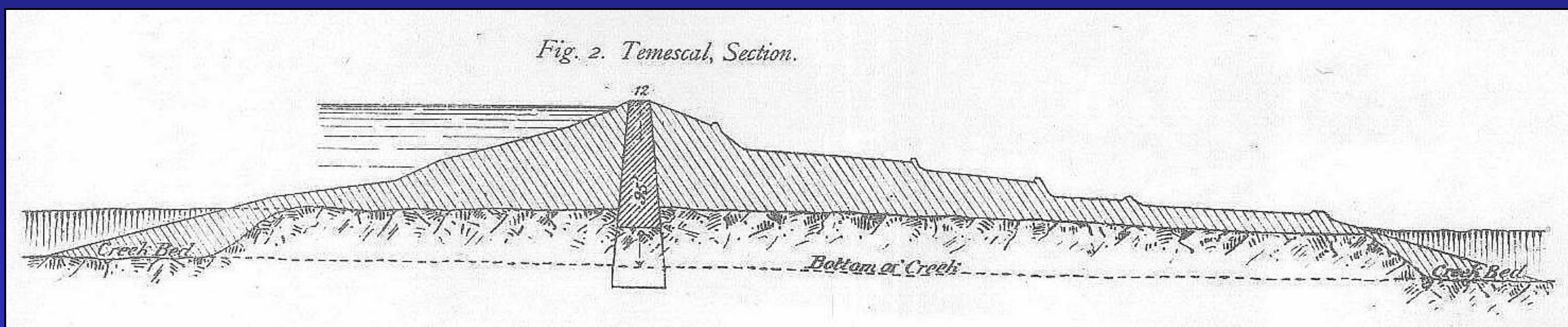
- **Buena Vista Reservoir** was constructed in 1868-69 using an earthfill embankment with riprap face, built to a crest elevation of 378 feet. It was built near what is now the southeastern tip of Elysian Park , in Los Angeles. It was built by privately owned Los Angeles Water Company as their first storage facility. This area is now part of Buena Vista Park, just off the Pasadena Freeway.



Temescal Dam and reservoir before lowering by 30 ft in 1934-35

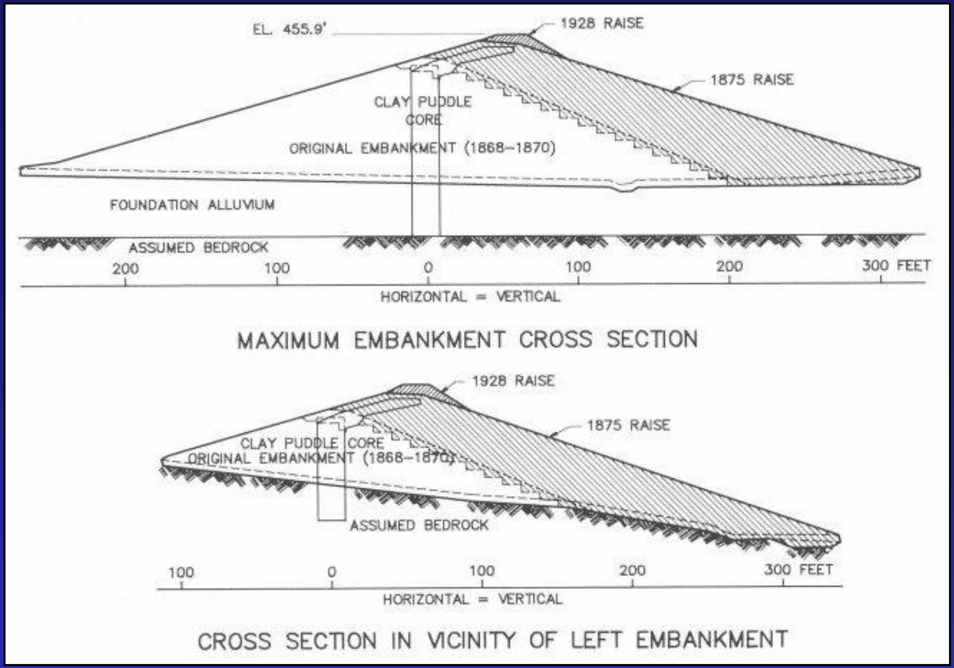


**Anthony Chabot (1813-88) also built the Chabot Dam on San Leandro Creek, the San Jose waterworks, the Vallejo waterworks, and Lake Chabot Dam in Vallejo**



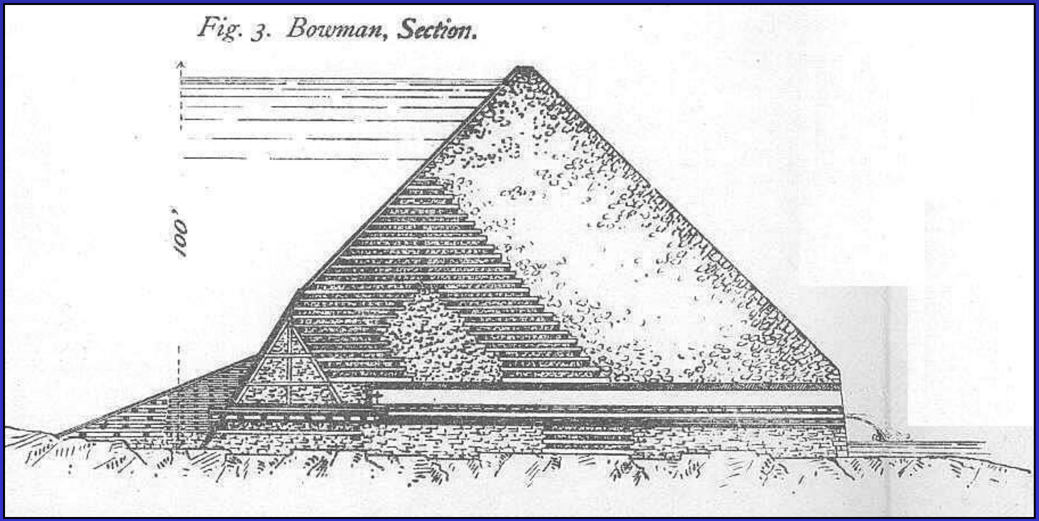

- **Temescal Dam** was designed by mining engineer **Anthony Chabot** by the hydraulic fill method between 1866-69 with 3:1 side slopes.
- It was raised 10 ft in 1886, with lowering of downstream slope to 5:1.
- The finished height of 115 ft made it world's highest dam for awhile
- Built unknowingly across the Hayward fault, it survived the M6.8 Oct 21, 1868 Hayward earthquake (though no surface fault rupture)
- The dam was ceded to EBRPD in 1934-35 and lowered by 30 feet.

# SITTING ON A MAJOR FAULT



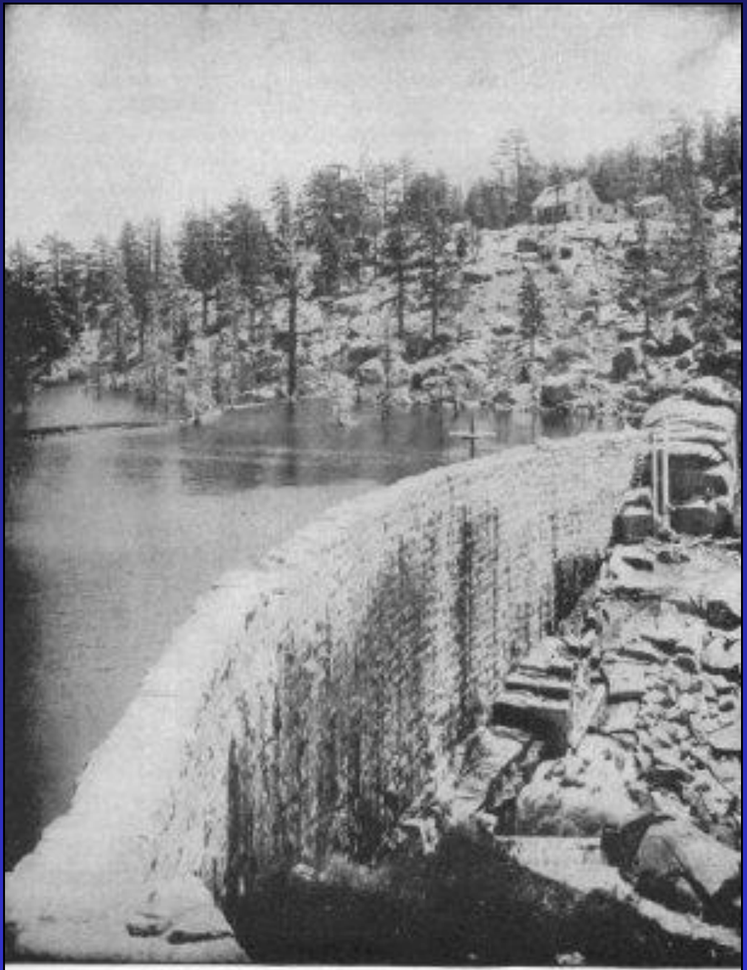

- **San Andreas Dam** was built to a height of 81 ft by the Spring Valley Water Company to provide water for San Francisco in 1868-70, and raised to a height of 97 ft in 1875 (the stippled area in the views at upper right).
- The $M_w$ 7.9 1906 earthquake offset ran through the abutment between the main embankment and the left abutment embankment (shown above right).
- The site was likely subjected to a peak ground acceleration (PGA) exceeding 0.7g, without any overt damage being noted (this speaks to the resilience of earth embankments). The dam was raised another 6 ft in 1928, shown as the small shaded area near the crest, above right.

# BOWMAN DAM (1875)




- **Bowman Dam** was California's second rockfill dam, built to supply water for hydraulic mining along the South Fork of the Yuba and upper Bear Rivers
- The upstream face was constructed with rock-filled timber cribs and sloped 0.58:1 (60 degrees) for the first 30 ft, then 1:1 (45 degrees) on both the up and downstream faces
- Originally 86 ft high, it was raised to 107 feet, making it the **highest dam in the world** between 1880-88
- In 1926 it was dismantled and replaced by a larger rockfill dam, 176 ft high, by the W. A. Bechtel Company.

# THE WORLD'S FIRST ARCH DAM; BEAR VALLEY DAM 1884



Bear Valley Dam.
(From "Eighteenth Annual Report U. S. Geological Survey.")

- A daring design by **Frank E. Brown, C.E.** (President of ASCE) and built of cyclopean masonry
- Formed the first **Big Bear Lake** in the San Bernardino Mountains

# BEAR VALLEY ARCH DAM

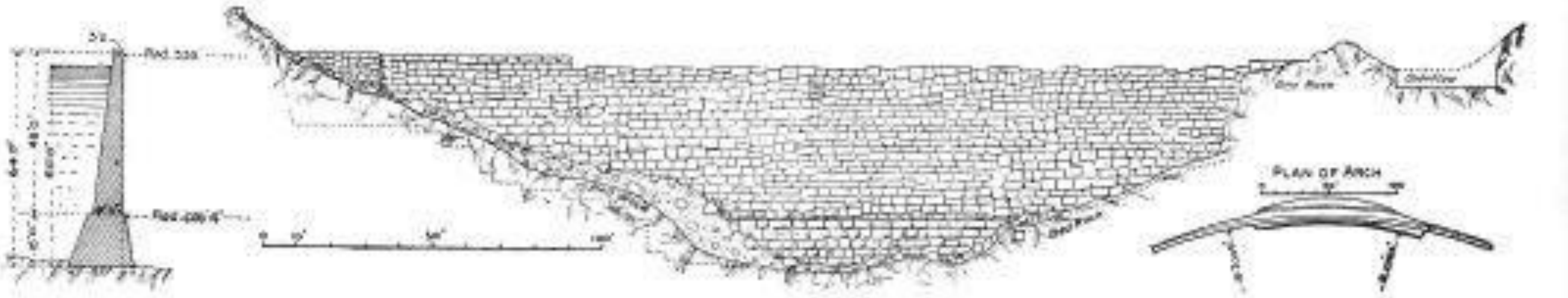
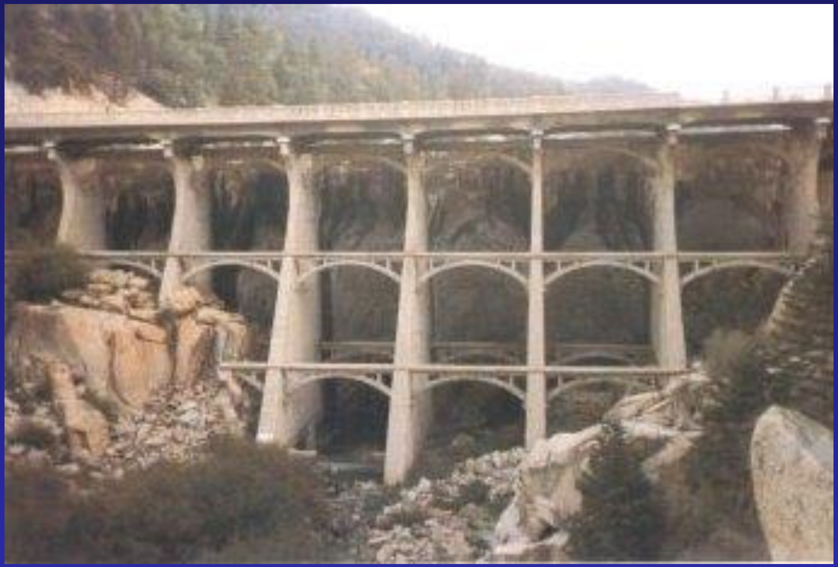



Figure 3–2 Bear Valley Dam—plan, section and elevation

- The old arch dam was 64 feet high and 300 feet long, constructed on a radius of 335 feet. The spillway was 20 feet wide and extended 8.5 feet below the dam crest. The design was cited and criticized over the succeeding years.
- Despite the concerns, the dam survived repeated ice loadings and 2 ft deep overtoppings, in 1909-10 and 1910-11, which washed away the earthen stabilizing berms.

# BIG BEAR VALLEY DAM



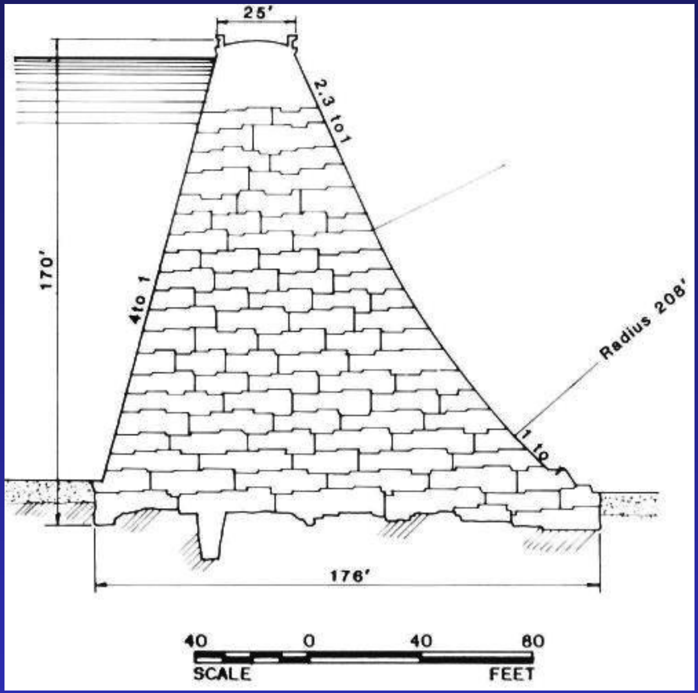

- A buttress dam designed by John S. Eastwood was built by the Bear Valley Mutual Water Company in 1911-12, which withstood significant overtopping in floods of January 1916
- The highway viaduct (upper right) was constructed across the dam in 1926 as part of the Rim of the World Highway
- When the lake is low, people can walk across the old arch dam, as seen in the postcard view at lower right

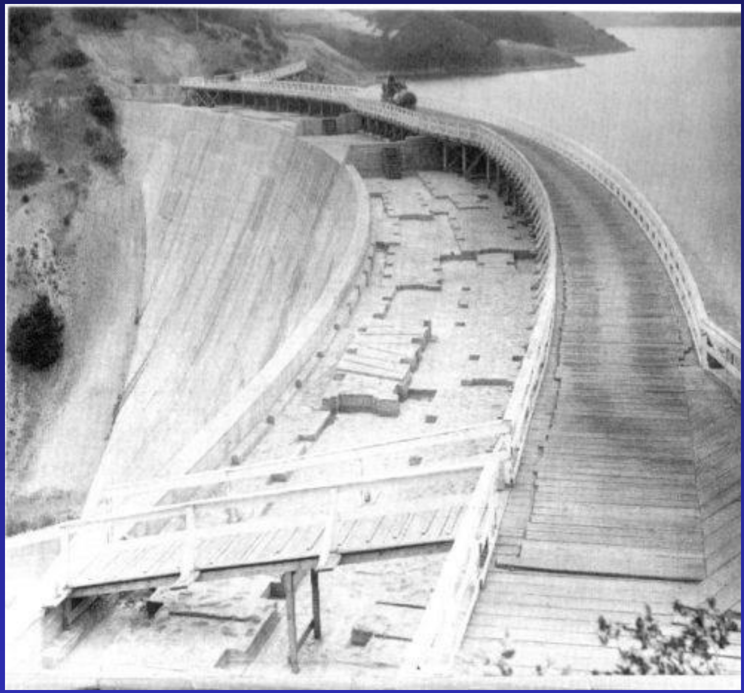
# LOWER CRYSTAL SPRINGS DAM -1888

The viaduct was removed and the dam heightened to increase storage and flood control capacity, as well as seismic upgrades, between 2009-12

- Designed by Hermann Schusler, Chief Engineer of the Spring Valley Water Co. of San Francisco. There was no suitable rock at the site, so concrete was used
- It was the first mass concrete dam in the world

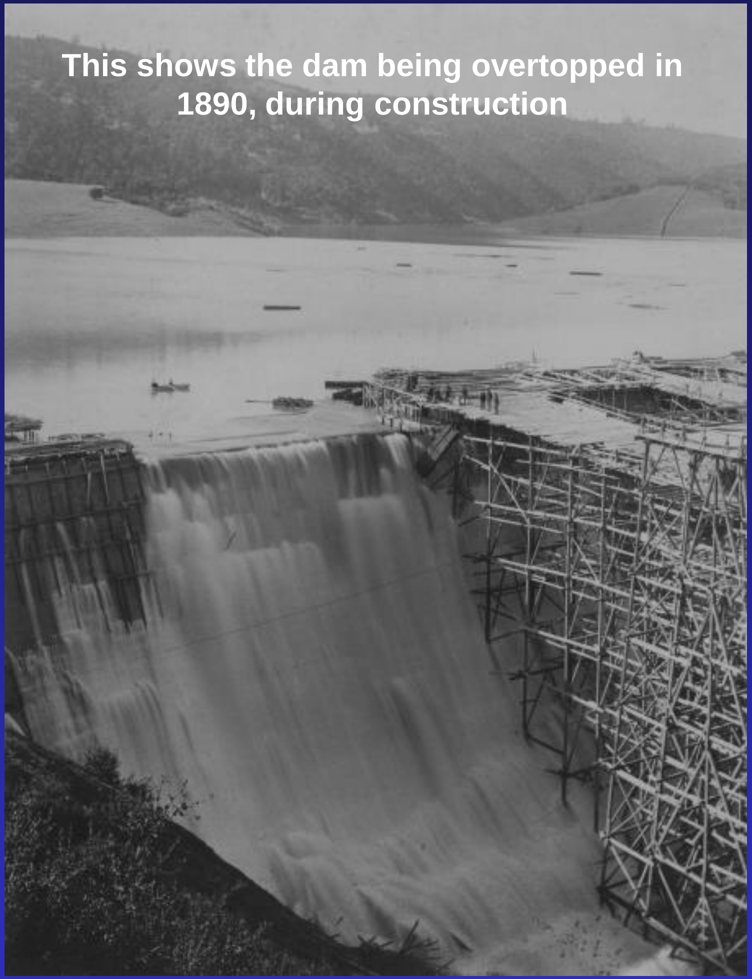
# CRYSTAL SPRINGS WAS THE FIRST MASS CONCRETE DAM IN THE WORLD

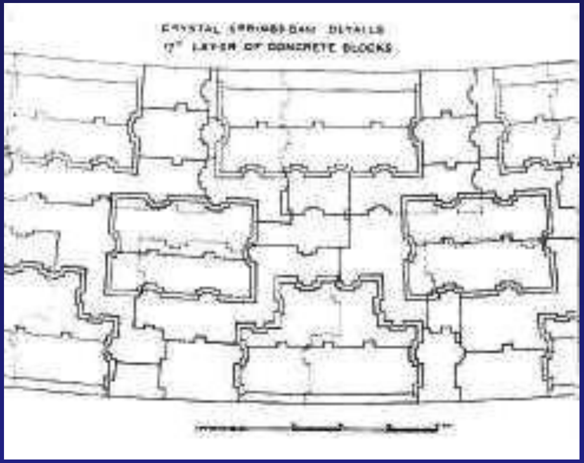


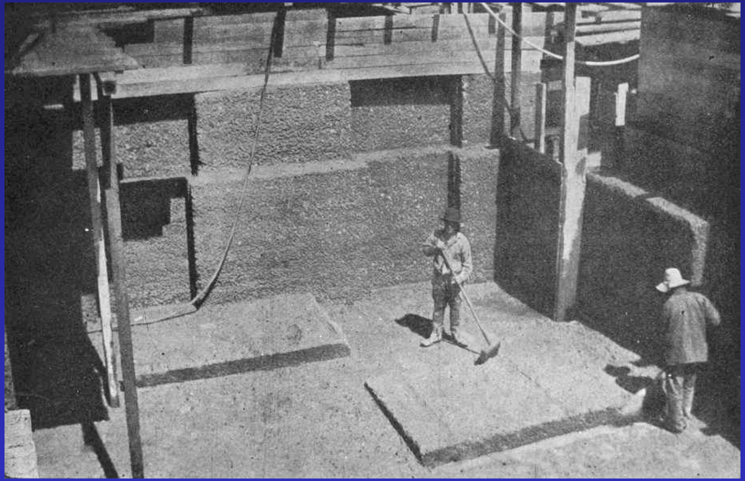



The system of interconnected blocks can be seen in the view, taken in 1909

- Intended to be 170 ft high, construction was halted at a height of 154 ft., with an arch radius of 632 ft.
- Situated 1000 ft east of the San Andreas fault, it survived the $M_w$ 7.9 1906 earthquake without damage, because the foundation rock is so intensely fractured


This shows the dam being overtopped in 1890, during construction



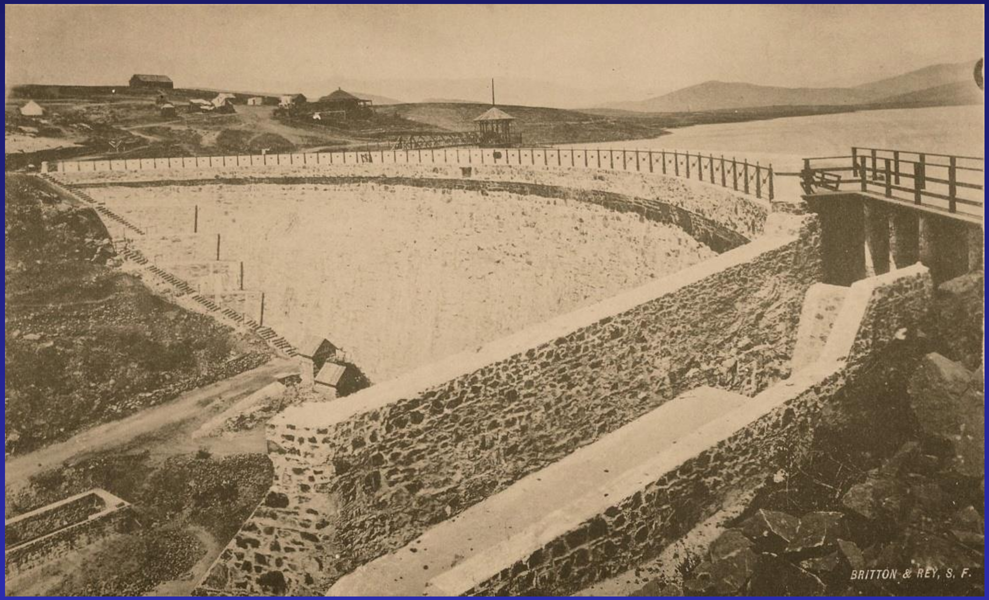



- **Crystal Springs Dam** was designed as a monolith of mass concrete, formed in an series of interconnecting blocks with grouted joints. All of the Portland cement was imported from England.
- The concrete mix was one barrel of Portland cement, two barrels of sand, 2/3 barrel of water and 22 $ft^3$ of crushed stone; which equates to 470 lbs of cement per cubic yard, making very strong concrete

# SWEETWATER DAM 1886


- **Sweetwater Dam** is a rubble masonry arch dam designed by **James D. Schuyler** in 1886 for the San Diego Land & Town Company. The original height was 90 feet, with a crest length of 380 feet on a radius of 213 feet. The original dam was 46 feet thick at the base and 12 feet thick at the top.

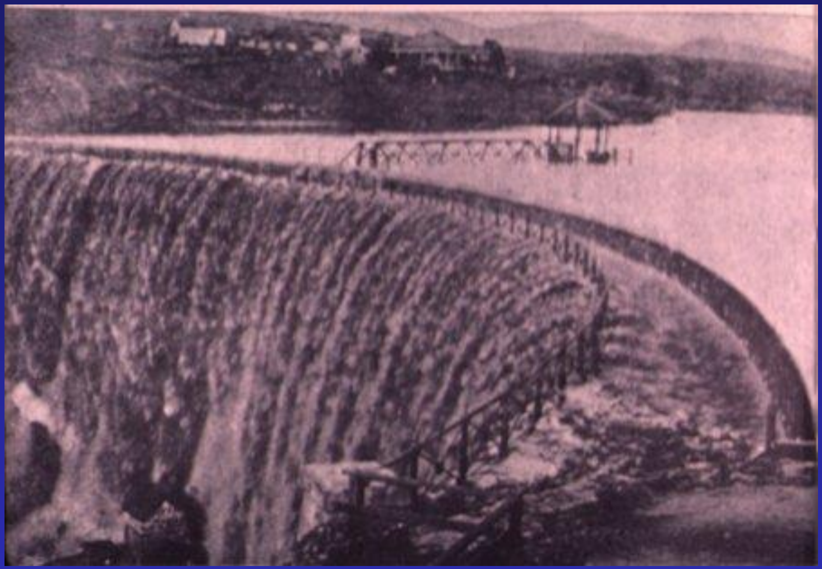
# ESTIMATING THE ADEQUACY OF "WASTE WEIRS" IN THE EARLY DAYS

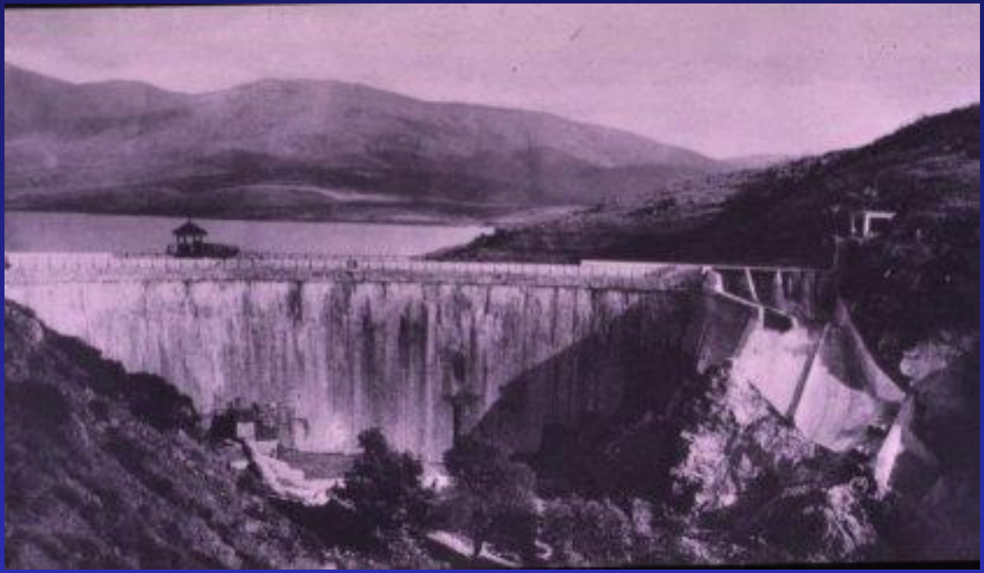




- At the October 1888 ASCE national meeting, former society President James B. Francis questioned the adequacy of the dam's spillway, given the tributary drainage area was 182 square miles. James D. Schuyler responded that the capacity was based on back-analyses of the 1884 flood in Sweetwater Creek. The design capacity of the "waste weir" (spillway chute) was 1800 cfs (upper right).

# SWEETWATER DAM OVERTOPPED in 1902





- In 1902 the watershed was subjected to 6 inches of rainfall in 24 hours, generating an average 24 hr discharge of 7200 cfs.
- The dam was overtopped for 40 hours, to a depth of 22 inches (shown at left). Although the dam was not damaged, the outlet works were essentially destroyed
- The spillway was enlarged and the dam parapet was raised two feet, as shown at right

# HEMET DAM 1891-95

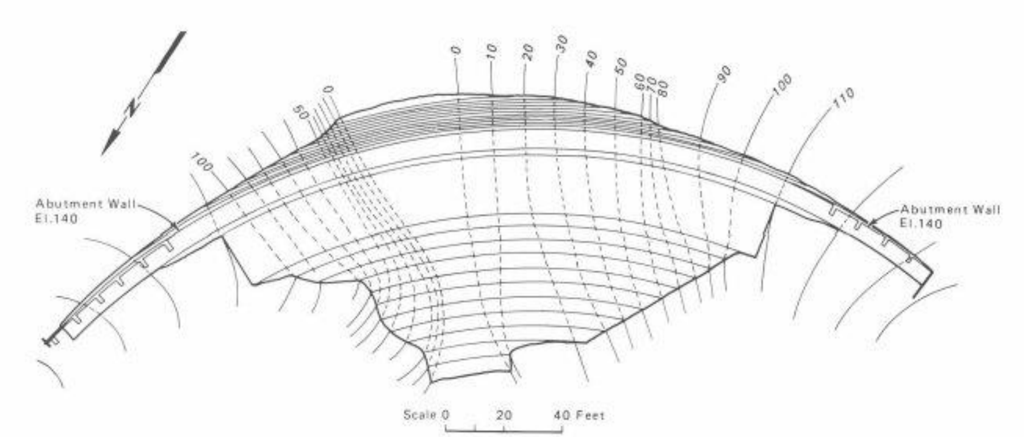
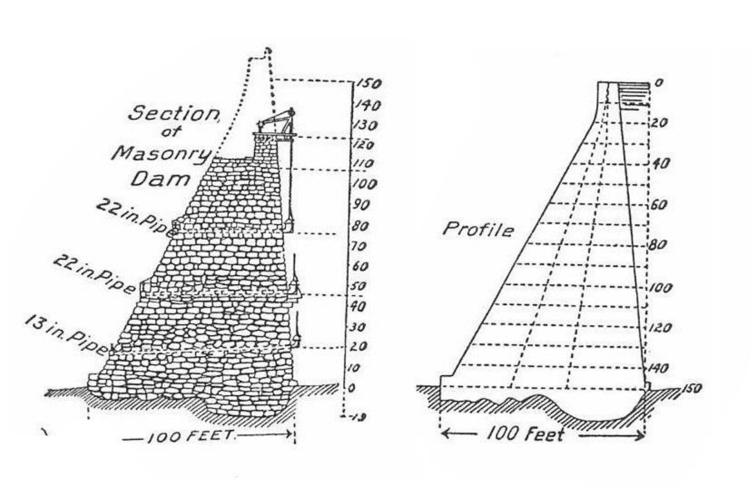
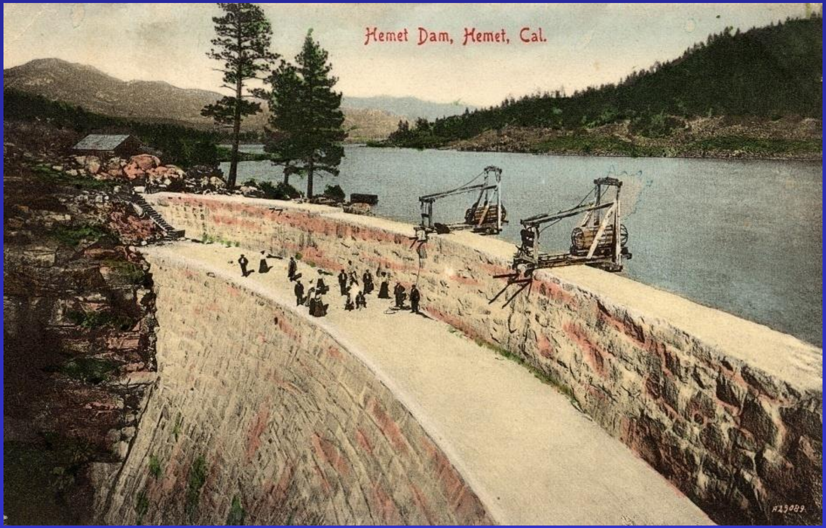



Figure 3–7 Plan of dam




Construction of Hemet Dam was halted about 40 feet below the original design crest, and the derrick frames and hoists were left-in place for many years thereafter. Note sheer size of the plum stones, compared to people walking on the crest.

- Hemet Dam was also designed by James D. Schuyler on the South Fork of the San Jacinto River in the San Jacinto Mountains
- Intended to be of cyclopean masonry 150 ft high, on radius of 224 ft. Construction was halted at 135.5 ft in 1895 (see photo at left)
- Large blocks of granite called “plum stones” were placed 6 inches apart and filled with cement mortar. 31,105 yds$^3$ of granite and 20,000 barrels of cement were used in its construction.
- It was overtopped several times without sustaining damage. A concrete arch 12.5 ft high was added to the dam in 1923.

# LOWER OTAY - HIGHEST ROCKFILL DAM IN THE WORLD

FIG. 5. LOWER OTAY DAM FOR SAN DIEGO WATER-SUPPLY ON OCT. 27, 1915

This view and Figs. 6 and 7 are reproduced from photographs taken by Allen Hazen, Oct. 27, 1915

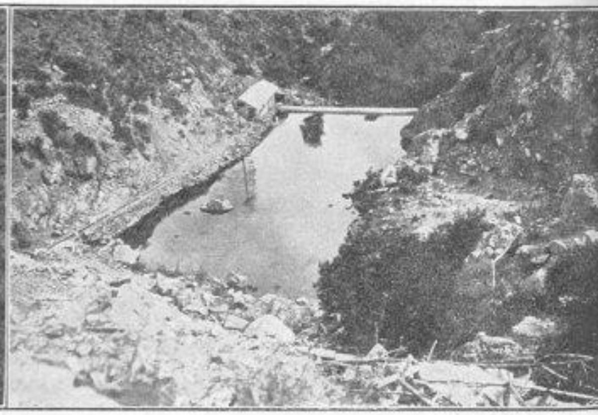


FIG. 6. VIEW OF DOWNSTREAM FACE OF LOWER OTAY DAM

Showing pool for impounding leakage and pumping house and pipe line delivering it back into reservoir

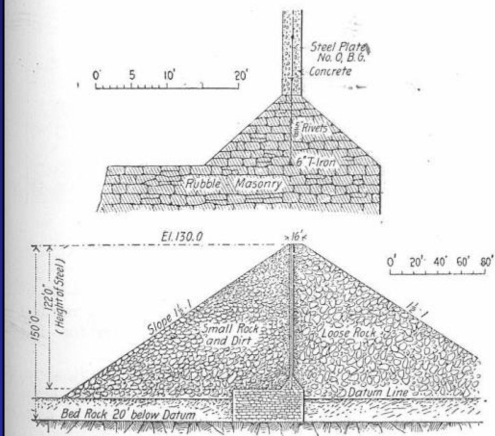
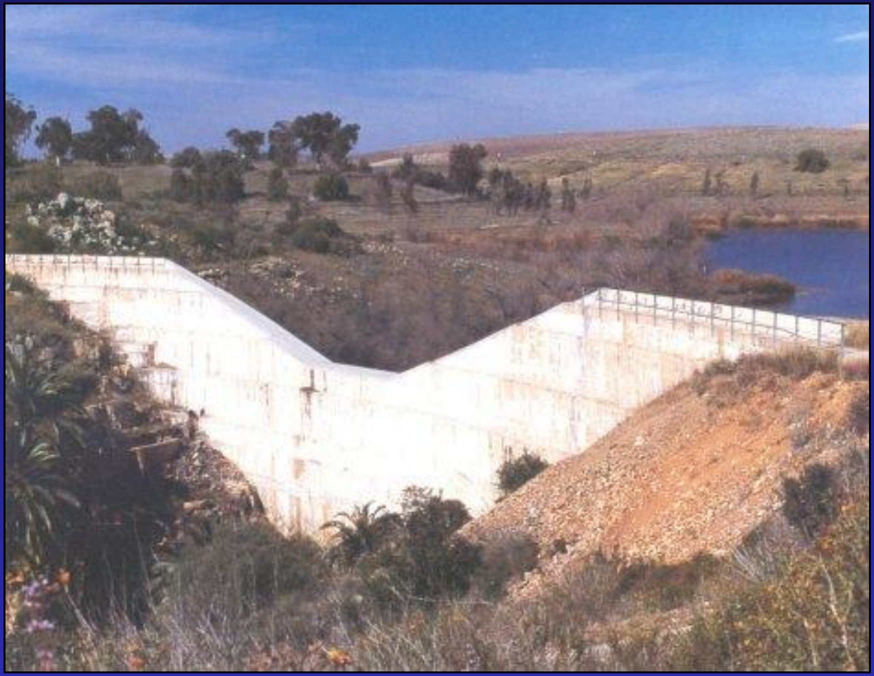



FIG. 2. CROSS-SECTION OF LOWER OTAY DAM AND ENLARGED SECTION OF STEEL CORE WALL AT BASE

Reproduced from "Engineering News," Mar. 10, 1898; dimensions of dam as built vary from this

- **Lower Otay Dam** was a 150 ft high loose rockfill embankment designed by developer E. S. Babcock. When completed in 1897, it was highest rockfill dam in world, until 1914.
- It was equipped with a ½" thick steel plate inside a 12" thick concrete diaphragm core wall. The rubble rock fill was placed 1.15:1 slopes (49 degrees).
- The daily leakage was between 225,000 and 400,000 gpd!

# FIRST REINFORCED CONCRETE DAM



- **Upper Otay Dam** was the world's first reinforced concrete dam, 89 ft high, 350 ft long, on a radius of 359 ft. Designed by H.N. Savage and built 1898-1901 along Proctor Creek, upstream of Lower Otay Dam and Reservoir
- The dam was overtopped 3 ft deep in the Jan 1916 flood
- The trapezoidal slit 22 ft deep (shown above) was cut in 1985 to accommodate the revised design overflow of 10,500 cfs

# Right-lateral offset of San Andreas Dam Discharge tunnel in 1906

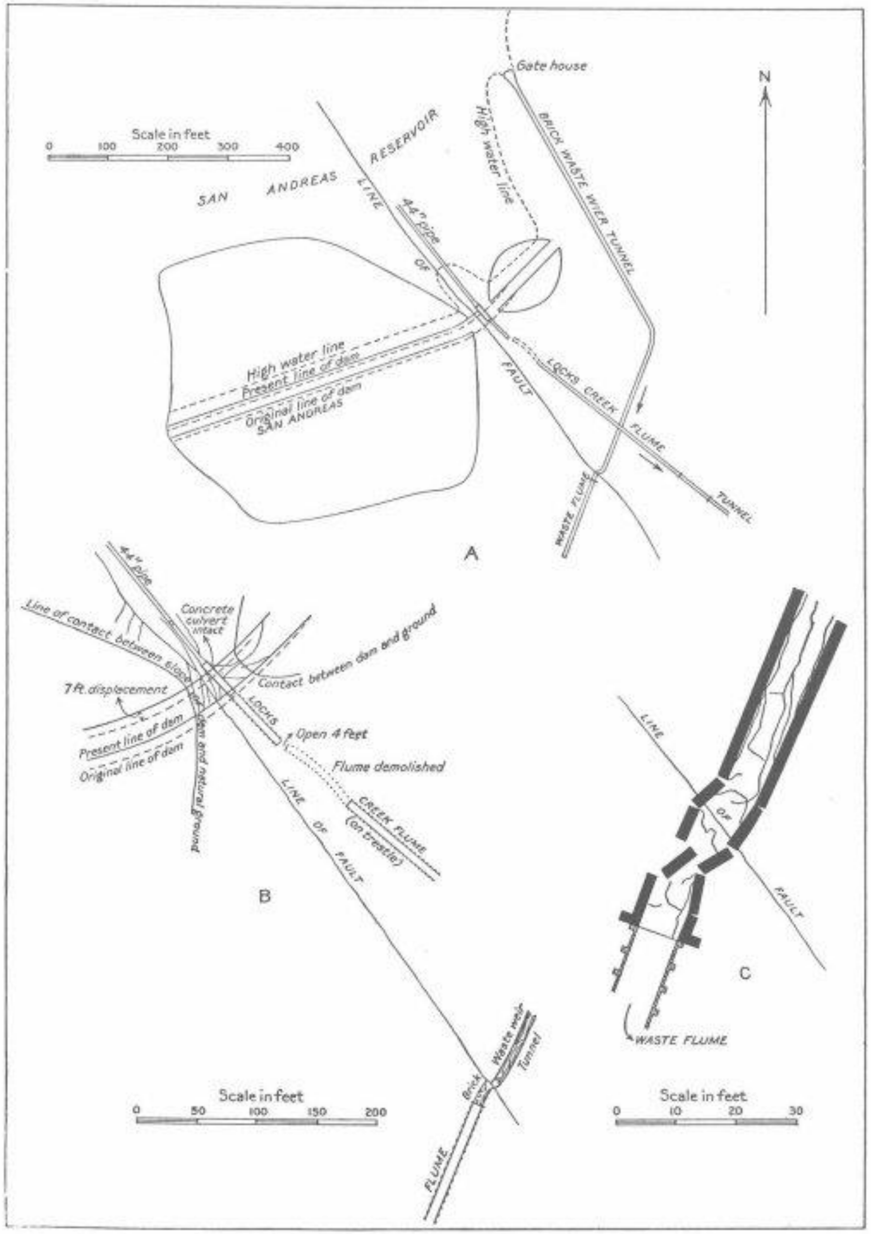
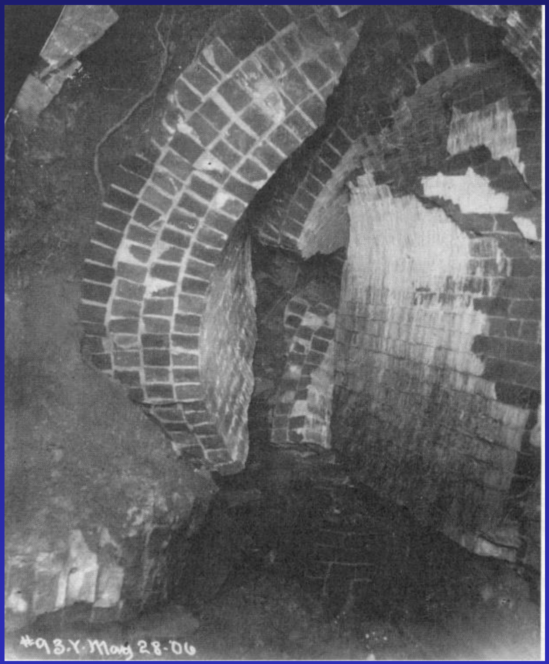



FIG. 36.—Intersection of San Andreas dam by fault. *A*. Plan of dam in two parts, with rock between. *B*. Relation of dam to waste weir tunnel. *C*. Detail of waste weir tunnel.




**Collapsed section of the brick-lined wastewater (spillway) tunnel, where it crossed the fault**

**Map at left shows the line a surface fault rupture of 7 feet in the shudder ridge between the two embankments of San Andreas Dam during the April 1906 $M_w$ 7.9 San Francisco earthquake (from Wood et al., 1908)**

# FAULT OFFSET OF OLD CRYSTAL SPRINGS DAM

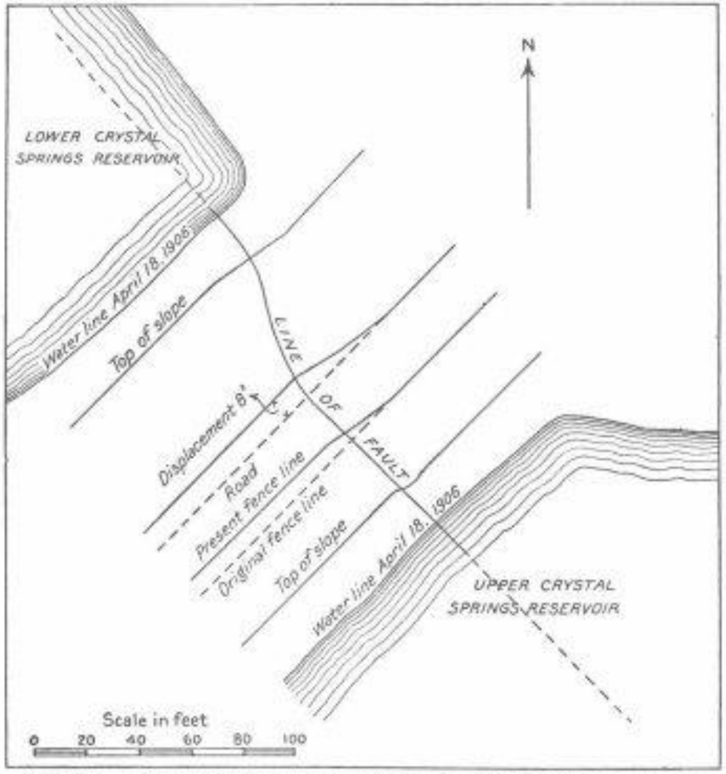



FIG. 40.—Map of fault-trace across old dam between Upper and Lower Crystal Springs Lakes. After H. Schussler.

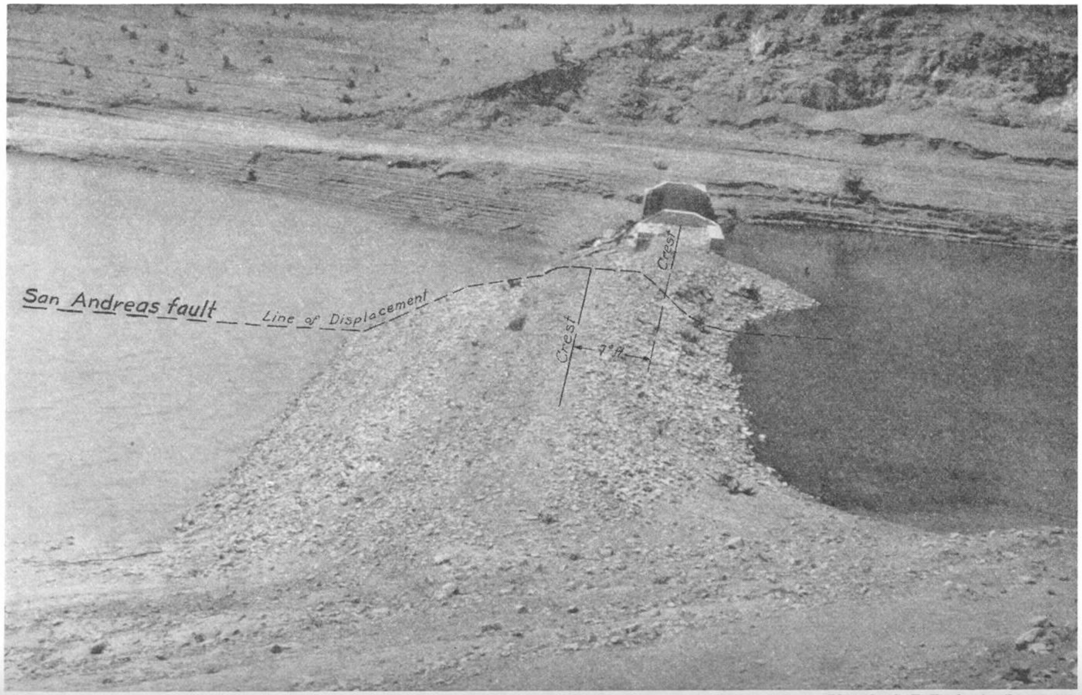



Photo by G. F. Engle, April 17, 1931

Fig. 2. View along the axis of the old dam in the San Andreas Valley (the same as fig. 1), showing the offset of about seven feet caused by the fault movement of April 18, 1906.

- During the April 1906 San Francisco earthquake, the old earthen dam between the upper and lower Crystal Springs Reservoirs was breached by an right-lateral offset of 7 feet.  Photo at upper right was taken 25 years later, during a low water stage.

