IMPACTS OF THE 1928 ST. FRANCIS DAM FAILURE ON GEOLOGY, CIVIL ENGINEERING, AND AMERICA

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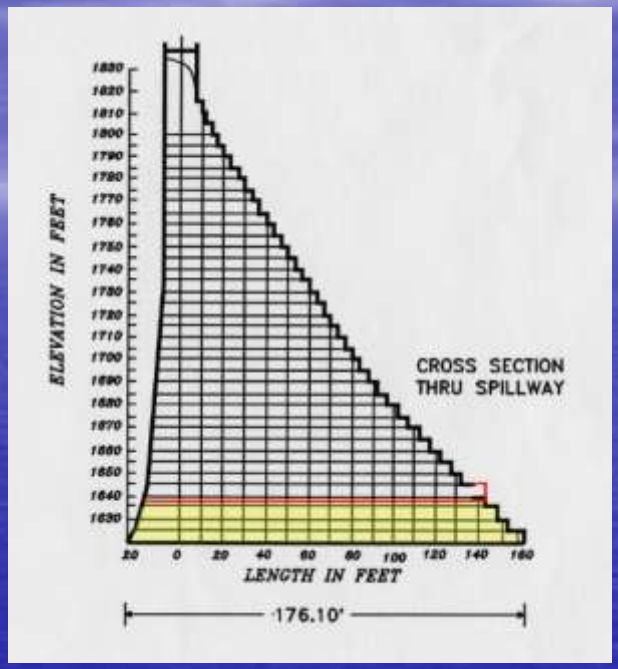
MISSOURI S&T University of Science & Technology

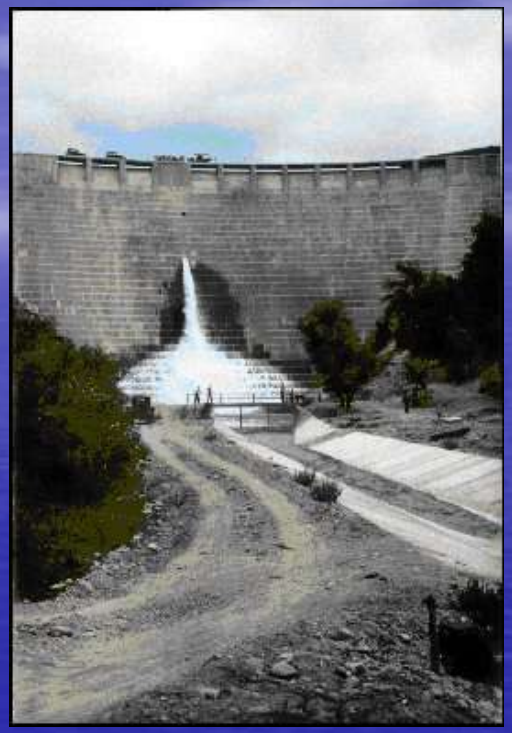
ENVIRONMENTAL ENGINEERING AEG GEOLOGISTS

ST. FRANCIS DAM (1926)



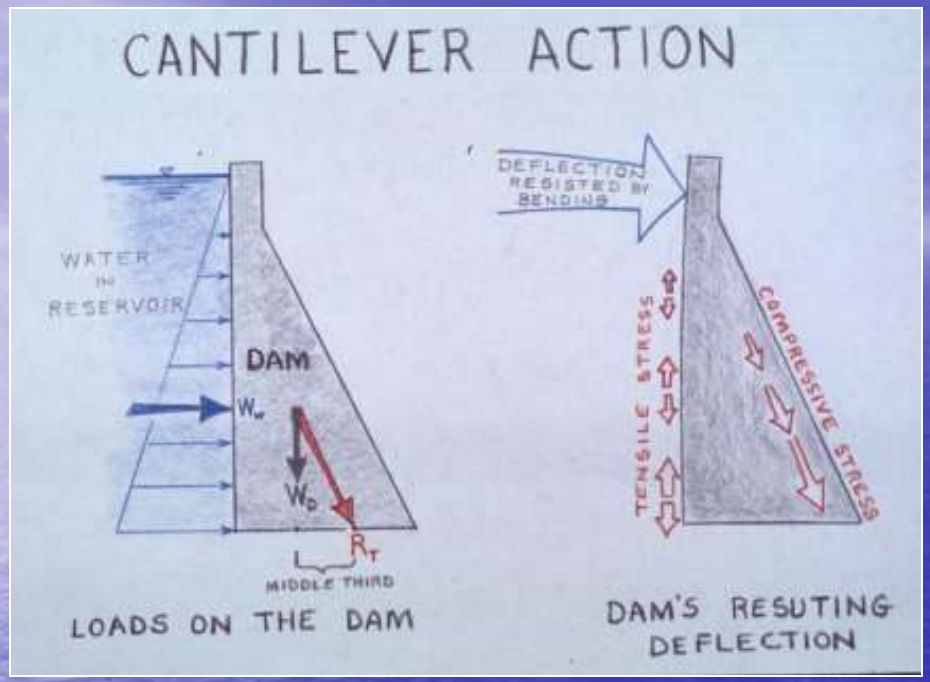
- **St. Francis Dam** was designed and built by the City of Los Angeles in 1924-26, to contain a year's water supply for the city south of the San Andreas fault
- The dam was designed as a curved concrete gravity dam 185 feet high because there was no clayey material on site to construct an earthen embankment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