# MANY ROCKFILL DAMS BULIT ON ALLUVIUM LEAKED SO MUCH THEY HAD TO BE ABANDONED

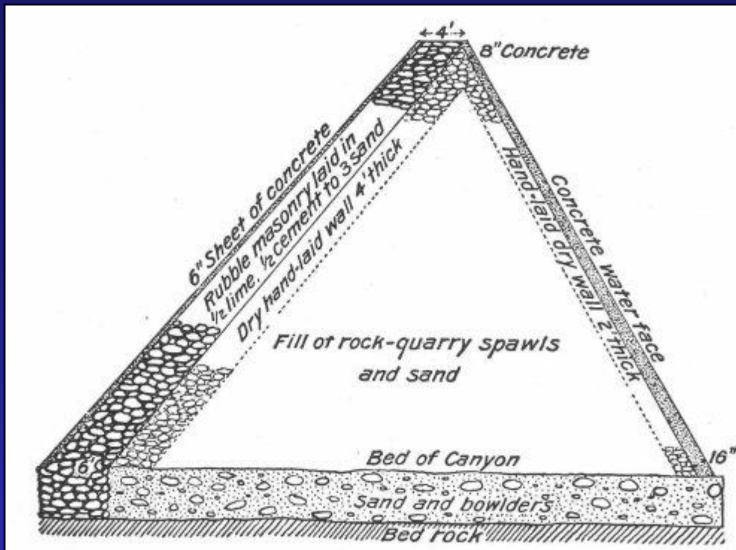
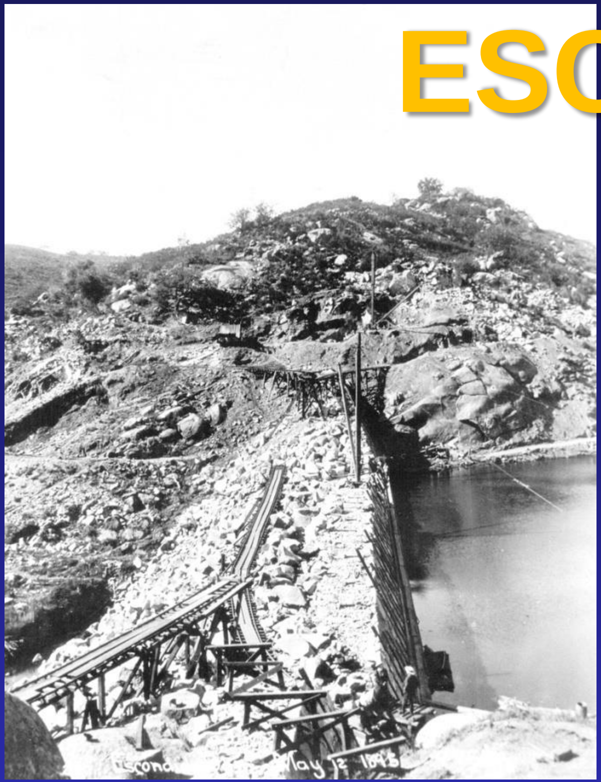
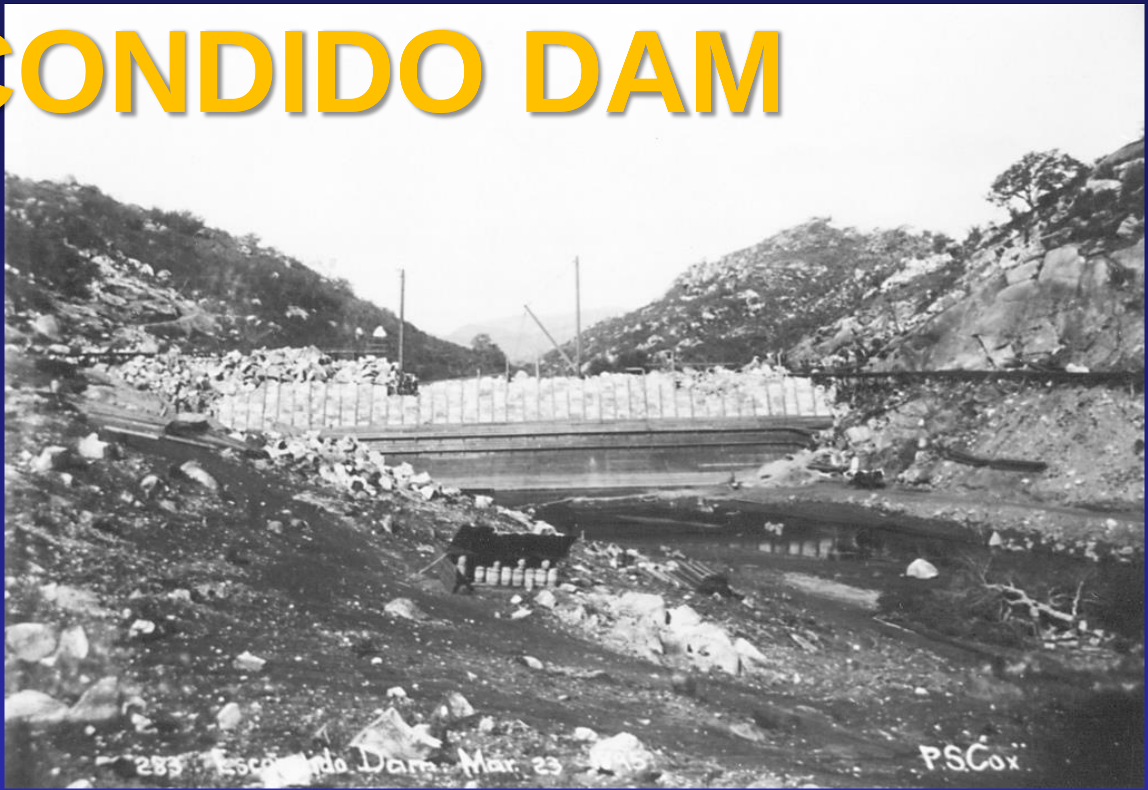


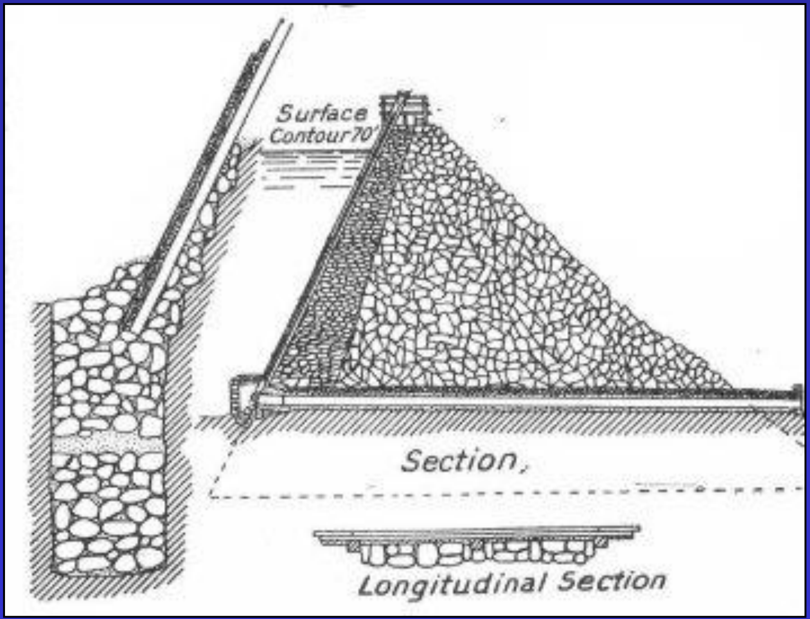

FIG. 62.—SKETCH OF RECONSTRUCTION OF CHATSWORTH PARK ROCK-FILL DAM.

- Early rockfill dams were built with steep side slopes and rubble fill, and often leaked profuse quantities of water
- Left: Chatsworth Park Dam was built in the west San Fernando Valley around 1900. It was 40 feet high but would only hold 10 feet of water. The rest leaked out through the alluvial foundation.
- Right: Escondido Dam leaked so badly that timber was placed over its upstream face (shown above) to reduce leakage.  But, when the lake level reached 57 feet (arrow), the reservoir began losing 100,000 gpd !

# ESCONDIDO DAM

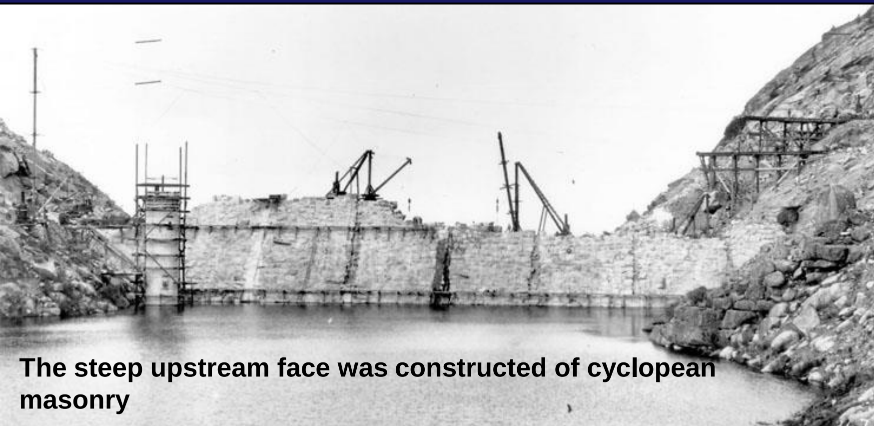




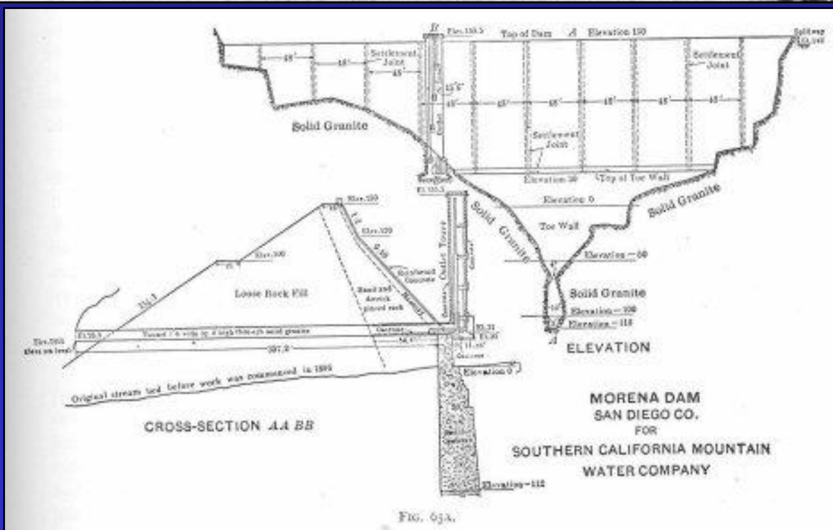




- **Escondido Dam** was one of the early rockfill dams in California, designed by **Frank E. Trask**. Its construction was supervised by **Harry Hawgood** in 1890-95, using 37,159 yds$^3$ of rock.
- It was 76 ft high, with a 10 ft wide course of hand-laid stone on the upstream face, inclined at 63.5 degrees
- It survived 12” overflow during the record storms of January 1916, but afterwards, was found to have settled 12”
- It was dismantled and replaced by **Lake Wohlford Dam** in 1926

# MORENA DAM



The steep upstream face was constructed of cyclopean masonry

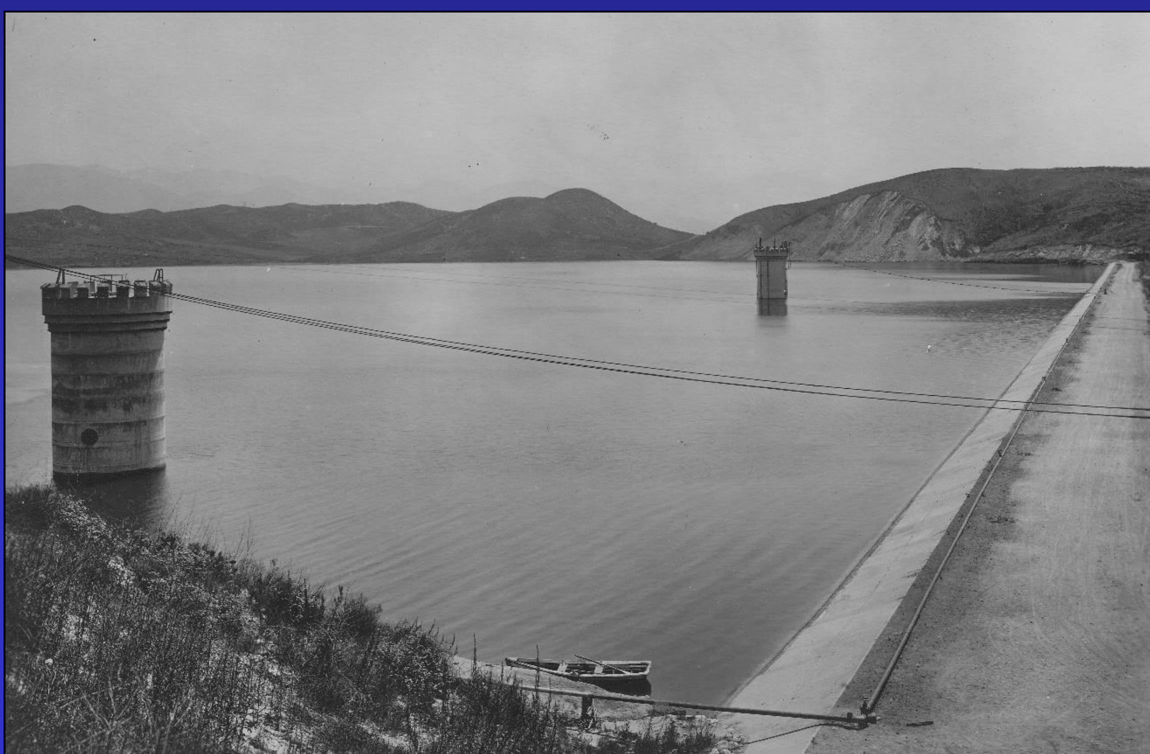



Right - Construction of the deep concrete cutoff wall commenced in 1893 and took six years to complete.

- **Morena Dam** was built between 1896-1911, and designed by **M. M. O'Shaughnessy, C.E.**, with construction supervised by **Hubert E. Green, C.E.** The dam included large granite blocks of 6 to 10 tons apiece (lower right)
- The rubble rockfill dam rose 120 ft above the bedrock chasm, but a concrete cutoff extended 142 feet below the bed of the stream, making it the **deepest dam foundation in the world**. Hubert Green battled with his construction foreman to place high quality concrete. The dam's upstream face was inclined 48 to 63.5 degrees! (lower left). Leakage varied between 33,600 and 57,800 gpd, depending on head. The dam was heightened to 177 ft above the creek bed in 1920.

# San Fernando Dam and Reservoir

- The original **San Fernando Reservoir** was constructed by the City of Los Angeles between 1911-17 using hydraulic "puddled fill technique," shown at left.

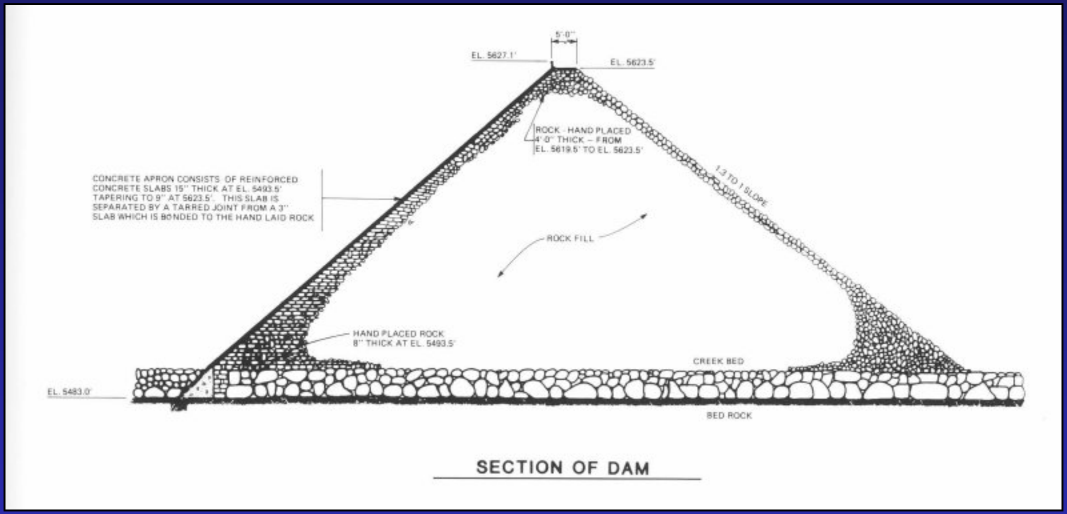


This view shows the dam in 1920, as originally completed, with a reservoir capacity of 10,870 ac-ft.

The embankment was raised 7 feet in four stages using rolled earthfill (over hydraulic fill). The last raise was completed in 1924-25, increasing its storage capacity to 14,670 ac-ft.

It was renamed **Lower Van Norman Reservoir** in 1945.

# STRAWBERRY ROCKFILL DAM (1916)

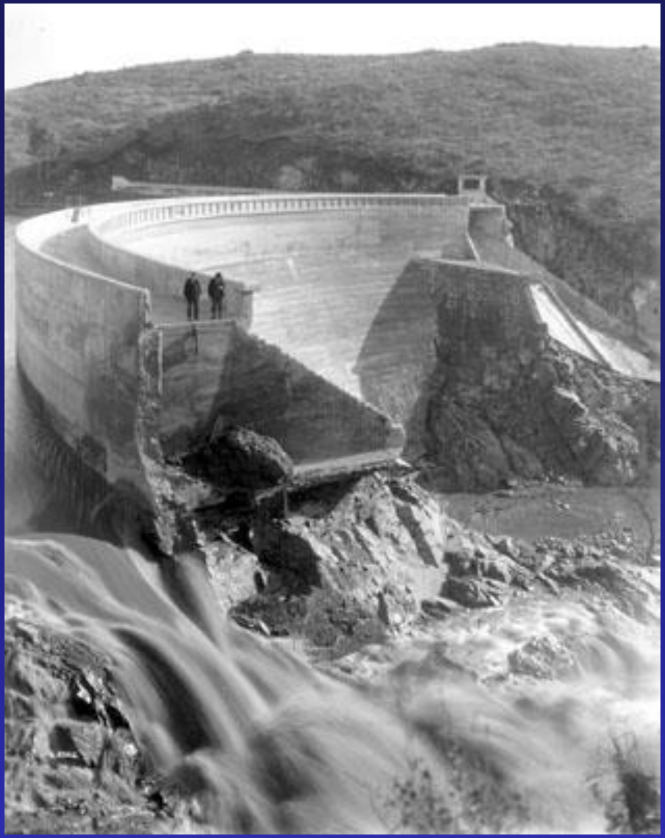



SECTION OF DAM

- **Strawberry Dam** is a 143 ft high concrete-faced rockfill dam built by Pacific Gas & Electric between 1913-16 on South Fork Stanislaus River, with slight upstream curvature
- The rock fill was "drop compacted" by allowing 'plum stones' to fall 20 to 70 feet from cableways! Hand-stacked facing stones were 2 to 5 tons apiece
- 1.3:1 (37.6$^{o}$) side slopes, it settled 2.1 feet (1.5%) in the first 20 yrs

# DAM SAFETY LEGISLATION

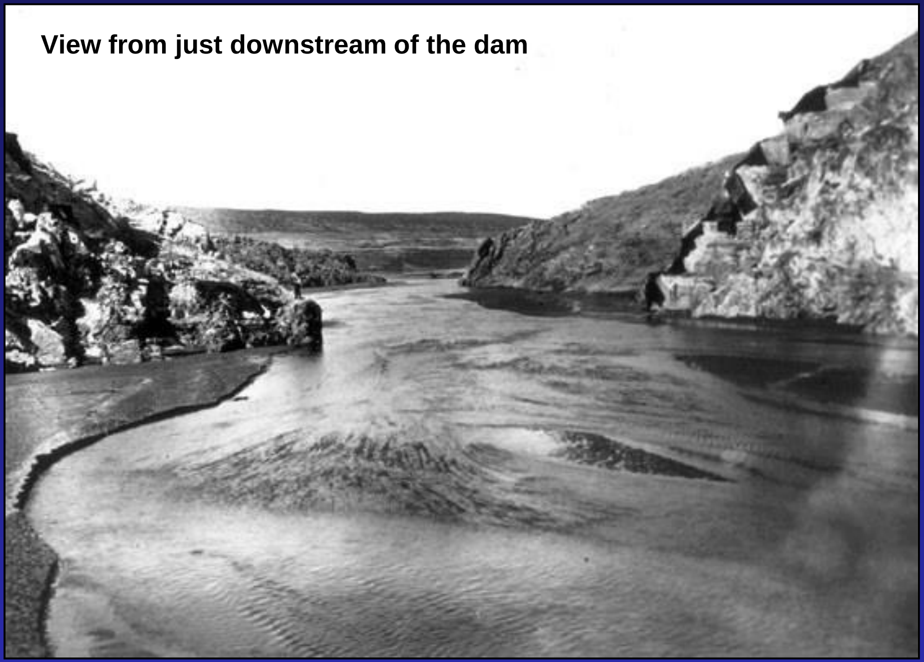
- In 1915 the State legislature passed a law requiring all plans for dams and reservoirs to be submitted to the State Engineer for approval, but the act provided no penalty for failure to comply.
- Following a 2-year study, in August 1916 the State Reclamation Board issued a report recommending that the State Engineer regulate all storage reservoirs.
- No further action was taken by the legislature until after January 1916 floods in Southern California

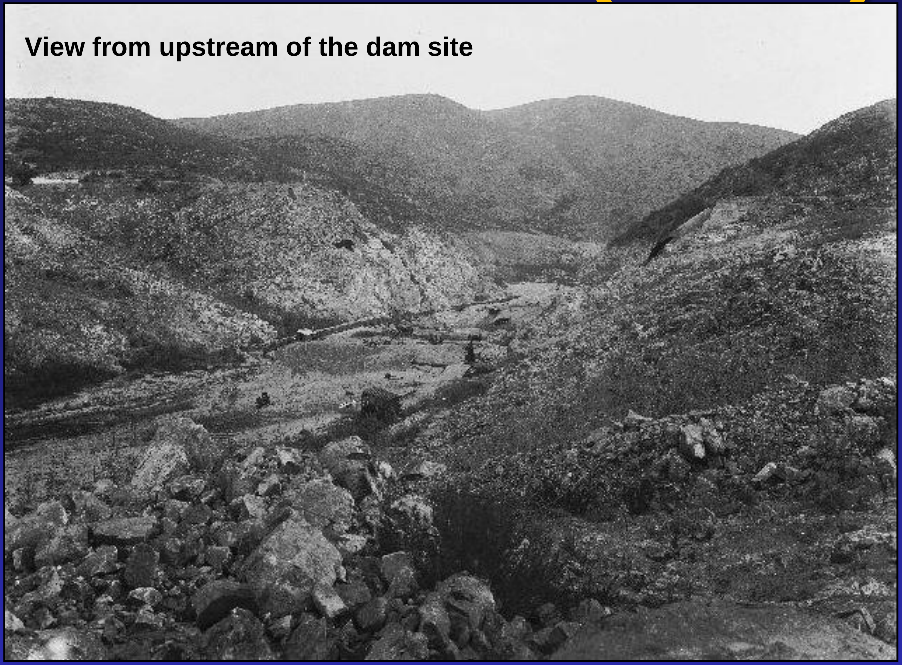


# RIGHT ABUTMENT FAILURE OF SWEETWATER DAM (1916)

- In 1910-11 James D. Schuyler prepared a plan that raised **Sweetwater Dam** 15 feet, increasing the reservoir capacity by 70%.
- In January 1916, 8 to 20 inches of rain fell on the area, causing a peak discharge of 45,500 cfs for an hour, and an average flow of 20,000 cfs over 24 hours. The dam was overtopped to a depth of 3.66 feet, washing out the south abutment dike (shown here). 8 people were killed by the flooding.
- We would never build an arch dam in such fractured rock today.

# LOWER OTAY DAM FAILURE (1916)




- On January 27, 1916 the Lower Otay Reservoir rose 9.5 ft between 7AM and 5 PM, when the flow began to overtop the dam
- When the overflow reached 3,500 cfs it triggered severe erosion of the dam, causing it to fail within five minutes. All of the dam's rock fill was removed within 15 minutes, by 5:20 PM. 40,000 acre-feet of water was released, killing 30 people.

# DAM SAFETY ACT OF 1917

**Public outcry followed failure of the Lower Otay and Sweetwater Dams in January 1916 in San Diego County**

- **The State Engineer was granted authority over all dams > 10 feet high or which impound > 9 acre-ft (3 million gallons), <u>with exception of</u>:**
  - **Dams for mining debris constructed by the California Debris Commission**
  - **Dams constructed by municipal corporations maintaining their own engineering departments**
  - **Dams and reservoirs that are part of water systems regulated by the State's new Public Utilities Act**

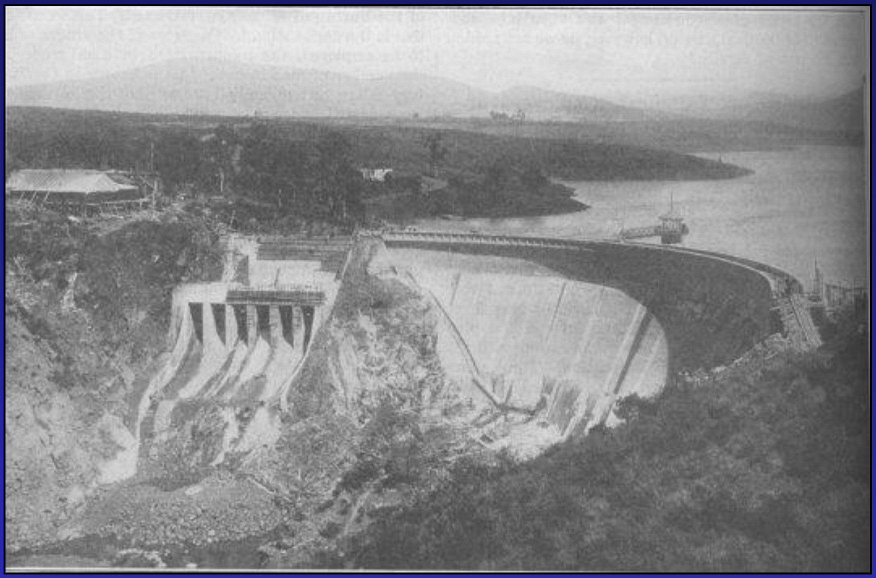
# State Railroad Commission

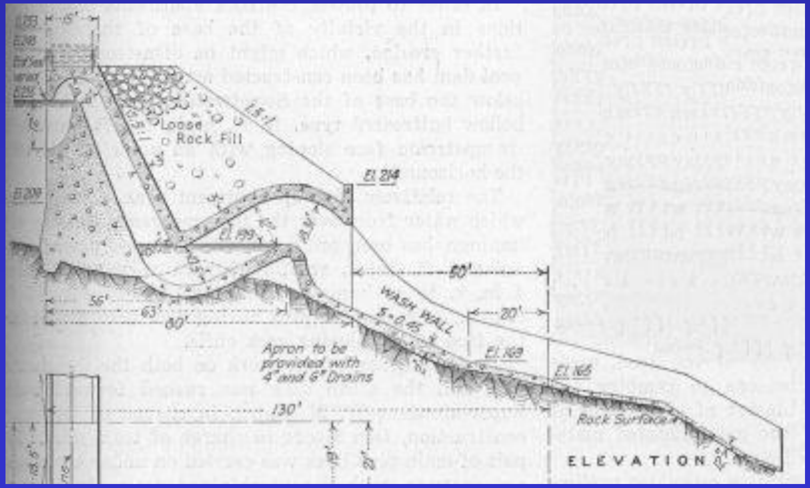
- The Railroad Commission was given authority over all dams owned by public utilities, beginning in 1917
- The commission exercised some oversight on 46 of 140 dams built in California between 1917-1929
- Municipal water agencies, such as EBMUD and LACoFCD, were exempt from State overview until August 1929

# DAM SAFETY AUTHORITY BETWEEN 1917-1929

- From 1917-1929 the State Engineer was given authority to review plans for dams prepared by irrigation districts, private companies, and individuals
- The State Railroad Commission was given authority to review dams and reservoirs owned by public agencies subject to the 1917 Public Utilities Act.
- In 1920 the Federal Power Commission began supervising dams for power projects involving the public domain.

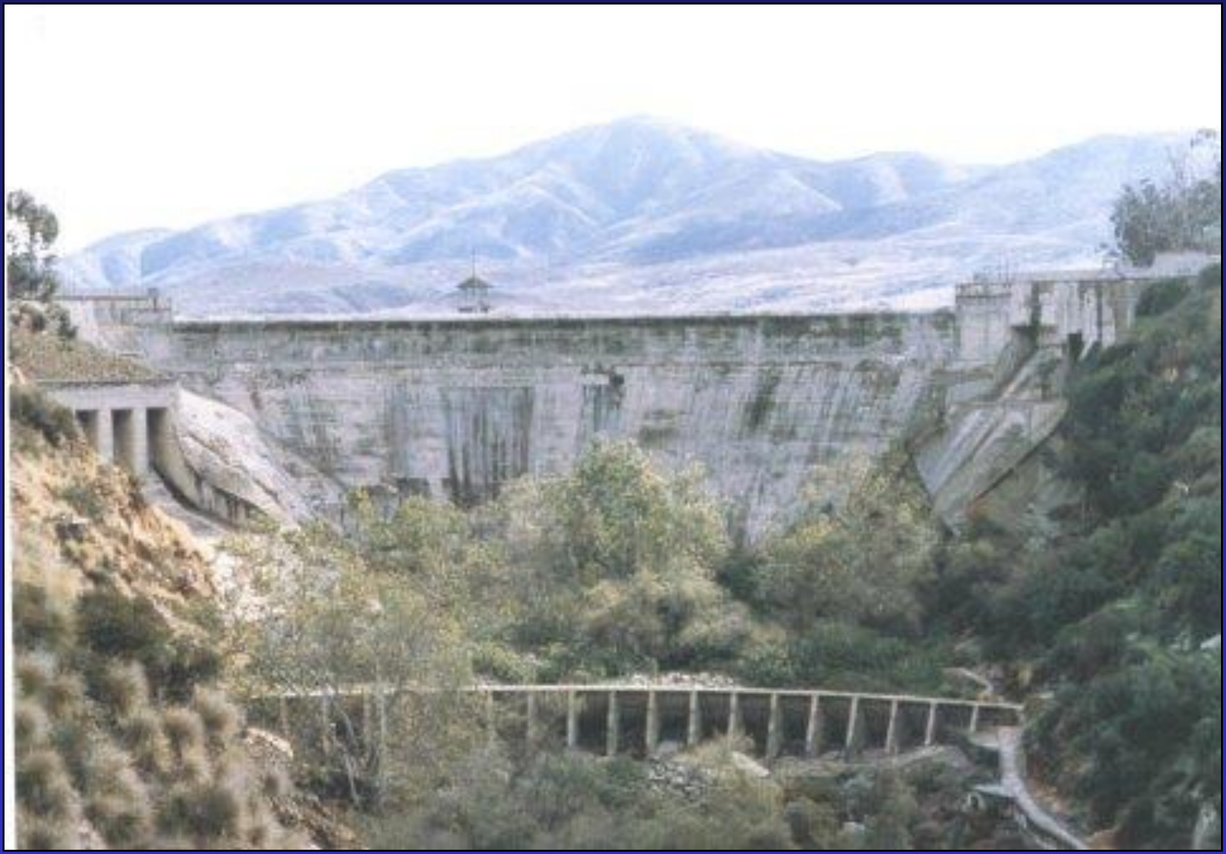
# SWEETWATER DAM SPILLWAY CAPACITY ENLARGED FOR THIRD TIME IN 1919





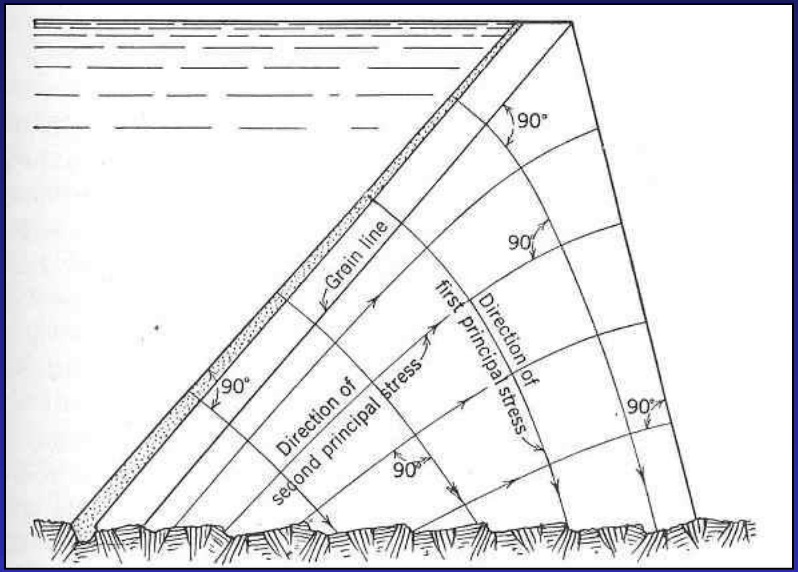

- A massive retrofit of Sweetwater Dam was undertaken in 1918-19 to repair damage caused by the 1916 flood.
- The spillway capacity was increased to 45,000 cfs by enlarging the existing spillways and constructing a series of siphon spillway chutes on the right abutment (shown at left).

# SWEETWATER DAM TODAY



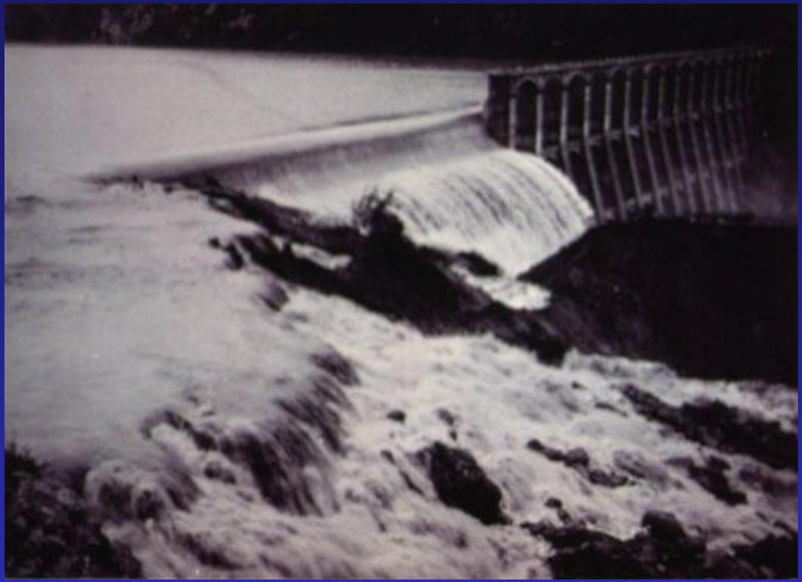
- Like an old soldier, the Sweetwater Dam remains in service, storing 27,690 acre-feet of water for the California-American Water Co. in San Diego County

# HIGHEST BUTTRESS DAM IN THE WORLD, BUT WITH CRACKS



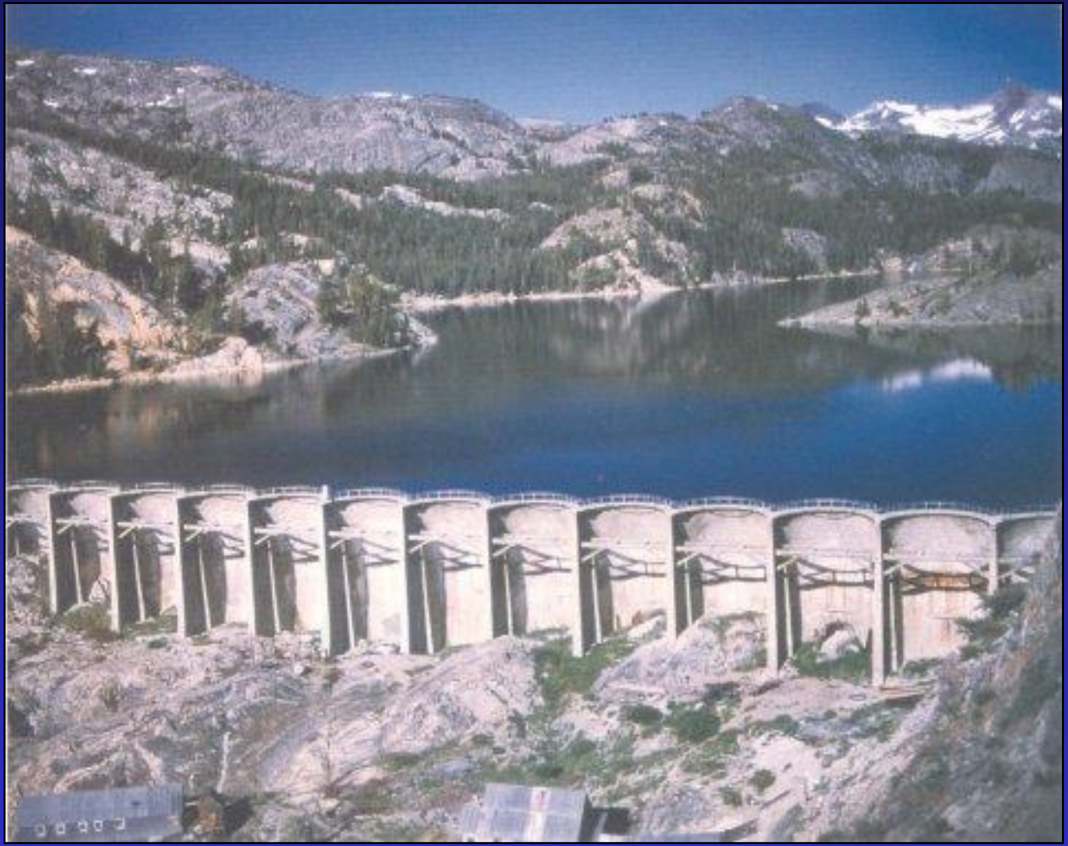

- **Lake Hodges Dam** was designed by the legendary John S. Eastwood, it was an inclined multiple arch, which became vertical in the top 15 ft
- At 136 ft high, it was the highest buttress dam in the world in 1918
- The buttress supports developed cracks parallel to the minimum stress trajectories. A professional debate erupted as to the cause of these cracks; being induced tension, or caused by shrinkage of the concrete
- This cracking problem was not explained until after instrumentation and study of similar cracks in Rodriguez Dam in 1929, by Fred Noetzli, Hubert Woods, and Roy Carlson.

# 1927 FLOOD AT LAKE HODGES



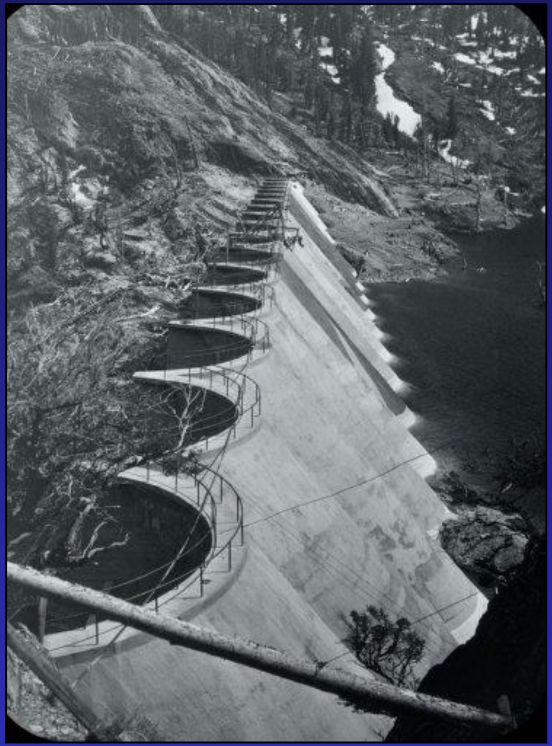
- **Lake Hodges spillway passing 45,000 cfs around 1:30 PM on February 16, 1927. Depth over spillway was 11 feet 8 inches. Reservoir drainage area was 303 mi$^2$.**
- **Concrete dam enthusiasts were quick to point out that buttress dams were better equipped to handle large bypass flow events without sustaining severe damage or failure…**

# GEM LAKE DAM -1916



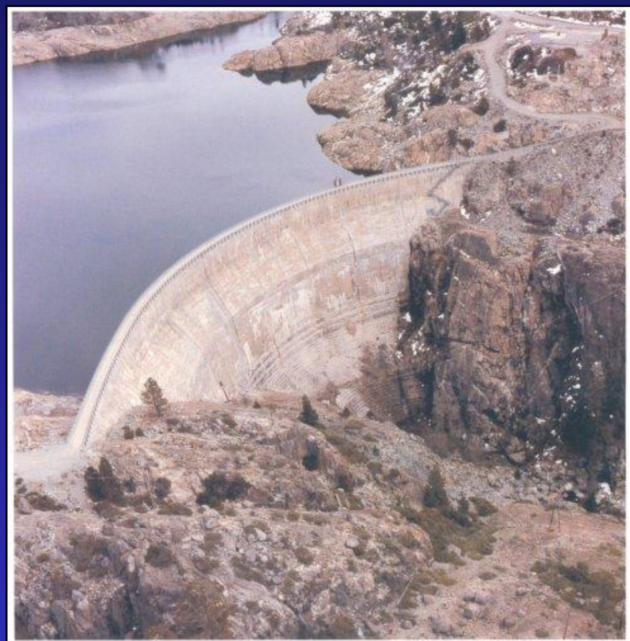
- Gem Lake and Agnew Lake Dams were built along Rush Creek on east side of the Sierra Nevada Mountains in 1915-16, at altitudes of 9000 and 8500 feet, respectively.
- Gem Lake Dam is 112 ft above the stream bed, with the highest cylinder arch being 84 ft high

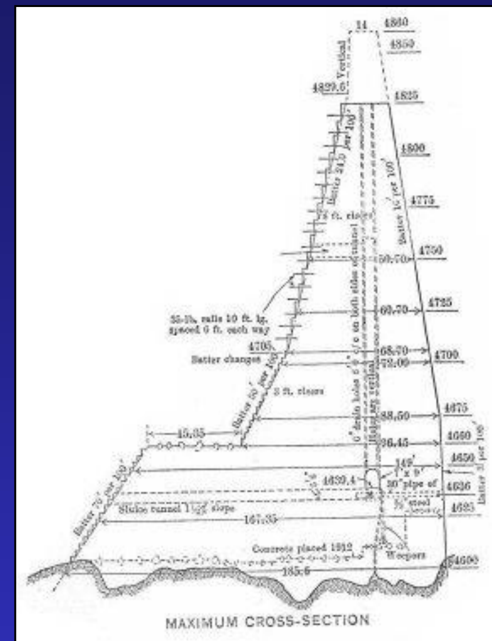
# FROST DAMAGE AT GEM LAKE



- After a few years seepage was observed in the zone below the winter water level. The concrete on the downstream side of the arches began to exhibit efflorescence and progressive deterioration, but the buttresses did not. Professor Raymond E. Davis of U.C. Berkeley was retained to investigate and recommend repairs. He found that a lower water/cement ratio was employed in the concrete on the buttresses.
- This and other studies of concrete deterioration eventually led to the American Concrete Institute recommending a w/c ratio of no more than 0.45 for poured concrete.

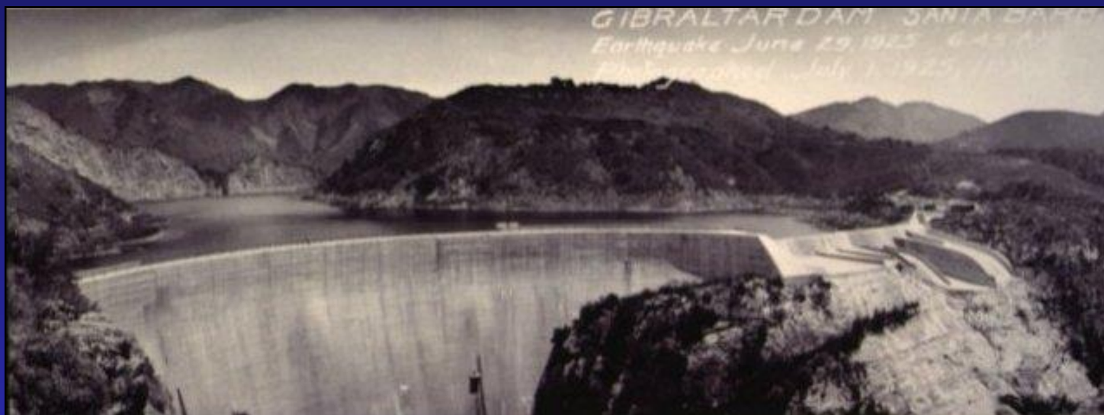
# WORLD’S HIGHEST CONSTANT-ANGLE / VARIABLE-RADIUS DAM






- **Lake Spaulding Dam** was begun in 1912 as a gravity dam with 400 ft radius on the South Fork Yuba River by PG&E
- In 1913 PG&E decided to switch to the variable radius design being promoted by Lars Jorgensen (the world’s first variable radius dam was then under construction at Salmon Creek, Alaska )
- It reached 225 ft in 1914; was raised 35 ft in 1916; and another 15 feet in 1919-20, for a total height of 276 feet, a world record.

# FIRST ARCH DAM WITH ARTIFICIAL THRUST BLOCK




- **As originally constructed in 1918-20, Gibraltar Dam was a 185 ft high constant radius arch dam designed by Quinton, Code and Hill of Los Angeles to provide water from the Santa Ynez River for the City of Santa Barbara**
- **All construction materials and site access supplied through a 4-mile long 42” x 48” water supply tunnel**
- **A 3000 $yd^3$ thrust block was built on the left abutment a year before the main dam to give it time to cure (above right)**

# AN ELEGANT DEBRIS DAM

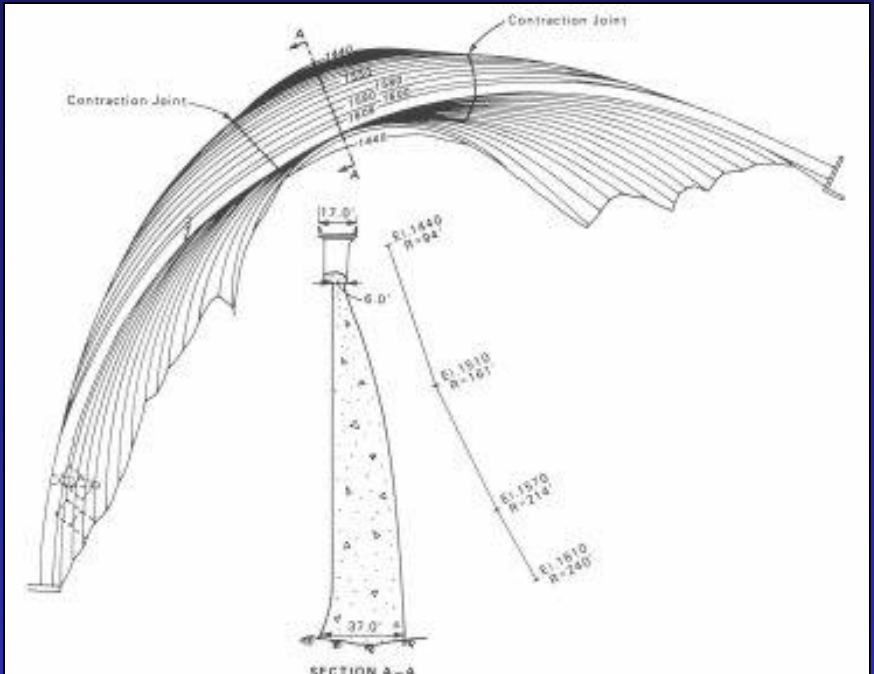
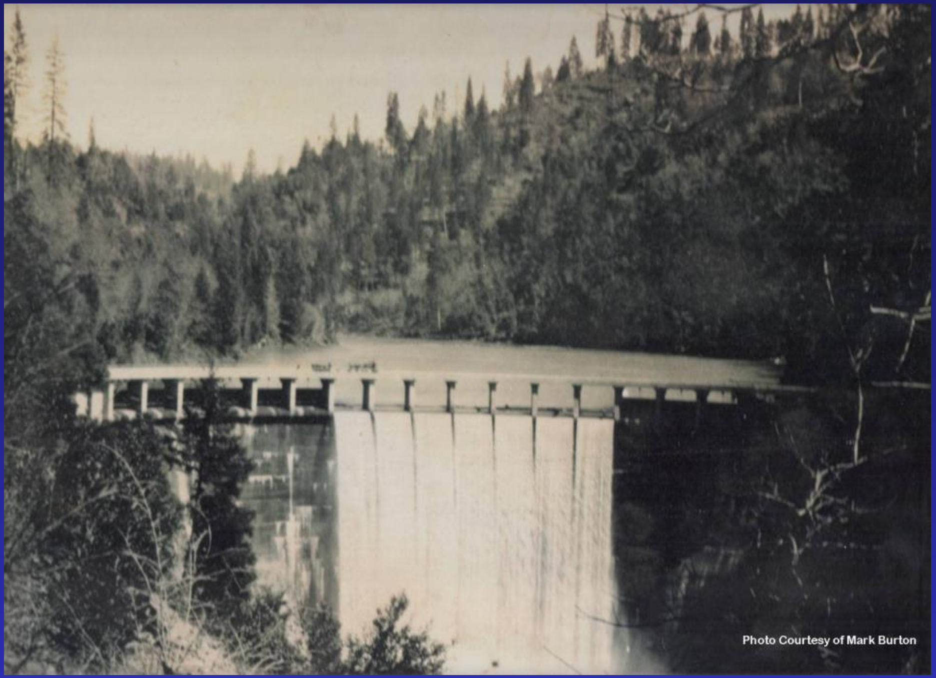


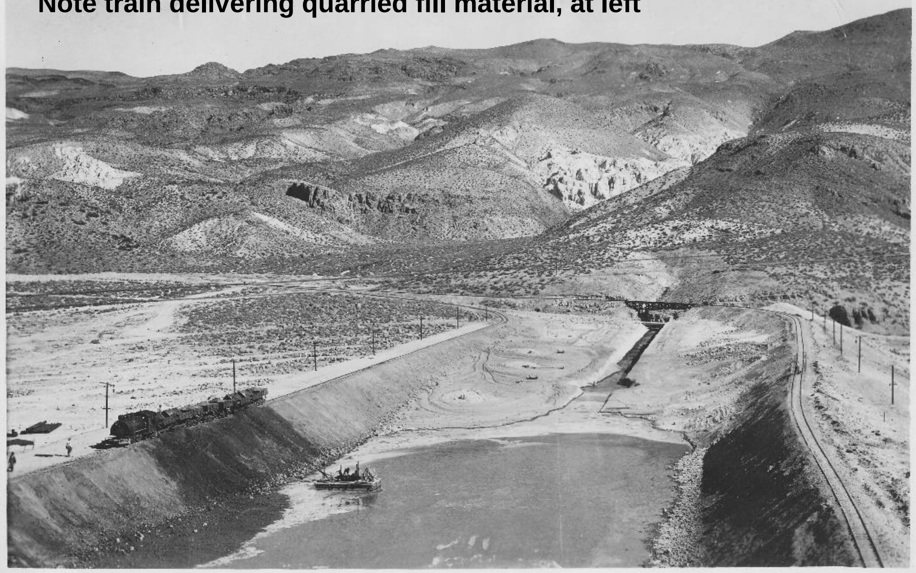

**Figure 3–12** Bullards Bar Dam

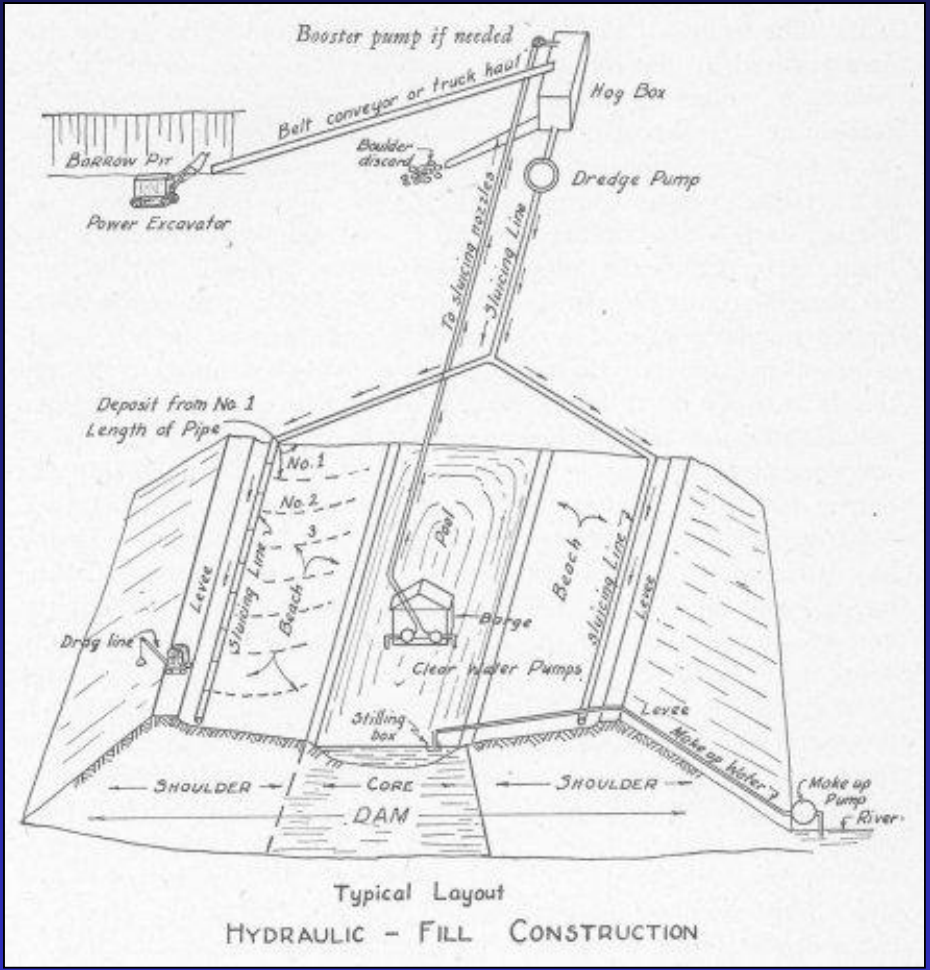



- **The old Bullards Bar Dam was a small, but elegant constant-angle arch dam built on the North Fork of the Yuba River in 1924 to retain hydraulic mining debris. It was intended to withstand overtopping without any reservoir flood storage, with a design overflow of 65,000 cfs over its crest**
- **It was replaced by New Bullards Bar Dam in 1967**

# HYDRAULIC FILL TECHNOLOGY

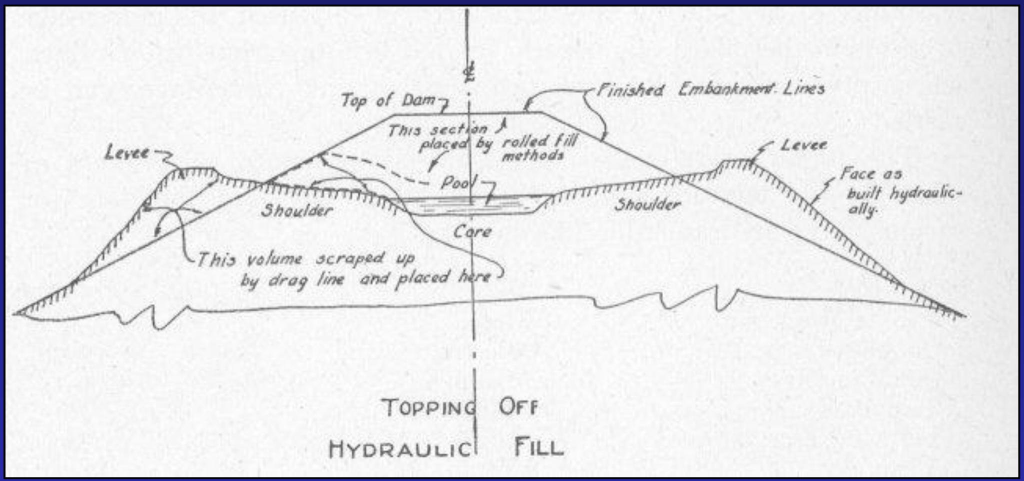
Haiwee Dam core pool, as viewed during construction  in 1912.
Note train delivering quarried fill material, at left

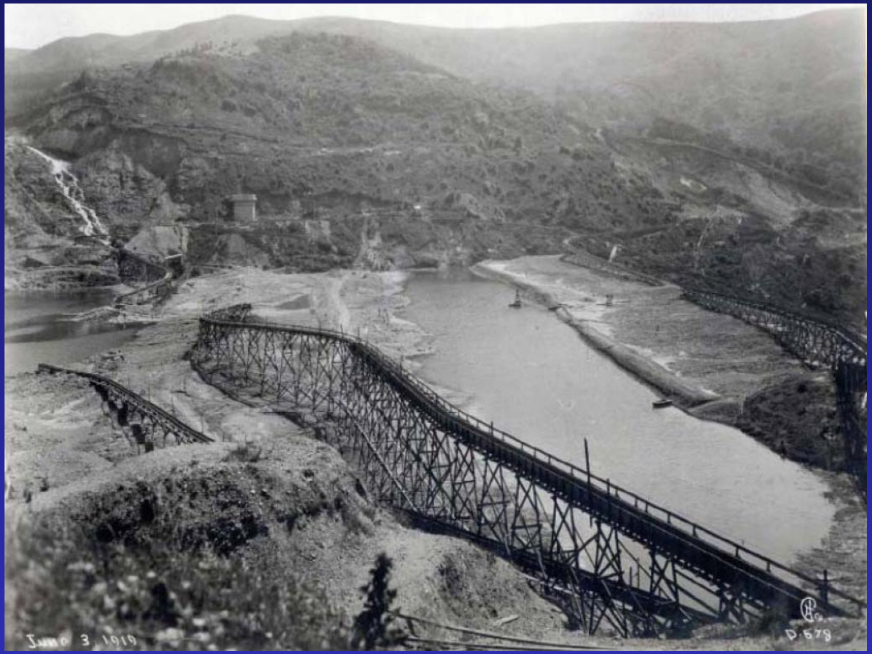





- **Prior to the Fort Peck Dam upstream shell failure in Sept. 1938, most earthfill dams were constructed using hydraulic monitors to sluice clayey sediments into a slurry that was piped to the dam site and deposited without benefit of mechanical compaction**

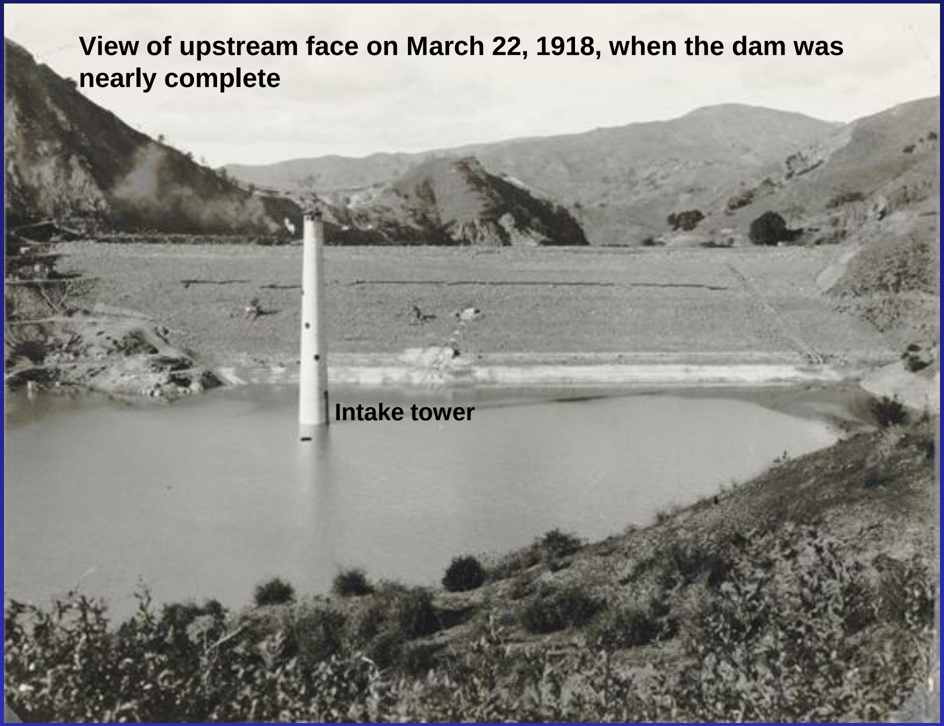
# PUDDLED CORES FOR LOW PERMEABILITY

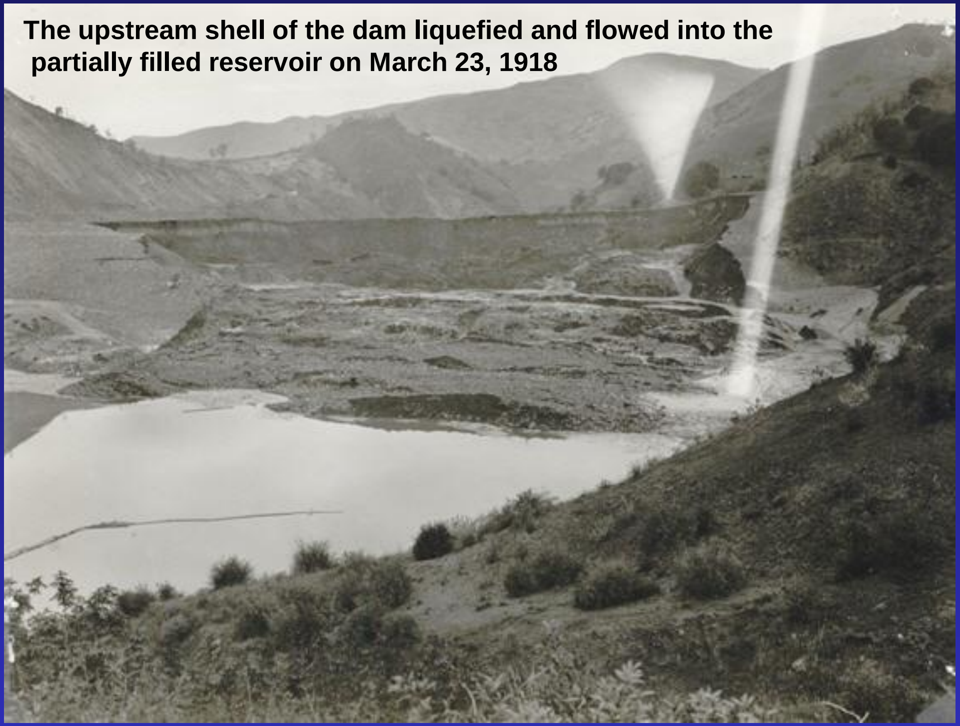


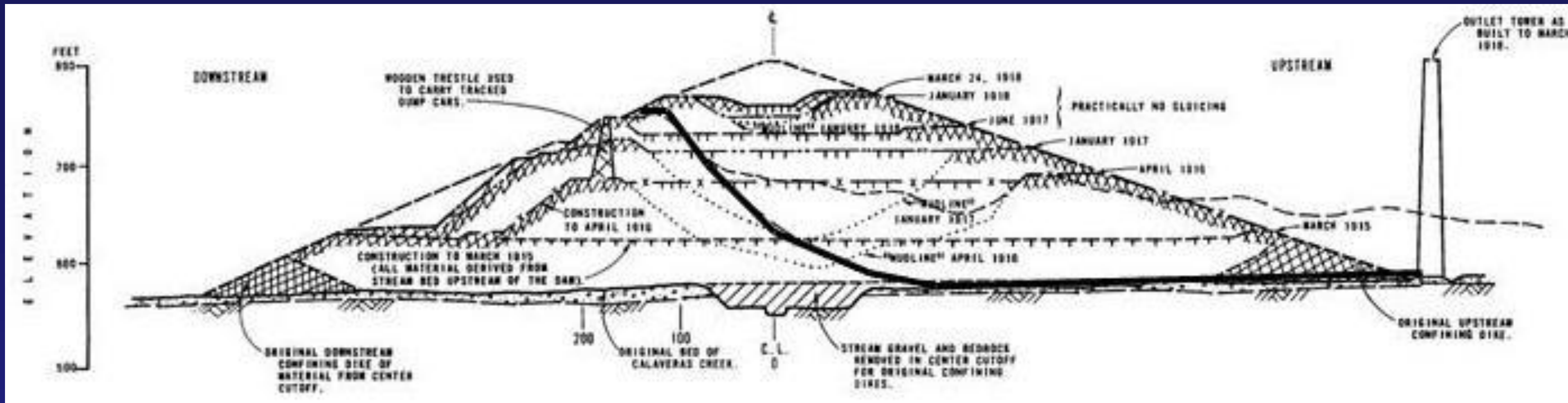
- The embankments of hydraulic fill embankments were raised by constructing temporary levees on either side and allowing the fines to "puddle" in a central "core pool"
- This central zone became the impervious core of the dam (San Pablo Dam is shown at right)

# CALAVERAS DAM SLIDE

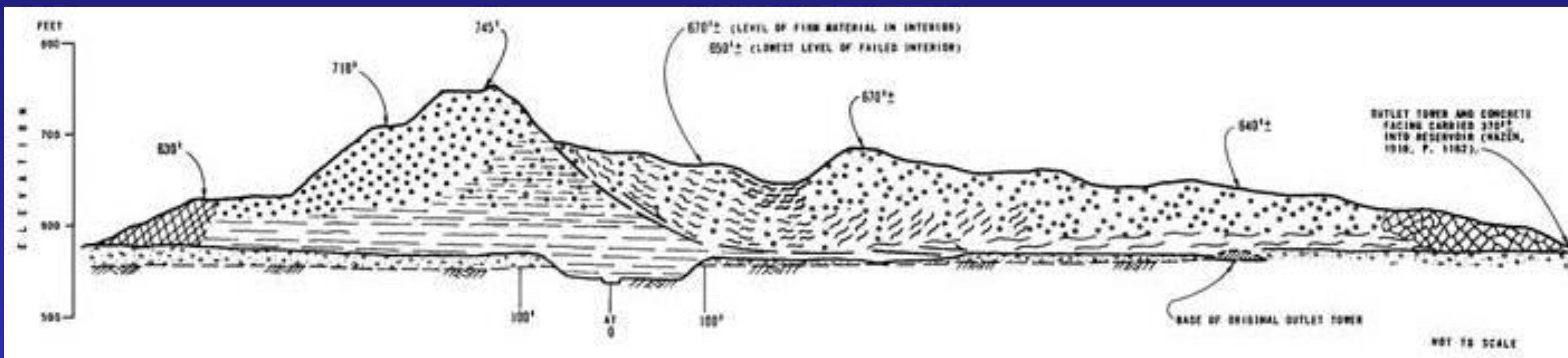


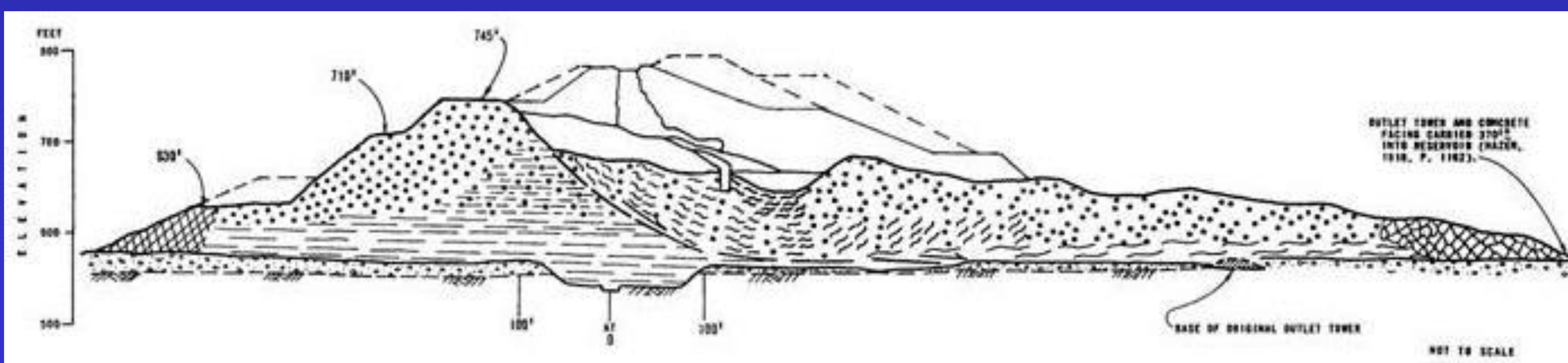

- **Calaveras Dam** was intended to be 240 ft high with a volume of 3 million yds$^3$ placed by hydraulic filling, making it the *largest earthfill dam in the world in 1918*
- On March 23, 1918, 800,000 yds$^3$ of fill slid upstream into 55 ft of water in five minutes, destroying the 230 ft high intake tower
- In 1923 construction was resumed on an embankment 25 ft lower, with flattened side slopes. This revised scheme was completed in 1925.




**Section through the Calaveras Dam when the upstream shell failure occurred in March 1918**




**Section through the liquefaction flow slide of the dam's upstream shell in March 1918**

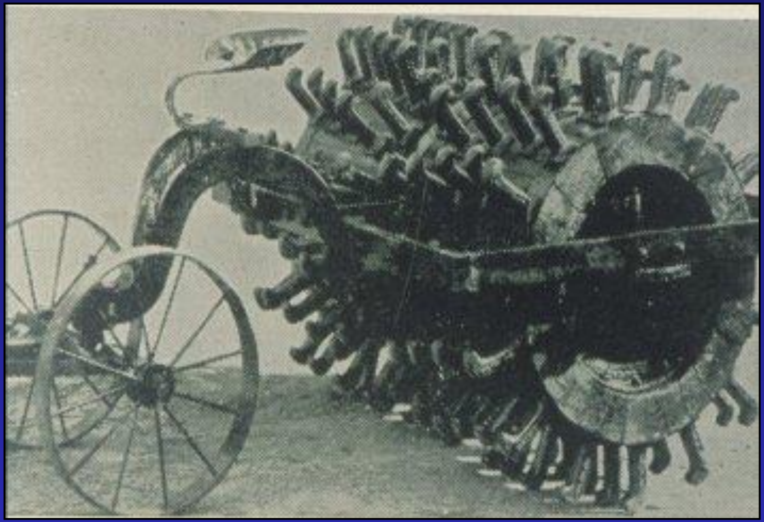


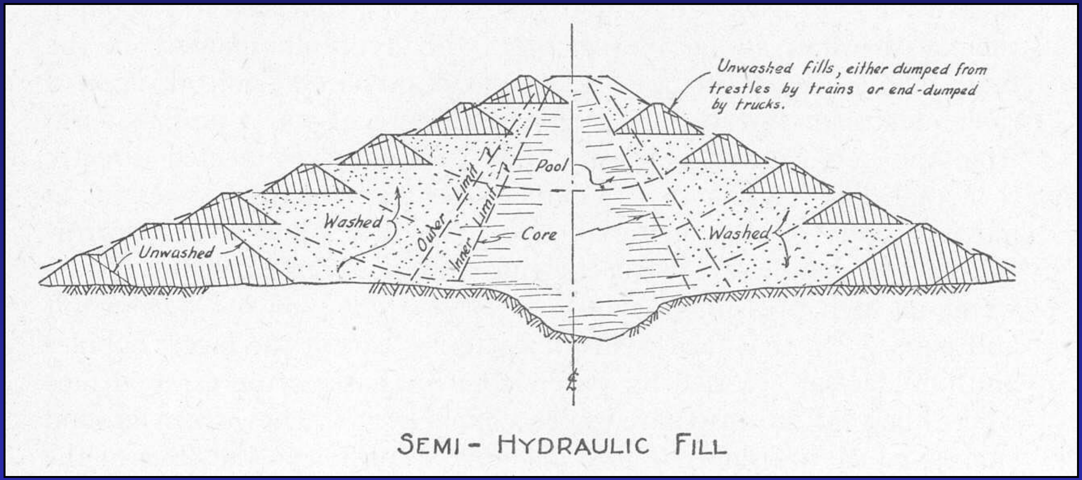

**Section illustrating how the dam was reconstructed sequentially, between 1923-25**

# SAN PABLO DAM (1920)

- The San Pablo Dam was a hydraulic fill embankment 220 feet high, constructed by the East Bay Water Company in 1918-20
- Its volume of 2,200,000 cubic yards made it the largest embankment dam in the continental United States until completion of Calaveras Dam in 1925. It did not fill until 1937, with water from EBMUD's Mokelumne River aqueduct arrived.
- Buttress fill zones were placed up and downstream of the original dam in 1967 and 1979-80 to increase seismic stability. The alluvium just downstream of the dam's toe was stabilized using Cement Deep Soil Mixing in 2008-10 to increase resistance to liquefaction of the alluvium.

# EVOLUTION OF EARTHWORK MACINERY AND TECHNIQUES



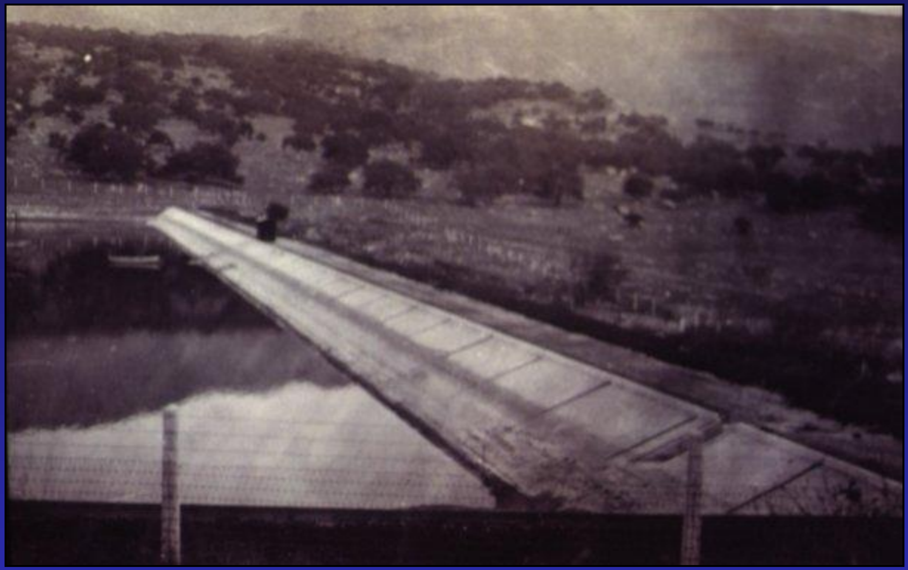


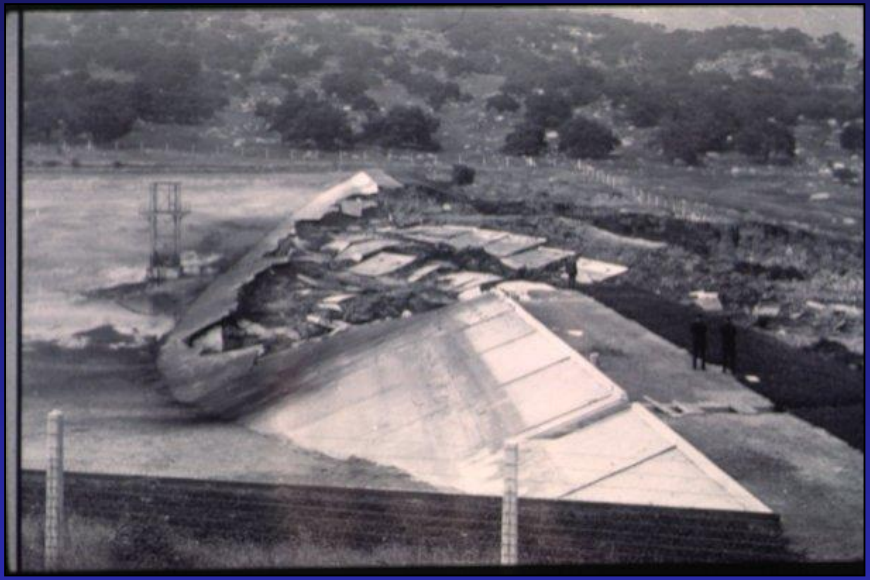

- The sheepsfoot roller (left) was patented by the Petrolithic Paving Co. of Los Angeles in 1904. It continued to evolve throughout the 1920s and 30s, becoming increasing larger
- In the 1920s the semi-hydraulic fill technique evolved for constructing embankment dams, where tamped fill prisms were employed on the flanks of an embankment, to bound a central core pool that employed the puddling to settle out the fines (silt and clay) fraction.

# First dam compacted with sheepsfoot rollers

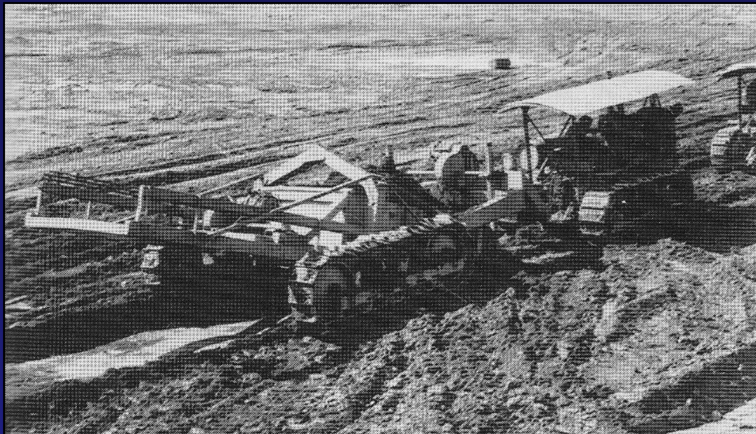
- The first earth embankment dam compacted with sheepsfoot rollers was the Henshaw Dam in in 1920-23 for the Vista Irrigation District in San Diego County, shown at left.

# FIRST EARTHQUAKE-INDUCED FAILURE



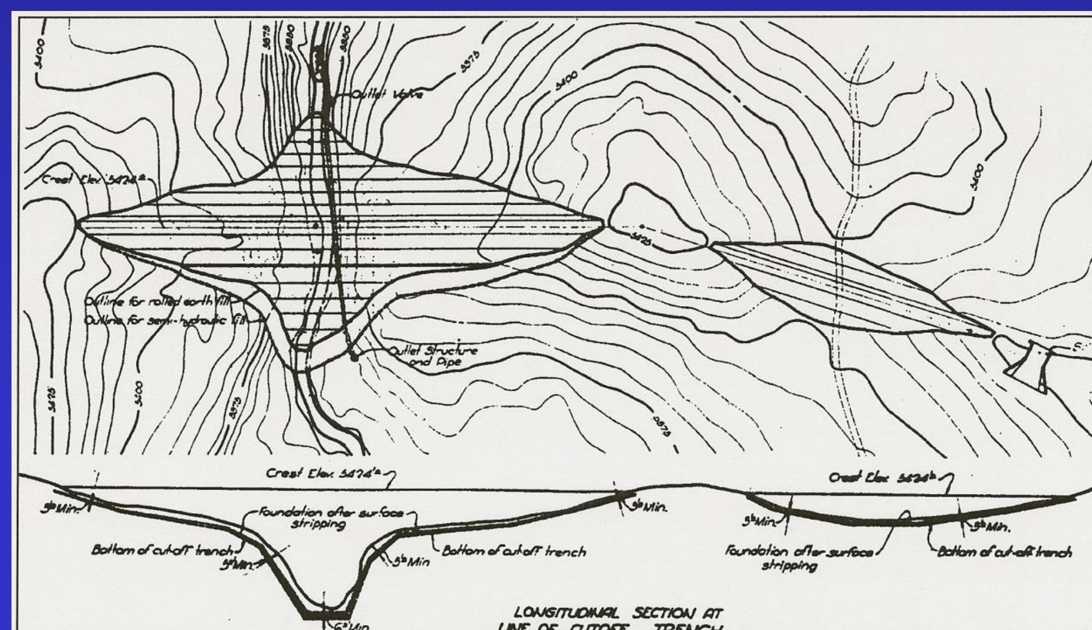


- The Sheffield Dam was a concrete-faced embankment dam 25 feet high and 720 long built in 1917 to retain 30 mg of water for the City of Santa Barbara (shown at left)
- At 6:44 AM on June 28, 1925 a $M_L$ 6.3 earthquake struck the Santa Barbara area, causing the uppermost portion of gravelly-sand foundation beneath the middle 300 ft of the dam to liquefy (shown at right), moving pieces of the dam up to100 ft downstream
- The dam was taken out of service in May 2004

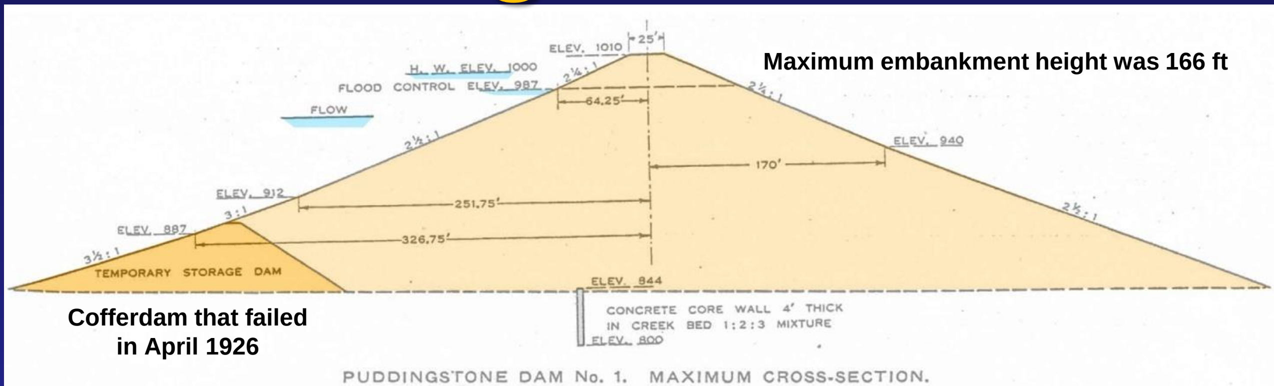


# FIRST DAM BUILT WITH SCRAPPERS

- **Philbrook Dam** was an 85 ft high earth fill and wing embankment built by Kaiser Construction for PG&E as a power supply reservoir in 1926, off the West Branch of the Feather River
- Kaiser retained R.G. Letourneau Construction Co of Stockton to move the earth with his patented telescoping scrappers, shown at left. The fill volume in both embankments was 142,000 yds$^3$
- It was the first rolled fill dam in the world constructed with mechanical scrappers

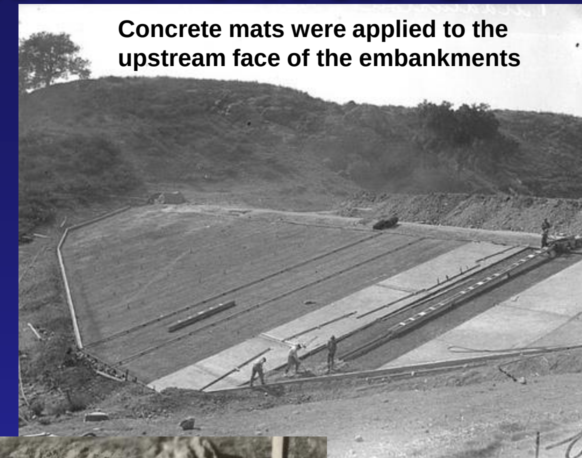


# Puddingstone Cofferdam Failure

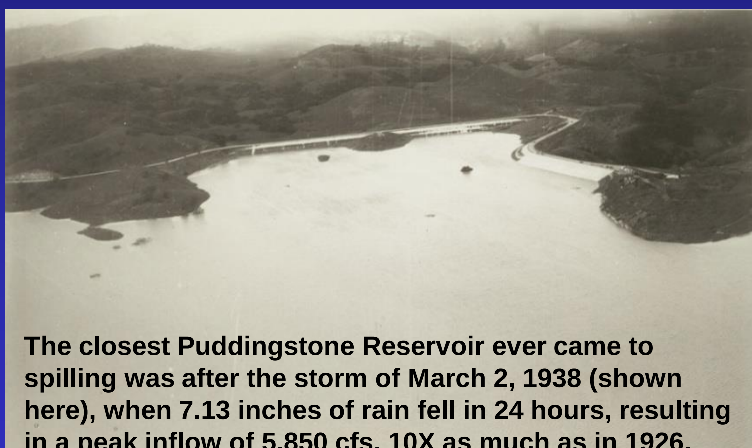



**Maximum embankment height was 166 ft**

**Cofferdam that failed in April 1926**

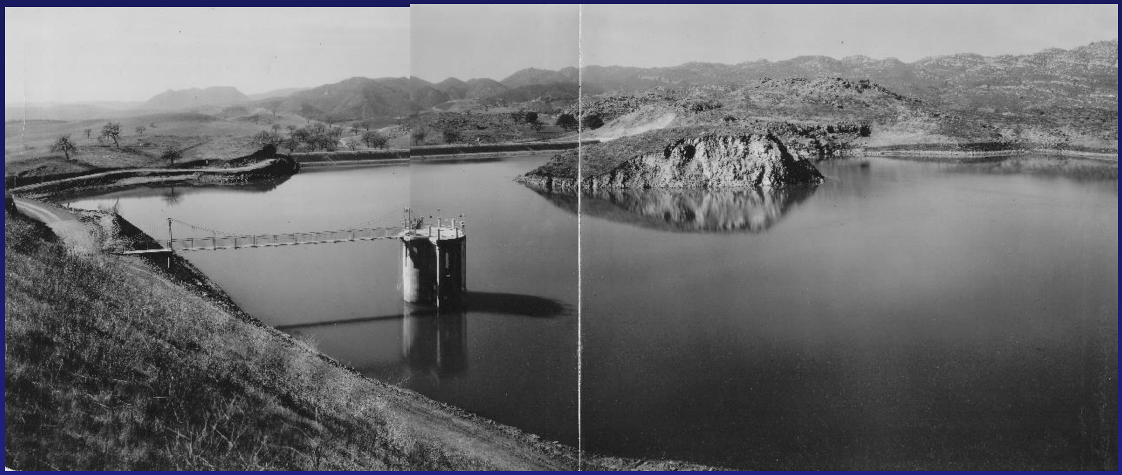


**Concrete mats were applied to the upstream face of the embankments**



**The closest Puddingstone Reservoir ever came to spilling was after the storm of March 2, 1938 (shown here), when 7.13 inches of rain fell in 24 hours, resulting in a peak inflow of 5,850 cfs, 10X as much as in 1926.**

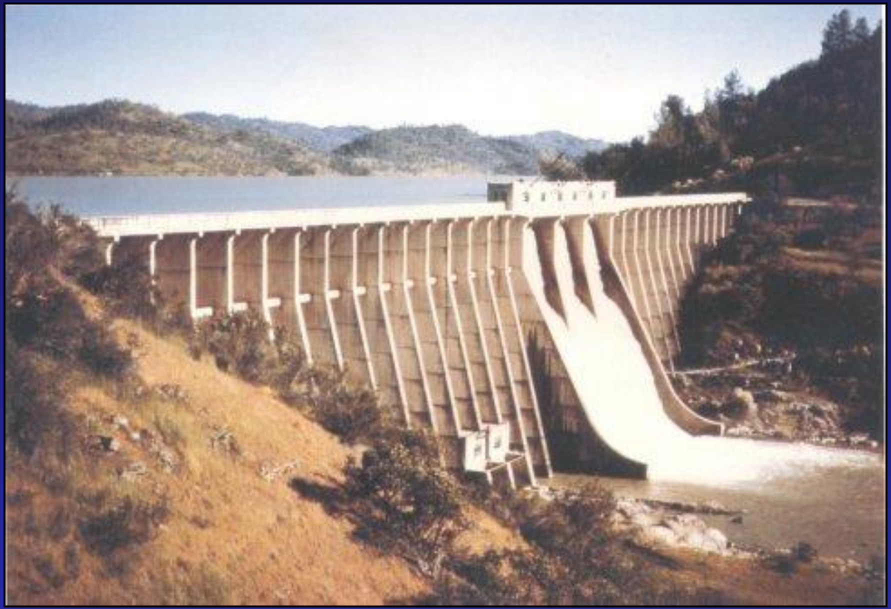
- **Puddingstone Dam and Reservoir** was built by Los Angeles City & County in 1925-28 along Walnut Creek, but also storing water diverted from San Dimas Creek. It was comprised of three rolled fill embankments up to 177 ft high, capable of storing 17,398 ac-ft. The soils were compacted with a sheepsfoot roller that employed ball-shaped heads, patented by contractor H.W. Rohl.
- Work began early in 1925 with excavation of a 5 x 7 ft outlet tunnel 700 ft long, about 35 ft above the streambed, while a 40 ft deep core wall was excavated into the creek channel and a temporary storage dam 53 ft high was to be constructed as a cofferdam. The cofferdam was only 45 ft high and storing about 500 ac-ft of water when storms dropped 8 inches of rain on the area in April 1926, producing an inflow of 500 cfs. This overwhelmed the outlet tunnel and the cofferdam began overtopping. 1 hr and 15 min later the cofferdam collapsed, resulting in a flood of 10,000 cfs lasting about 15 minutes, which eroded 18,000 yds$^3$ of fill. Oddly, the reservoir has never spilled since that first year of construction.

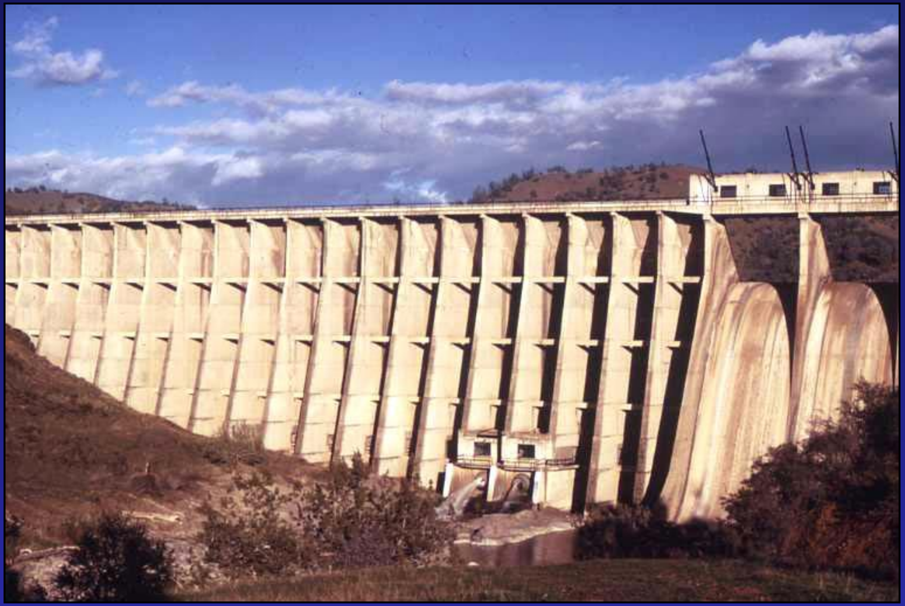


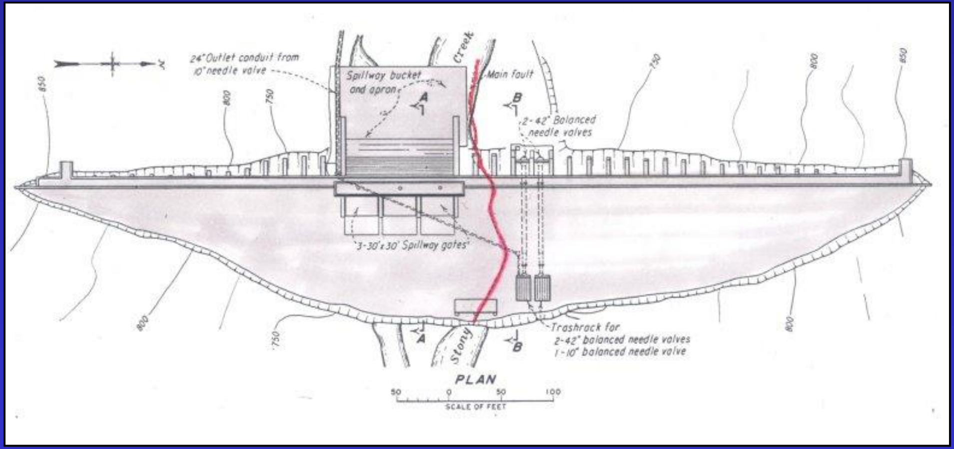
# CHATSWORTH RESERVOIR –
## damaged by quake and eventual abandonment


- Chatsworth Dam and reservoir was built by the City of Los Angeles for their Los Angeles Aqueduct in 1918, with a capacity of 10,000 acre-feet.
- It was built of hydraulic fill and tamped fill on the crest, and provided with a paved concrete face. It was constructed on a pervious foundation of unconsolidated late Quaternary age alluvium
- The M 5.2 Santa Monica Bay earthquake of August 30, 1930 caused noticeable vertical cracking of the embankment crests, due to partial liquefaction and lurching, which increased leakage.
- The dam was eventually taken out of service in August 1969 because of increasing concerns about water quality due to algae plumes in the shallow bays and urban storm water influx. After the 1971 earthquake, additional concerns for seismic safety led to its abandonment as a storage facility.

# FIRST DAM BUILT OVER A FAULT








**Stoney Gorge Dam was built for the Bureau of Reclamation by the Ambursen Dam Co. in 1926-28.**

- **A flat slab buttress structure was selected with 18 ft wide noncontinuous slabs because it was thought the best system to accommodate minor foundation movements along the fault exposed in the dam's foundation during construction (shown in red, below left).**

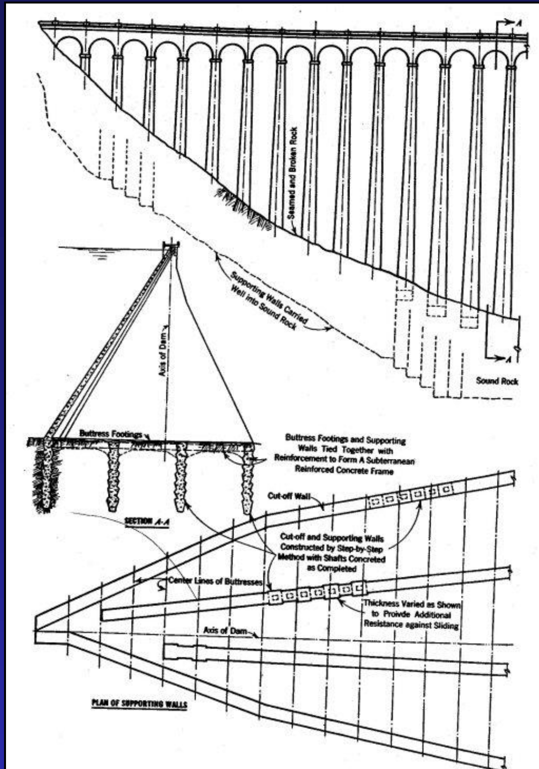



FIG. 8.

# ANOTHER BUTTRES DAM BUILT OVER A FAULT

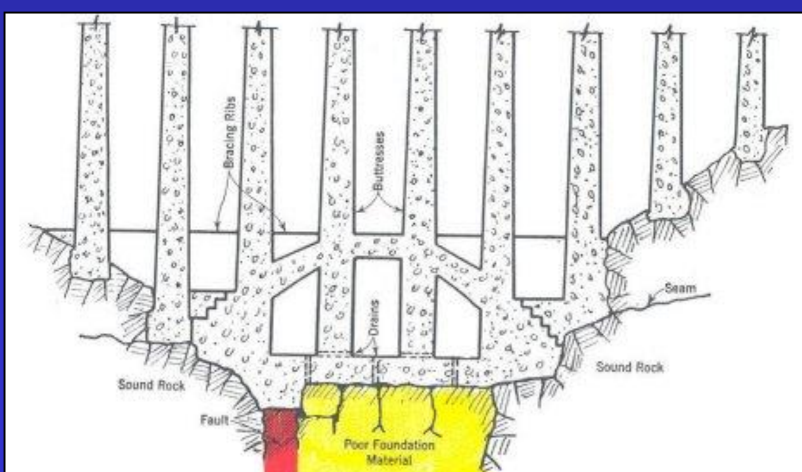
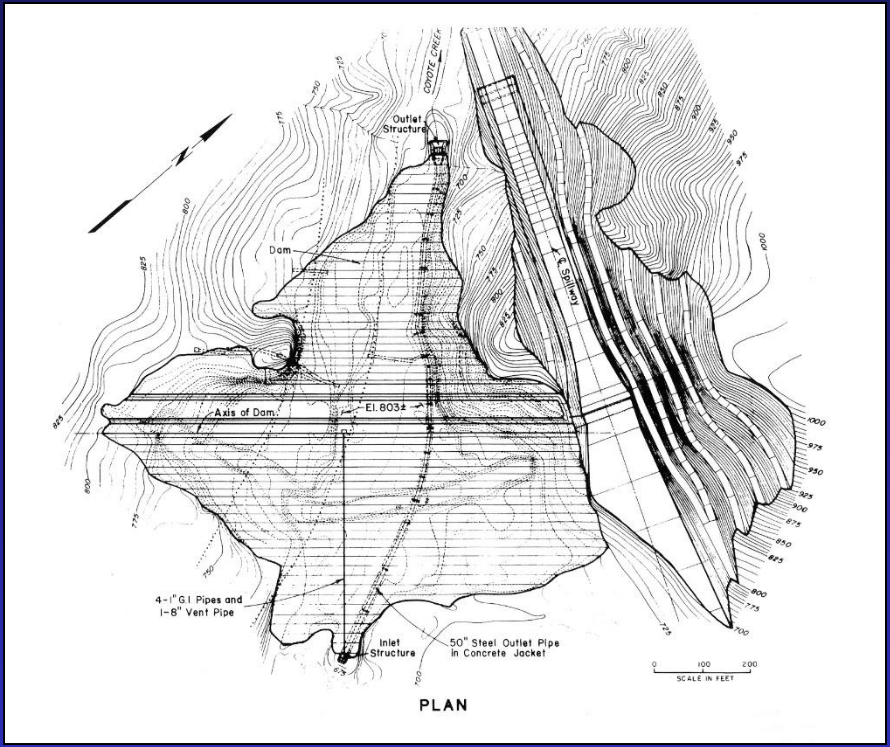



FIG. 9.

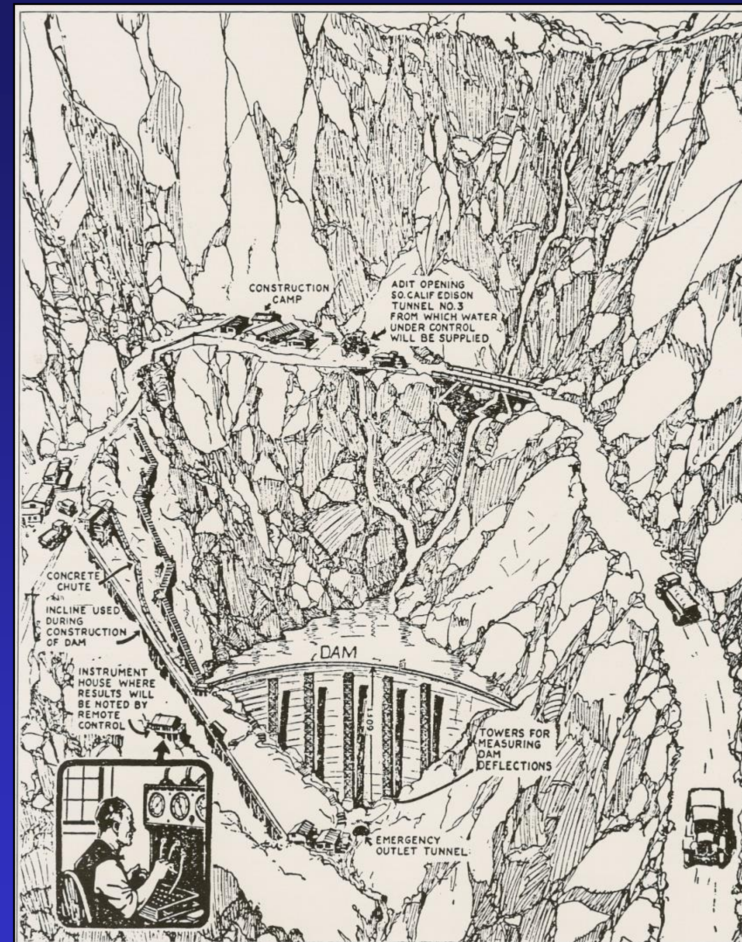
- **Rodriguez Dam** is a 240 ft high buttress dam constructed along the Tijuana River, just south of the border, in 1930. The height above stream bed was 187 ft. The faulted zone was bridged with an enormous arch (lower right), so the dam's buttresses would not bear on the fault (shown in red).