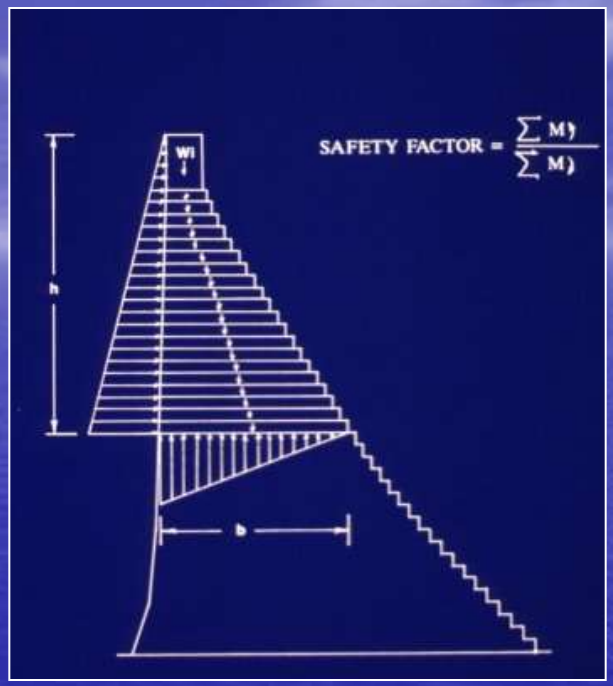
FATEFUL DESIGN CHANGES



- While under construction, the population of Los Angeles was increasing dramatically
- In order to increase reservoir storage, it was decided to raise the dam 10 feet on two occasions, raising the dam's height by 11% without any compensatory increase in base width
- This resulted in a dam 205 feet high with storage of 38,160 acre-feet

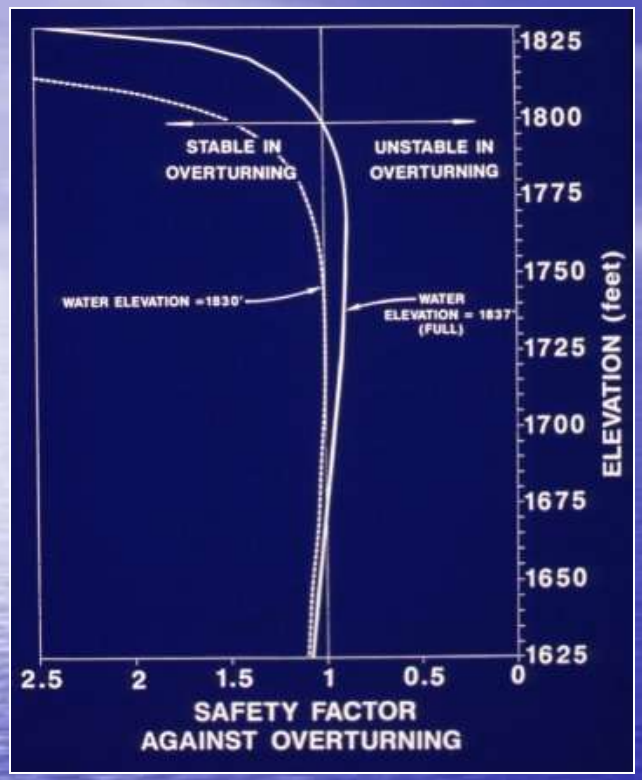
CANTILEVER FORCES

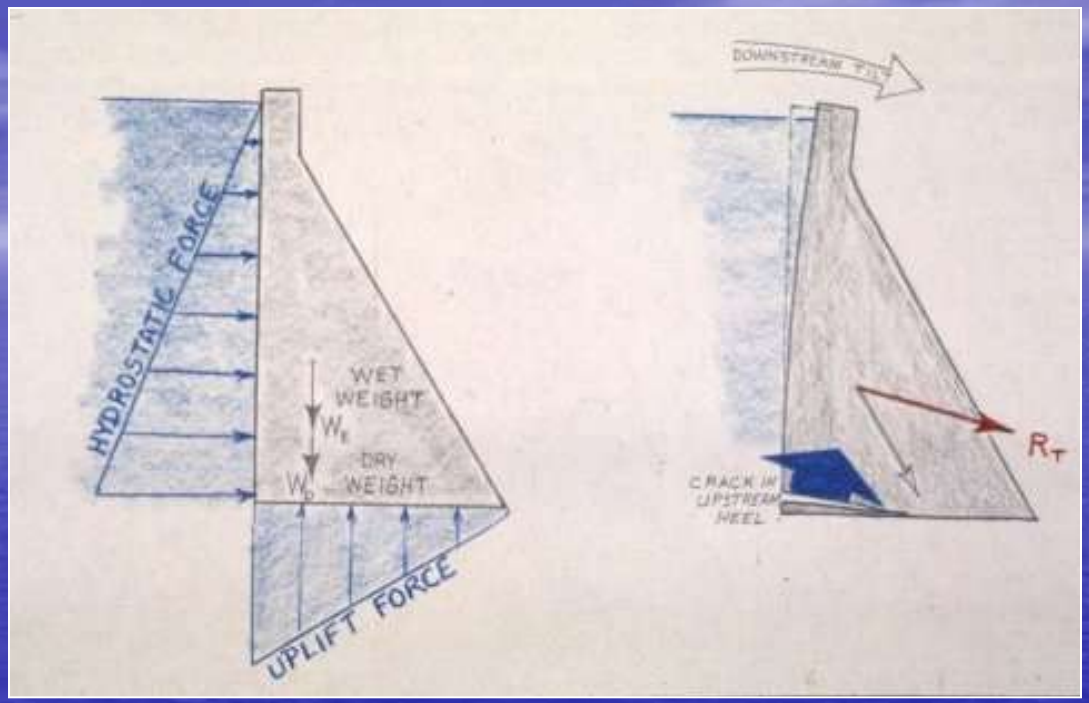




- **St. Francis Dam** was a gravity structure, deriving its stability from its dead weight.
- The ratio between the dead load acting vertically and the hydrostatic force acting horizontally determines the overturning factor of safety