# COYOTE DAM and CALAVERAS FAULT

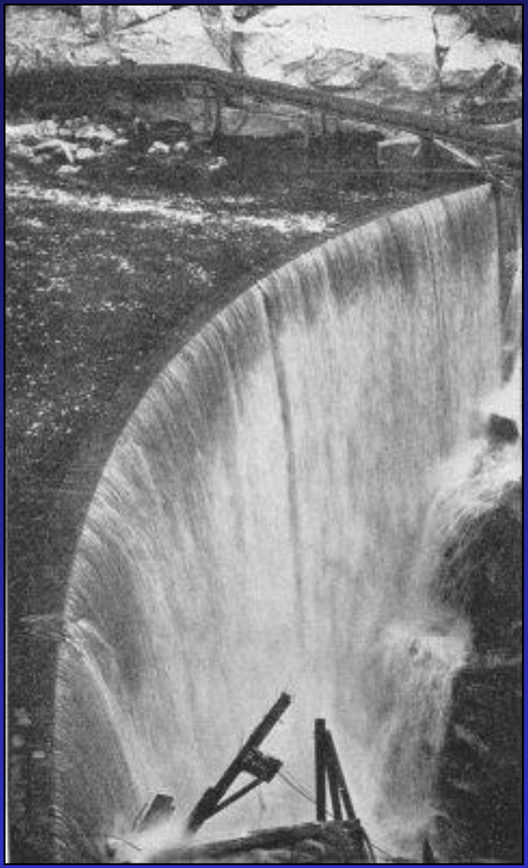

- **Coyote Dam** was built along Coyote Creek east of Morgan Hill by the Santa Clara Valley Water District between 1934-36, storing 10,000 acre-feet of water
- **It was knowingly built across the active 1000-ft wide trace of the Calaveras fault, and has performed well to date.**

# STEVENSON CREEK TEST DAM




- In the early1920s the engineering profession came to recognize that a rational method of designing arch dams was lacking.
- In the spring of 1926 The Engineering Foundation decided to build and instrument a test structure in California, along a tributary of the San Joaquin River, east of Fresno

# TWO KINDS OF TESTS



- The Stevenson Creek Test Dam developed maximum arch stresses of 207 psi at the crown and 879 psi at the abutments. 429 psi compression was measured at the downstream toe and 380 psi tension at the upstream heel (base).
- The dam survived overtopping in November 1926 (see right)

# STEVENSON CREEK ELEVATION AND SECTION

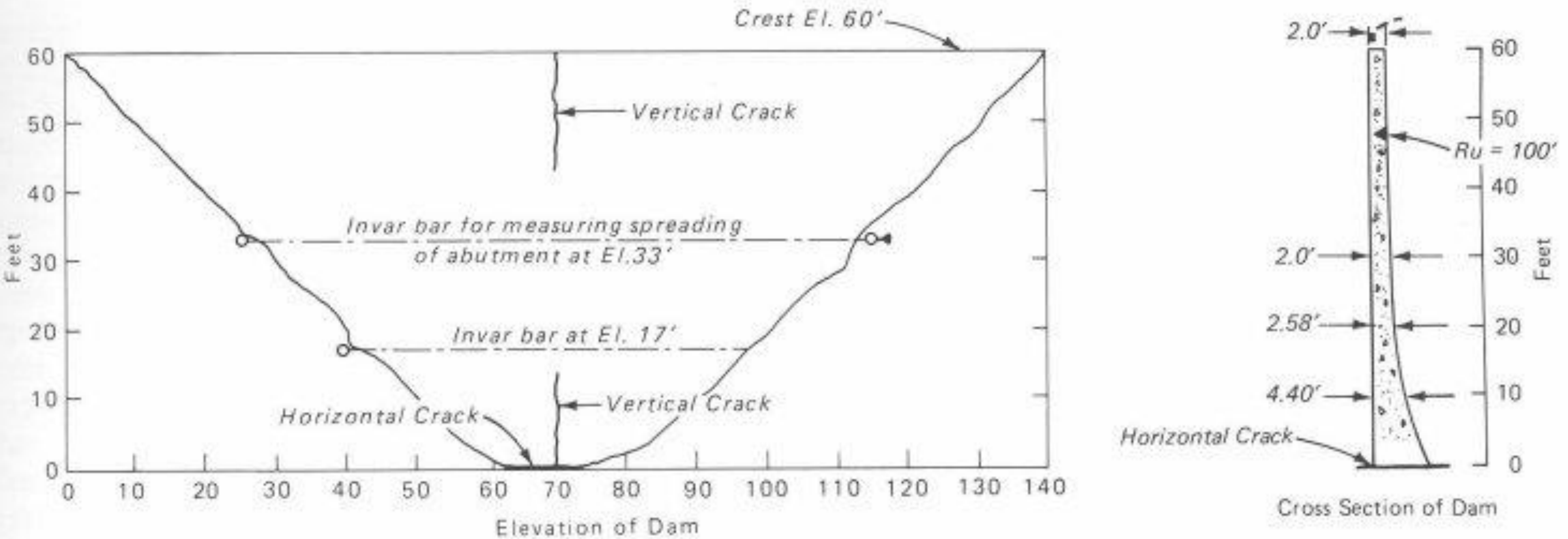



**Figure 3–25** Stevenson Creek Test Dam—cracks in dam

- The test dam was a simple thin arch, 60 ft high on a constant radius of 100 ft. The dam was 7.5 ft wide at the base and 2 ft at crest. The original plan was to heighten to 100 ft.
- The reason for the high slenderness ratio was to obtain reliable deflection data to validate model studies

# TEST DAM RESULTS GAVE BIRTH TO TRIAL LOAD ANALYSIS FOR ARCH DAMS

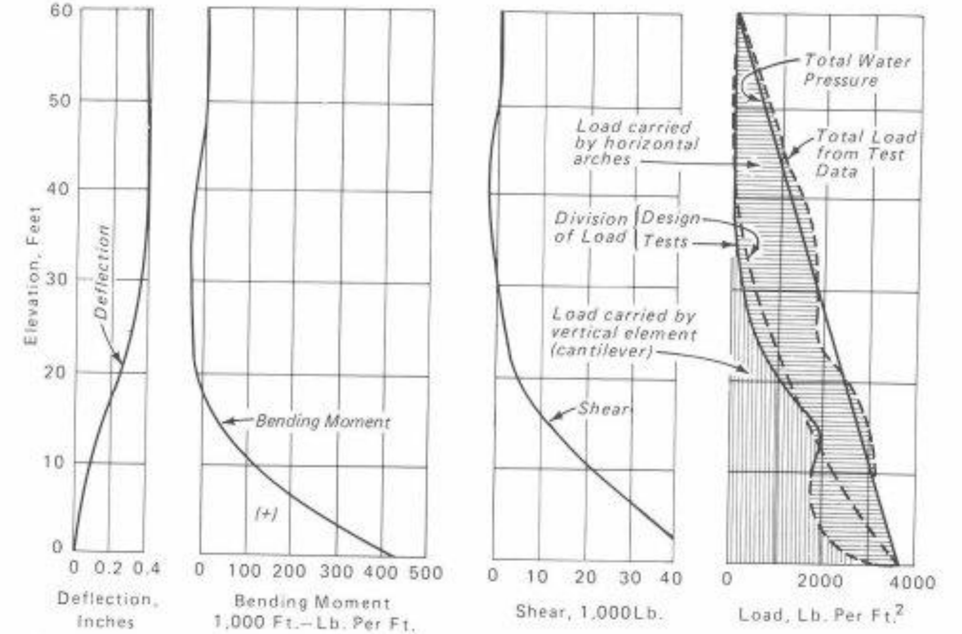
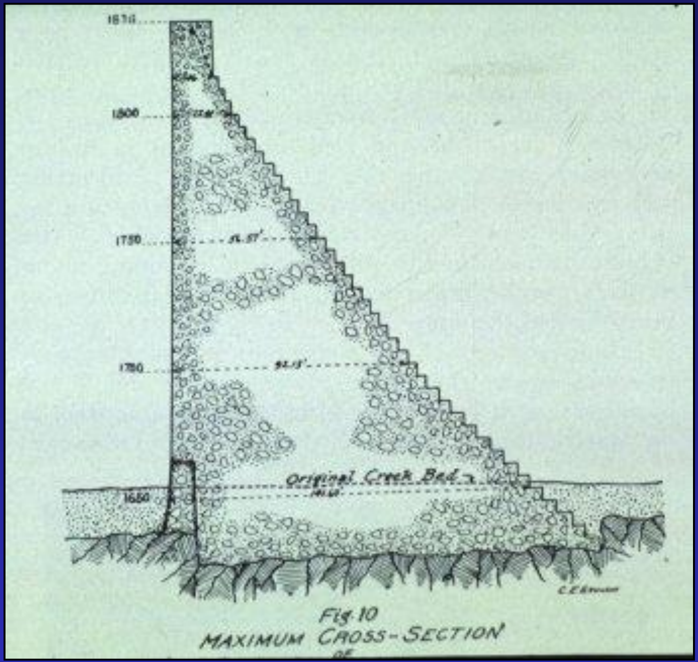



**Figure 3–26** Stevenson Creek Test Dam—deflections, moments and load distribution

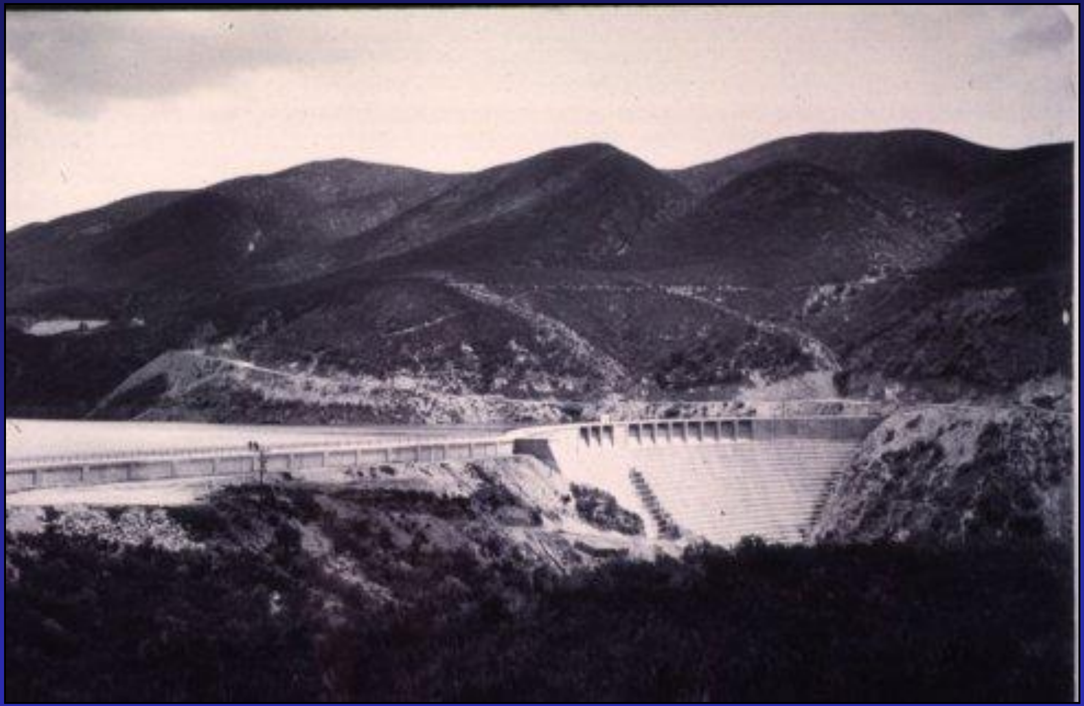
- **After concrete testing at U.C. Berkeley and 1:12 model studies conducted by the Bureau of Reclamation at the University of Colorado, the *Trail Load Analysis Method* was developed and accepted by the engineering profession for design of arch dams, beginning around 1929**

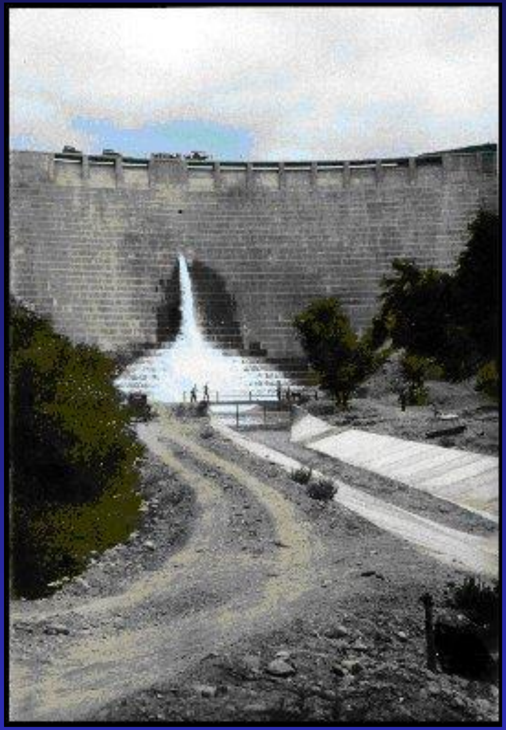
# ST. FRANCIS DAM (1924-26)

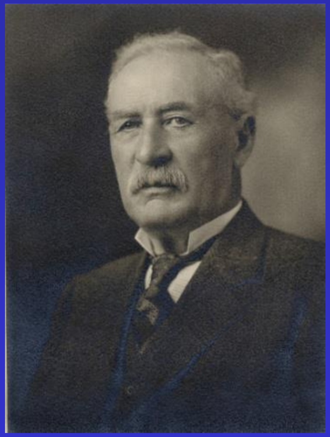



- **St. Francis Dam** was built by the City of Los Angeles in 1924-26, to contain a year's water supply for the city, south of the San Andreas fault
- The dam was originally envisioned as a curved concrete gravity dam 185 feet high because there was no clayey material on site to construct an embankment structure

# FATEFUL DESIGN CHANGES



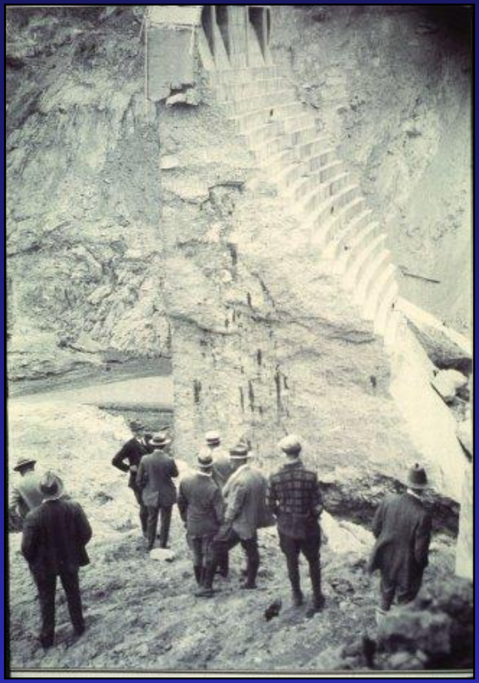




William Mulholland
(1855-1935)

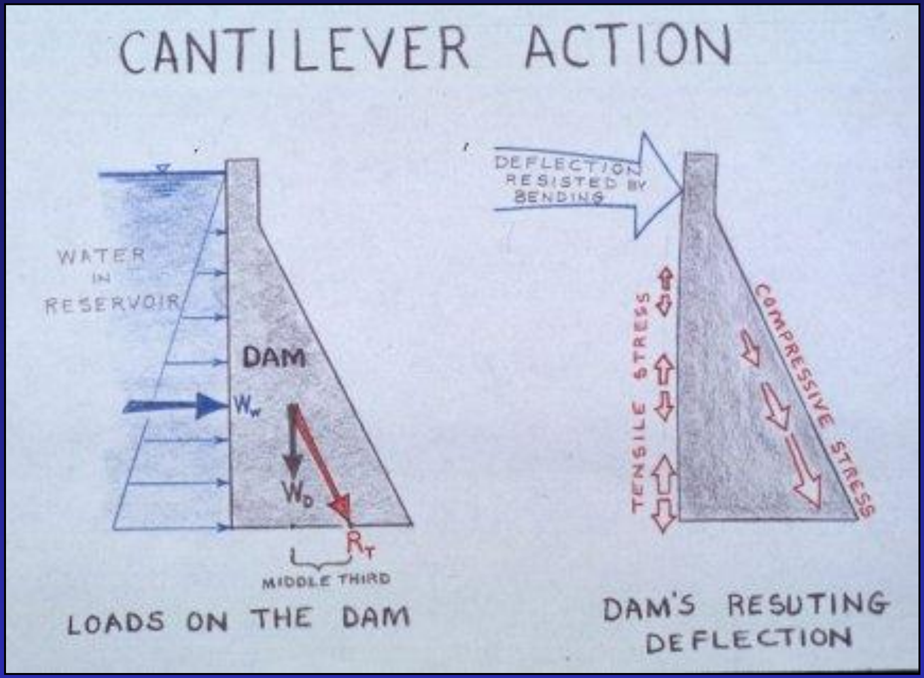
- **While under construction, the population of Los Angeles was increasing dramatically**
- **In order to increase reservoir storage, Chief Engineer William Mulholland decided to raise the dam 10 feet on two occasions, increasing the dam’s height by 11%, without any increase in base width**
- **This resulted in a dam 205 feet high with storage of 38,160 acre-feet; the second largest reservoir in southern California at the time**

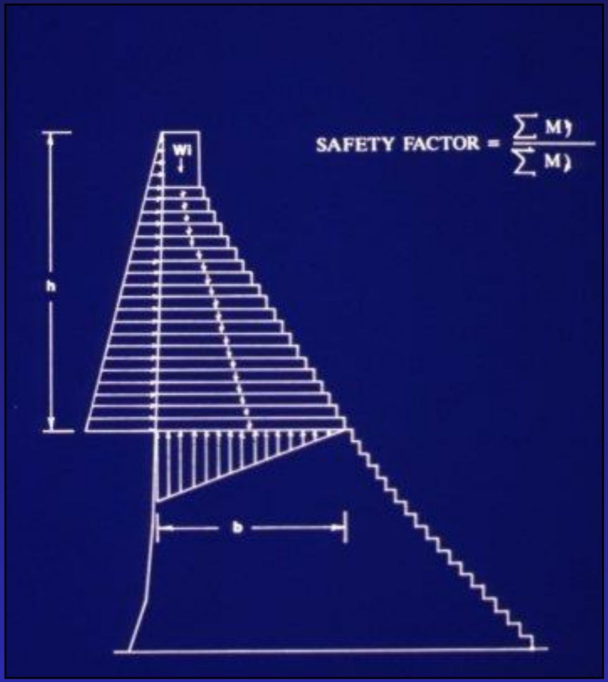
# Inquiries and a demands for justice



- A flood wave 140 ft deep swept down the canyon, killing at least 431 people; of which 179 bodies were never recovered
- 13 different panels investigated the St Francis failure
- Most blamed the failure on hydraulic piping along a ancient fault running beneath the dam's right abutment
- The City of Los Angeles paid out $14 million in damages

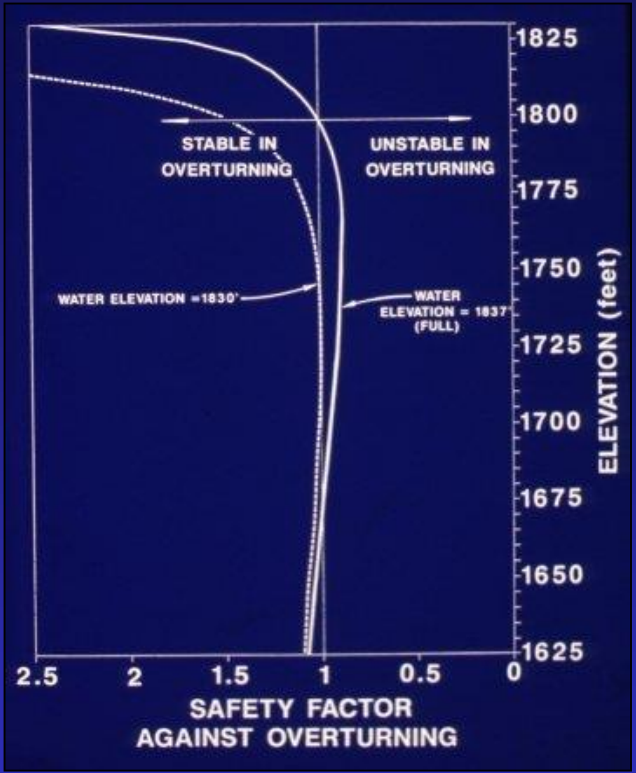
# CANTILEVER FORCES

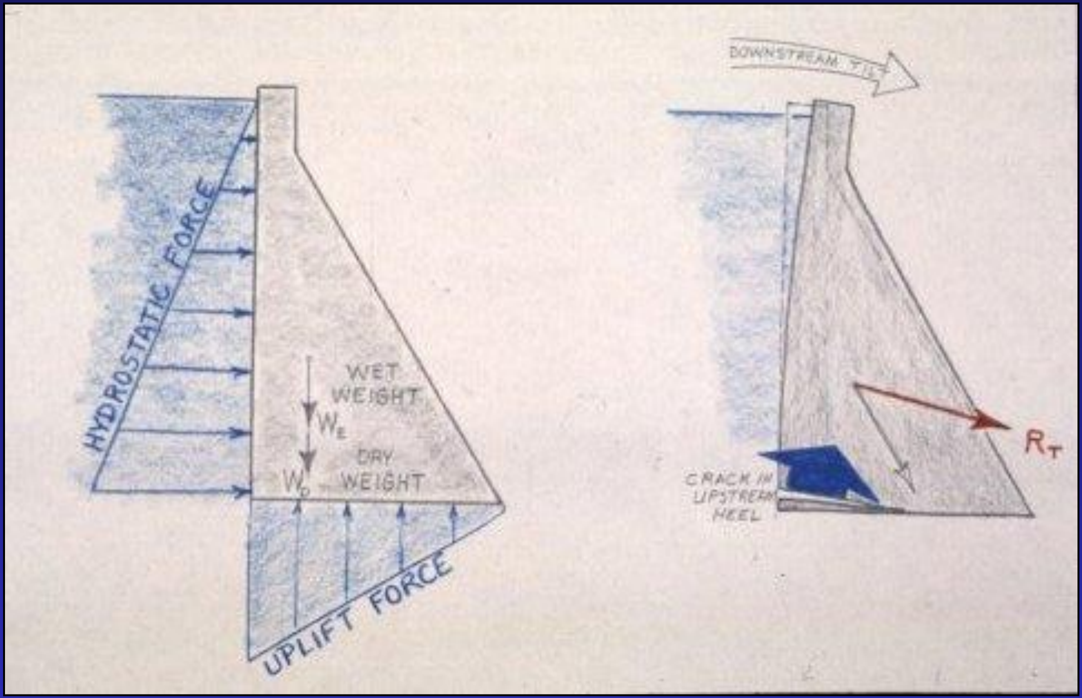



- **St. Francis Dam** **was a gravity structure, deriving its stability from its dead weight.**
- **The ratio between the dead load acting vertically and the hydrostatic force acting horizontally determines the overturning factor of safety**

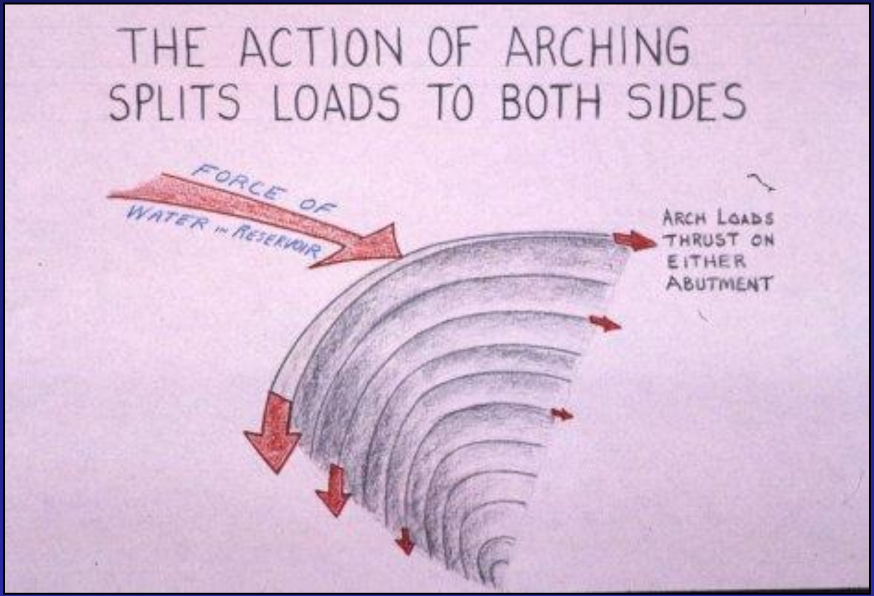
# UNSTABLE IN OVERTURNING

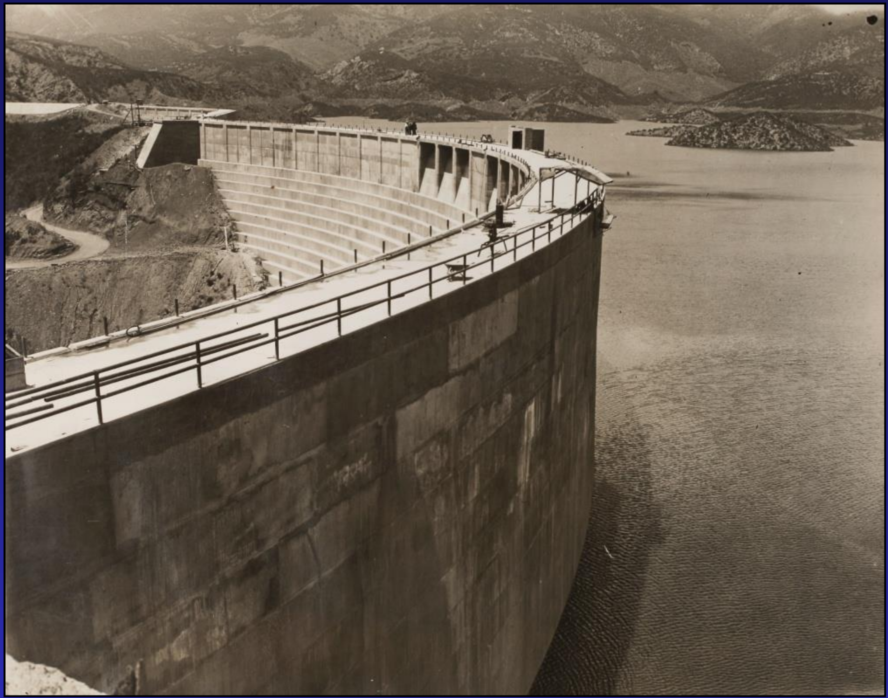



- Modern analyses reveal that when the reservoir rose within 5 feet of spillway crest, the dam became unstable
- A crack could then developed in the upstream heel
- A *heel crack*, such as that found after the failure, shown at lower right, would shift the resultant thrust far downstream, making it unstable in overturning

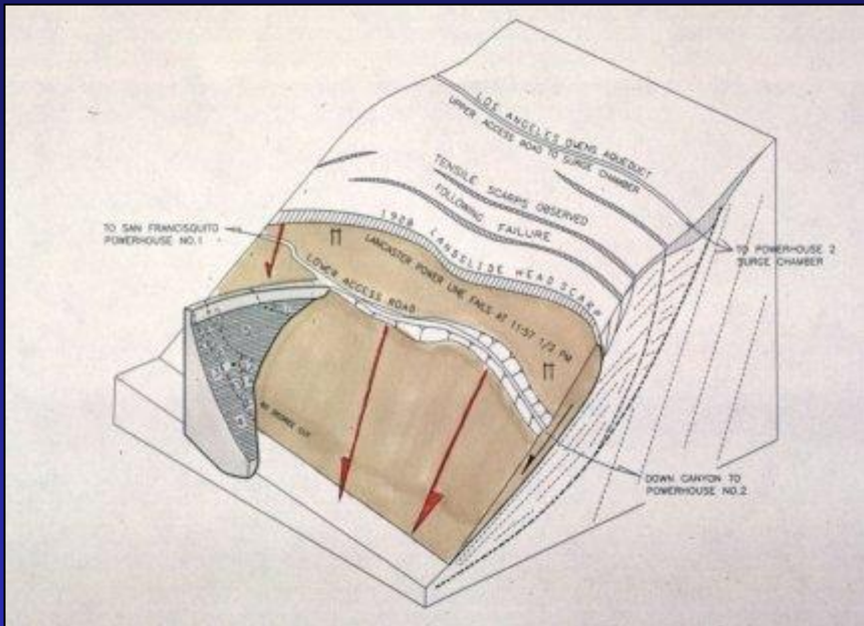
# CONTRIBUTION OF ARCHED SHAPE



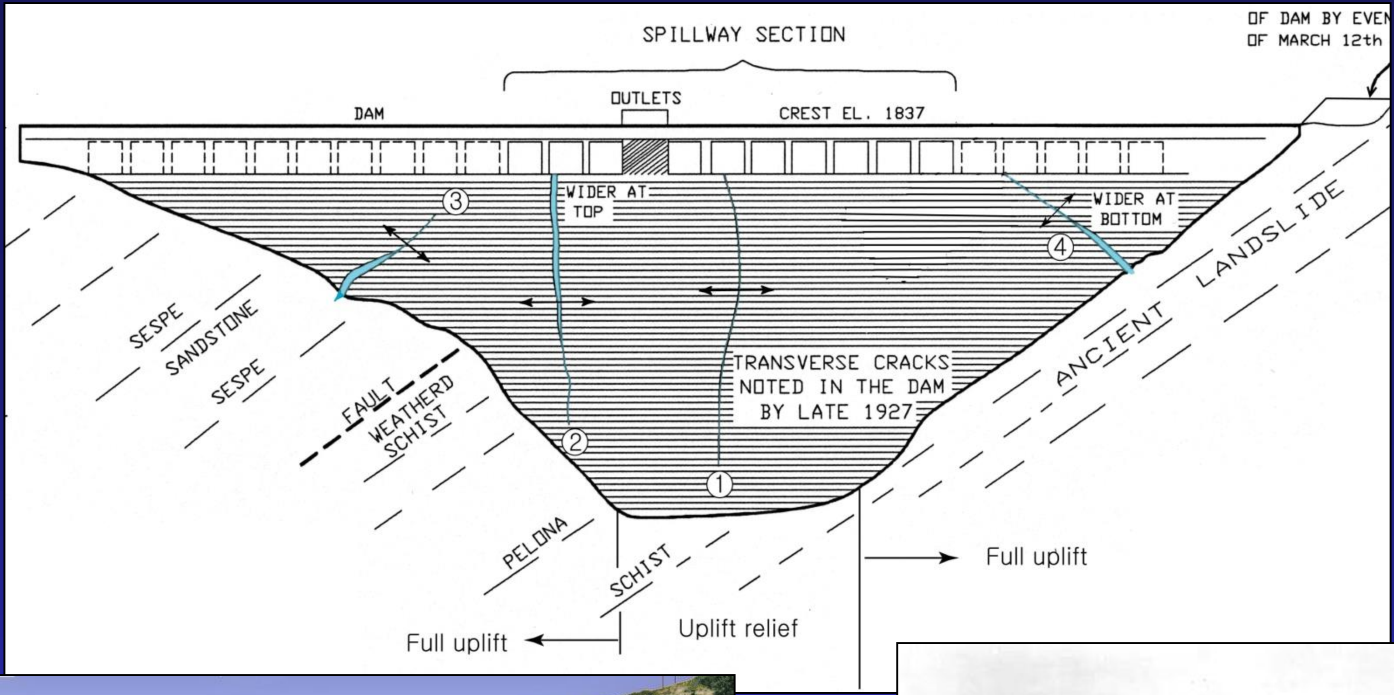



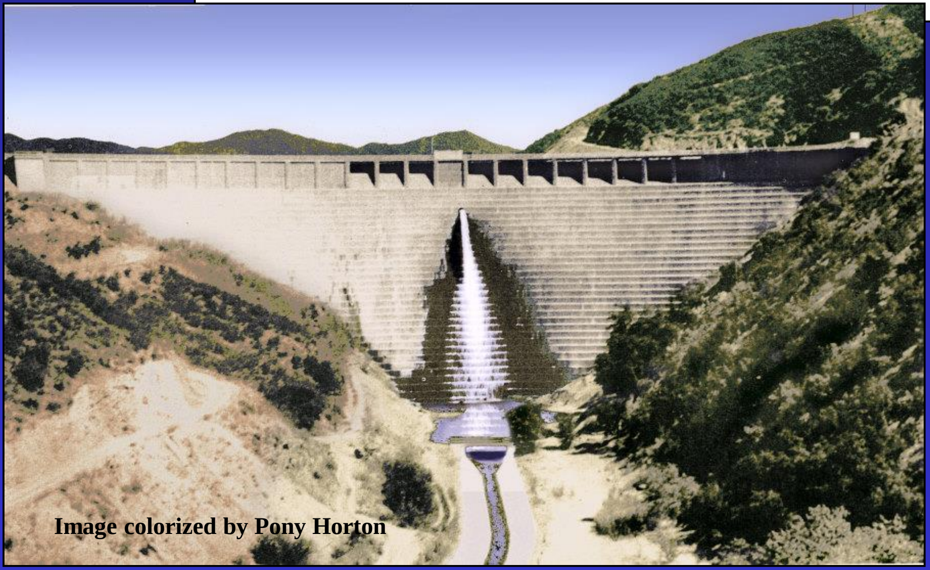

- **St Francis Dam was arched upstream on a 500-ft radius, but was not designed for arch action.**
- **The arch loads on St. Francis become significant when the reservoir rose to within 11 feet of spillway crest, exceeding 10,000 psf**

# LEFT ABUTMENT LANDSLIDE

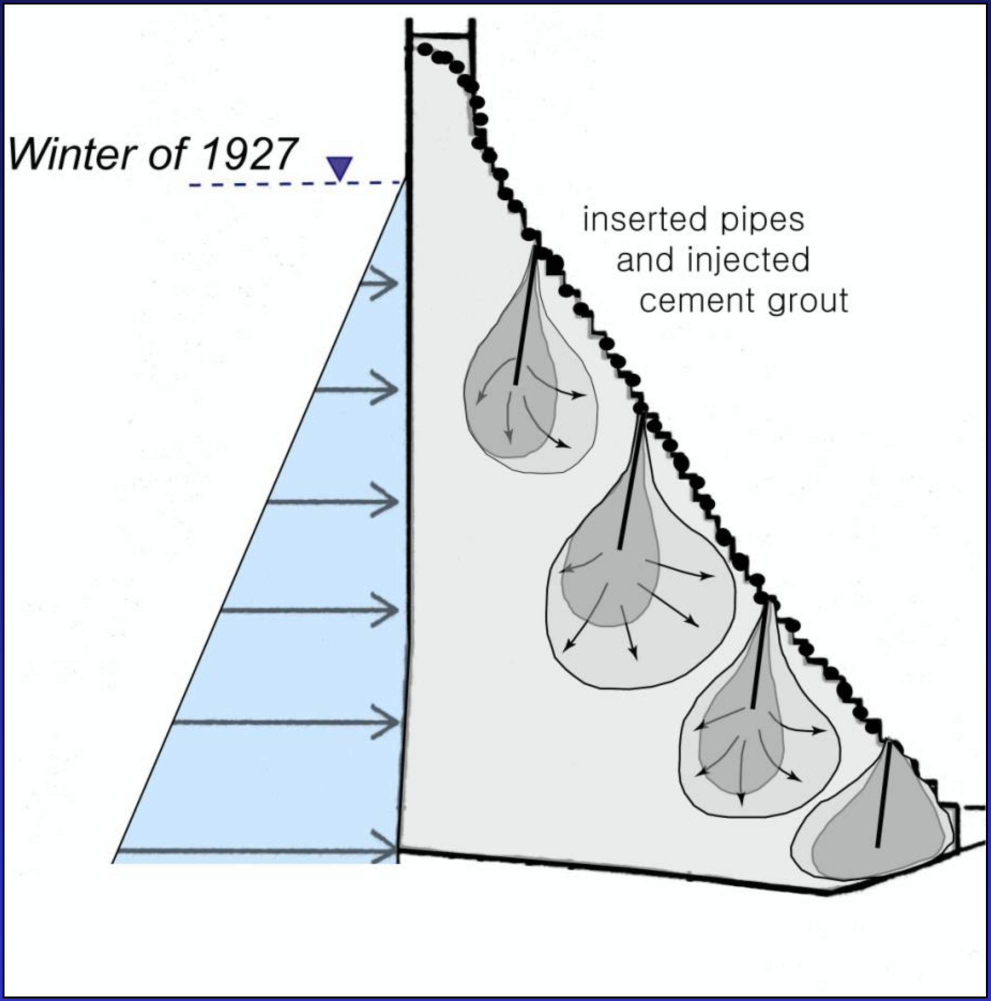


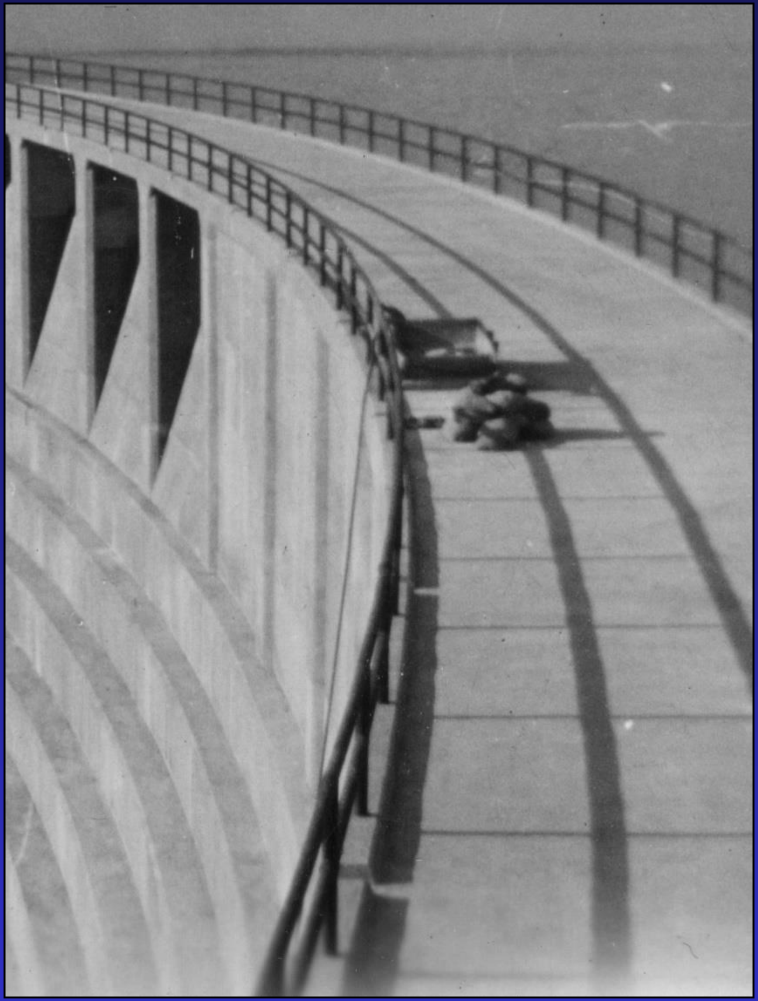

- **Around midnight March 12/13, 1928 a massive landslide occurred along the dam's left abutment**
- **The landslide involved 1.52 million tons of schist moving against the dam's 271 thousand tons of concrete, so the schist won**



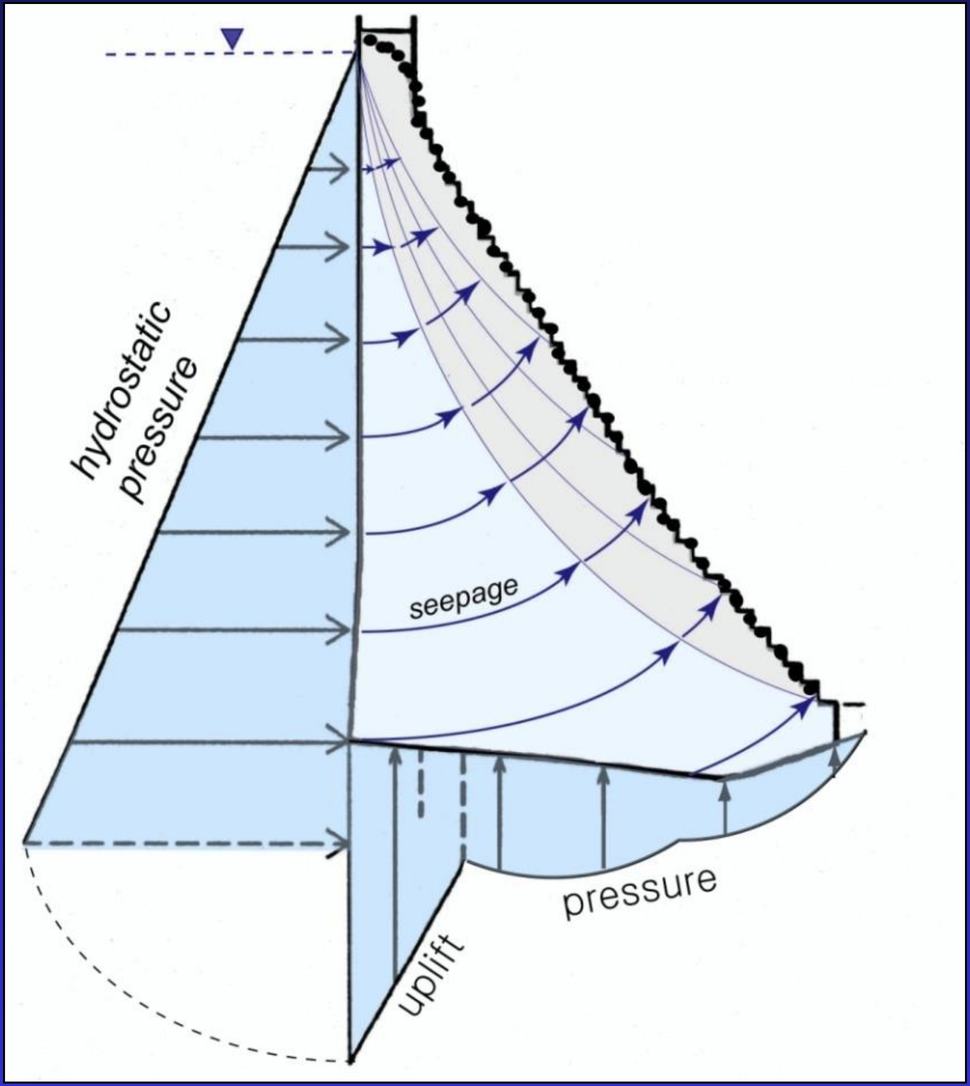



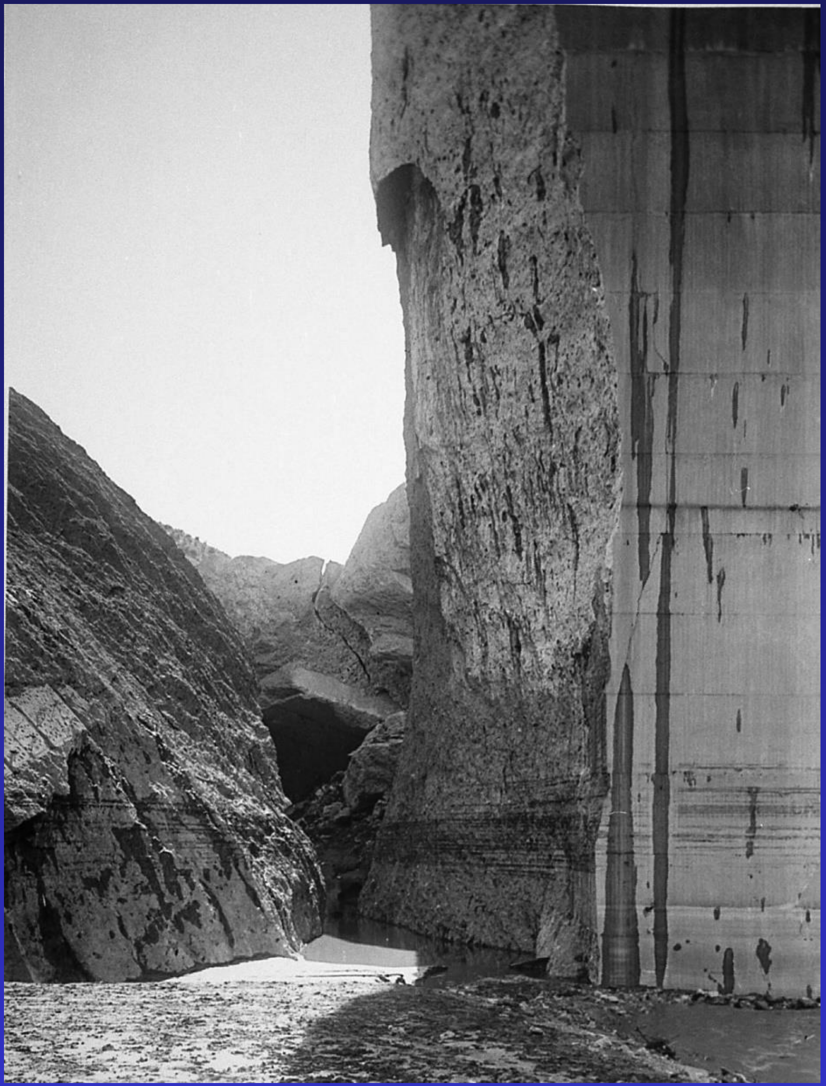

**Four prominent shrinkage cracks developed in the main dam, allowing leakage of water, which increased as the lake level rose.**



**In January-February 1928 William Mulholland ordered the four transverse shrinkage cracks to be caulked with oakum, to prevent loss of cement grout injected into the openings.**

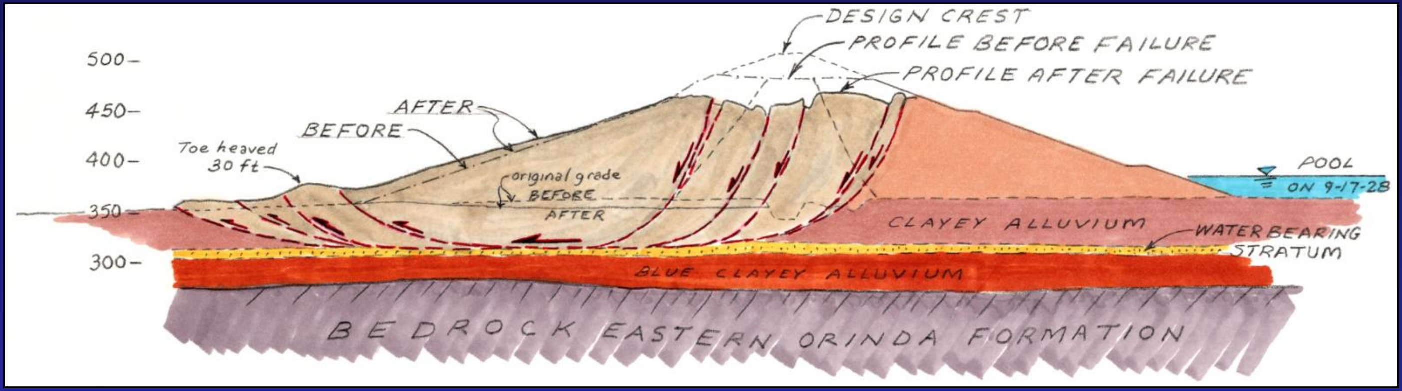


**If the transverse shrinkage cracks were sealed at the dam's downstream face, full hydrostatic pressure would develop *between* adjacent blocks of the dam. This factor, more than any other, likely led to the structure's untimely and catastrophic failure.**

# FIRST SUCCESSFUL USE OF SPIN

Aerial photo of the slump



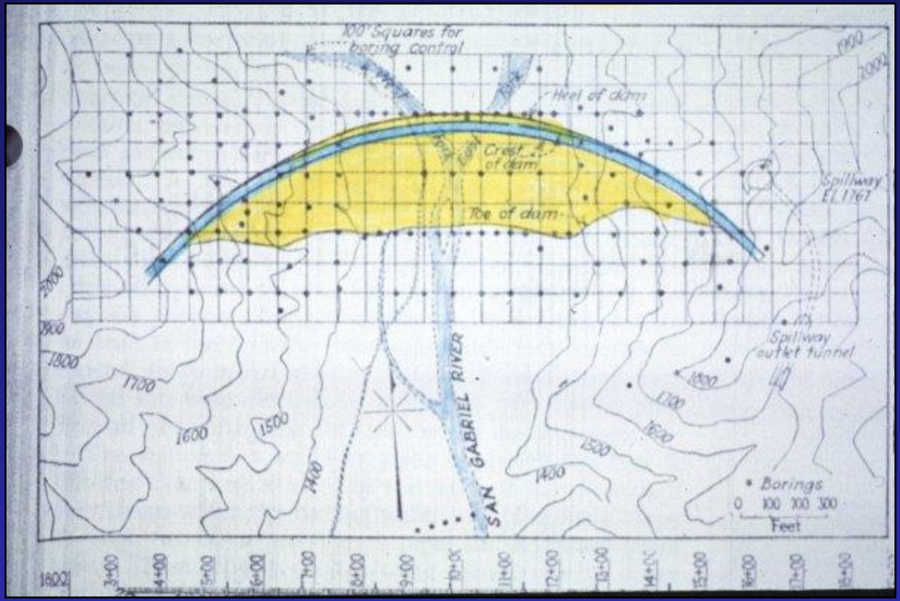

Cross section through the Lafayette Dam at the time of failure

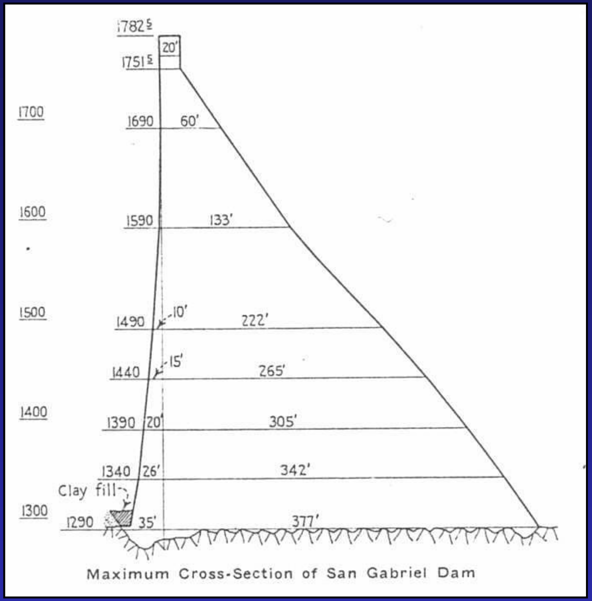
- The160 ft high **Lafayette Dam** was an earthfill structure placed at a record rate of 9000 yds$^3$ per day in 1928 by George Pollack Construction Co. for EBMUD. This rapid loading led to high pore pressures developing in the clayey foundation
- Between Sept. 17-21, 1928 the embankment suffered “excessive settlement” of 26 feet! It was never called a “landslide”!
- The dam was eventually completed in 1932, but with only 37% of the original storage capacity

# DAM SAFETY LEGISLATION of August 14, 1929

- In the wake of the St. Francis Dam failure, the State Engineer was given authority to review all non-federal dams > 25 feet high or which impound > 50 acre-feet of water
- The legislation allowed the State to employ consultants, as deemed necessary
- The State Engineer was given $200K and asked to examine all dams in the State within three years and issue recommendations.
- The State Engineer was also granted authority to supervise the maintenance and operation of all non-federal dams

# SAN GABRIEL DAM at THE FORKS SITE

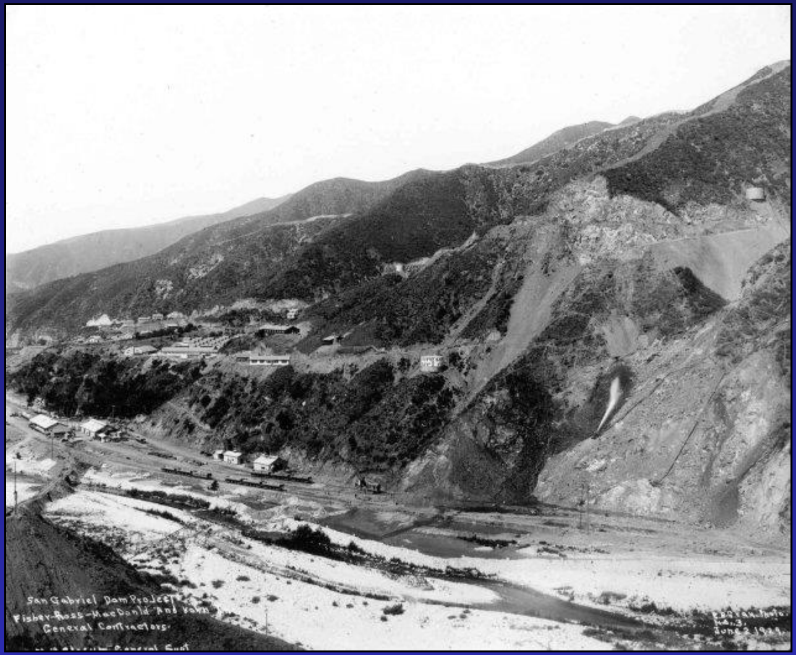


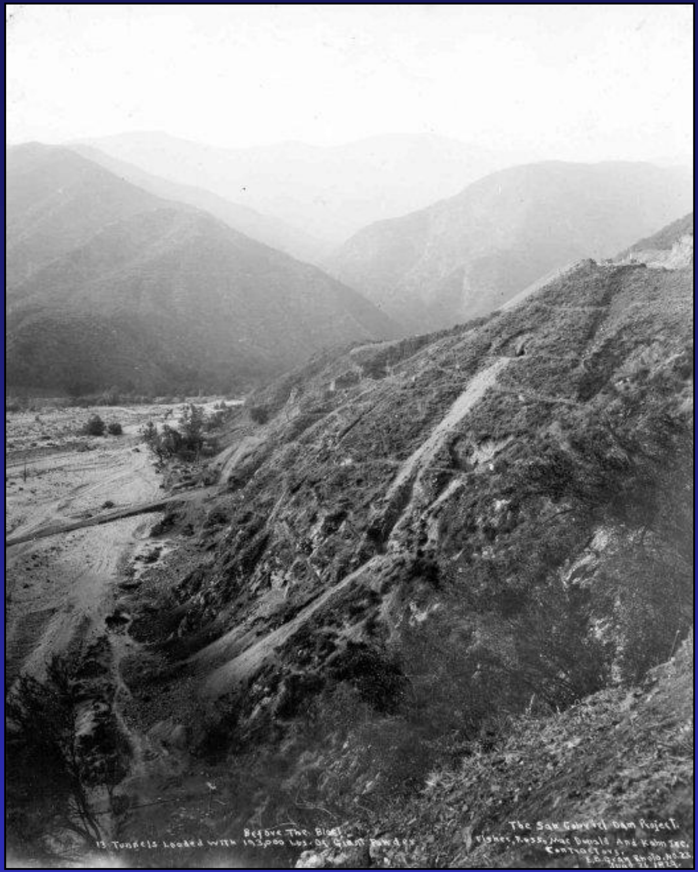


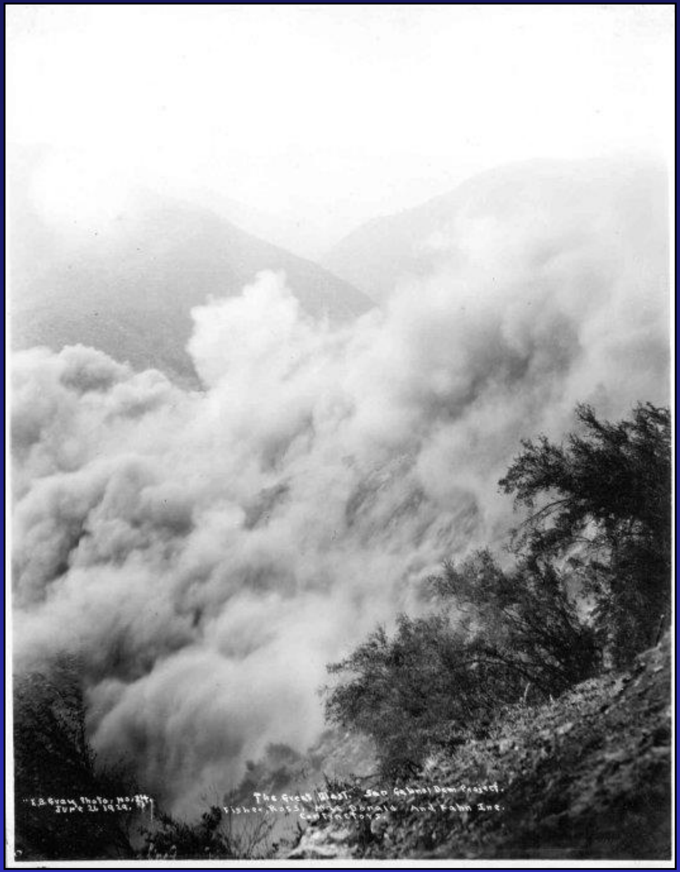
- A $26 million bond was approved by voters in LA Co in 1924 for construction of flood control structures
- The kingpin feature of this program was the **San Gabriel Dam**, a concrete gravity arch dam 512 feet high and 2,500 ft long, with volume of 3.8 million yds$^3$
- When designed in 1927-28 it was the highest and largest concrete dam ever conceived

# 700,000 yds$^3$ of abutment excavation



- Construction began in Sept. 1928, 6 months after the St Francis Dam failure. A rail line and contractors village for 500 men was built by the dam site (left view)
- By February 1929, abutment stripping began, removing 100,000 yds$^3$ per month (right view)




- On June 26, 1929 the contractor detonated 193,000 lbs of dynamite produced by the Giant Powder Co., distributed in 13 “coyote tunnels” excavated into the right abutment, bringing down 160,000 yds$^3$ of rock
- On September 16, 1929 a massive landslide occurred in the same area, involving 200,000 yds$^3$ of additional rock debris

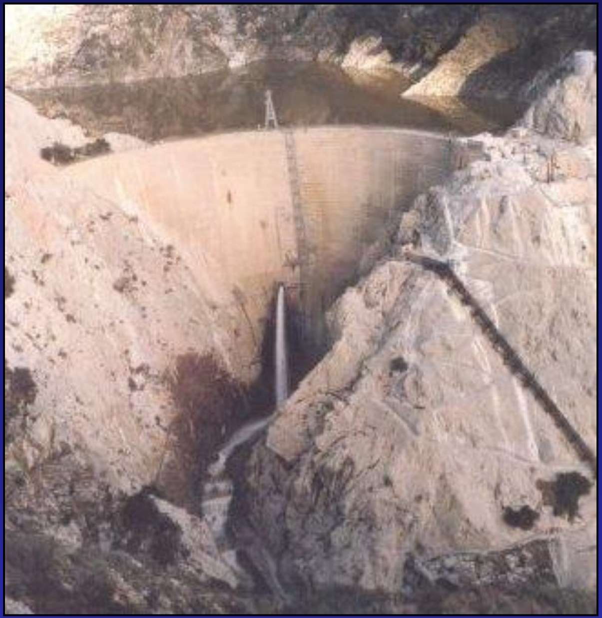
# FIRST DAM CANCELLED BY THE STATE

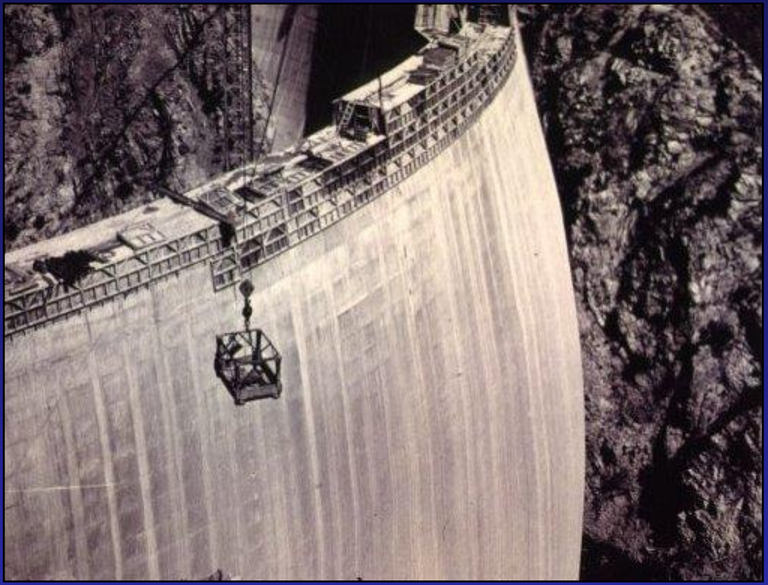
- Acting under newly legislated authority in August 1929, the State Engineer convened an independent inquiry of the problems at San Gabriel Dam in early November 1929
- The panel included Jack Savage, George Elliot, M.C. Hinterlider, George Louderback, Ira Williams and Charles Berkey
- On Nov 26$^{th}$ the panel issued a report stating that the proposed dam "cannot be constructed without creating a menace to life and property"
- As a supplemental suggestion, the board recommended an earth and rockfill dam of "conservative design" might be employed in San Gabriel Canyon
- LACFCD subsequently built a record height rockfill dam one mile downstream, in 1934-38

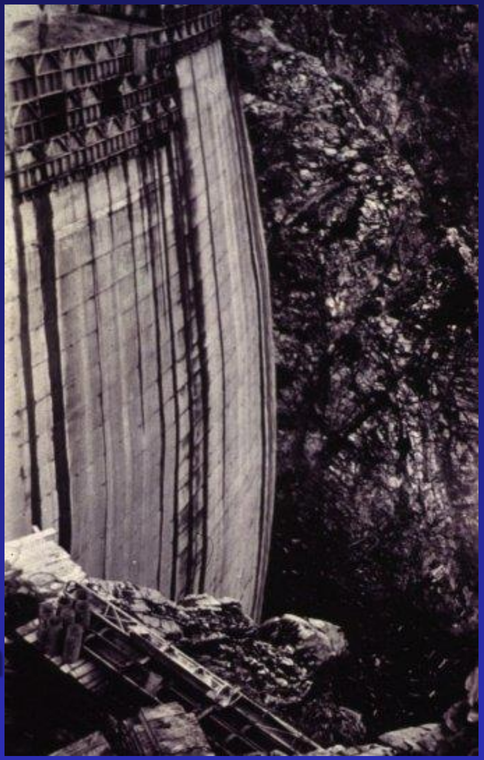
# FIRST DAM THAT SENT ELECTED OFFICIAL TO JAIL

- After the County rescinded their construction contract on Dec 8, 1929, the contractor filed a lawsuit to recover damages for breach of contract, claiming 773,646 yds$^3$ had been excavated
- A Grand Jury was appointed in Feb 1930 to investigate the validity of the claims, finding that 83,433 yds$^3$ were outside the "pay line"
- Nevertheless, the contractor was paid an additional $831K in 1930, for "additional excavation" at $2.95 per yd$^3$ (they were paid $1.85 million in total)
- In the summer of 1933 former County Supervisor Sydney T. Graves was found guilty of accepting a $80,000 bribe from the contractor to hasten the board's approval of their claims

# WORLD'S HIGHEST DAM IN 1929



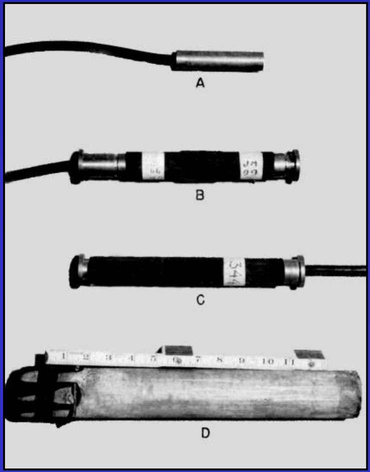




**Pacoima Dam, a constant angle arch dam 372 feet high, was designed and built by the LA County Flood Control District**

Roy W. Carlson
(1900-90)

As Pacoima Dam began construction, the County hired Roy Carlson as their concrete and soil testing engineer. He developed the world's first strain meter that could be embedded in concrete (shown at right). Carlson also developed an adiabatic calorimeter and electrical-resistance thermometers to ascertain why concrete temperature increased during curing and how best to avoid cracking caused by these stresses.



# STATE INSPECTION of DAMS 1929-31

- Between August 1929 and November 1931 the State inspected 827 dams
- One third found adequate
- One third required further examination, such as borings or subaqueous inspection, before a determination could be made
- One third found to be in need of alterations, repairs or changes; frequently involving spillway capacity

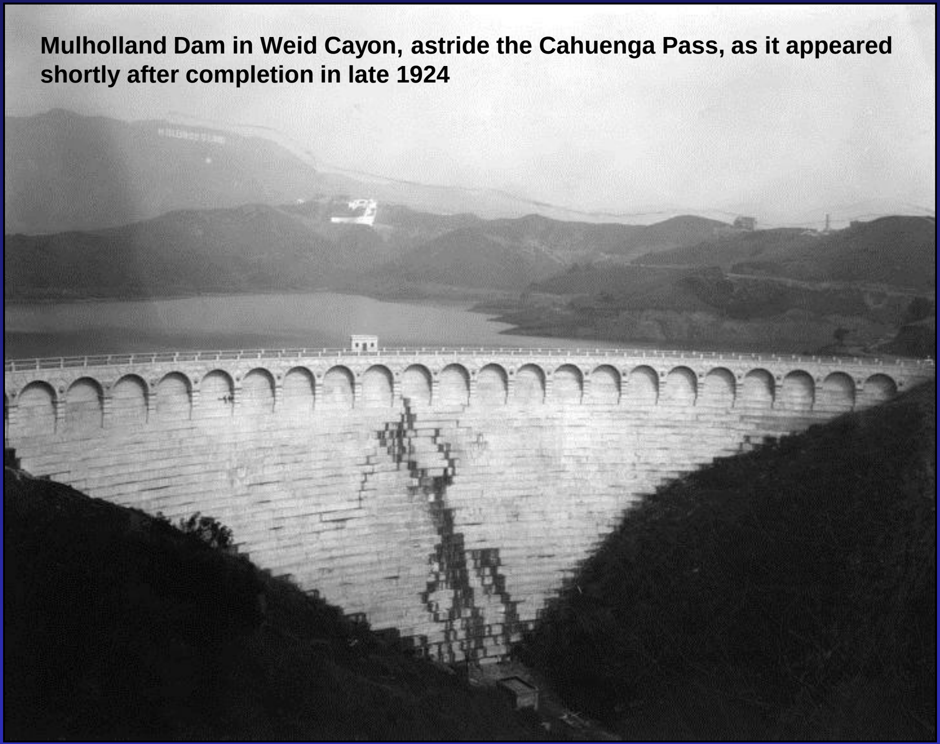
# RECORD FILL PLACEMENT

R. G. Letourneau in 1931

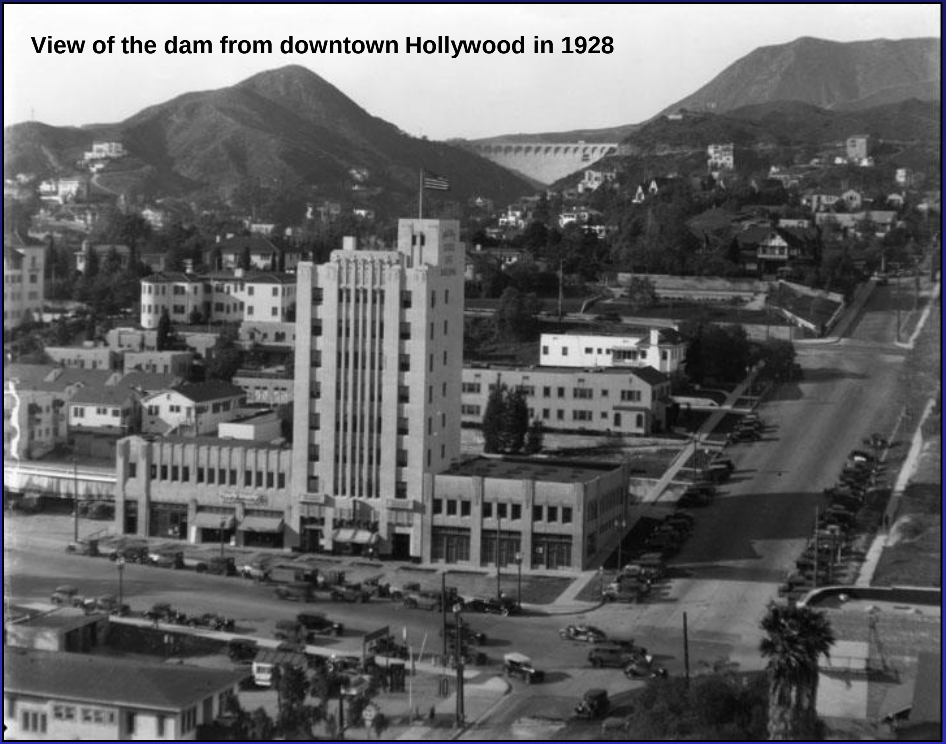
Letourneau Model A Carryall Scrapper at Santiago Dam in 1931

- In July 1931 earthmoving pioneer R. G. "Bob" Letourneau brought his 9 $yd^3$ capacity Model A Carryall scrappers to Orange County to grade the 136 ft high Santiago [Creek] Dam (Lake Irvine) for the Orange County Flood Control District
- Letourneau placed 400,000 $yds^3$ of compacted fill in the first month, setting a record for rolled fill construction
- The job was completed in the spring of 1932 with a final volume of 790,000 $yds^3$

# MULHOLLAND DAM DILEMMA



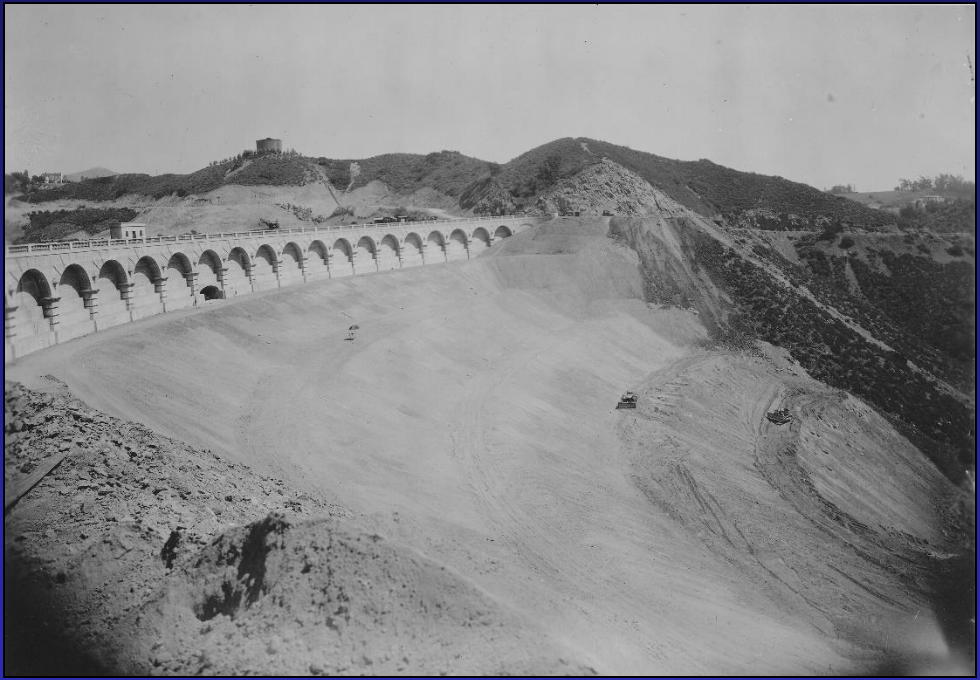
Mulholland Dam in Weid Cayon, astride the Cahuenga Pass, as it appeared shortly after completion in late 1924

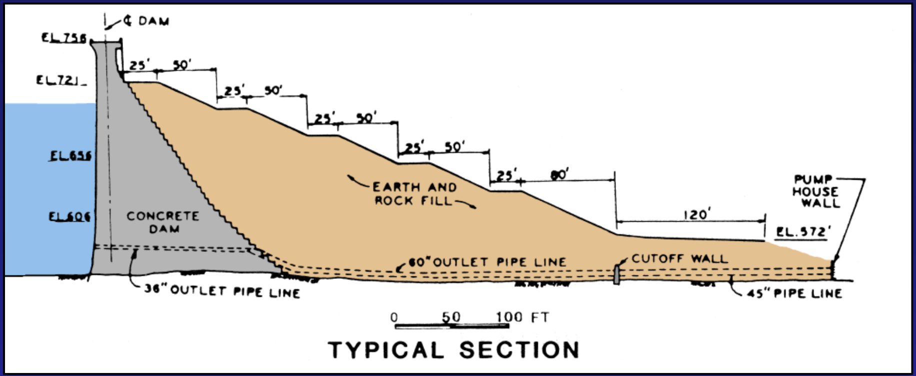


View of the dam from downtown Hollywood in 1928

- Weid Canyon Dam was a 195 ft high concrete gravity arch dam built in 1923-24 by the City of Los Angeles, and re-named Mulholland Dam when it was dedicated in December 1924, retaining Hollywood Reservoir
- It was virtually identical to the ill-fated St Francis Dam, causing the citizens of Hollywood, living beneath the structure (upper right) to clamor for its drainage or removal after the St Francis failure in March 1928
- Between 1928-31 the City appointed three different panels to investigate its stability

# MOST PEER-REVIEWED DAM IN AMERICA



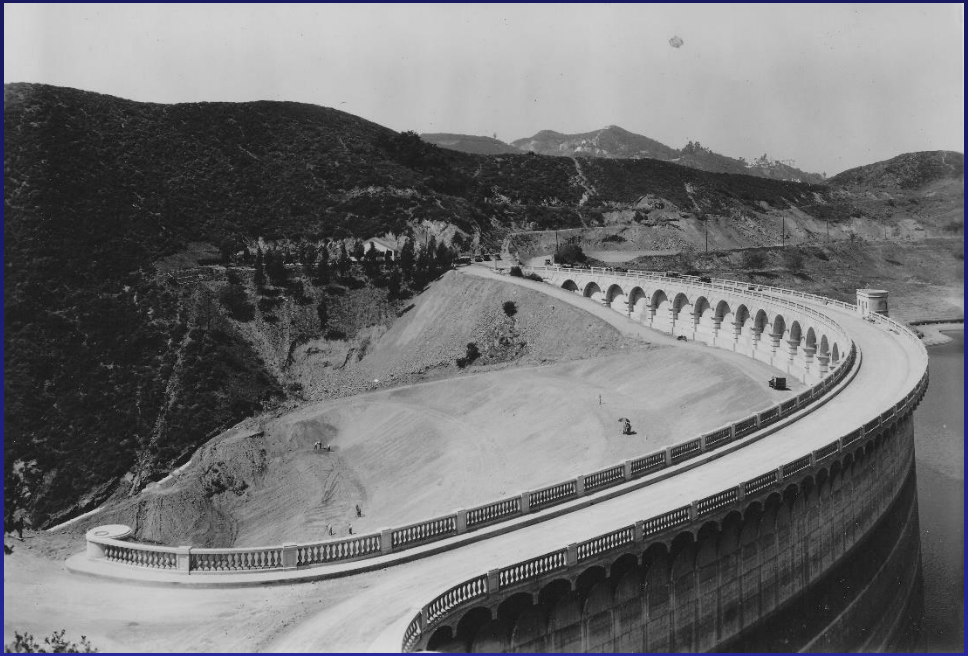



**In 1933-34 the City of Los Angeles placed 330,000 $yds^3$ of fill against the downstream face of Mulholland Dam, making it one of the most conservative dams in the state**

**Soon after the failure of the St. Francis Dam a Committee of Engineers & Geologists to Assess Mulholland Dam was appointed to reviewed the safety of the sister structure to St. Francis. This was followed in January 1930 by the External Review Panel to evaluate the Mulholland Dam, convened by the State of California. In March 1930 the City of Los Angeles Board of Water & Power Commissioners appointed their own Board of Review for Mulholland Dam. A fourth panel, the Board of Engineers to Evaluate Mulholland Dam, was appointed in 1931 to examine the feasibility of abandoning Mulholland Dam. This was followed by an external Geological Report of the Suitability of Foundations for Mulholland Dam in late 1931, appointed by the Board of Water & Power Commissioners.**

**The decision was eventually made to permanently draw down Hollywood Reservoir, from 7,437 ac-ft to no more than 4,000 ac-ft (the reservoir is usually maintained around 2,800 ac-ft), and to place an enormous buttress fill in lower Weid Canyon, to bolster the dam's resistance against hydraulic uplift and earthquake forces, and screen it from public view. This work was carried out in 1933-34, shown above left.**

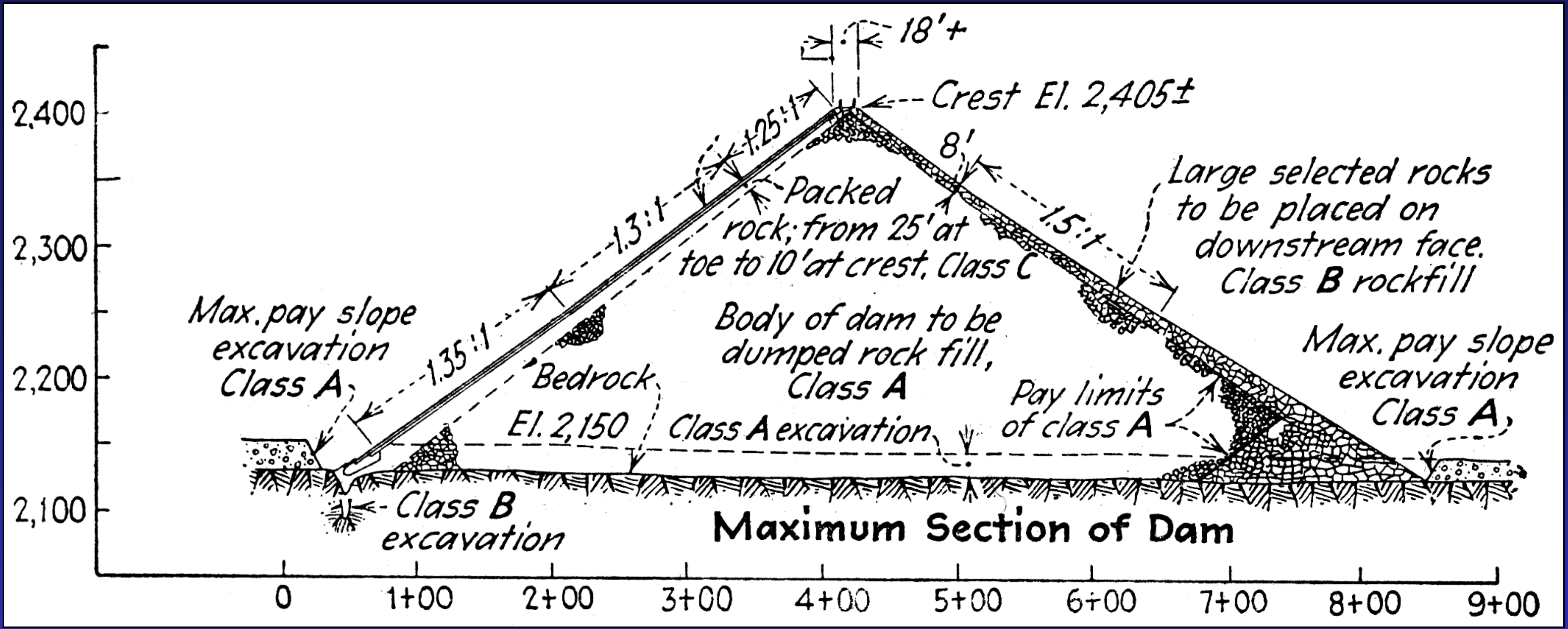
# Out of sight, *out of mind….*



A camouflaged Mulholland Dam still retains Hollywood Reservoir

- **LADWP undertook a vigorous program of re-vegetation on the new buttress fill (lower left), which succeeded in screening the dam from most everyone's consciousness**

# HYDROCOMPRESSION OF ROCK FILL



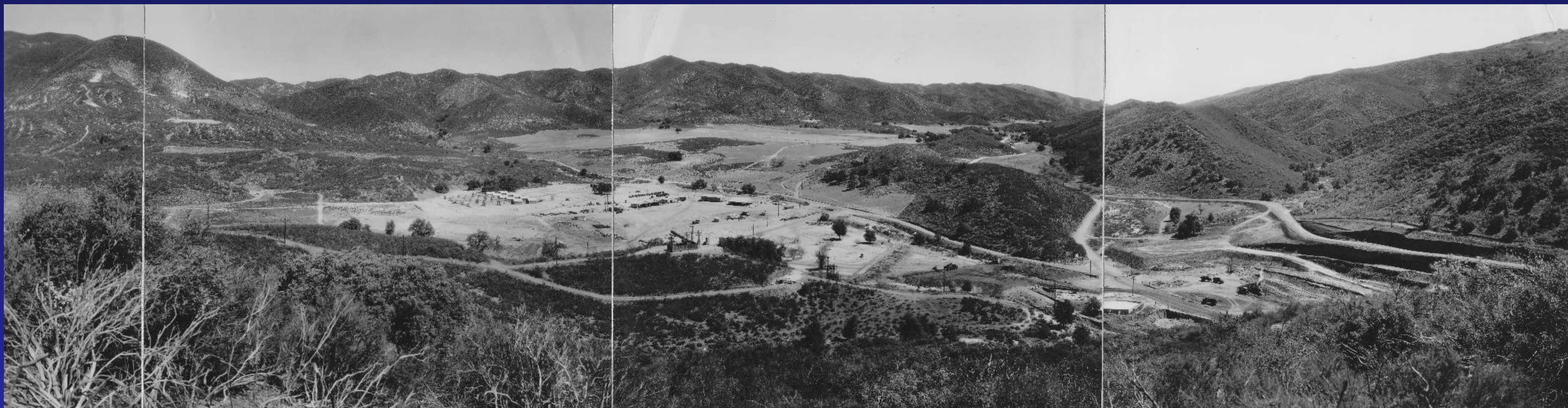

- **Cogswell Dam**, a 242 ft high rockfill structure, was built by LACFCD as **San Gabriel Dam No.2** between 1932-35 (the name was changed in 1952). Boulders weighing as much as 30 tons were incorporated into the 5 million $yd^3$ fill. Much material was sluiced into the canyon during the early going (1932), without benefit of mechanical compaction.
- After severe winter rains in early 1934, the embankment settled as much as 12 feet, destroying the concrete slab lining the upstream face.
- A consulting board was convened (Harza, Steele, and Reed), which recommended removal and replacement of the old facing, covering it with timber and sluicing of additional 60,000 $yds^3$ against the downstream face

# COGSWELL DAM TODAY



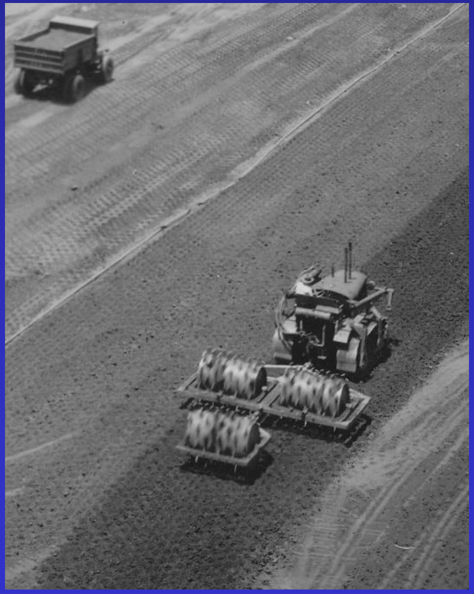
- **Cogswell Dam underwent seismic upgrades and debris removals in the 1990s. The 2009 Station Fire burned 90% of its watershed, necessitating the removal of an additional 3.33 million yards of sediment**

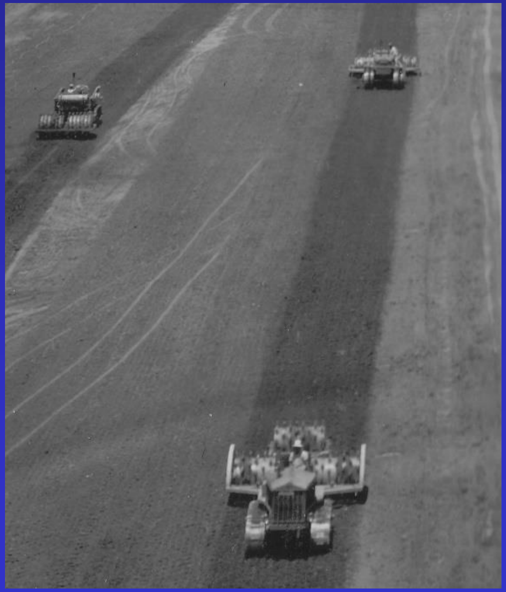
# BOUQUET CANYON RESERVOIR



Panorama of the project site on September 1, 1932, showing the construction workers camp near center, which now lies beneath the reservoir.  The main embankment was constructed at far right.

- **Bouquet Canyon Dam** was the replacement structure for the St Francis Reservoir was comprised of two embankments built in Bouquet Canyon in 1933-34
- The City's resident field engineer was the same man who had served in this capacity on the ill-fated St Francis Dam, **Ralph R. Proctor**





- The two Bouquet Canyon zoned fill embankments were constructed by the Los Angeles Department of Water & Power between 1932-34
- These were the first embankments constructed using the standard Proctor Compaction Test (ASTM D-698)

# PROCTOR'S FOUR ARTICLES in 1933

Engineering News-Record

Vol. 111 New York, August 31, 1933 No. 9

*First of Four Articles on the Design and Construction of Rolled-Earth Dams*

## Fundamental Principles of Soil Compaction

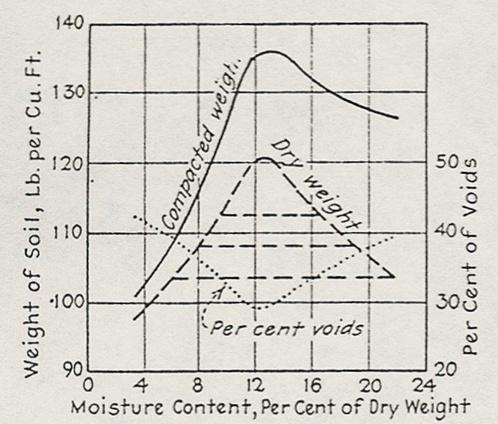
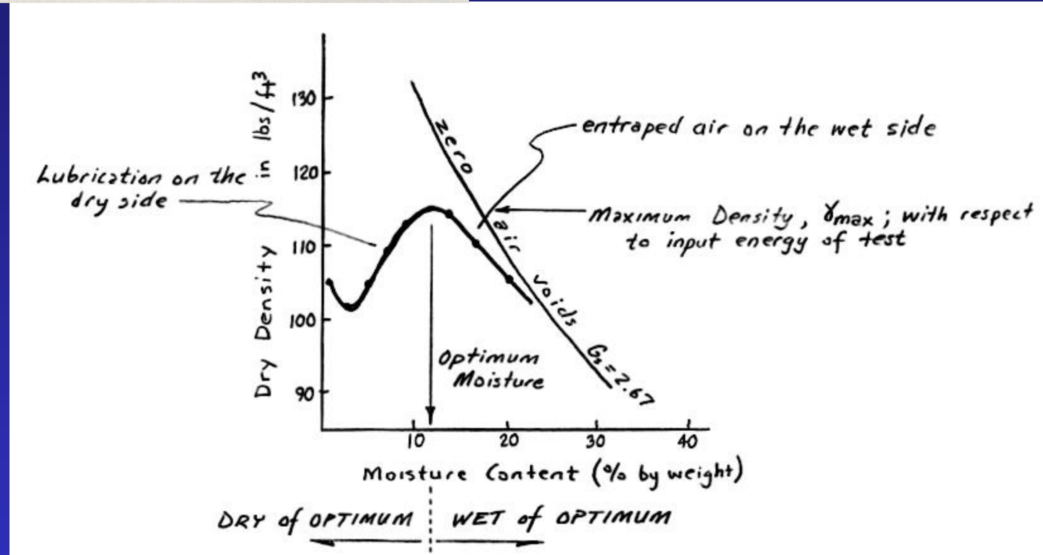
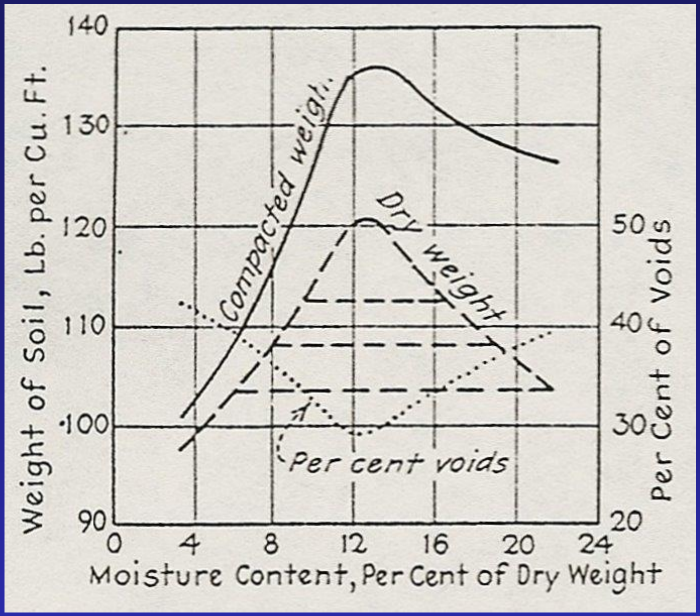



Fig. 2—Graph showing the effect of moisture content on the compacted weight, dry weight and voids of a soil when compacted by a particular method.




- **Ralph Proctor** devised an alternative method to California Test 216 introduced by the State Division of Highways in 1929, which measures the ***maximum wet density*** (**'compacted weight,' shown above left), and controls the compactive effort based on the total weight, not the volume, of the test sample (Caltrans still uses this alternative test procedure).**
- **The primary advantage of Proctor's procedure is that the test results could be computed onsite, as evaporation of the compacted sample is not necessary. This allowed immediate adjustment of the soil water content, which was the *critical variable* the contractor needed to know.**

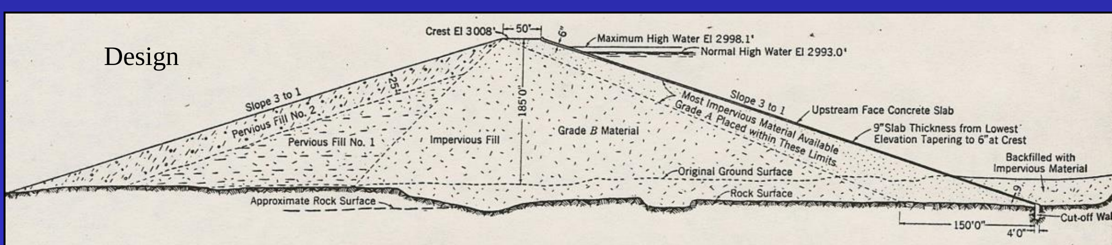
# BIRTH OF THE COMPACTION TEST

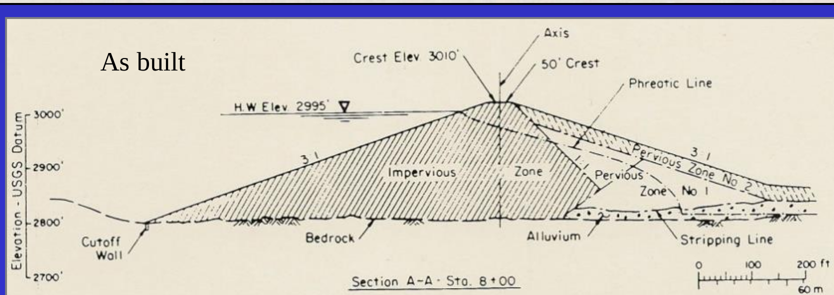


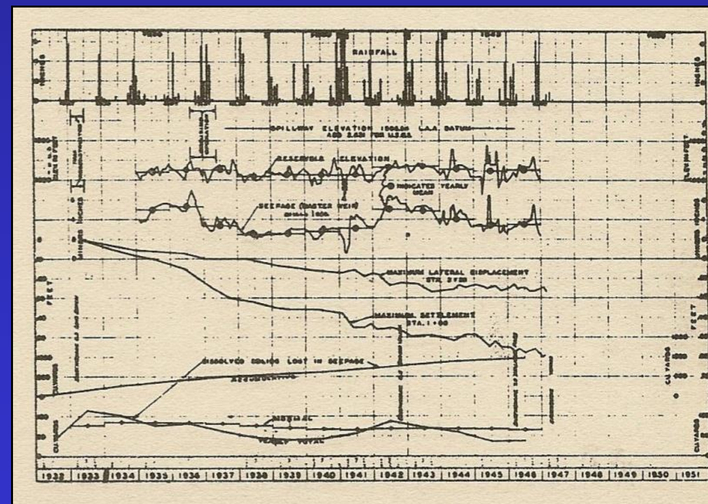

Ralph R. Proctor
(1894-1962)

- **Ralph Proctor** was charged with developing a test scheme for the earth fills at Bouquet Canyon which would engender confidence in the City's ability to build safe dams in the wake of the St Francis disaster
- What he came up with has been known as the "Proctor Compaction Test," which remains in use world-wide

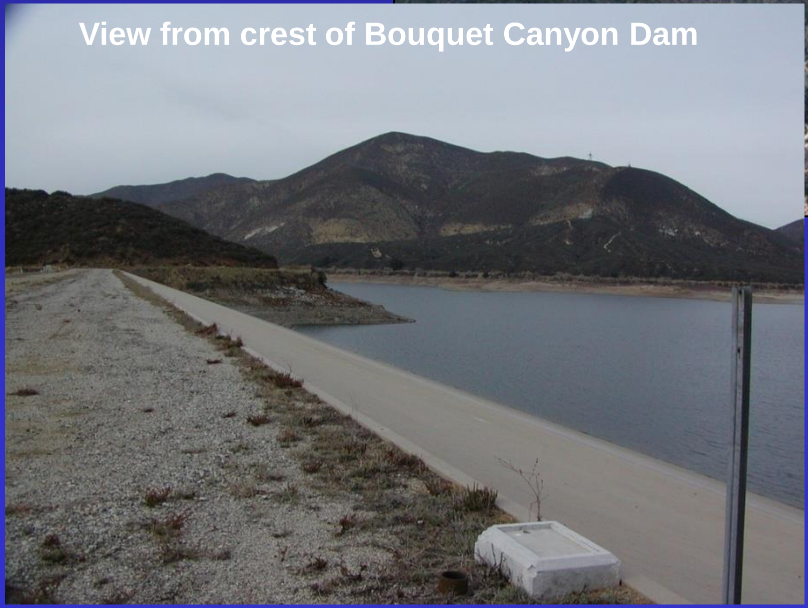
- Upper - The main embankment of Bouquet Canyon Dam was completed in March 1934, with concrete paving of the upstream face.
- Middle - Original design for main embankment
- As-built section thru main embankment – but in opposite direction
- Below right – Long-term monitoring of embankment




Form used to show 20 years record of rainfall, reservoir stages, seepage, lateral displacement and settlement of crest of dam, and dissolved solids in seepage water, together with earthquake, repair, grouting and related data.

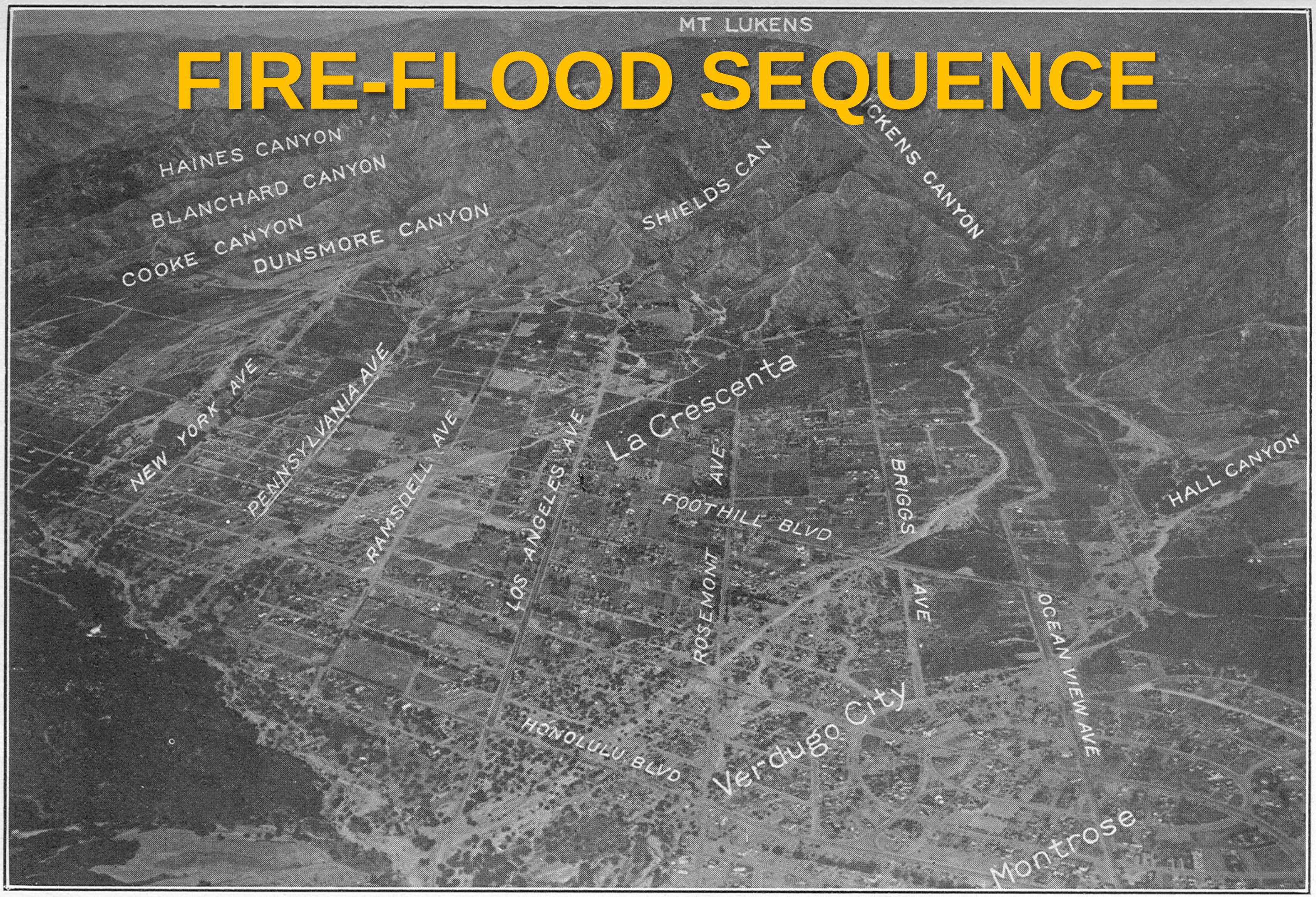




- The Bouquet Canyon embankments were carefully monitored over the next 20 years. They ushered in a new era of mechanically compacted embankments.  Their 3:1 upstream faces were re-lined with new concrete slabs in 1981.

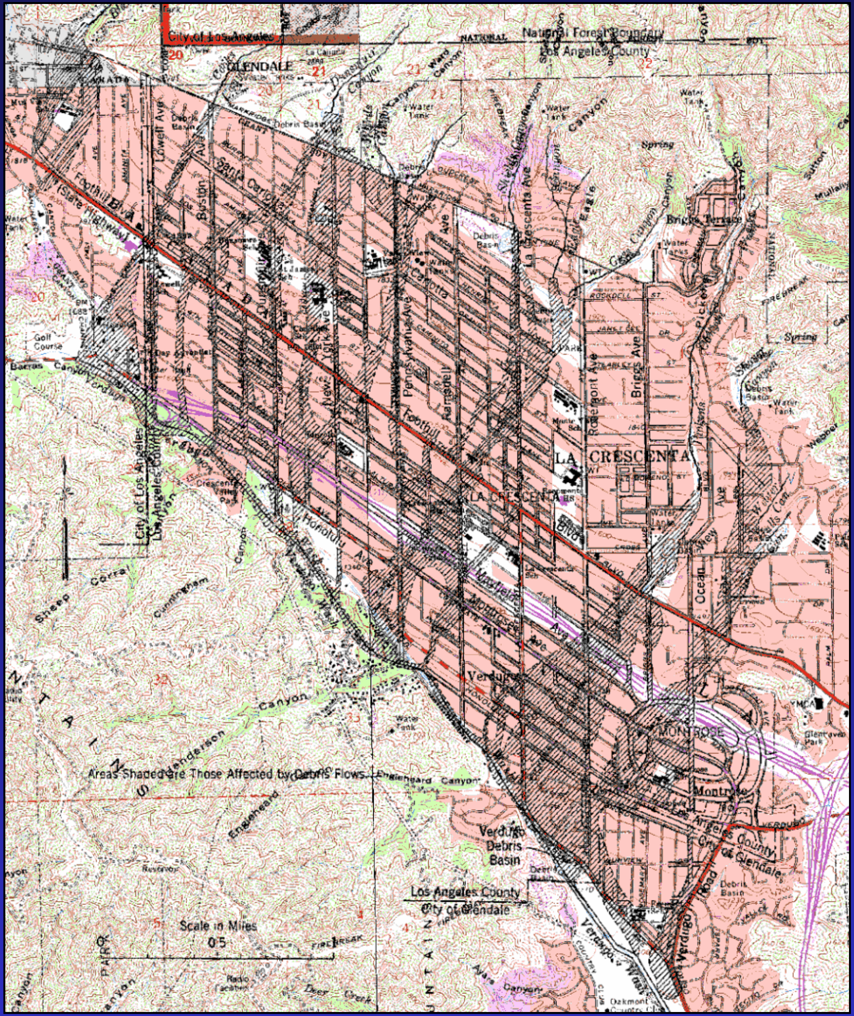
# 6-Year Program of Dam Safety Inspection 1931-36

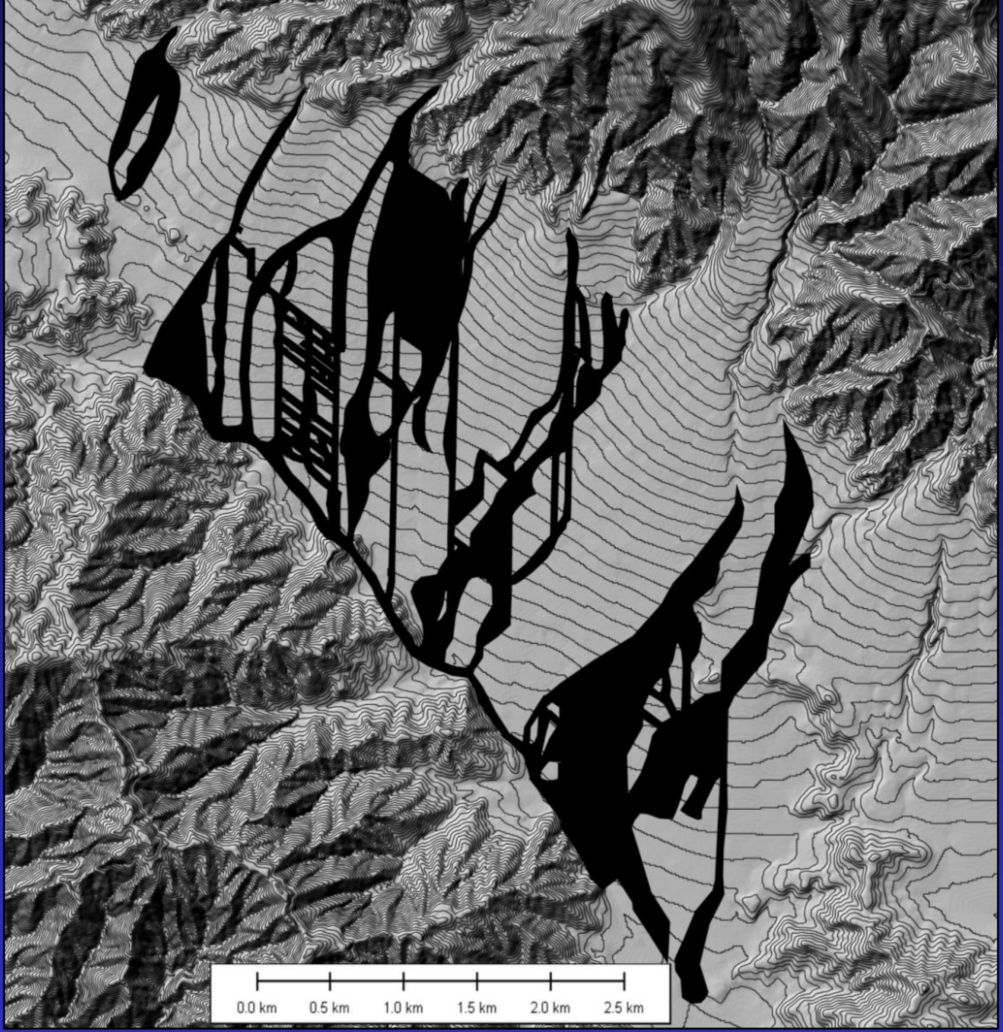
- In July 1936 the second series of inspections were concluded by the State
- 950 dams were inspected; with 588 of these dams being under the State’s jurisdiction
- One third of these dams were found in need of repairs
- New dam construction was under State observance from August 1929 forward.

# FIRE-FLOOD SEQUENCE



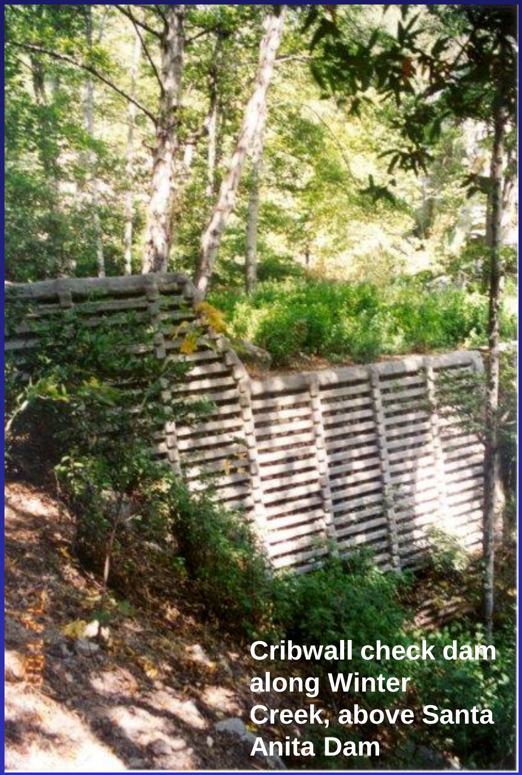

- The Dec 31, 1933-Jan 1, 1934 Montrose-LaCresenta debris flows damaged or destroyed 600 homes and killed 44. At least 600,000 cubic yards of material was deposited on the fan that evening (the actual volume appears to have been considerably higher).