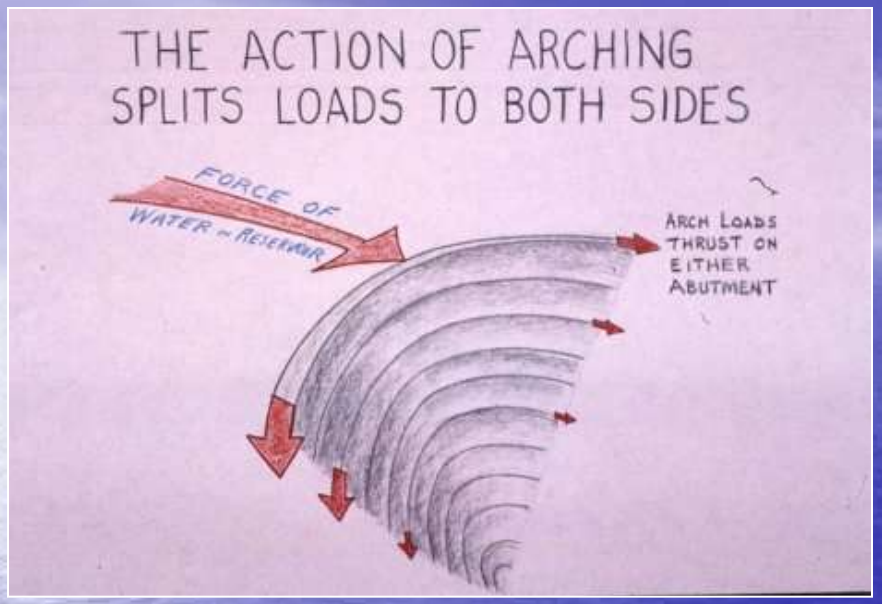
UNSTABLE IN OVERTURNING

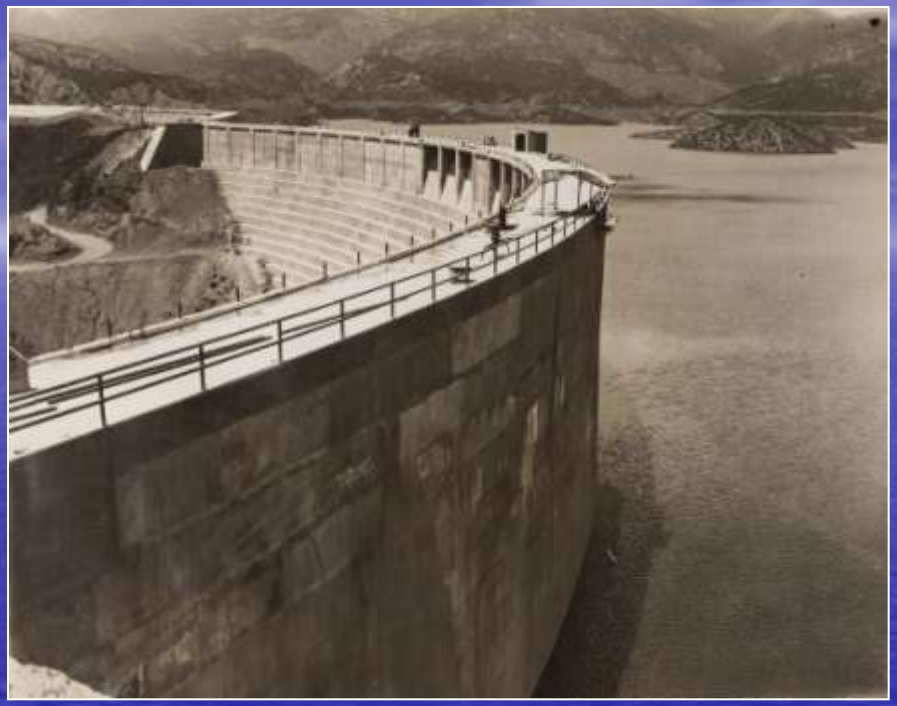




- Modern analyses reveal that when the reservoir rose within 5 feet of spillway crest, the dam became unstable
- A crack could then developed in the upstream heel
- A ***heel crack***, such as that found after the failure, shown at lower right, would shift the resultant thrust far downstream, making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

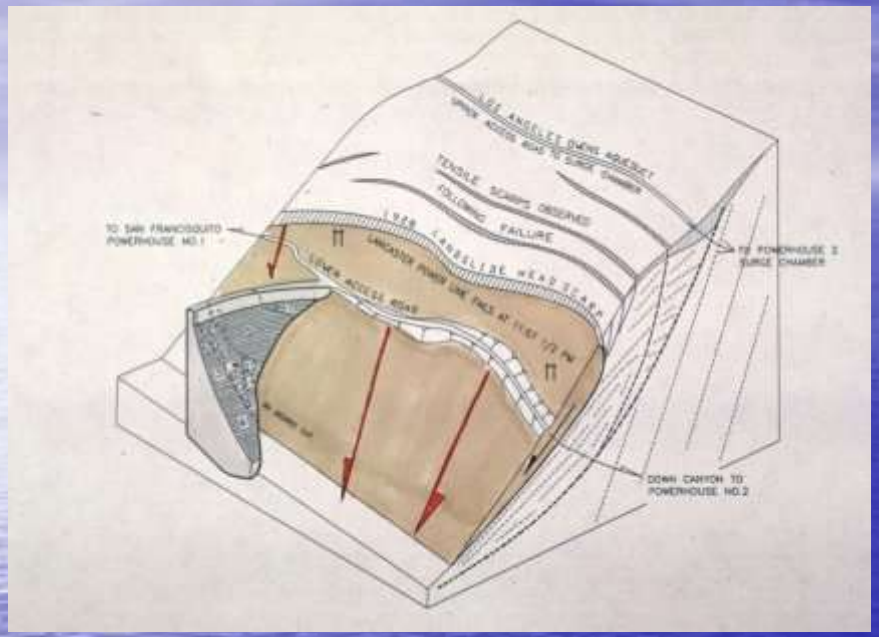
CONTRIBUTION OF ARCHED SHAPE





- **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

Inquiries and demands for justice

- A flood wave 140 ft deep swept down the canyon, killing at least 420; of which 179 bodies were never recovered
- 13 different panels investigated the St Francis failure
- Most blamed the failure on hydraulic piping along the inactive *San Francisquito fault* beneath the dam's right abutment
- The City of Los Angeles paid out $14 million in damages

BENEFITS THAT CAME FROM THE ST. FRANCIS TRAGEDY-1

- Engineering geologic input on dams became commonplace in the 1930s (it had been all but absent in the 1920s).
- Review of all federal dams
- Increased dam safety legislation in California
- Professional engineering registration
- State-mandated arbitration hearings for victims of natural disasters

BENEFITS THAT CAME FROM THE ST. FRANCIS TRAGEDY-2

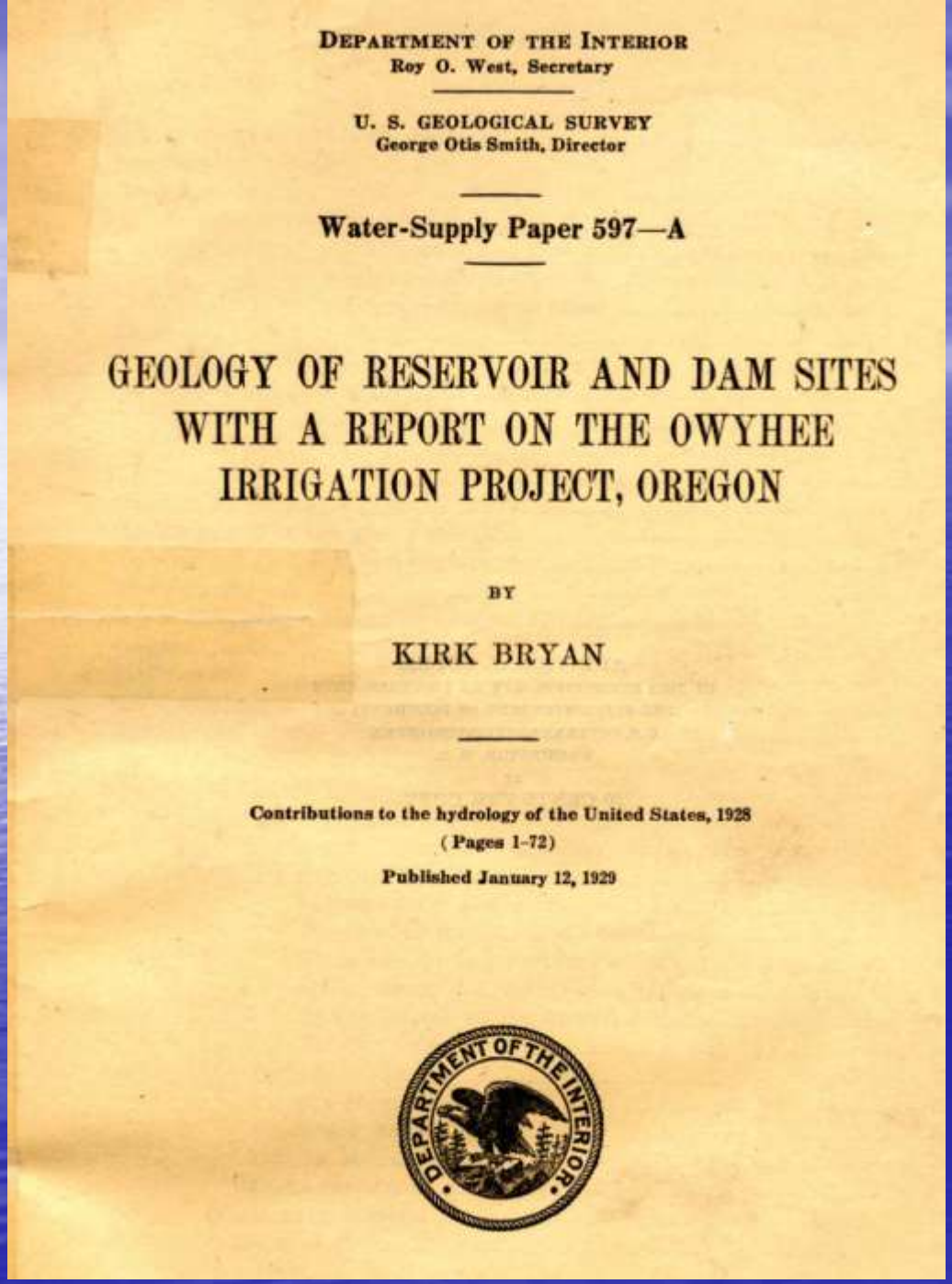
- Impact on passage of the Boulder Canyon Project Act and the design of Hoover Dam
- AIME and ASCE conferences on foundations for high dams
- Increased awareness of uplift theory and effective stress
- State review of San Gabriel Dam at The Forks
- Retrofit of Mulholland Dam
- External Peer Review and the Proctor Compaction Test