- **Left: DRG overlay of 1934 Montrose-LaCresenta debris flows, which occurred several weeks after a series of brush fires in the watersheds at upper right. This is known as a *fire-flood sequence*.**
- **Right: DEM overlay of same map. Note flow paths along streets. Los Angeles County constructed nine debris basins to catch debris from these watersheds. These basins were severely tested in the spring of 2010.**

# DEBRIS DAMS and BASINS



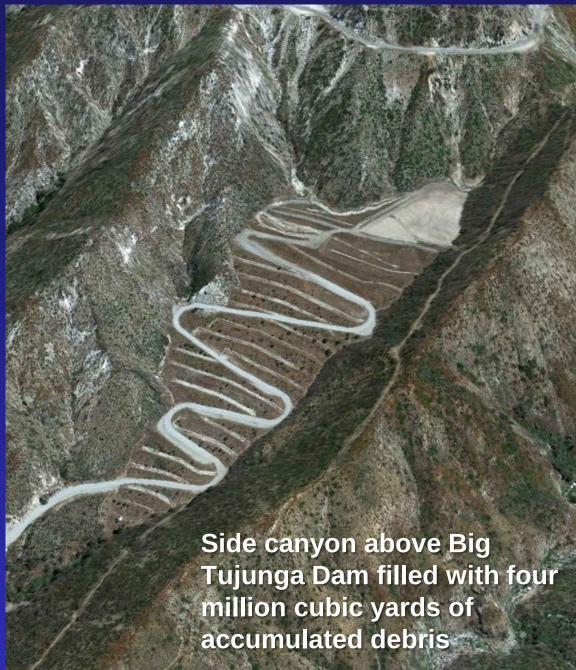
Cribwall check dam along Winter Creek, above Santa Anita Dam

Gould Debris Basin above La Cresenta

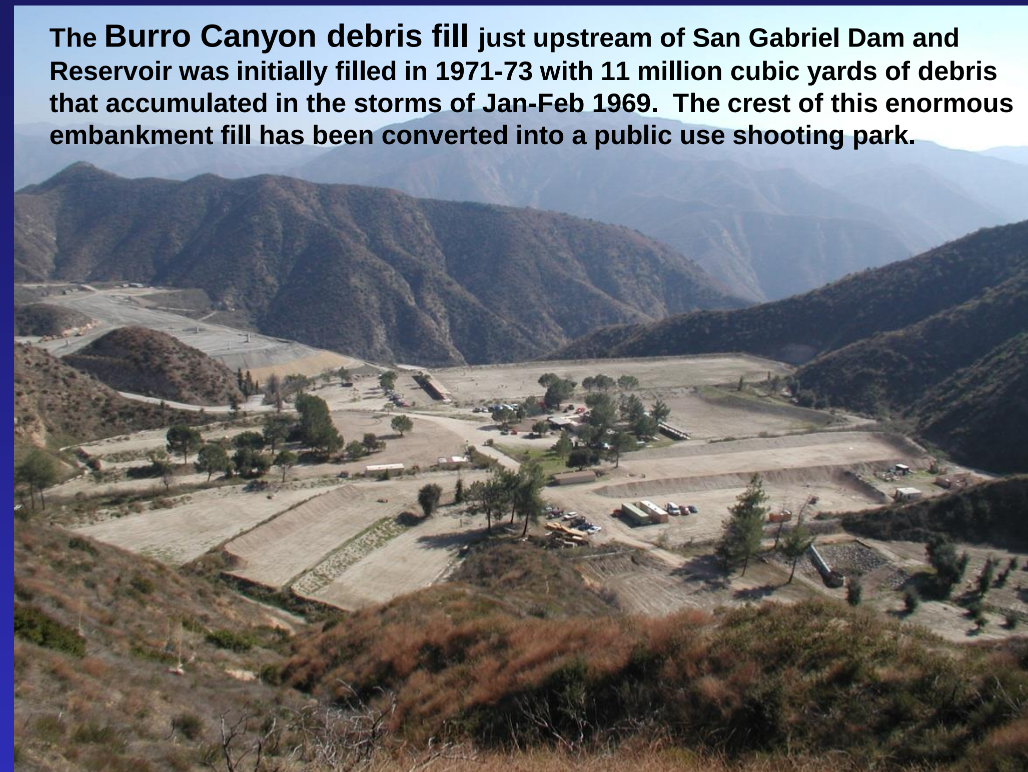
Crews mucking out a small debris basin in Los Angeles County.  Note perforated riser intake tower.

**Between 1925-60 the Los Angeles County Flood Control District constructed 93 dams for debris storage and hundreds of smaller check dams, intended solely for bed stabilization. The debris basins are periodically mucked out to preserve storage capacity (see lower right).**

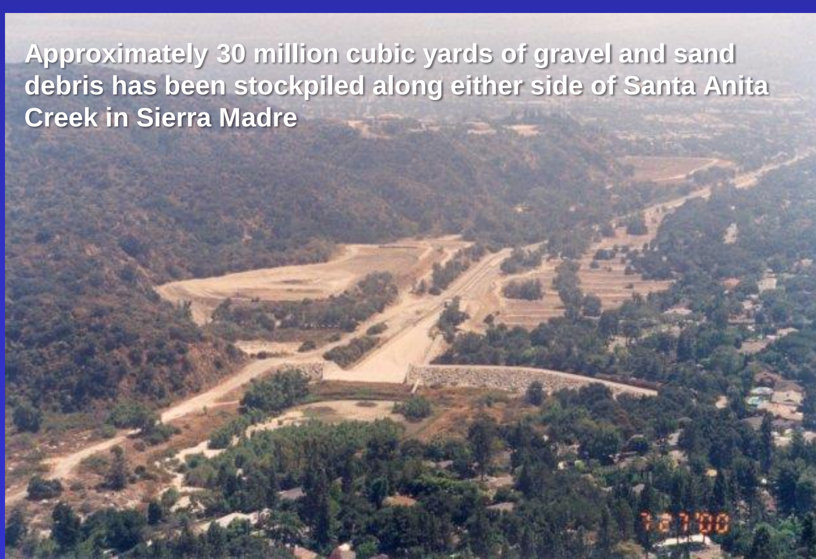
# SEDIMENT MANAGEMENT



Side canyon above Big Tujunga Dam filled with four million cubic yards of accumulated debris



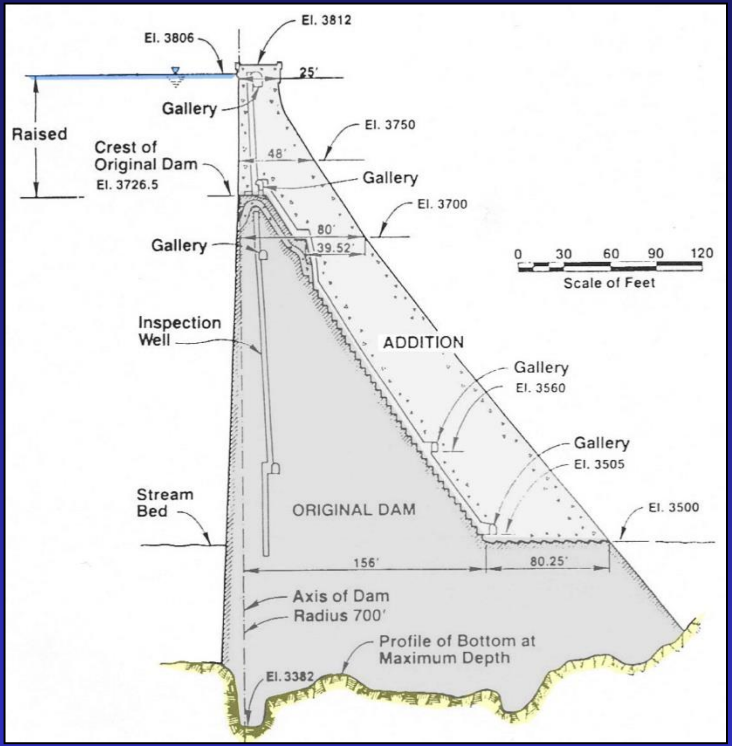
The **Burro Canyon debris fill** just upstream of San Gabriel Dam and Reservoir was initially filled in 1971-73 with 11 million cubic yards of debris that accumulated in the storms of Jan-Feb 1969. The crest of this enormous embankment fill has been converted into a public use shooting park.



Approximately 30 million cubic yards of gravel and sand debris has been stockpiled along either side of Santa Anita Creek in Sierra Madre

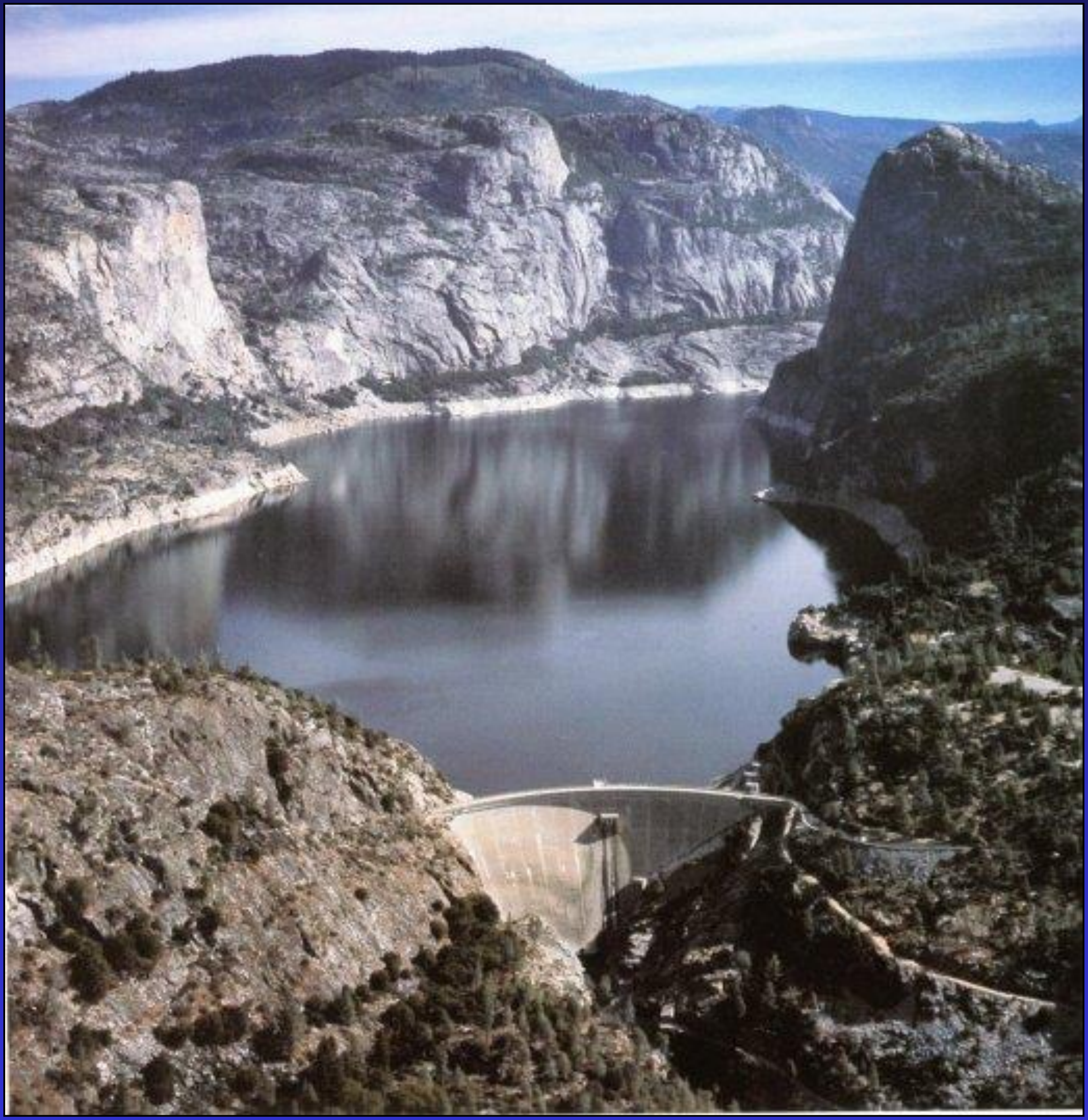
Each year Los Angeles County excavates millions of cubic yards of granular sediment deposited in reservoirs and debris basins. This material is often stockpiled in tributary mountain canyons (above left and right), or on the alluvial terraces just downstream of the mountain front (lower left).

# CHALLENGE OF BUILDING A DAM IN STAGES, 15 YEARS APART




- **O'Shaughnessy Dam** was constructed in two stages: between 1919-23 to a height of 344 ft, and again, in 1935-38 to the final height of 430 ft
- Unprecedented obstacles, including: higher strength concrete, artificial cooling of the mix and method of attachment had to be overcome. 2 to 4 ft wide joint between the two were used, which was grouted after concrete cured.

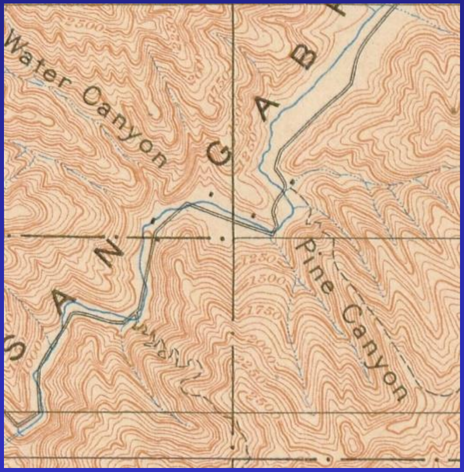
# O’Shaughnessy Dam in Yosemite Park



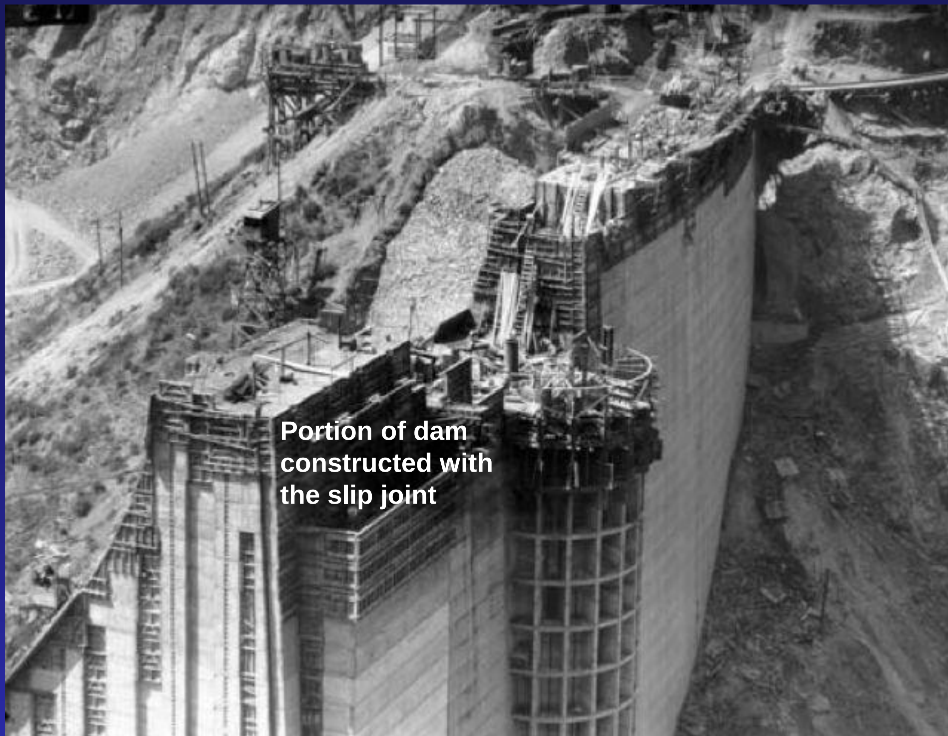
- The most controversial dam in California is the O’Shaughnessy Dam on the Toulumne River, damming Hetch Hetchy Canyon in Yosemite National Park.
- Between 1901 and 1913 the City of San Francisco and the federal government wrestled over granting permission for the dam. John Muir used the Sierra Club in his campaign to stop the dam, and the ultimate decision was made by President Theodore Roosevelt.

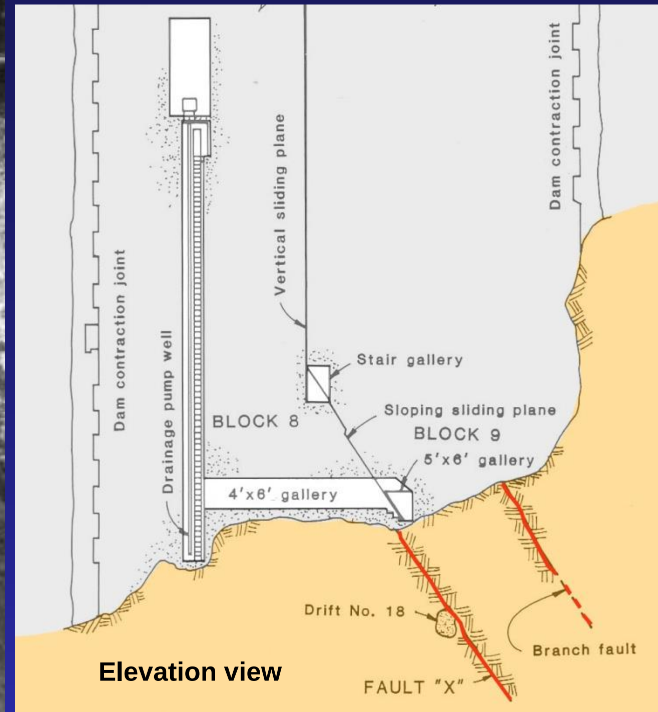
# MORRIS DAM (1934)

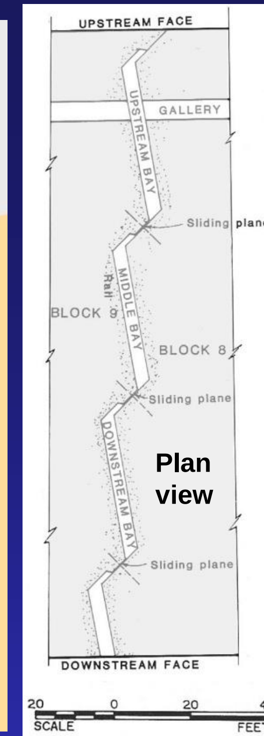
Originally named the 'Pine Canyon Dam' for a tributary at the dam site (below), the dam's name was changed to Morris Dam to honor Samuel Brooks Morris (1890-1962), Chief Engineer of the Pasadena Water Department.




- **Morris Dam** is a concrete gravity dam built in lower San Gabriel Canyon in 1933-34 (originally named the **Pine Canyon Dam**). It was unique in many ways:
- First mass concrete dam that employed low-heat cement to reduce internal stresses
- First dam designed for pseudostatic seismic loads
- First gravity dam designed for physical fault offset
- First dam to have its dynamic properties evaluated




**Morris Dam was built with a baffle slip joint (shown at middle and far right) designed to accommodate up to 6.5 ft of dip-slip fault offset**

- **A Board of Consultants decided to construct the dam with a baffle joint capable of accommodating up to 6.55 ft of fault offset**
- **During excavation of the foundation a late Quaternary age fault was discovered near the right abutment. It was explored and examined**
- **It was decided to build a slip joint in the dam**

# FAULT JOINT IN MORRIS DAM

- Since 1934 about 2.5 inches of vertical offset has been accommodated by the fault joint in Morris Dam, with the right abutment side down.
- No significant leakage has been observed along the joint

# FIRST DYNAMIC PROPERTIES EVALUATION OF A DAM

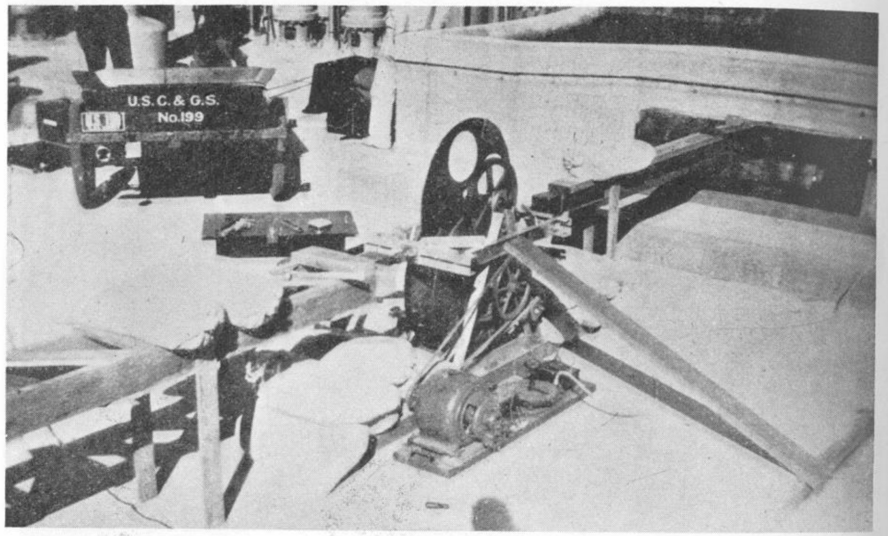



Fig. 9. The vibrator in test position on top of Morris Dam.

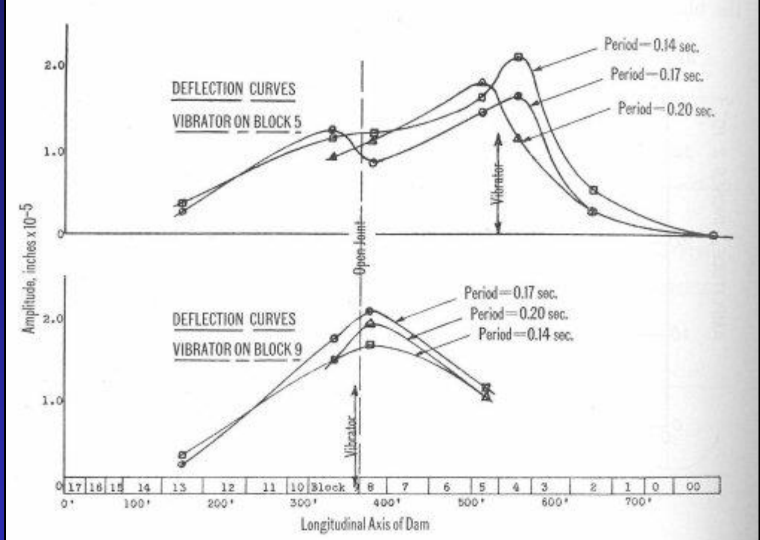
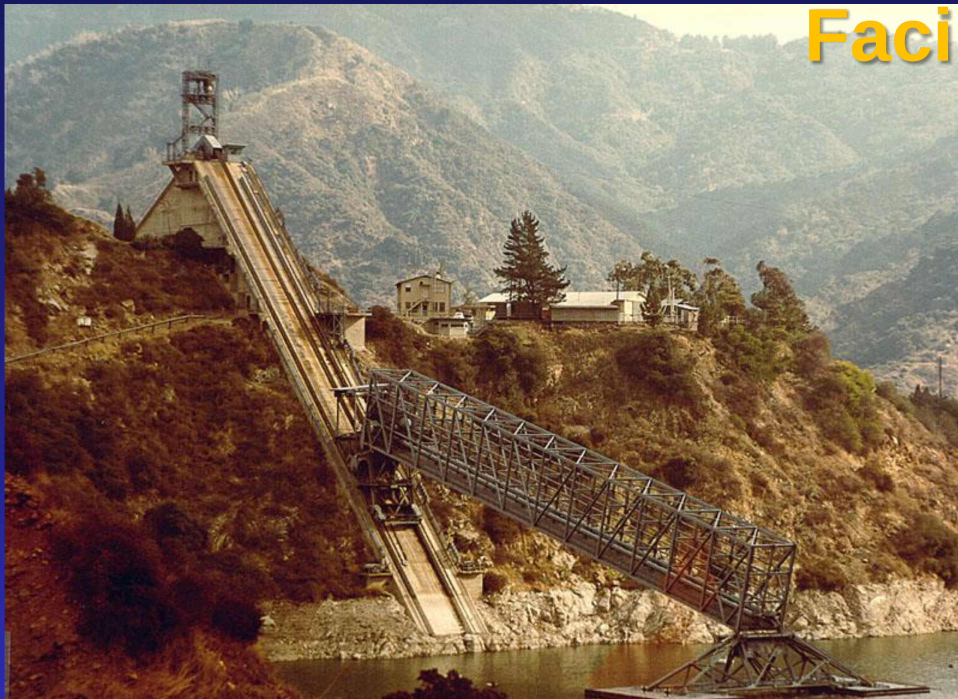
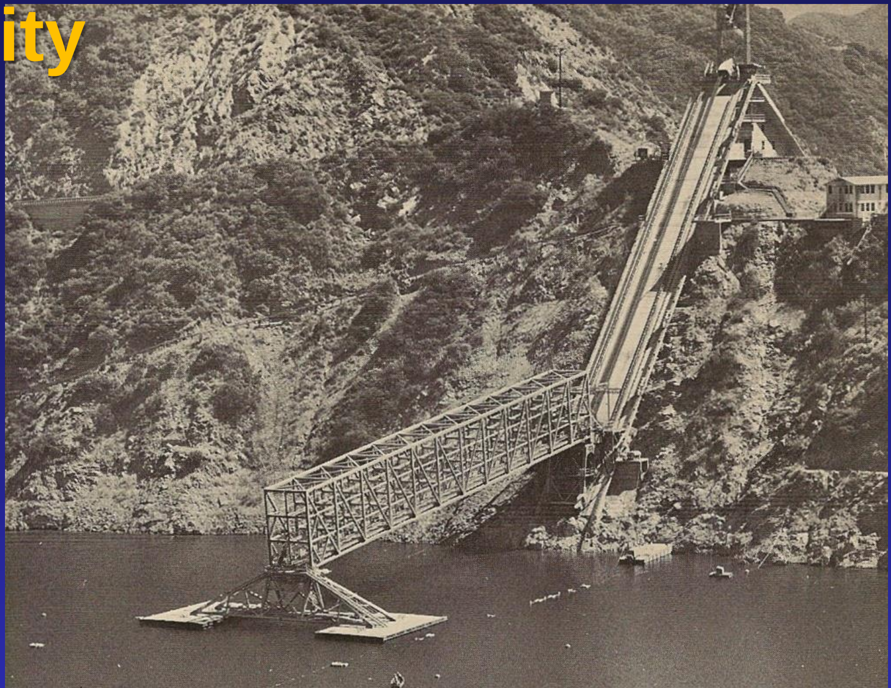



Fig. 13. Deflection curves of Morris Dam.

- **In the wake of the $M_s$ 6.25 March 1933 Long Beach Earthquake, the U.S. Coast Geodetic Survey allotted funds for the determination of dynamic properties of important structures**
- **They hired a young engineer named John Blume (at left), who built a dynamic exciter and used it on Morris Dam to determine the fundamental periods of vibration and deflection characteristics.**

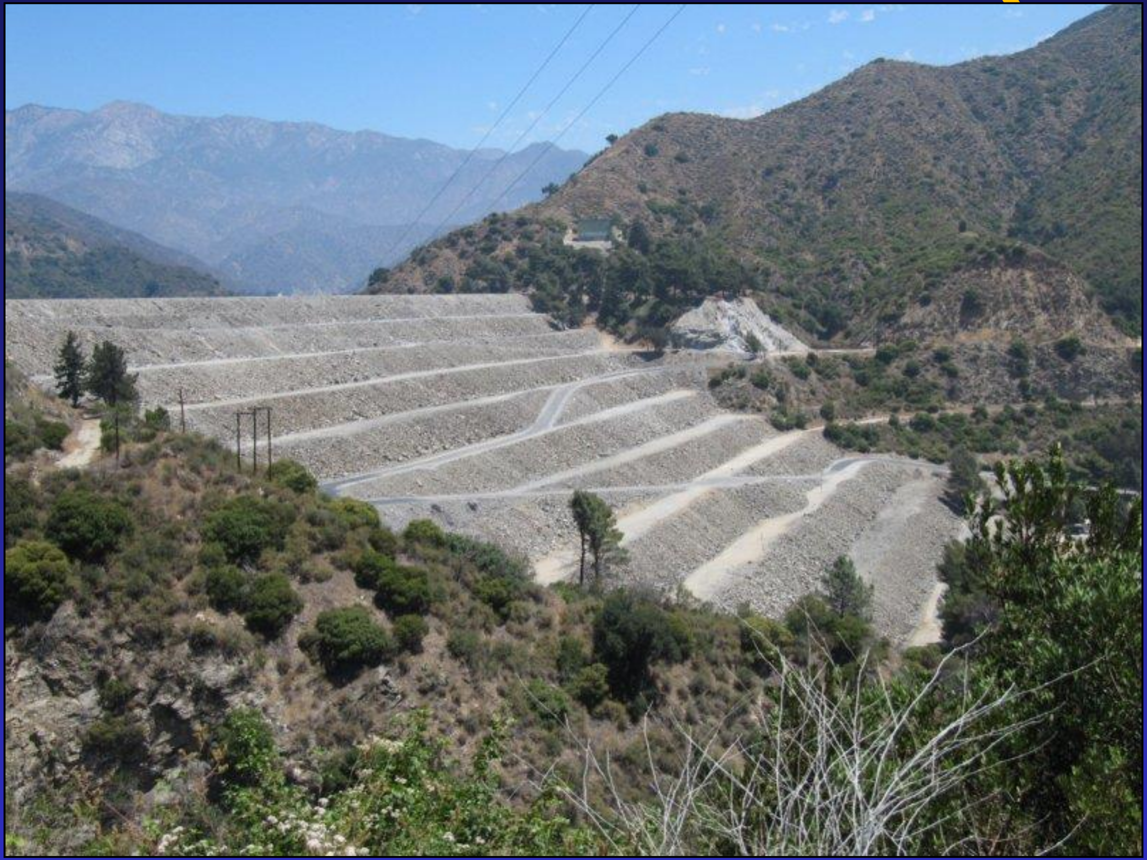
# Naval Ordnance Testing Station- Morris Dam Testing Facility





- During World War II Caltech scientists were hired by the Navy to develop a reliable air launched torpedo (Mk 13)
- They built a variable angle launcher at Morris Reservoir and all the Navy’s air launched weapons were developed here between 1943 and 1993 (it was dismantled in 1996-97).
- Chosen for remoteness of the site (to insure security) and fact that Morris Dam had been designed for dynamic loading

# SAN GABRIEL DAM (1937)



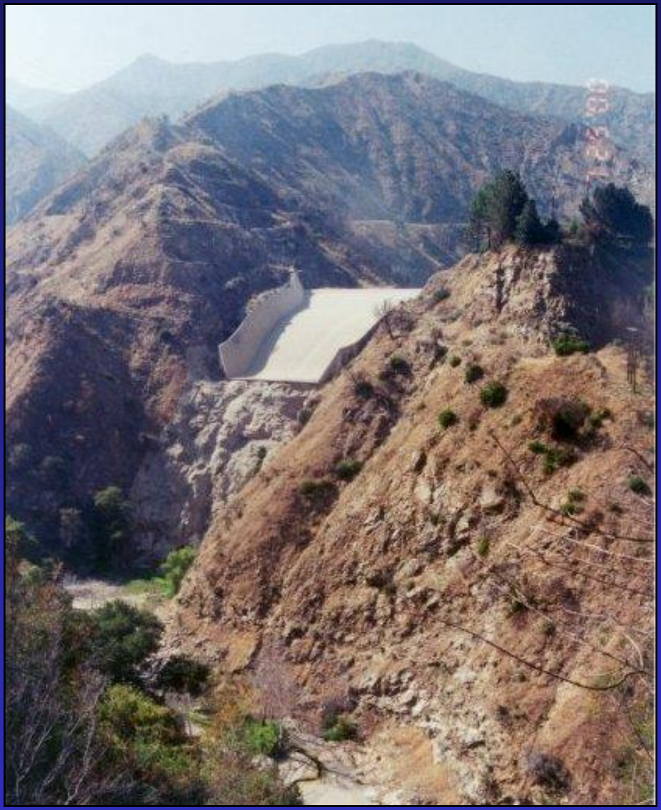
- **San Gabriel Dam No. 1** was completed in July 1937 as the **highest rockfill dam in the world**
- It is 355 feet high, with 3:1 side slopes, necessitating a 2000 ft wide base with a volume of 10,572,000 $yds^3$
- After 1969 storm season, a record 11 million yards of sediment was removed from the reservoir floor

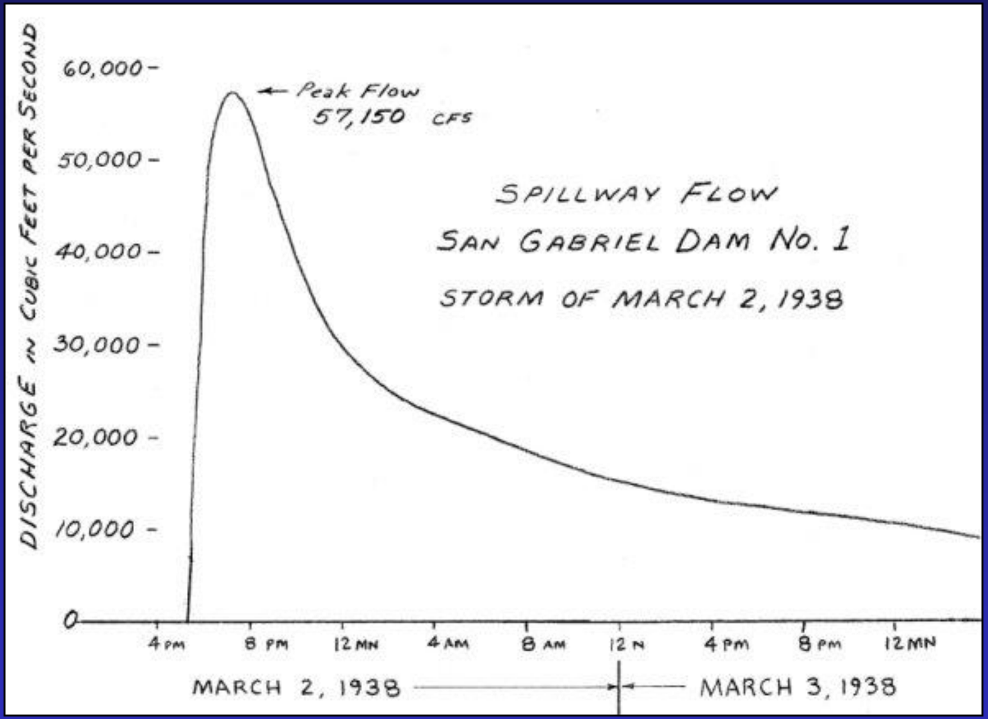
# COMPACTING ROCK FILL

**Paul Baumann (1892-1983) supervised the design and construction of the San Gabriel Dam in 1935-38. The record high rockfill dam contained 10,572,000 yds$^3$ of disaggregated metamorphic rock, which presented compaction challenges.**


- **Image at upper left show the Allis Chalmers sheepsfoot roller that employed *replaceable* "hammerhead tips," designed by Paul Baumann (above left). Lower left image shows the spiked roller using hardened steel tips, introduced in 1954. Image at lower right shows the grid roller developed by Gardner Byrne Construction Co of Los Angeles in 1947, acquired by Hyster in 1949. All three types were used by the Los Angeles County Flood Control District. during construction of rock and earth fill dams from 1935 onward.**

# NEAR BRUSH WITH DISASTER






- **Just 8 days after the San Gabriel spillway was paved it passed a record flood of 57,150 cfs on March 2, 1938**
- **The reservoir inflow of 94,380 cfs deposited 8.3 million cubic yards of sediment in just 36 hours**
- **The spillway has never been used since!**

# FEDERAL FLOOD CONTROL ACTS

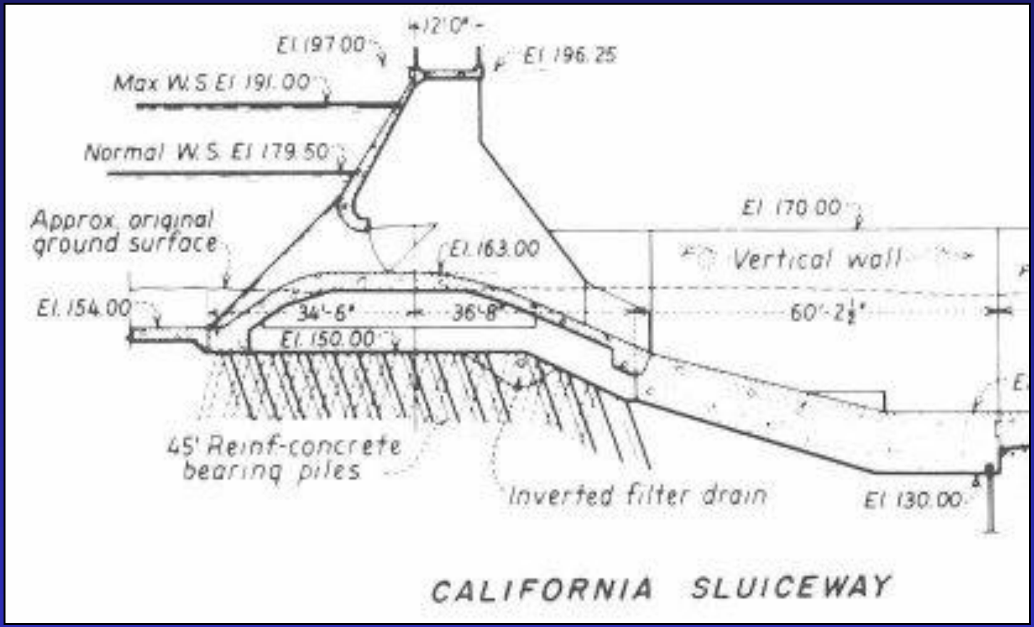
- Damage like that shown above along the channelized Los Angeles River in the March 1938 flood spurred the Federal Flood Control Acts of 1936, 1941 and 1944, which placed the U.S. Corps of Engineers into a prominent role to help provide flood control nationwide, on a 65/35 shared cost basis with local agencies.

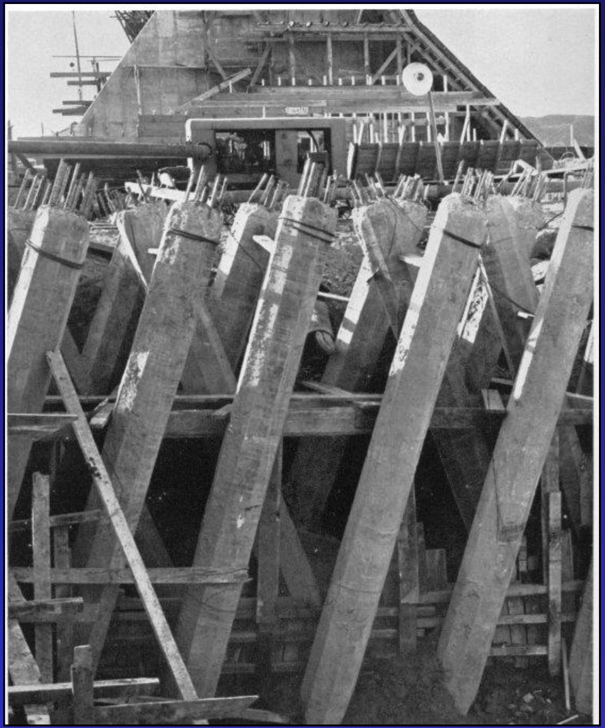
# IMPERIAL DAM and DESILTING WORKS

Site of Imperial Dam.

- Imperial Dam is a buttress dam 50 ft high and 3,430 ft long, completed in 1938. Located 17 miles upstream of Yuma
- Water for the Gila and All American Canals is diverted here
- Deep unconsolidated soils infill the channel, large settlements predicted
- 4 layers of subdrain filters were constructed beneath the dam and spillway apron to reduce uplift and piping

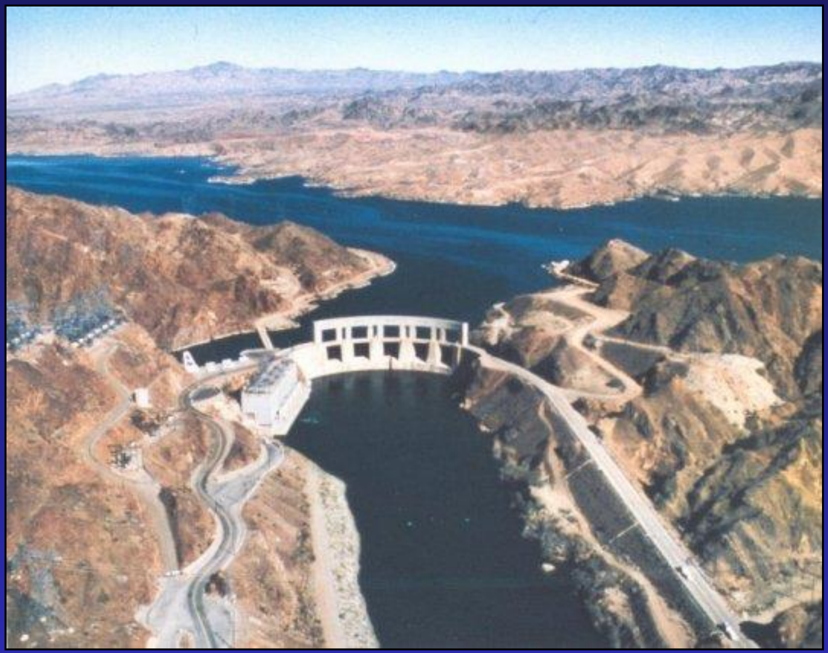
# FIRST DAM BUILT ON PILES

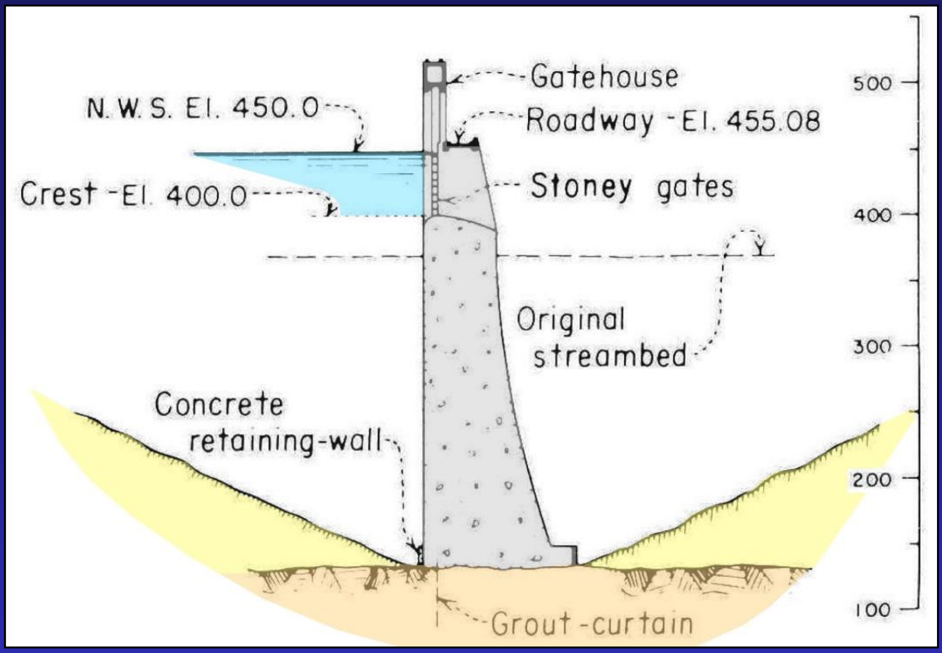


- **Imperial Dam** was built on battered concrete piles to check settlement of the main buttress dam structure because of soft alluvial soils underling the site were prone to future consolidation-induced settlement.
- The dam is designed as a floating structure, with rubber seals between buttress bays.