State-mandated arbitration hearings for victims of natural disasters

- Thousands of wrongful death lawsuits were filed against the City of Los Angeles following the St. Francis failure
- The State enacted special legislation to adjudicate financial compensation of the victim's surviving next-of-kin, omitting compensation to attorneys.
- A council of 14 arbitrators was selected from Los Angeles and Ventura Counties, who used established methods of estimating remaining life worth and made compensatory awards to the legitimate survivors.
- This legislation was used by the State Attorney General's Office to effect a reasonable process for compensating victims of natural disasters seeking damages for personal injuries, wrongful death, pain and suffering, etc., because of failures of state-owned facilities or equipment.
- It has been used several times, including: the 1955 and 1964 floods in northern California, and the 1989 Loma Prieta earthquake.

Review of All federal dams

- Soon after St. Francis Dam failed, the federal government ordered a through safety inspection and review of all their dams; due to the public outcry



DEPARTMENT OF THE INTERIOR
Roy O. West, Secretary

U. S. GEOLOGICAL SURVEY
George Otis Smith, Director

Water-Supply Paper 597—A

GEOLOGY OF RESERVOIR AND DAM SITES WITH A REPORT ON THE OWYHEE IRRIGATION PROJECT, OREGON

BY

KIRK BRYAN

Contributions to the hydrology of the United States, 1928
(Pages 1-72)
Published January 12, 1929

DEPARTMENT OF THE INTERIOR

Establishing Standards

- **The U.S. Bureau of Reclamation hired Prof. Kirk Bryan to prepare a document entitled: *"Geology of Reservoir and Dam Sites," which was published in 1928 as* U.S. Geological Survey Water Supply Paper 597-A.**

ENVIRONMENTAL ENGINEERING AEG GEOLOGISTS

Engineering Geologic Input became mandatory for all high dams

- The Bureau of Reclamation hired Dr. Frank A. Nickel in 1931 as their first full-time engineering geologist, to work at Hoover Dam
- The Corps of Engineers hired E.B. Burwell, Jr. as their first engineering geologist in 1931
- In 1933 the Tennessee Valley Authority hired their first engineering geologist
- In 1934 the California Division of Water Resources was established, hiring a staff of five engineering geologists (which grew to 134 by 1968)

In 1928 the Metropolitan Water District hired Prof. Leslie Ransome of Cal Tech to advise them in planning their 241-mile long Colorado River Aqueduct across the Mojave Desert

The aqueduct included 92 miles of tunnel and was constructed between 1934-37

The American Society of Civil Engineers convened a special Symposium on High Dams at their annual meeting in San Diego in October 1928

- *Past Experiences with High Dams and Outlook for the Future*, by A.J. Wiley

- *Classification, selection, and Adaptation of High Dams*, by D.C. Henny

1928 ASCE Symposium

- *High dams: The Viewpoint of the Geologist*, by F.L. Ransome, Esq.
- *Construction methods and Plant Layout at Coolidge Dam*, by J. G. Tripp

- The four invited papers were published in 29 pages of the 1929 ASCE Proceedings
- The four articles and the ensuing discussions occupied 102 pages of the Society's 1931 Transactions, 7% of the entire volume.
- Much of the discussions addressed the problems with St. Francis Dam

1929 AIME Symposium

- In February 1929 The American Institute of Mining and Metallurgical Engineers sponsored a technical symposia titled *Geology and Engineering for Dams and Reservoirs* at their annual meeting in New York, which was published as AIME Technical Publication 215. Nine contributions in 112 pages, including:

- Karl Terzaghi of MIT on the "*Effect of Minor Geologic Details on the Safety of Dams*"
- Charles Berkey of Columbia University on "*Responsibilities of the geologist in engineering projects*";
- Kirk Bryan of Harvard University on "*Problems involved in the geologic examination of sites for dams*"; and
- Chester Wentworth of Washington University on "*The Geology of Dam Sites*"