# DEEPEST DAM FOUNDATION



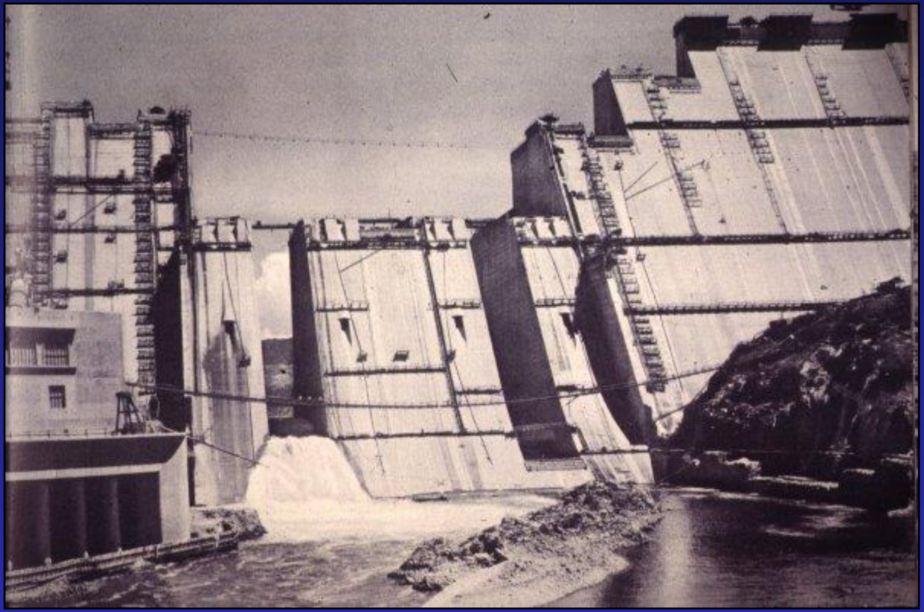


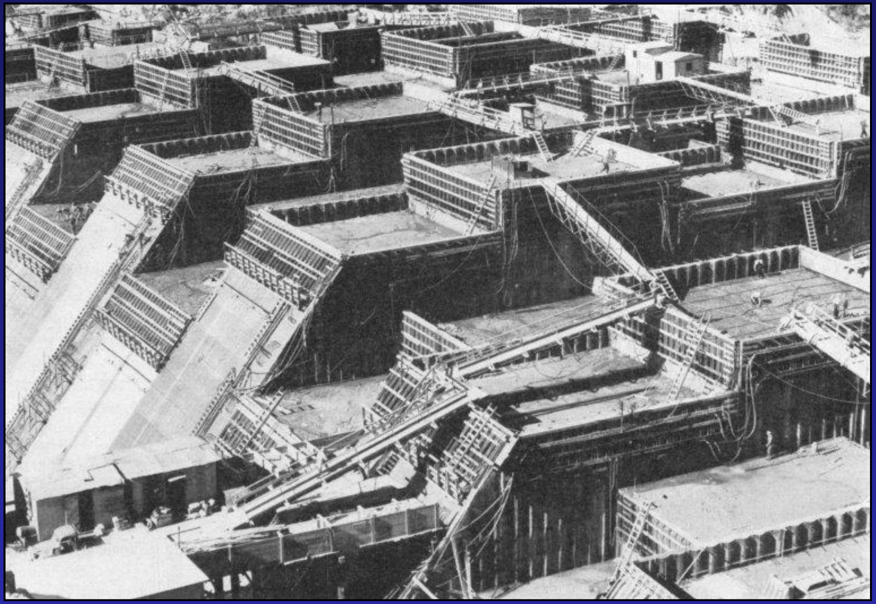

- **Parker Dam** was constructed between 1934-38 along the Colorado River by the Bureau of Reclamation, but paid for by the Metropolitan Water District of Southern California
- Intakes into Lake Havasu convey water for use in Southern California (from 1938) and central Arizona (from 1979)
- 235 feet of channel excavation was required, a record at that time
- Only 85 feet of the 320 foot high structure protrudes above the Colorado River channel

# FIRST ARCH DAM WITH TWIN THRUST BLOCKS

- The Camp San Luis Obispo Dam was designed by Leeds, Barnard, Hill and Jewett in 1941 for the US Army. It was 185 feet high with a design reservoir capacity of 45,000 ac-ft
- It was renamed Salinas Dam and Lake Santa Margarita after the Second World War.
- It is now operated by City of San Luis Obispo

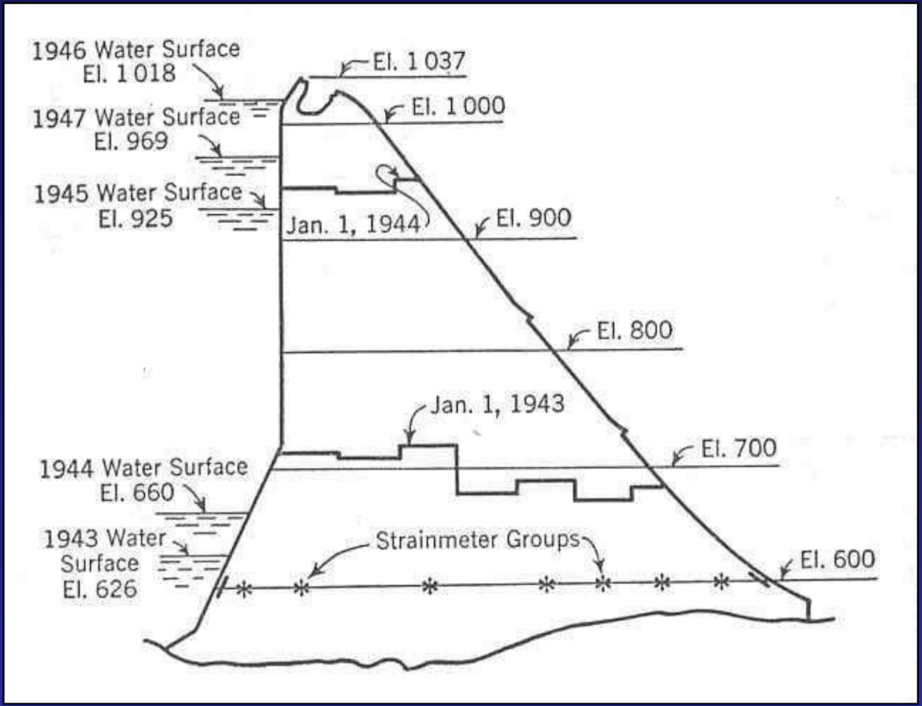
# FIRST FULLY INSTRUMENTED DAM

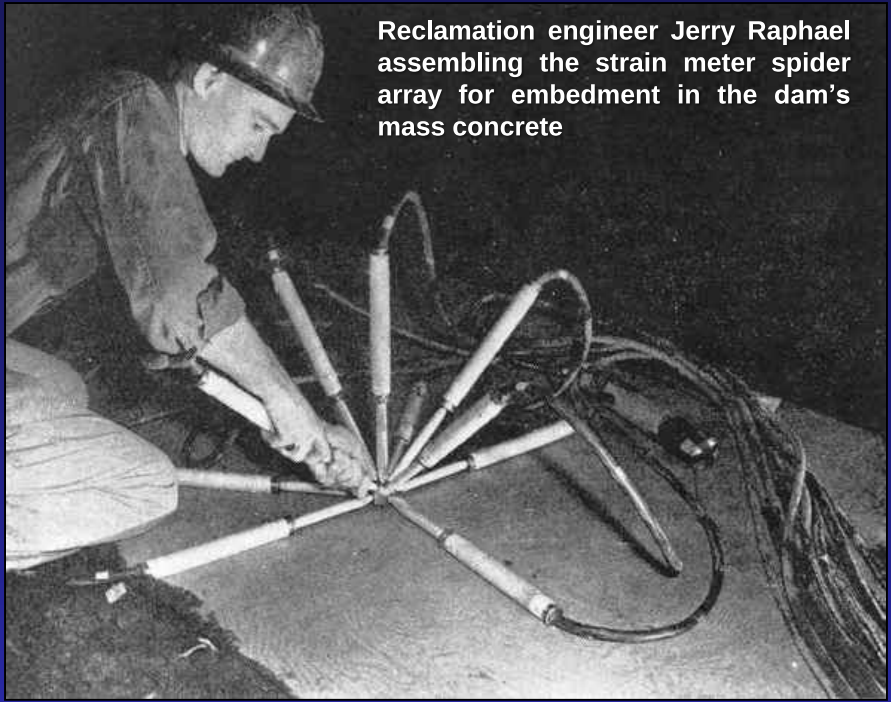




Frank T. Crowe, C.E.
1882-1946

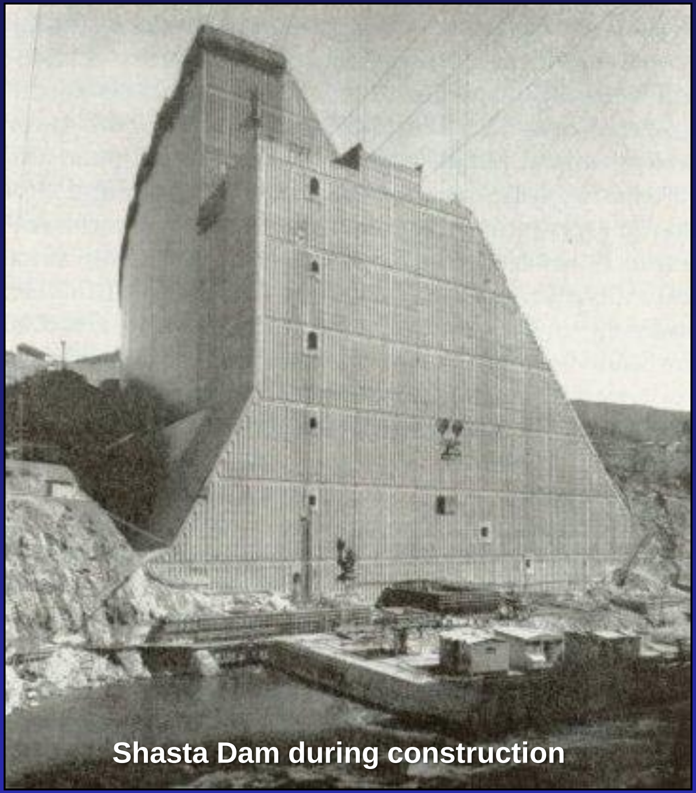
- **Shasta Dam** was built by the US Bureau of Reclamation as the northern unit of their Central Valley Project, between 1938-45
- Curved concrete gravity dam 602 ft high and 3,500 ft long, laid out on 2,500 ft radius, with a volume of 6.27 million yds$^3$ of concrete, requiring 6 million barrels of cement (4 sacks/yd$^3$ ). Up to 11,790 yds$^3$ of concrete was poured per day
- Last dam designed by legendary Reclamation engineer Jack Savage and built under the supervision of legendary construction manager Frank Crowe. Both men had fulfilled similar roles at Hoover Dam
- Shasta Reservoir's capacity of 4.55 million acre-feet is the largest in California

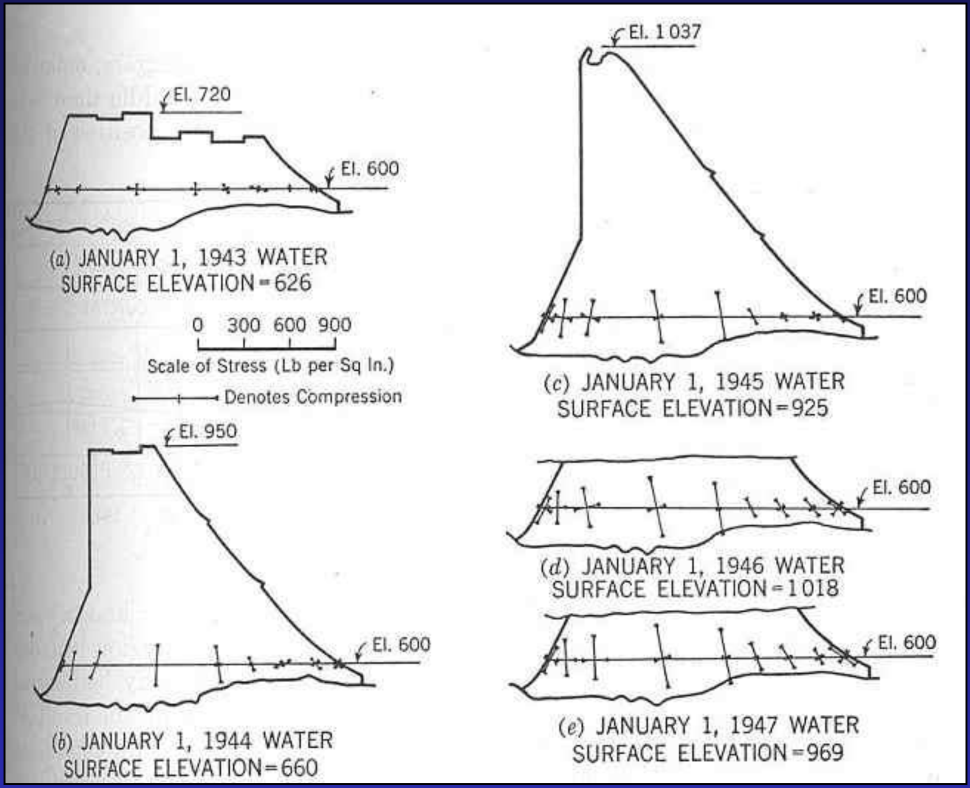


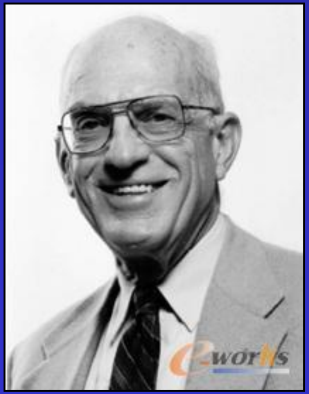



Reclamation engineer Jerry Raphael assembling the strain meter spider array for embedment in the dam's mass concrete

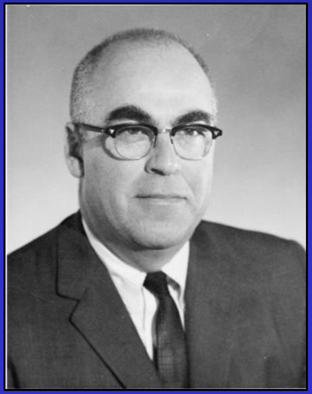
- Decision was made to fully instrument the dam while pouring the concrete
- The embedment of Carlson strain, stress and temperature meters allowed engineers to study the three-dimensional behavior of the dam through construction and into its service history
- These data allowed design assumptions to be validated, as well as monitor safety.
- These data showed Shasta Dam exhibited extremely conservative behavior, making it a good candidate for future heightening



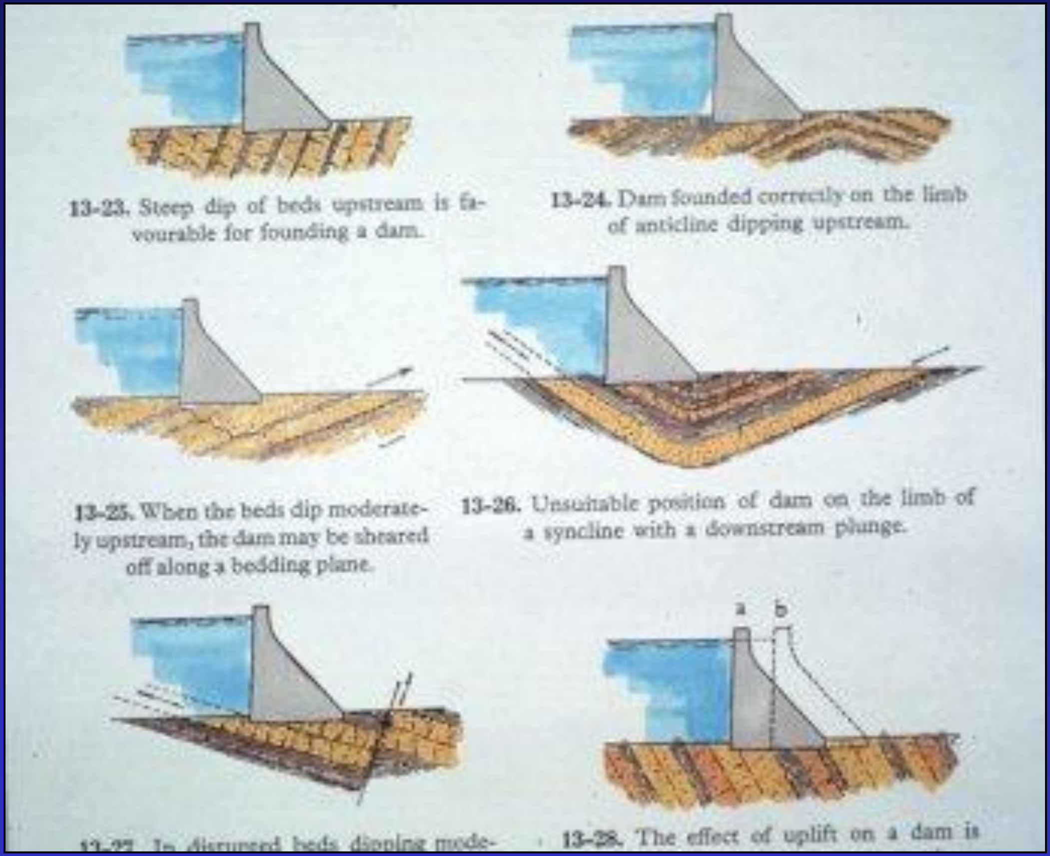
Ray W. Clough
(1920 - 2017)



Jerome M. Raphael
(1913-89)

- **Analyses of the collected data led to reconsideration of methods of stress analysis for concrete gravity dams**
- **Jerry Raphael was recognized with ASCE's Moissieff Award in 1954 for his paper describing *"Stresses in Shasta Dam"***
- **These data became background material for formulation of the finite element method of analyzing dams, by Raphael and Ray W. Clough at U.C. Berkeley in the early 1960s**

# APPRECIATING VARIABILITY OF FOUNDATION CONDITIONS




The results of the studies at Shasta Dam allowed a better understanding between dam structures and their foundations, which recognizes the unique foundation conditions of each dam site.

Shasta's surprising performance was ascribed to the upstream dip of extremely resistant strata (lower left), which blunted the inclination of the resultant thrust upstream.

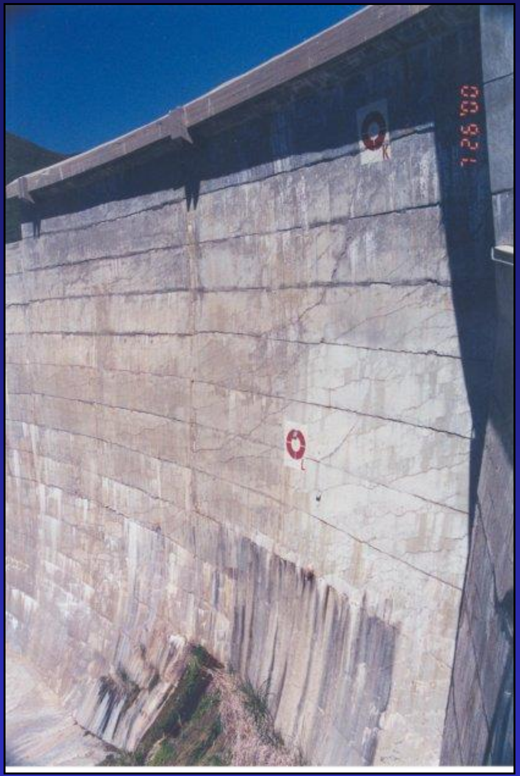
# FIRST 'DRY FILL' EMBANKMENT

- The **Hansen Flood Control Basin** was constructed shortly before World War II (1938-41) as a dry compacted fill, to speed the job up and because it was intended to be a normally dry retention basin
- The Corps also built the Sepulveda, Lopez, Santa Fe, Prado, Whittier Narrows, and San Antonio flood retention basins in the Los Angeles area between 1938-57.

# MATILIJA DAM (1947)

- **Matilija Dam** was 190-ft high constant angle arch dam designed by the Donald R. Warren Co. of Los Angeles in 1946. The designers recognized the need for using low alkali Portland Type II Cement and imported coarse aggregate from over 100 miles away (Irwindale) to better resist abrasion than onsite materials.
- Extreme case of cracking distress caused by alkali aggregate reaction because of glassy andesites and chalcedonic chert which somehow found their way into fine aggregate fraction of upper 40 feet. After studies in 1965, 1975 and 1977 the central crest was lowered in three steps, by as much as 40 feet.

# ALKALI AGGREGATE REACTION



- **Alkali aggregate reaction** was discovered in the early 1940s, as a handful of concrete structures began to experience expansion cracking.
- 40 years would pass before the precise mechanism was discovered; that being a chemical reaction between opaline quartz and the cement paste

# SLATED FOR REMOVAL

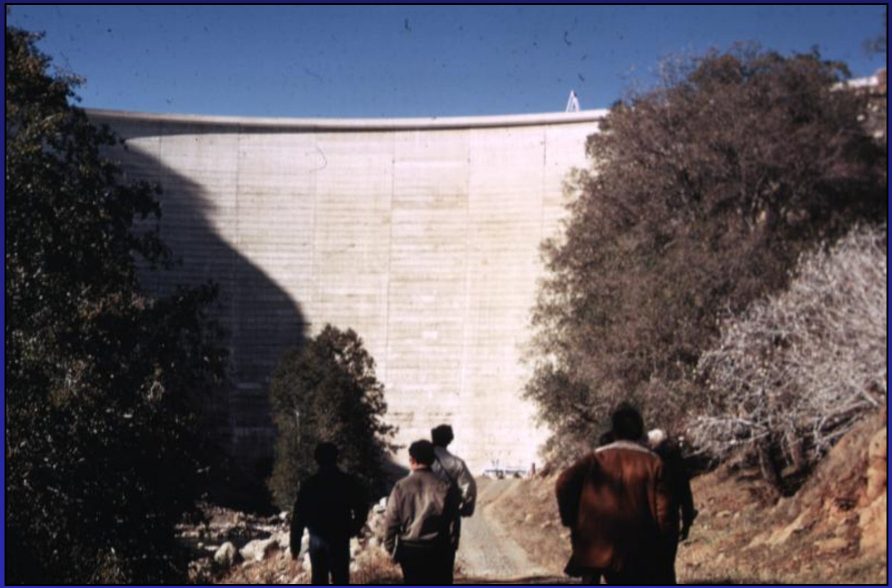
- By 1966 Matilija Reservoir had filled with 6 million cubic yards of sediment.  Matilija Creek used to support steelhead trout, migrating up Ventura River from Pacific Ocean
- Current plans call for its removal, after studies by USBR, USGS and USCOE are concluded and a source of funding is found

# REPLACING ONE DAM WITH ANOTHER

Figure 7–8 Drum Afterbay Dam replacement

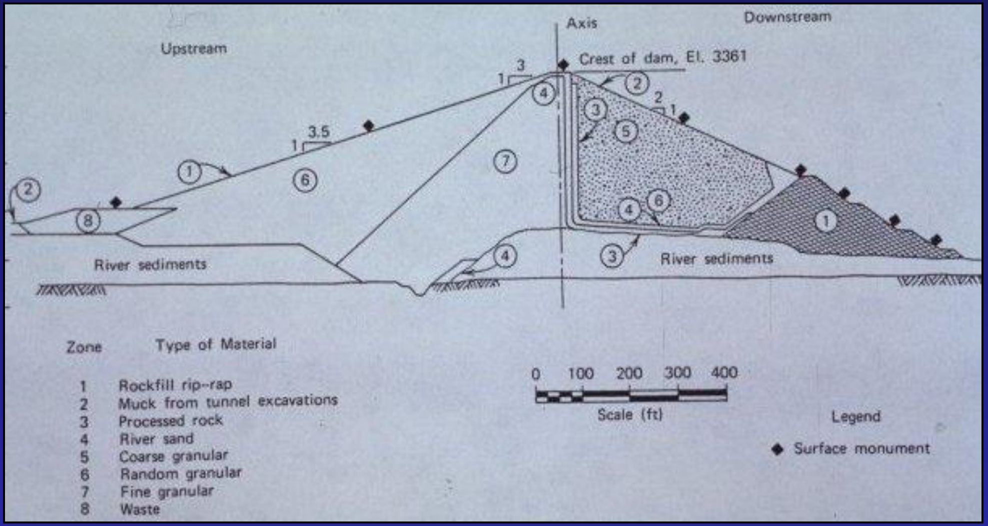
- **Drum Afterbay Dam** was constructed by PG&E on the Bear River in 1924. It exhibited alkali aggregate reaction thru interaction of pyrite in the schist aggregate with the cement paste. The dam was replaced in 1966, as shown here.

# FIRST DOUBLY- CURVED THIN ARCH DAM IN AMERICA

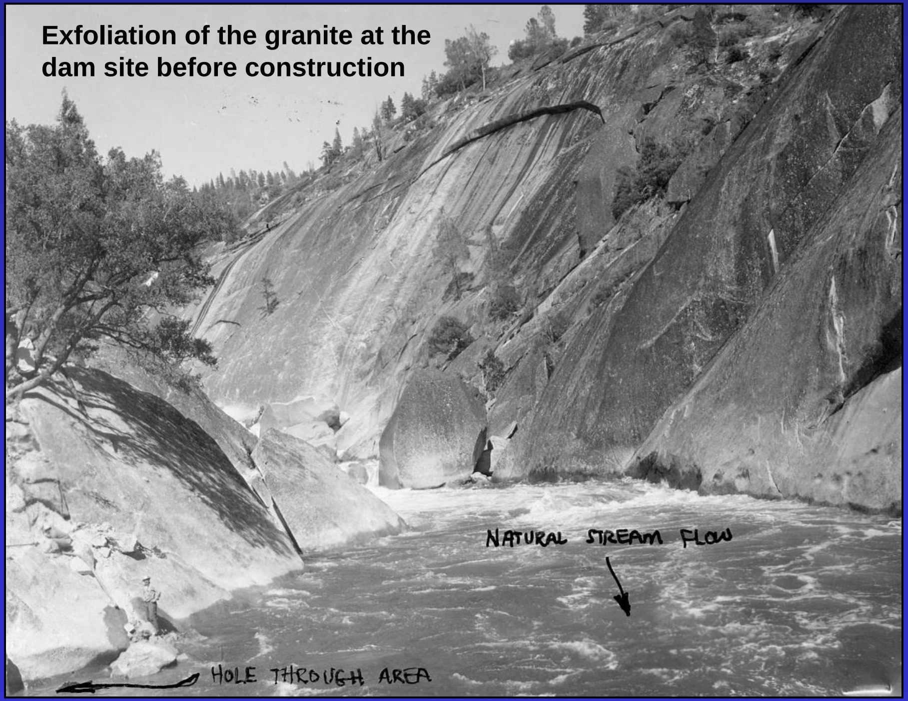


- **Monticello Dam** is a medium thickness doubly-curved thin arch dam designed by the Bureau of Reclamation.
- It was 304 ft high, 100 thick at base and 12 ft thick at crest. Completed in 1957.
- Lower left: It also has the largest glory hole spillway in America, 72 ft in diameter narrowing to 28 ft, with a discharge capacity of 48,800 cfs

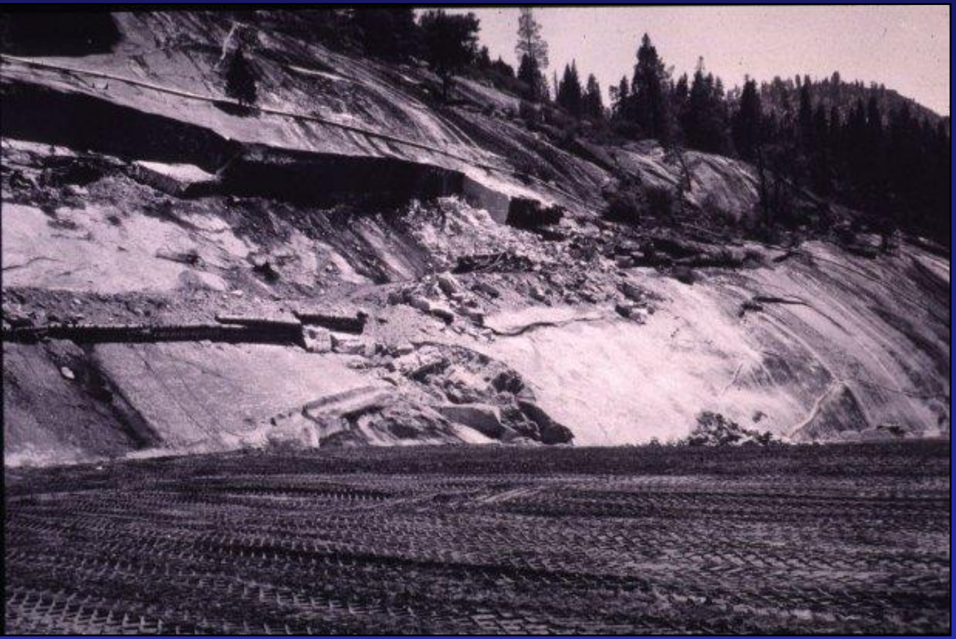
# MAMMOTH POOL DAM - 1960

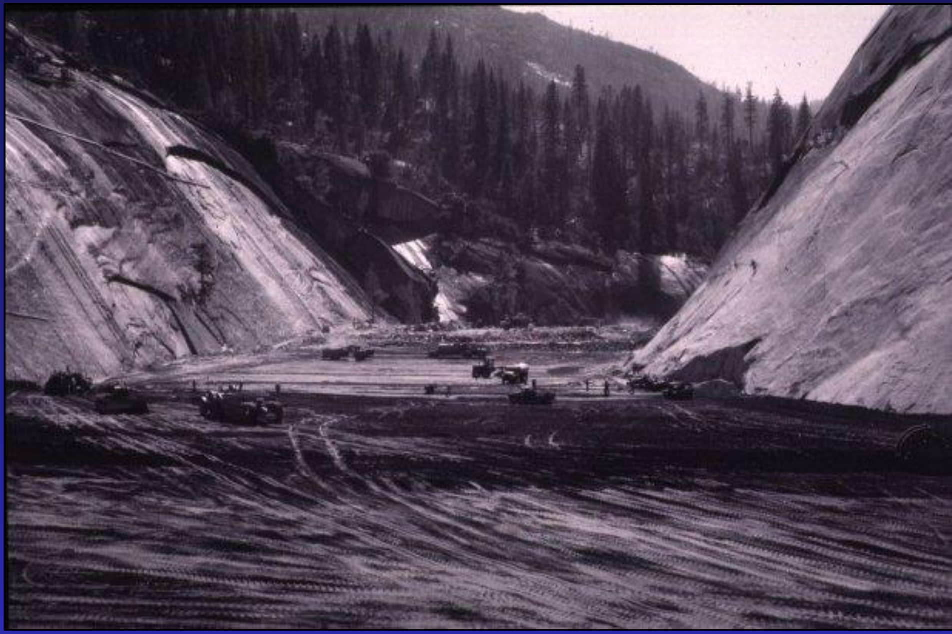



- **Mammoth Pool Dam** is a zoned rockfill built against some of the strongest rock in California. The Mt Givens Granodiorite; which has unconfined compressive strength of around 37,000 psi



# BATTLING EXFOLIATION

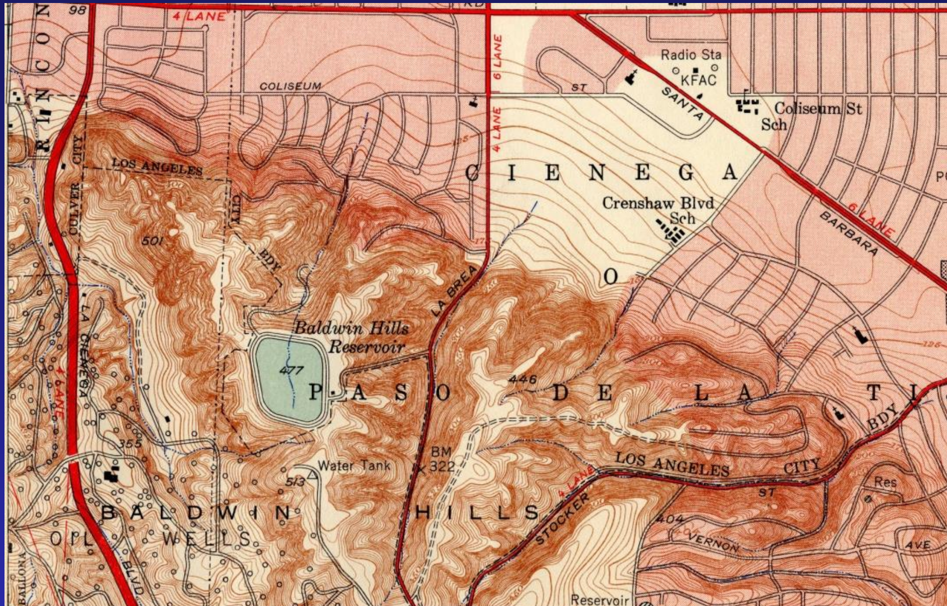




Karl Terzaghi (1883-1963)

- During construction of **Mammoth Pool Dam** on the upper San Joaquin River in the late 1950's, thick slabs of the Mt Givens Granodiorite kept popping outward, as the outer rock was removed.
- Famed foundation engineer **Karl Terzaghi** was brought in as a consultant. He recommended placing the fill against the granite abutments, then grouting the exfoliation joints when the dam was finished.

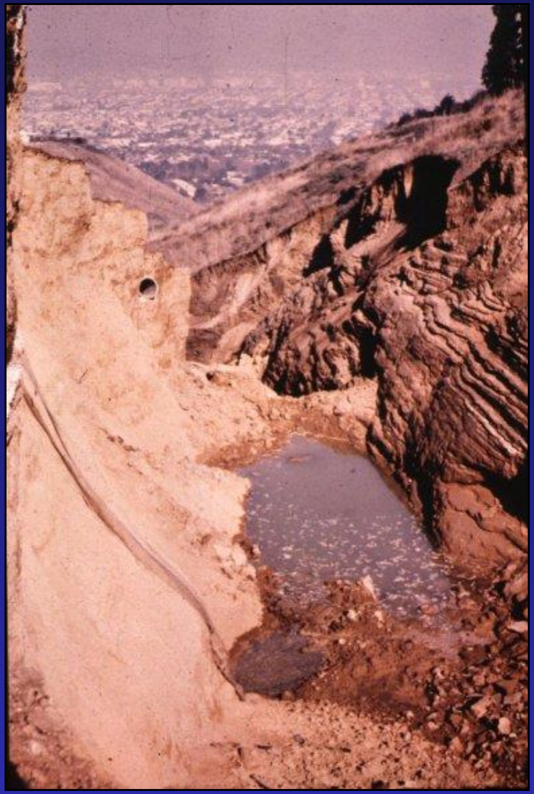
# BALDWIN HILLS RESERVOIR




- **Baldwin Hills Reservoir** was an offstream municipal reservoir designed and built by the Los Angeles DWP in 1947-54. Its design capacity was 897 acre-feet. The grading volume was 859,000 $yds^3$
- On Saturday December 14, 1963 the caretaker noticed an unusual sound of water at the spillway intake, beginning around 11:15 AM
- By noon a DWP engineer was summoned and all outlets and inlets were opened to drain the reservoir of 738 ac-ft of water in storage. It would have taken 24 hrs to drain the entire reservoir

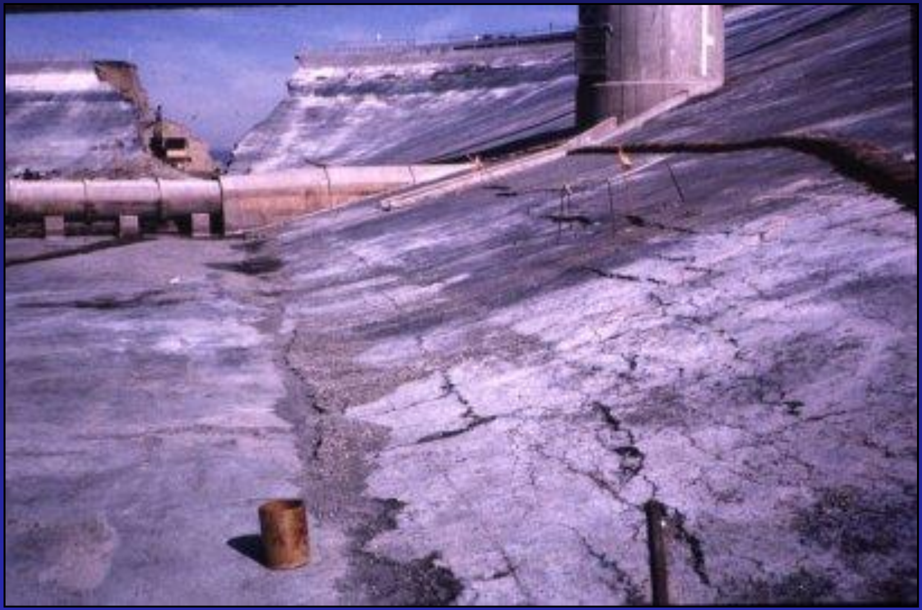
# LIVE NEWS COVERAGE

- The Los Angeles Police Department and local media were alerted shortly after noon that a failure was imminent.
- At 3:38 PM a complete breach of the south embankment occurred, with increasing discharge spilling up to 4,300 cfs
- The flow spilled down a steep ravine towards Cloverdale Ave., destroying 41 and damaging 986 homes, and killing 6



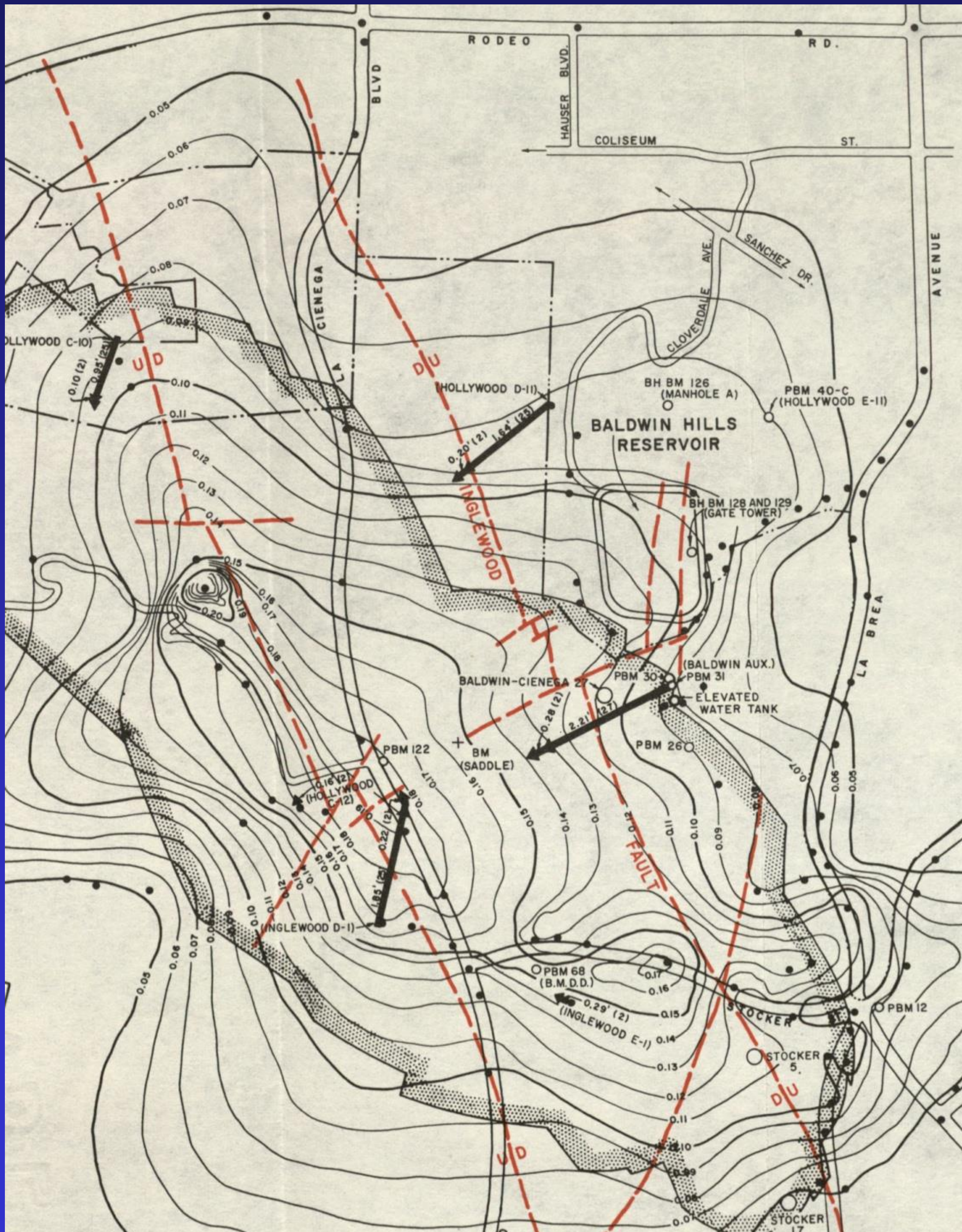
- The outflow continued for 77 minutes, till 4:55 PM
- Afterwards, the eroded chasm was 90 feet deep and 70 feet wide, curiously dry in appearance afterwards (right)
- The water had leaked through the abutment rock of the underlying Pico Formation, having first been noted at an elevation of 400 feet on the downslope face, 82 feet below crest

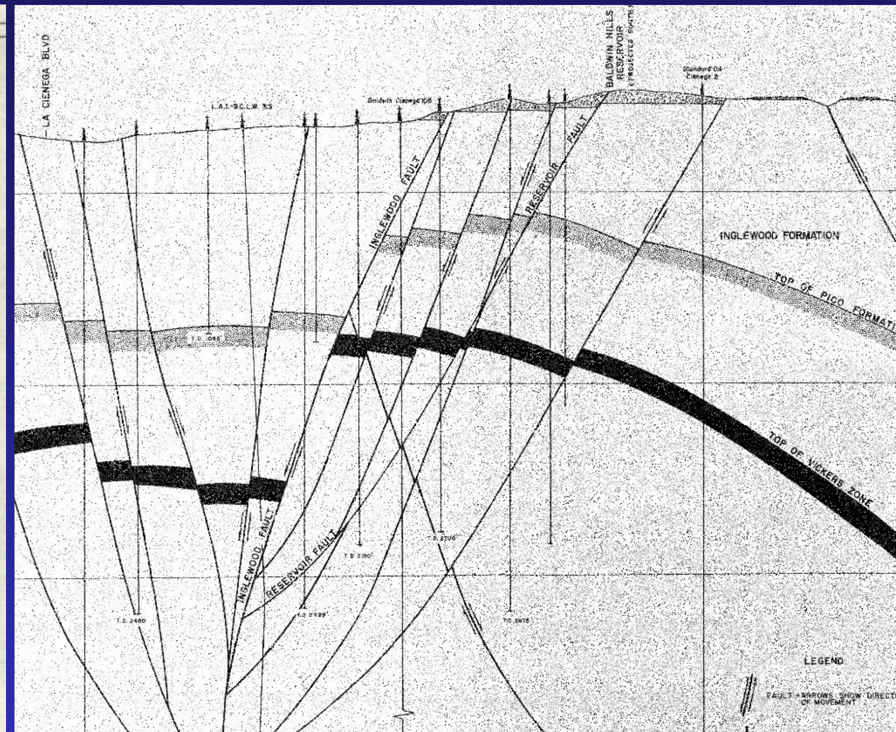
# Instrumentation cannot save a flawed design



- The eroded chasm extended into the reservoir floor along a linear north-south trend (left)
- Subsequent examination revealed an active fault scarp extending through the reservoir floor, shown in right view
- Up to 12 inches of vertical offset was noted along four strands of this fault exposed in the reservoir floor, diminishing towards the southerly side of the reservoir.  The fault dipped 70 degrees west

# ALARMING RATES OF SETTLEMENT




Map and section views showing faults and annual rates of subsidence measured in the Inglewood Oil Field. Note movement vectors in vicinity of the Baldwin Hills Reservoir (2.21 ft in WSW direction). A little over 1.5 feet of subsidence was measured along the Reservoir fault during the 9 year life of the reservoir! This subsidence was likely engendered by petroleum withdrawal over the previous 20+ years.

# BEGINNING OF REALITY TELEVISION

**KTLA Channel 5 employed the world's first television-equipped news helicopters. Their live coverage helped publicize the evacuations ordered by the Los Angeles Police Department.**

The Van Nuys News

CENTRAL VALLEY EDITION

108 PAGES

AND VALLEY GREEN SHEET

Established 1911

## Six Killed, 60 Houses Destroyed as Dam Collapses in Baldwin Hills

Consider City Liability In Reservoir Disaster

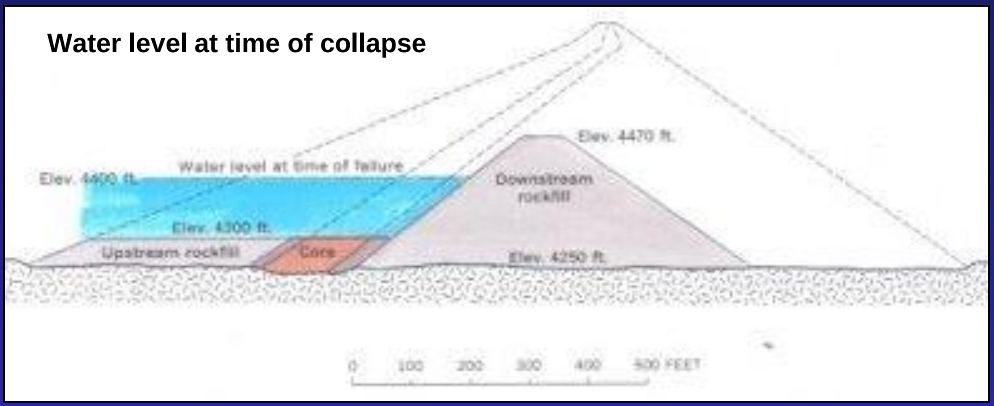
Fear More Bodies Buried Under Mud

- **Public outcry was enlivened by the real time simulcasting of the entire event, beginning around 12:30 PM.**

# Public Outcry stimulates political reaction
# DAM SAFETY LEGISLATION of September 17, 1965

- **Passed in wake of the December 1963 failure of the Baldwin Hills Reservoir, covered live on television.**
- **Jurisdiction for State overview of dams expanded to include *offstream storage facilities*, such as municipal reservoirs.**
- **Dams > 25 feet high which impound >15 ac-ft of water and dams >6 ft high which impound >50 ac-ft of water**

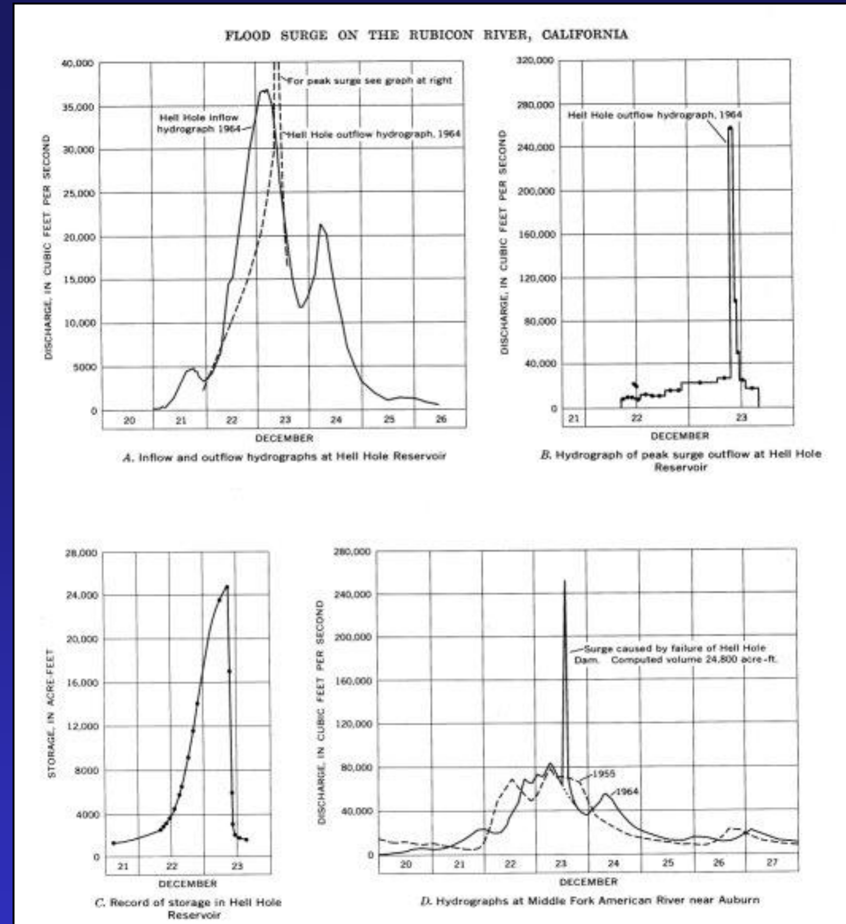
# FAILURE OF HELLHOLE DAM DURING CONSTRUCTION (1964)





- **Hellhole Dam**, a zoned rockfill, was under construction on the Rubicon River west of Lake Tahoe at the time of the December 1964 storms
- The downstream shell had been filled to a height of 220 feet, about half the planned height of the dam (see section view at left)
- There was 70 feet of freeboard between the reservoir and the shell when the storms began

# SPECTACULAR FLOOD



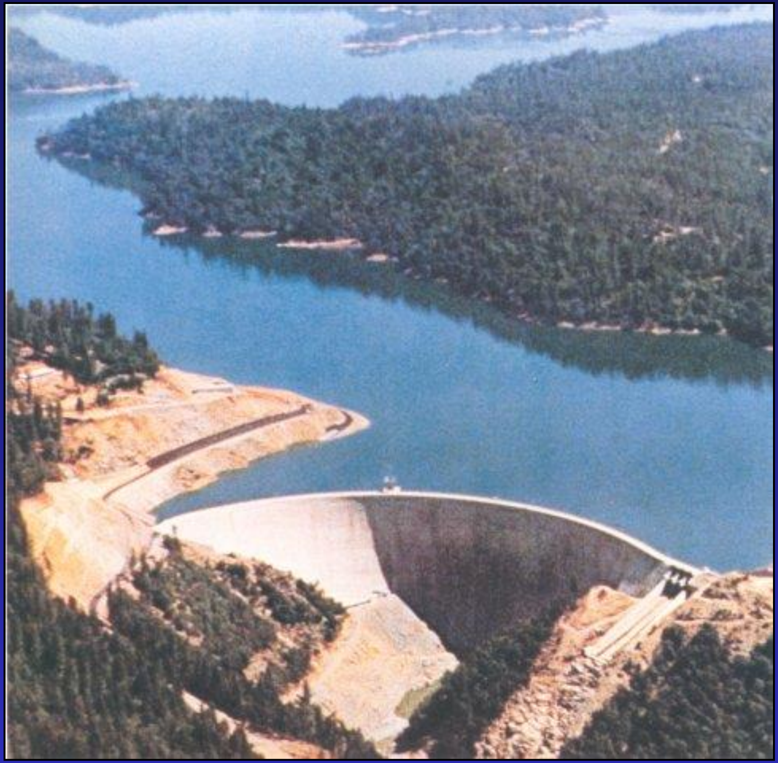
Flow and storage data associated with the failure of Hell Hole Dam in December 1964.

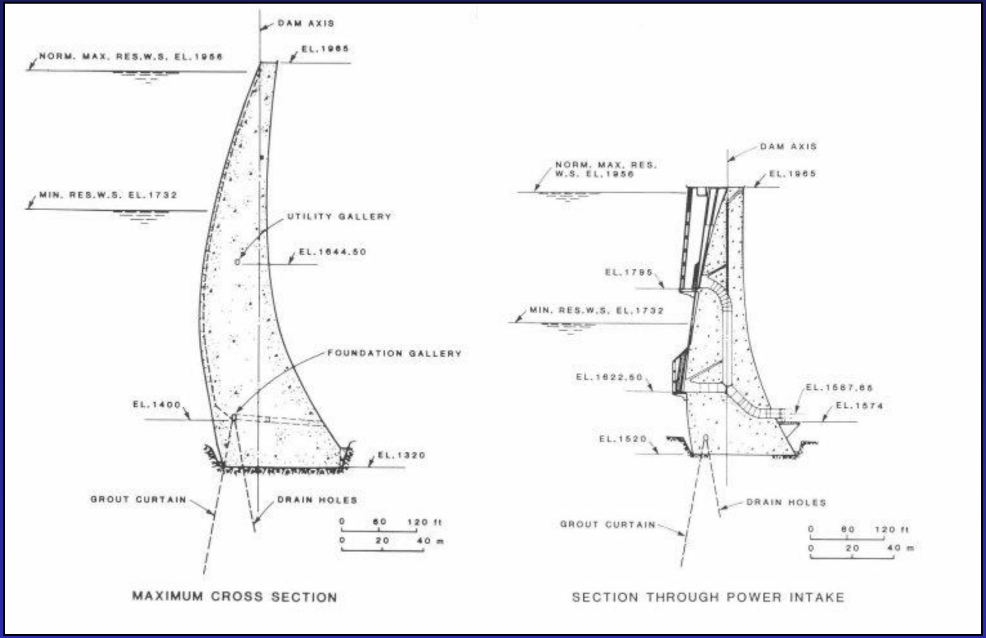
- The flood breached the rock shell around 9:30 AM on December 23, 1964 (left), releasing 24,800 ac-ft.
- The peak flow down the Rubicon River reached 240,000 cfs (right), clearing out the channel

# HELLHOLE DAM AS COMPLETED

- **Hellhole Dam** was rebuilt and completed in 1966, to a height of 410 feet.  It has operated without incident since.

# NEW BULLARDS BAR DAM (1969)



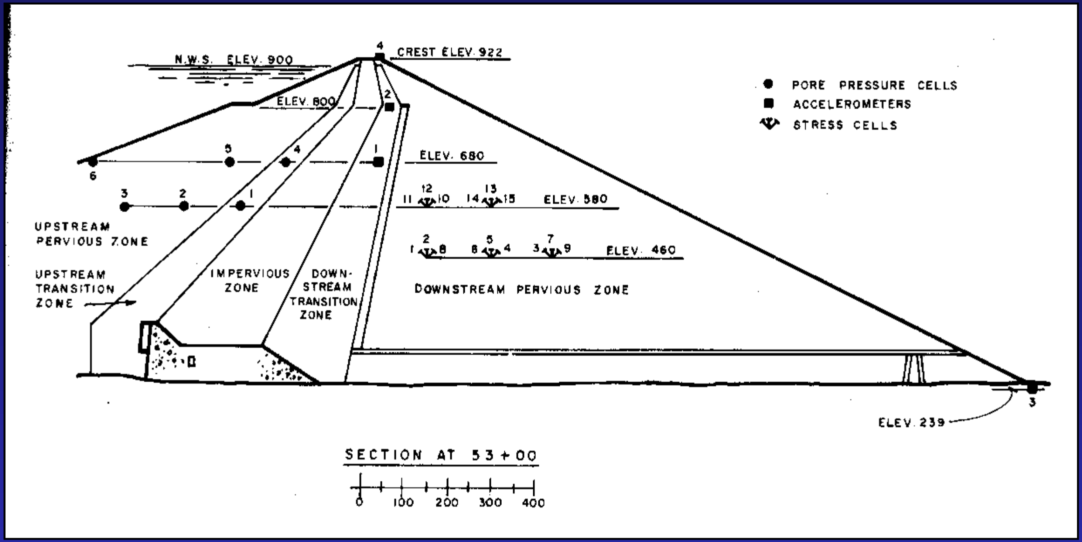


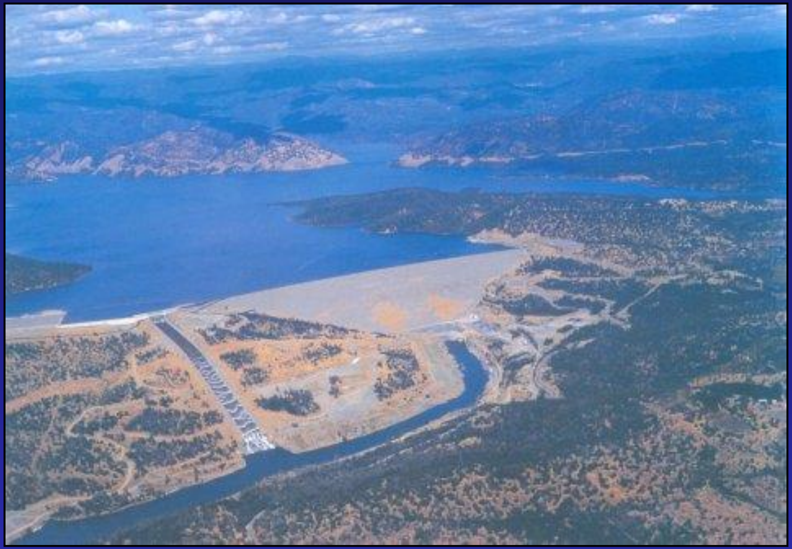

- At 635 ft high with a 2,200 ft long crest, the **New Bullards Bar Dam** is one of the largest double curvature concrete arch dams in the USA
- It was completed along the North Fork of the Yuba River in November 1969
- It was not designed for seismic loading

# HIGHEST DAM IN THE WORLD (1967)

- At 770 feet high and 5,600 feet long, Oroville Dam was the highest dam in the world when it was completed on the Feather River in 1967. It was designed by the California Department of Water Resources and included 80 million yds$^3$ of soil and rock.
- The original design concept had been a massive concrete multiple arch dam, which would have been the world's largest of that type.