Hoover Dam Threatened

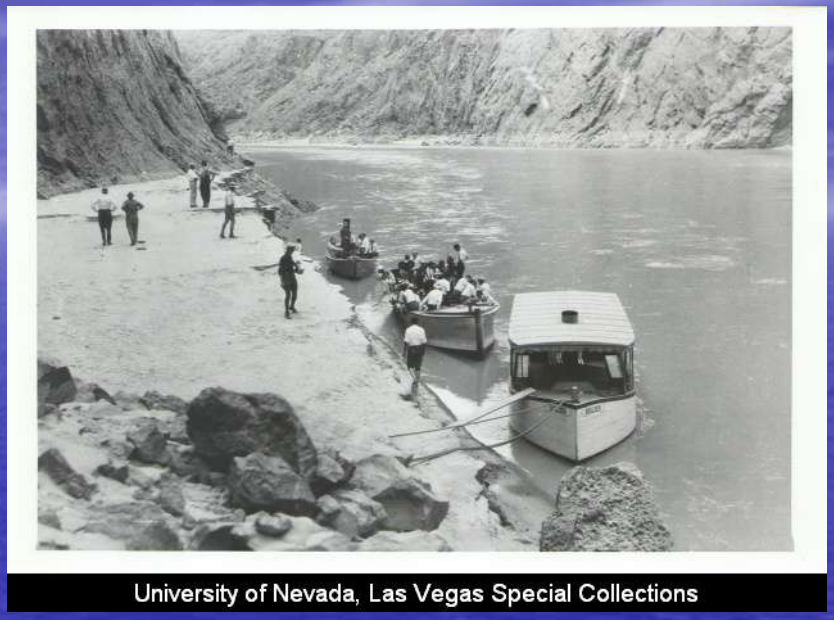
- The St. Francis Dam failure endangerd passage of the Boulder Canyon Project Act, which had been introduced in Congress twice each year since 1922.
- The Act sought $150 million to build the tallest dam ever conceived (740 feet) in Boulder Canyon.
- After years of debate, the Act passed the US House of Representatives on May 15, 1928. But, it died in the Senate after a successful filibuster by Arizona and Utah senators, who assuaged that Boulder Dam was being promoted by the "*same Los Angeles interests who brought us the St. Francis Dam catastrophe.*"
- In late May a compromise was reached. In order to placate fears about a colossal failure like St. Francis, Congress passed a joint resolution that created a Colorado River Board to review the plans of the proposed Boulder Canyon Project.

Colorado River Board Appointed in May 1928

MGEN William L. Sibert (Chair), Elwood Mead (advisor), and includes geologists Charles P. Berkey (Secretary) and Warren J. Mead; and engineers Daniel W. Mead and Robert Ridgway (note that half of the panel members were named Mead!).

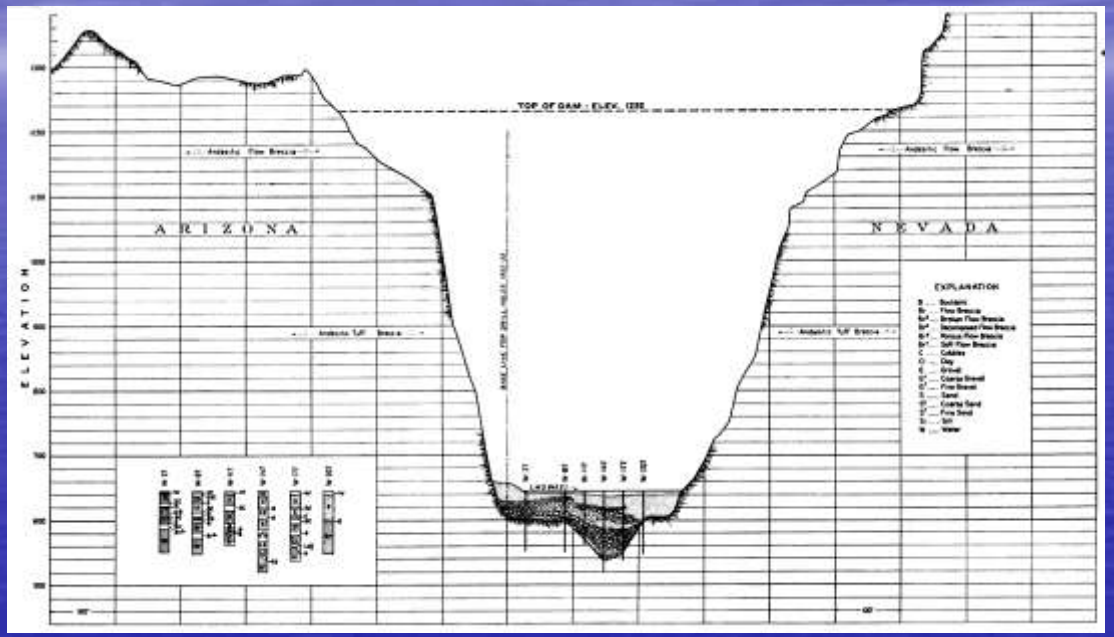
Board investigates dam sites

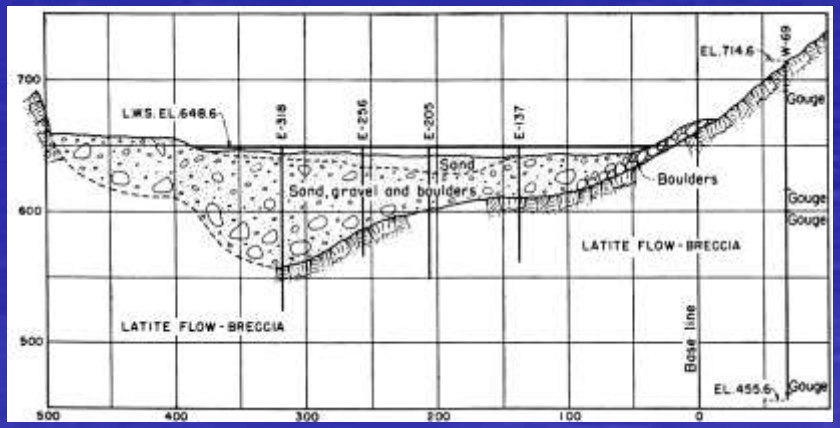
University of Nevada, Las Vegas Special Collections



University of Nevada, Las Vegas Special Collections

Colorado River Board chooses Black Canyon site in Nov 1928





The CRB recommended important changes:

- Build the dam in Black Canyon instead of Boulder Canyon, at the position chosen by engineering geologist Homer Hamlin in 1920.
- Reduce foundation contact pressure from 40 tons per square foot (tsf) to 30 tsf;
- Increase capacity of river bypass diversion tunnels from 100,000 cfs to at least 200,000 cfs (25 yr flood);
- Spillway capacity should be > 110,00 cfs;
- Increase volume of flood storage;
- All-American Canal can be built north of the Mexican border; and
- Electricity generated by dam could be absorbed by the expanding market of greater Los Angeles.
- These additions increased the projected cost to $165 million, of which, $48.7 million was earmarked for construction of Hoover Dam

CALAIFORNIA 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 was given full authority to supervise the maintenance and operation of all non-federal dams

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

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.

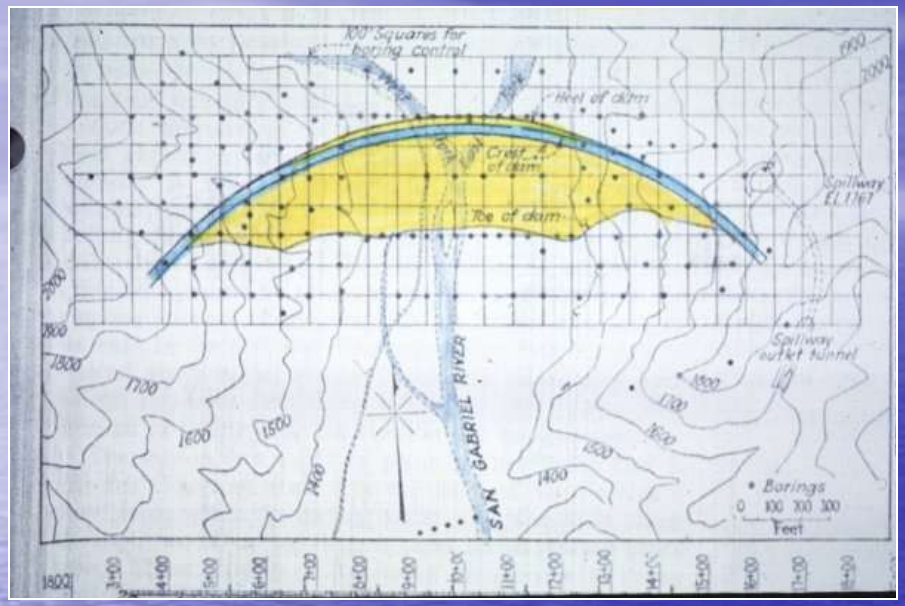
Professional engineering registration

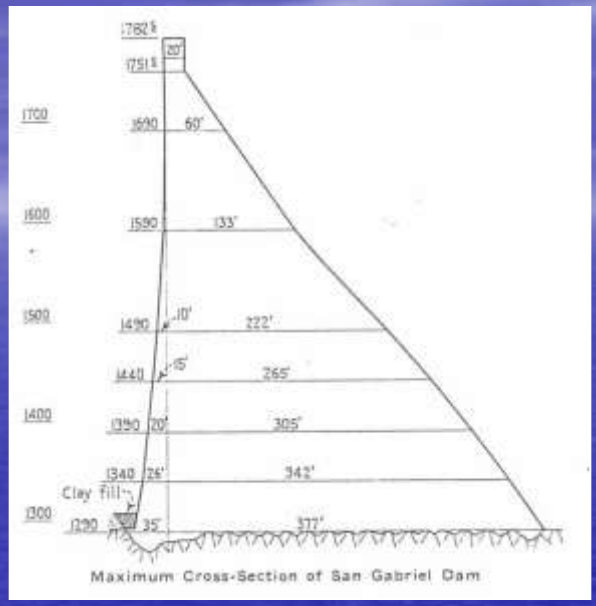
- The **Civil Engineers Registration Bill** sailed through the state legislature in early July 1929 and became law on August 14th, even though it was opposed by a number of professional organizations, such as the American Institute of Mining Engineers and the American Society of Mechanical Engineers.
- The act defined civil engineering and mandated that any person who practices or offers to practice civil engineering in any of its branches must be registered, and created **The Board of Registration for Civil Engineers**.
- The act also directed that civil engineers in state service must be duly registered if they served in a capacity of 'Assistant Engineer" or higher.
- The **California Supreme Court** quickly issued rulings that a contract for engineering services was invalid if the party undertaking to furnish engineering services was not registered.

One PE for every 1,000 people!

- **5,700 individuals** applied for civil engineering registration during the first year applications were accepted, more than double what the state board had expected. Grandfathering was allowed for 10 months, until June 30, 1930
- After **June 30, 1930** new applicants were required to take a written examination.
- Many of those who applied for grandfathering were asked to appear before the three man board (appointed by the governor) for oral interviews, to ascertain if they had entered the profession through the labour ranks of construction
- Of those who applied the first year, slightly more than 5,000 were accepted, providing the State of California with about **one registered engineer for every 1,000 people then living in the state!**