# OROVILLE DAM (1967)

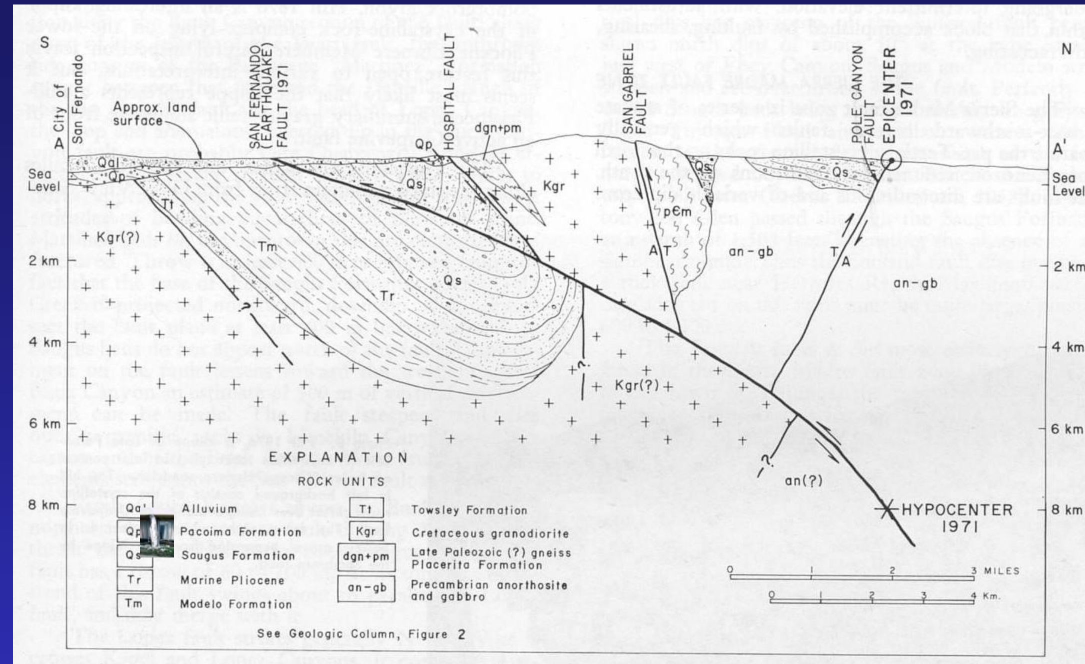


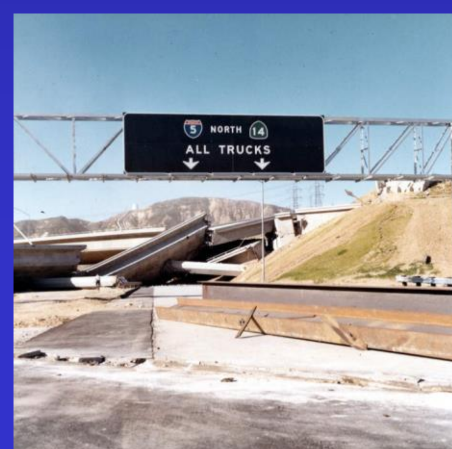
- **Oroville was the largest non-federal dam ever built in the United States.**
- **It utilized a novel concrete base core block and took advantage of coarse aggregates left over from hydraulic dredge mining, lying 5 to 7 miles downstream**
- **It was the most heavily instrumented earthen dam up to that time**

# 1971 San Fernando Earthquake

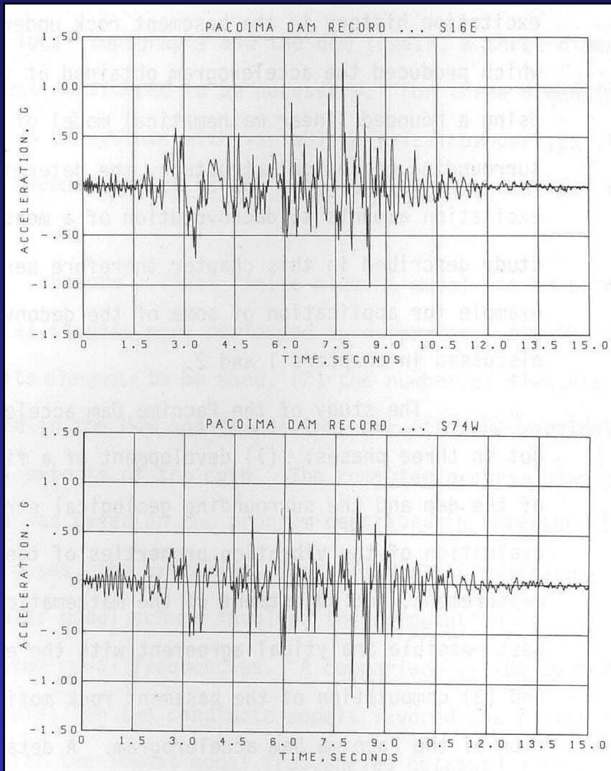
The shaking felled two hospitals, several freeway viaducts, and the Lower Van Norman Reservoir . It occurred along the San Fernando Thrust, shown at upper right.

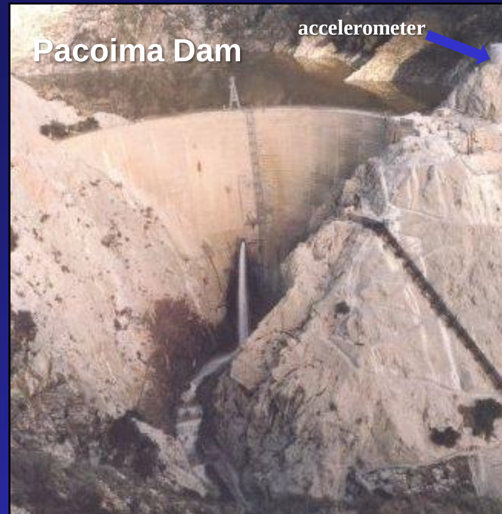


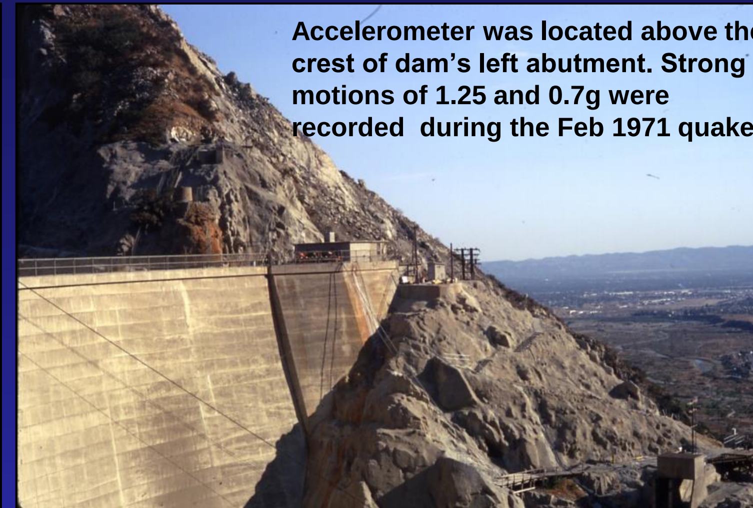

The 1971 San Fernando Earthquake occurred at 6:00 AM on February 9, 1971, with a Moment Magnitude of 6.6



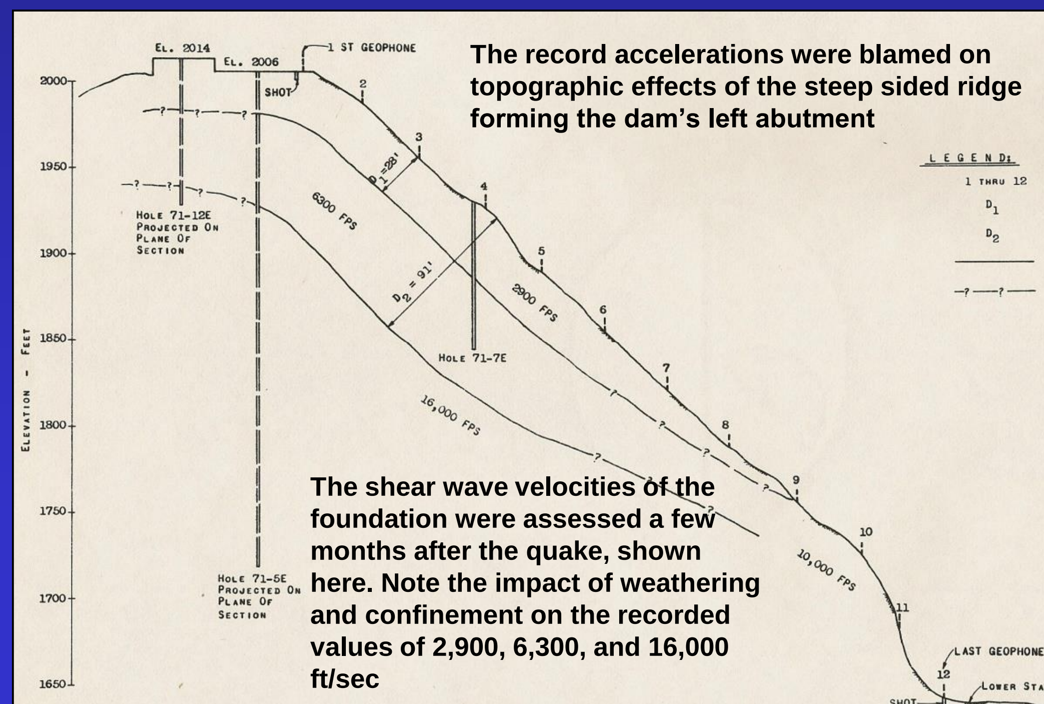

# RECORD HIGH ACCELERATIONS



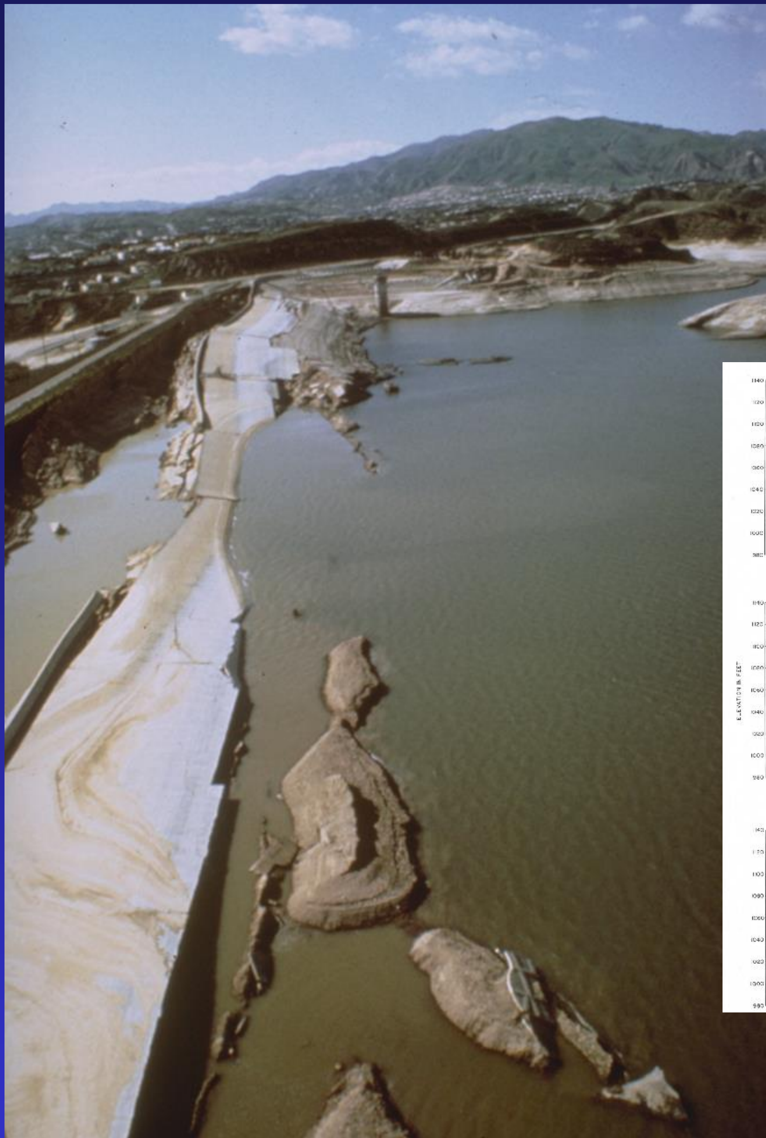




- The strong motion recorder on the left abutment of **Pacoima Dam** registered record high accelerations of **1.25g** horizontal and **0.70g** vertical during the 1971 San Fernando earthquake

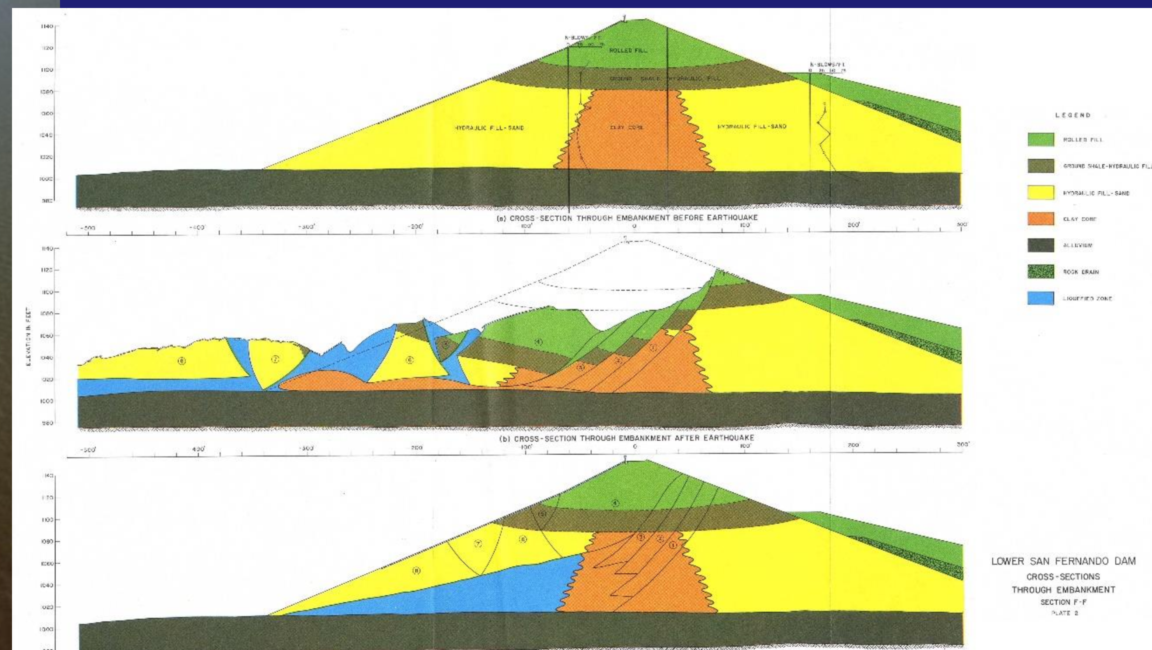


# LOWER VAN NORMAN RESERVOIR FAILURE

- **Lower San Fernando Dam** was built by the City of Los Angeles as part of the Los Angeles Aqueduct in 1916-18, using puddled hydraulic fill. A rolled fill addition seven feet high was placed in 1924-25.
- The embankment failed during the Feb 9, 1971 $M_w$ 6.7 San Fernando Earthquake, but no water was released



# LIQUEFACTION SEQUENCE




- **Careful forensic evaluations by the geotechnical engineering group at U.C. Berkeley unraveled the dam's failure by liquefaction of a zone of low density sandy hydraulic fill (shown in blue) in the above sections**
- **The State subsequently slated 59 other dams for detailed assessment of vulnerability to seismic loading, beginning in 1973.**

# Impacts of the 1971 San Fernando earthquake on dam safety

- In the wake of the Lower San Fernando Dam (Van Norman Reservoir) failure, the State Division of Safety of Dams (DSOD) joined with the Los Angeles Dept of Water & Power and the National Science Foundation to support research by Professors H.B. Seed (Berkeley) and K.L. Lee (UCLA) to determine the cause of the liquefaction. These studies were summarized in a series of articles by Seed, Lee, Idriss, and Makdisi that appeared in 1975.
- In December 1971 DSOD identified 29 hydraulic fill embankment dams in California for dynamic analyses. These dams were subsequently evaluated using the new Seed & Idriss approach.
- By 1975 DSOD requested new dynamic analyses of 59 dams, 14 of which were placed in the highest rank of urgency (six of these were already under evaluation).
- Between 1975-80 DSOD, nine more dams of the 59 were evaluated, while owners initiated reassessments of 19 more dams on their own.
- By 1983 53 of the 59 dams had undergone through reevaluations. Satisfactory performance was predicted for 28 of theses dams, eight required additional freeboard, and seven were earmarked for extensive alteration or replacement. These included: Upper and Lower San Fernando, Chatsworth, Upper San Leandro, Chabot, San Pablo, Fairmont, Lake Arrowhead, Silver Lake, Lower Franklin, Dry Canyon, and Sheffield Dams.
- Upper and Lower San Fernando, Upper San Leandro, and Lake Arrowhead were re-built; San Pablo and Chabot were retrofitted; Chatsworth and Sheffield were abandoned.

# The OROVILLE EARTHQUAKE (1975)

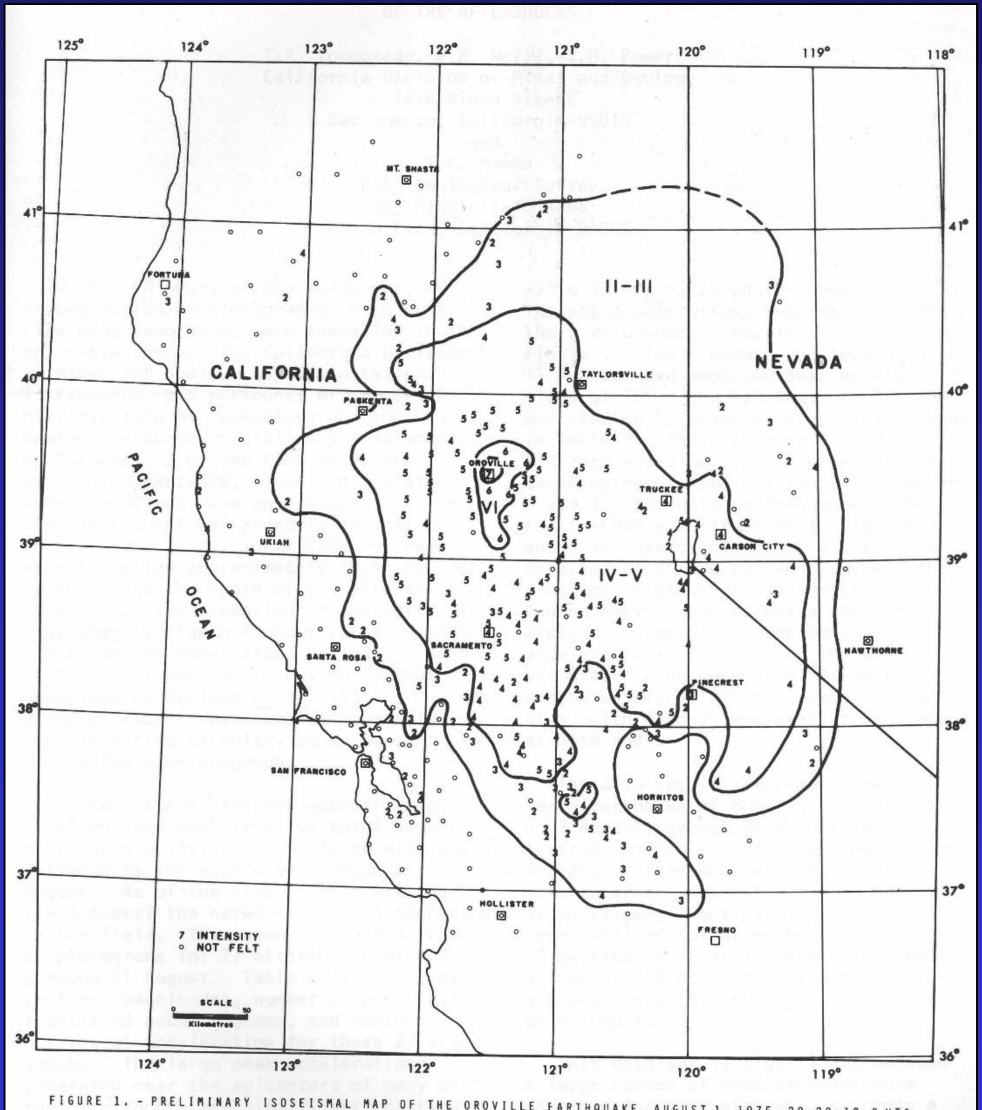
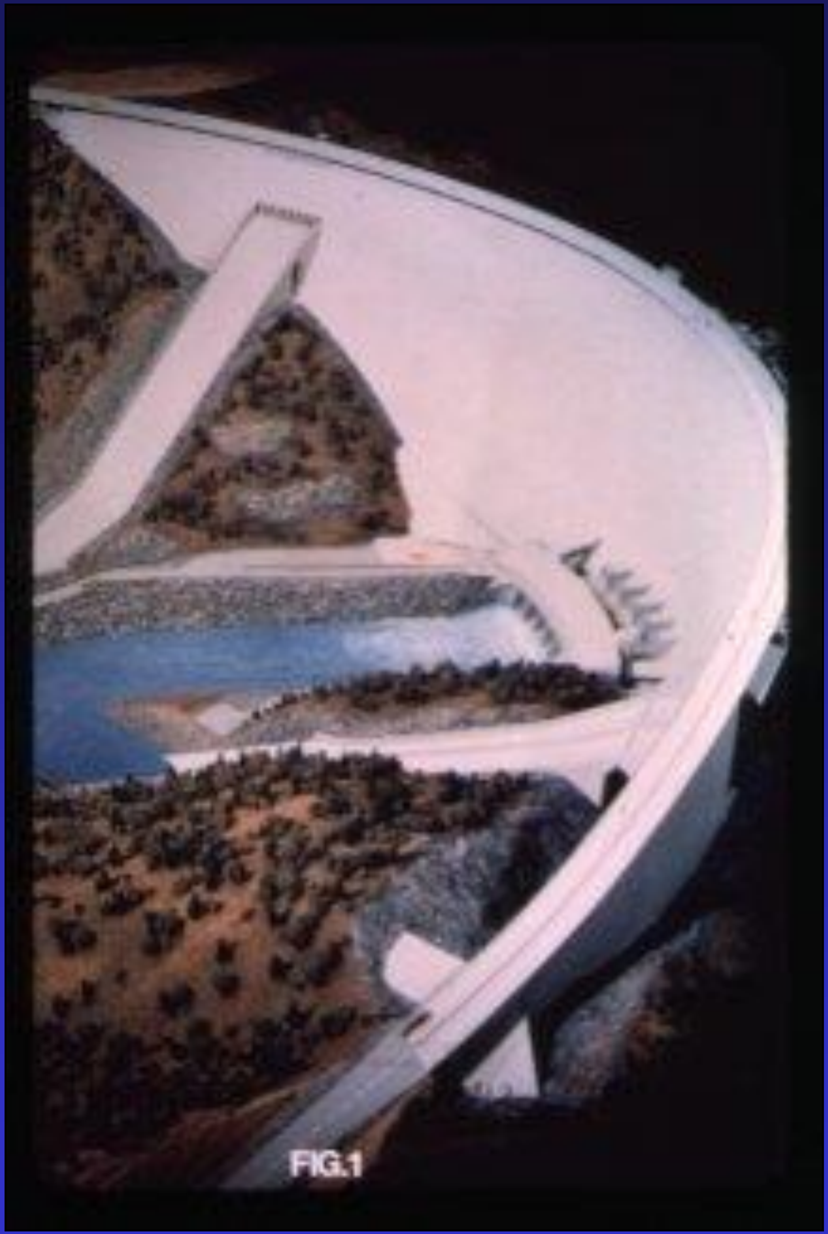



FIGURE 1. - PRELIMINARY ISOSEISMAL MAP OF THE OROVILLE EARTHQUAKE, AUGUST 1, 1975, 20:20:12.8 UTC

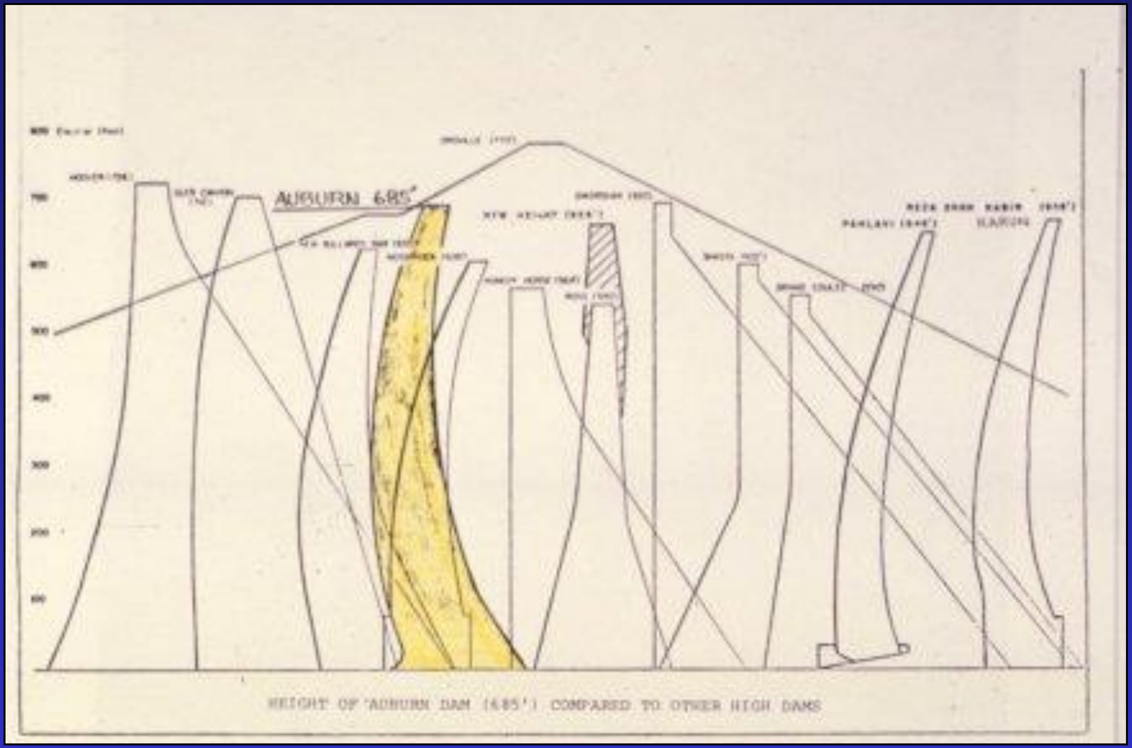
- **On August 1,1975 a $M_b$ 5.9 (later upgraded to M6.1) earthquake occurred a few miles downstream of Oroville Dam, ushering a new cognizance of seismicity in the Sierra Foothills that would significantly alter the outcome of the world’s largest three-centered arch dam, then under construction at Auburn.**




# Most controversial dam project in California

- The **Auburn Dam** was designed by the Bureau of Reclamation in the mid-1960s to be the largest three-centered thin arch dam in the world.
- It was designed assuming that the Sierra Foothills were without any active seismicity

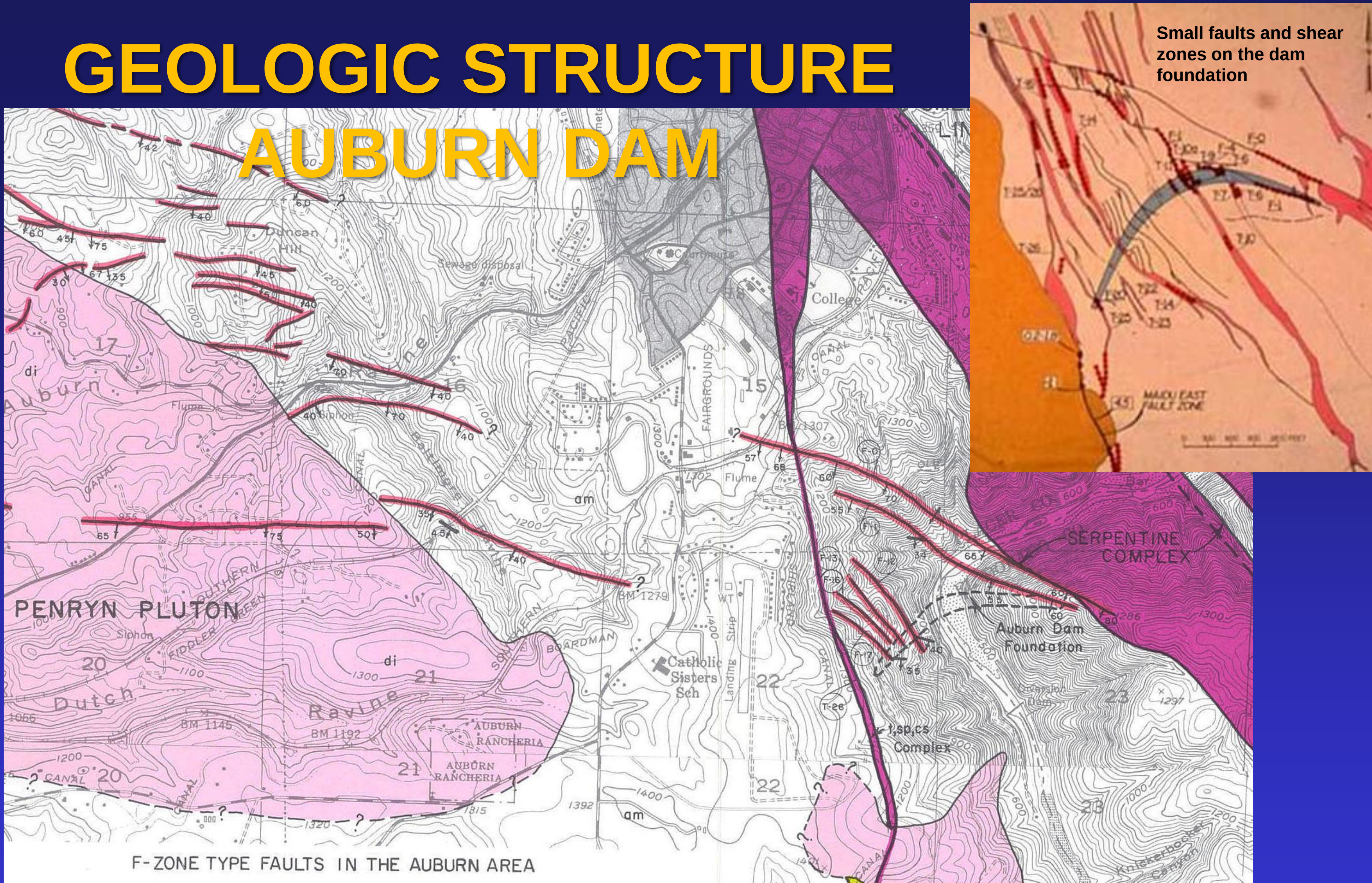
# COMPARISON OF AUBURN WITH OTHER HIGH DAMS




- **Auburn Dam was designed to be 685 feet high with a base thickness-to-height ratio of 0.285 (New Bullards Bar is 0.264), but the base thickness-to-crest length ratio was only 0.077. Only Crystal Dam in Colorado has a lower ratio.**

# GEOLOGIC STRUCTURE

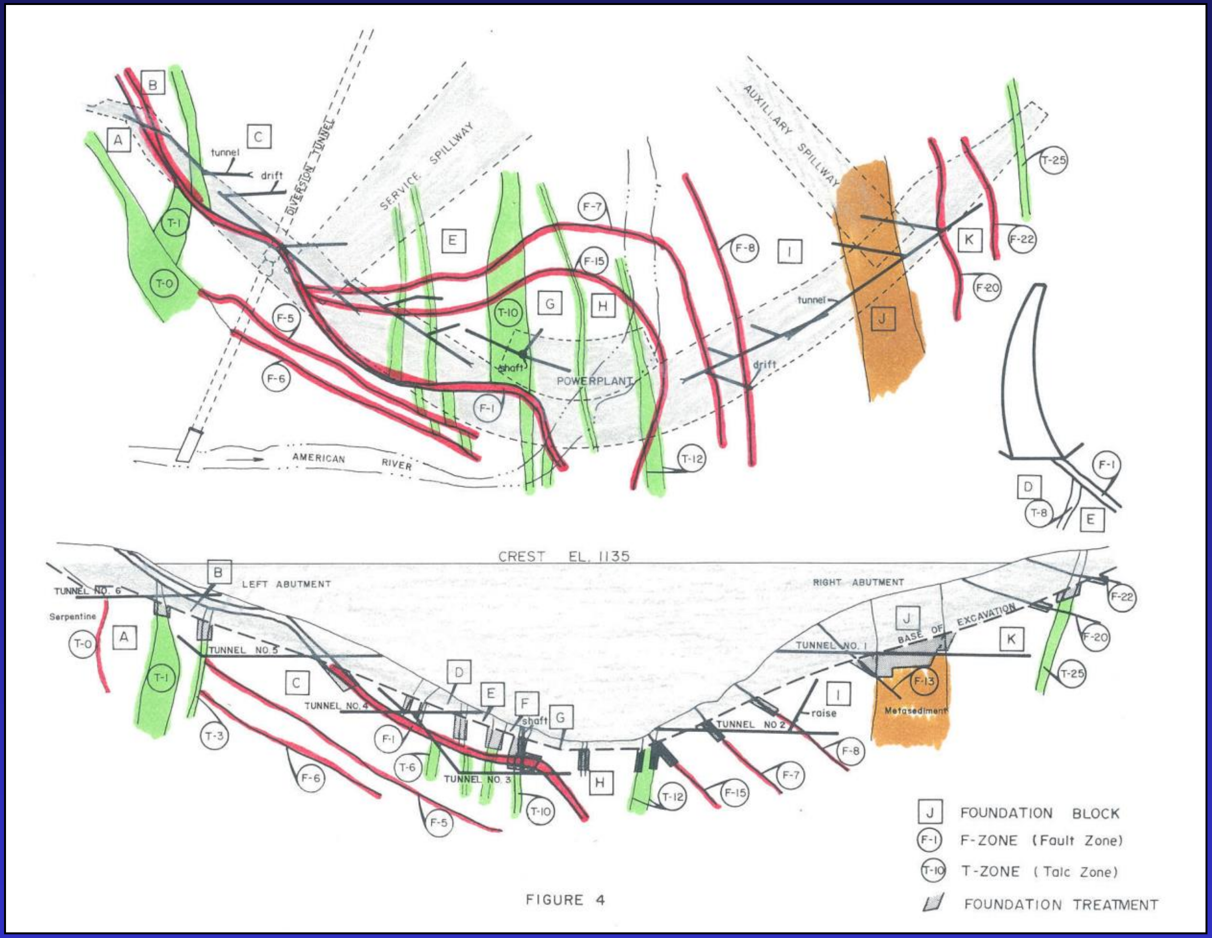
## AUBURN DAM




- The dam site sat astride a serpentine complex, a few miles east of the old Penryn Pluton, emplaced as part of the Sierra Batholith about 55 Ma. Extensional 'scissors faults' have cut the foothills area since that time.

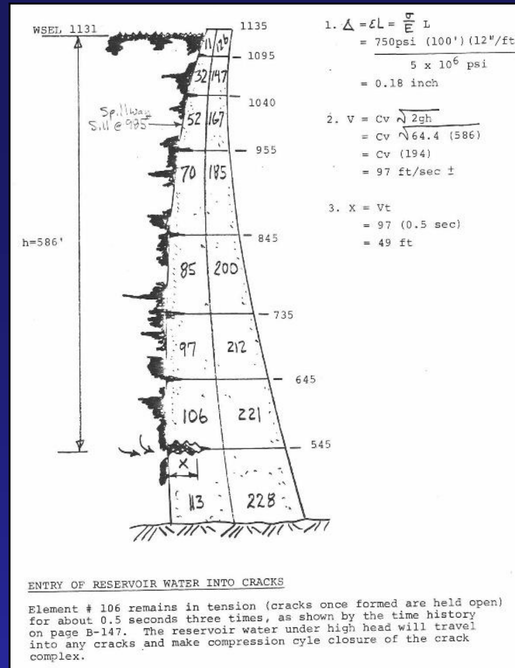
# DETAILED GEOLOGY OF DAM SITE

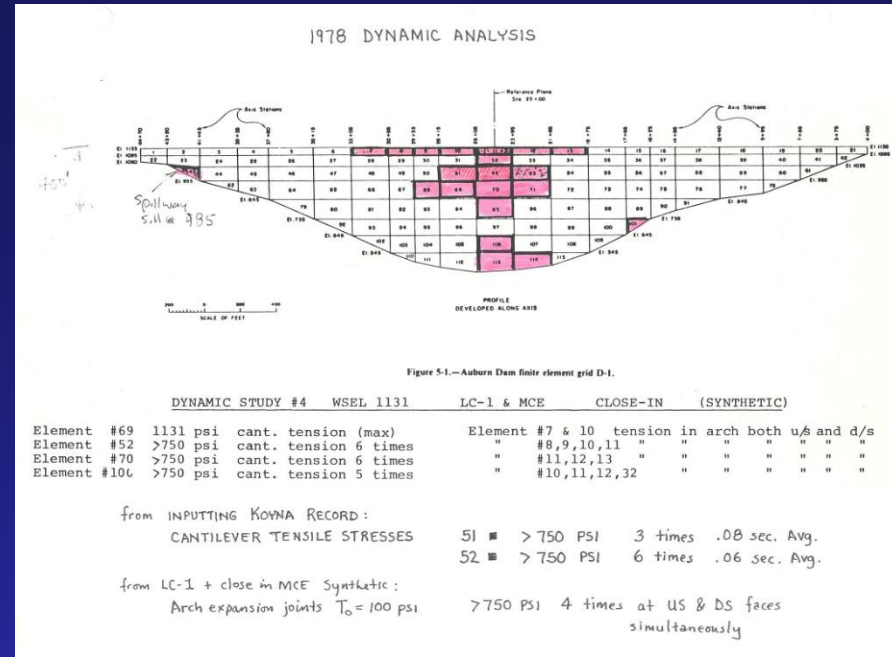

Looking at the massive keyway excavation for the dam's left abutment




- A number of old faults (red) and shear zones (green) were mapped at the Auburn Dam site during the early to mid 1970s, while the abutments were being excavated (shown at left). Subsequent analyses of these faults (many years later) showed them to be of Mesozoic age.

# AN ARMY OF ONE




Donald C. Rose, PE, CEG
(1933-2008)

- The M 6.1 quake of August 1, 1975 occurred 10 km south of Oroville Dam, dispelling the assumption that the foothills region was aseismic.
- Don Rose was an engineering geologist and structural engineer who was Vice President of Tudor Engineers in San Francisco. After the M 6.1 Lake Oroville earthquake in 1975, he published an article demonstrating that the proposed Auburn Dam was likely vulnerable to earthquake shaking.
- In May 1976 the Bureau of Reclamation agreed to undertake a more thorough investigation of the region's seismicity, hiring Woodward Clyde Consultants to perform a $4 million study. The dam was cancelled three years later.

# AUBURN COFFERDAM FAILURE

- A 207 feet high earthfill embankment cofferdam was constructed upstream of the Auburn Dam site in 1973-74
- A 33 ft diameter diversion tunnel was completed in 1971 with a maximum capacity of 74,000 cfs (photo R. Christopherson, American River College)

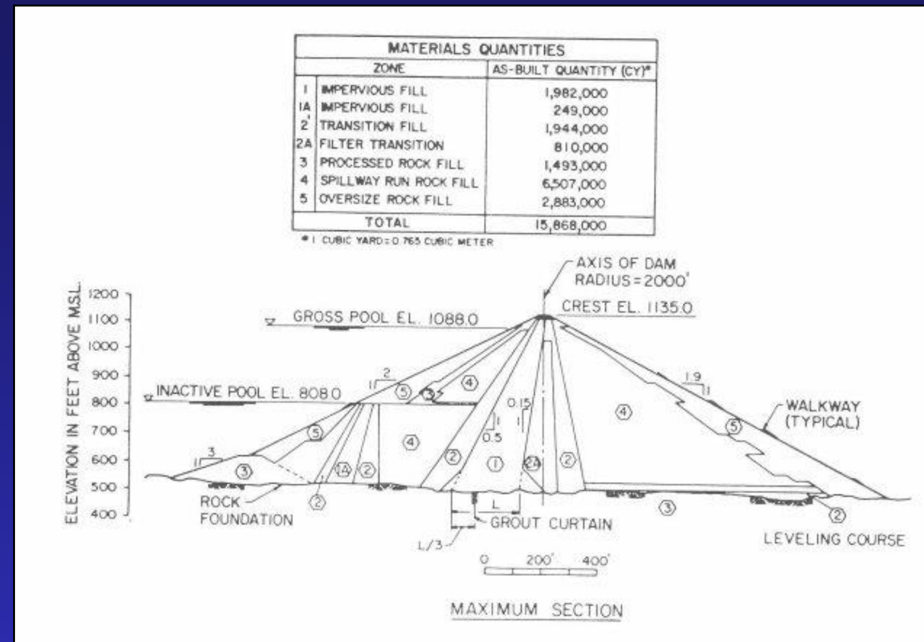
- In the early morning hours of February 18, 1986 the lake impounded by the cofferdam began rising 10 feet per hour, and began overtopping the right abutment area around 9 AM, when this picture was taken (photo by Robert Christopherson).

- **View of the cofferdam breach around noon on Feb 18th, when the outflow exceeded 100,000 cfs, forcing Folsom Reservoir (downstream) to begin releasing 130,000 cfs; 15,000 cfs beyond the downstream levee capacity** **(Photo by Robert Christopherson)**

- By early afternoon the flood peaked around 250,000 cfs, with a flow depth of 50 feet (shown here). By 4 PM the surge leveled out and the diversion tunnel was able to accommodate the incoming channel flow (Photo by Robert Christopherson)

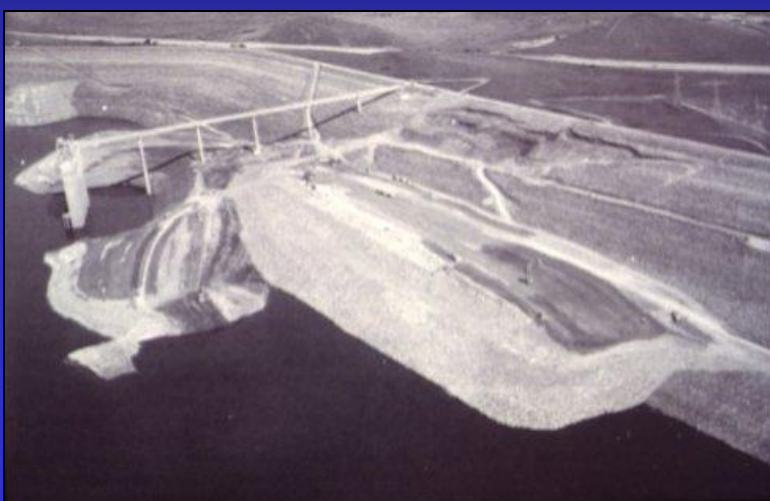

- Remains of the Auburn cofferdam after the Feb 18, 1986 failure. Two million cubic yards of material were eroded, excavating 25 feet beneath the original foundation, into metamorphic rock. The outbreak channel was filled with sediment to depths of between 20 and 100 feet.

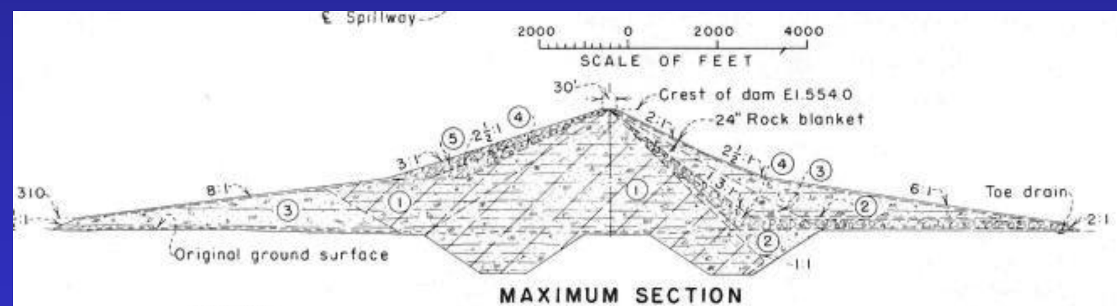
# END OF THE BIG DAMS ERA




- In 1974-75 the State of California fought the U.S. Corps of Engineers over the building of **New Melones Dam** on the Stanislaus River. The feds won, but the fight signaled the end of the dam building era in California
- New Melones, a towering 607 ft high rockfill, was completed in November 1978, shortly after New Exchequer and New Don Pedro Dams.

# UPSTREAM SHELL FAILURE of SAN LUIS DAM (1981)






- In September 1981 a 1,700 ft long slide occurred in the upstream face of San Luis Dam, involving 1.4 million yds$^3$ of earth in the repairs.
- Overconsolidated clayey colluvium left in-place beneath the dam lost strength over a period of 14 years, because of cycling of the reservoir pool.

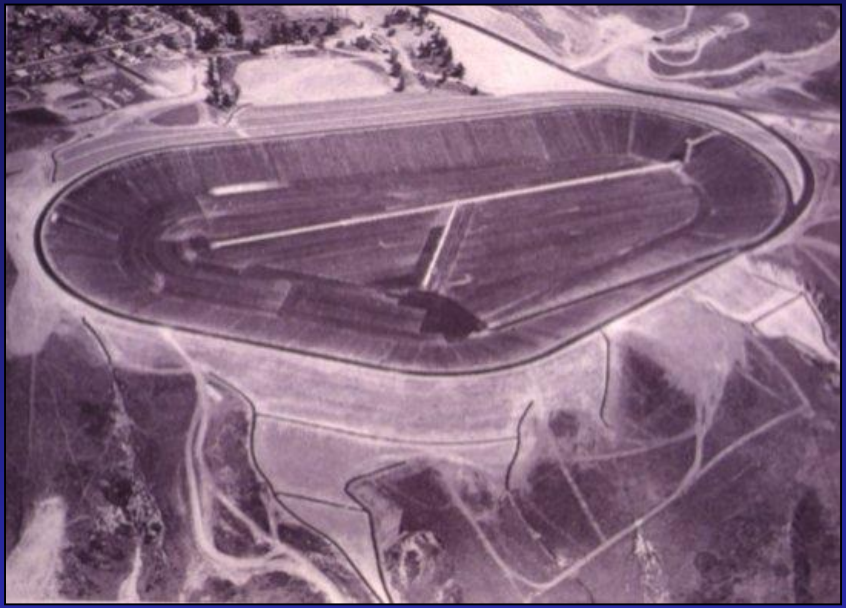
# Record flows of 1983 on the Colorado River

- These views show some of the high flows being passed through Parker Dam (above) and flooding the Buckskin Point-Colorado River State Park area, just below the dam
- The flooding was unnecessarily severe because of flawed runoff models then employed by the Bureau of Reclamation

# Record flows of 1983 on the lower Colorado River

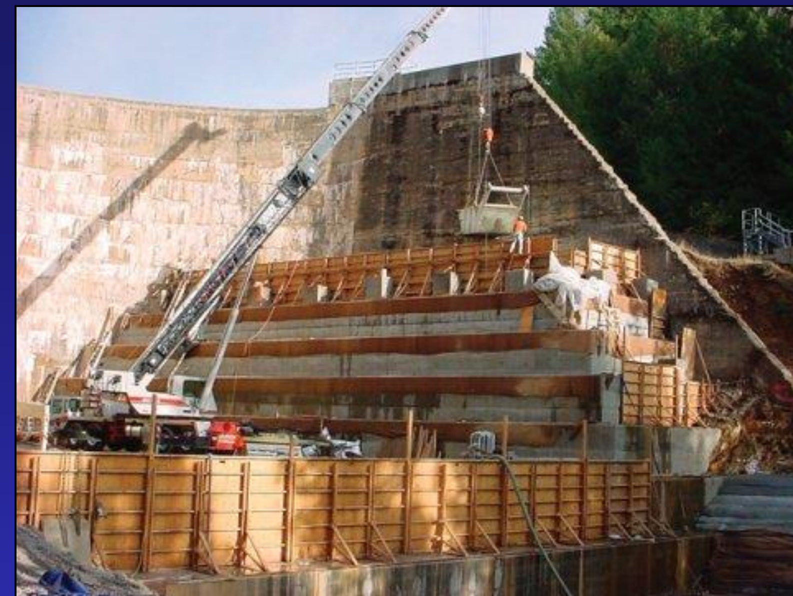
- Aerial oblique view of the high water of summer 1983 overflowing the weir of Imperial Dam for the first time since the dam’s completion in 1942
- Lower image shows inundation of vacation homes along the river in the Palo Verde Valley, near Blythe.

# GARVEY RESERVOIR 1954-1988



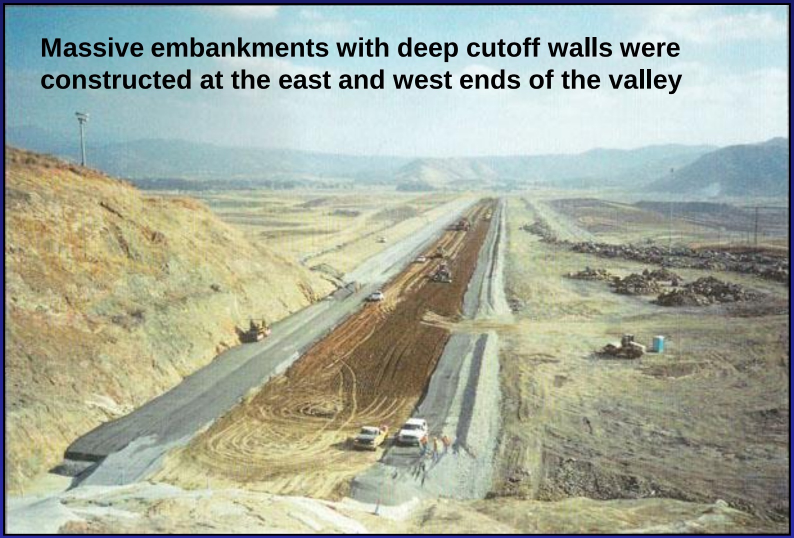
- Garvey Reservoir was designed and built by the Metropolitan Water District in 1952-54 as an offstream storage reservoir. The embankments were up to160 ft high and involved 3 million $yds^3$ of grading on marine sandstones of the Repetto Formation of lower Pliocene age, in the Repetto Hills in Monterey Park, just east of downtown Los Angeles.
- The reservoir was shaken during the Whittier Narrows earthquakes on Oct. 1st ($M_L$ 5.9) and 4th, 1987 ($M_L$ 5.6). Piping leaks extended up into the lined reservoir floor, through openwork gravels, resulting in sand boils forming in the yards of homes constructed below the southern side of the facility. This was the first time hydraulic piping had proliferated beneath a continuous Hypalon reservoir liner.
- After several investigations, the State DSOD has refused to permit refilling and the reservoir is presently empty.

# RETROFIT of EXISTING DAMS



- **Webber Creek Dam** is typical of many older structures across California. A multiple arch structure built in 1923-24, it was retrofitted in 2000-02 to increase seismic stability using **rolcrete technology**: a dry mix of concrete placed like compacted earth, which becomes stronger as it cures.

# Diamond Valley Lake (largest offstream reservoir in the world)



Massive embankments with deep cutoff walls were constructed at the east and west ends of the valley

The **Eastside Reservoir Project** was constructed by the Metropolitan Water District between 1995-99 in the Domenigoni Valley, just south of Hemet. The reservoir is named **Diamond Valley Lake**.

It forms the largest reservoir in Southern California, with a capacity of 800,000 ac-ft. This is intended to provide a six month supply of water for MWD's 17 million customers, almost doubling the agency's previous storage capacity.

Colorado River water is pumped into the reservoir from MWD's San Diego Canal, seen in the foreground

- The project's three dams, the longest of which extends more than two miles, required an embankment volume of more than 110 million cubic yards of earth and rock.
- The dams were completed in December 1999, requiring excavation of 40.5 million cubic yards of foundation material at a cost of $1.9 billion.
- It took three years to fill the 4,500-acre reservoir with water from the Colorado, Feather, and Sacramento Rivers.

# THE LAST BIG DAM ?

- **Seven Oaks Dam**, 550 ft tall and 37.6 million yds$^3$, was completed in November 1999. It was designed by the Corps of Engineers and funded in 1986, following 20 years of environmental studies and legal battles.
- It is located along the upper Santa Ana River adjacent to the north trace of the San Andreas fault, near Mentone, CA