SAN GABRIEL DAM at THE FORKS SITE

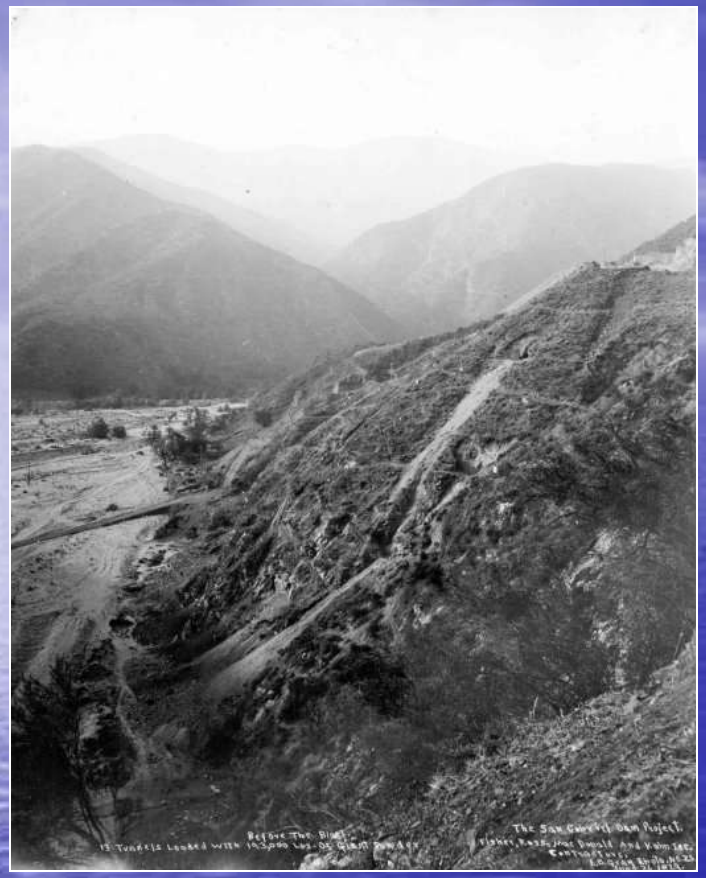




- A $26 million bond was approved by voters in LA Co in 1924 for construction of flood control structures
- The kingpin feature of this program was the **San Gabriel Dam**, a concrete gravity arch dam 512 feet high and 2,500 ft long, with volume of 3.8 million yds^3
- When designed in 1927-28 it was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

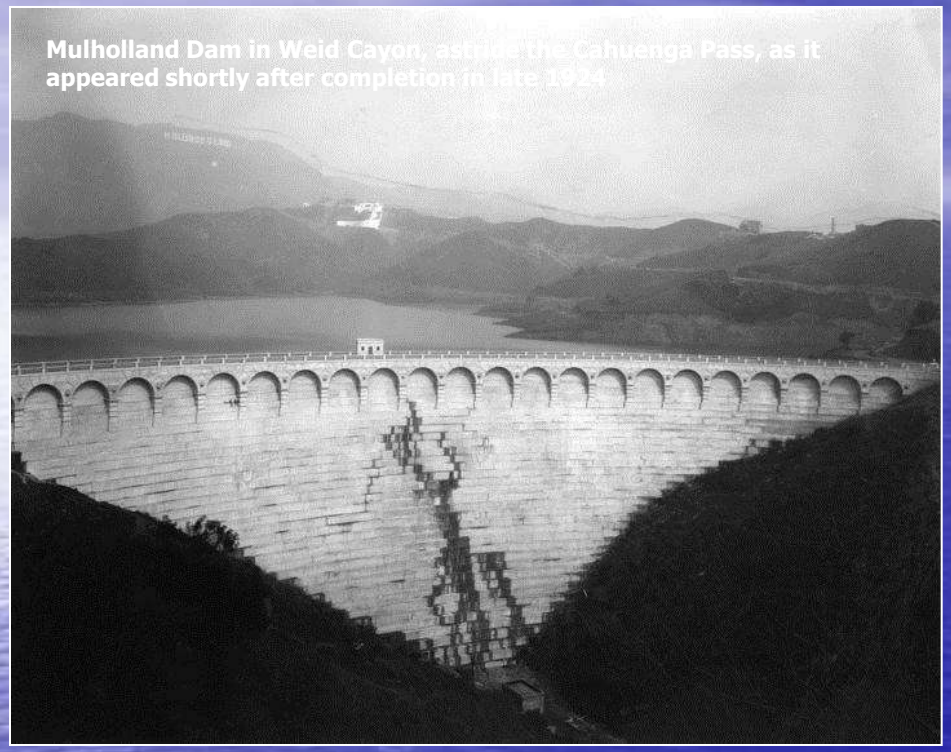
FIRST DAM CANCELLED BY THE STATE

- 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 26th 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

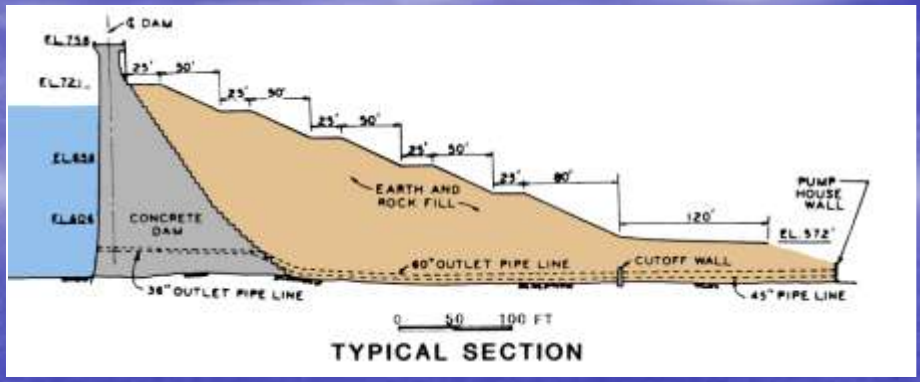
MULHOLLAND DAM DILEMMA


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

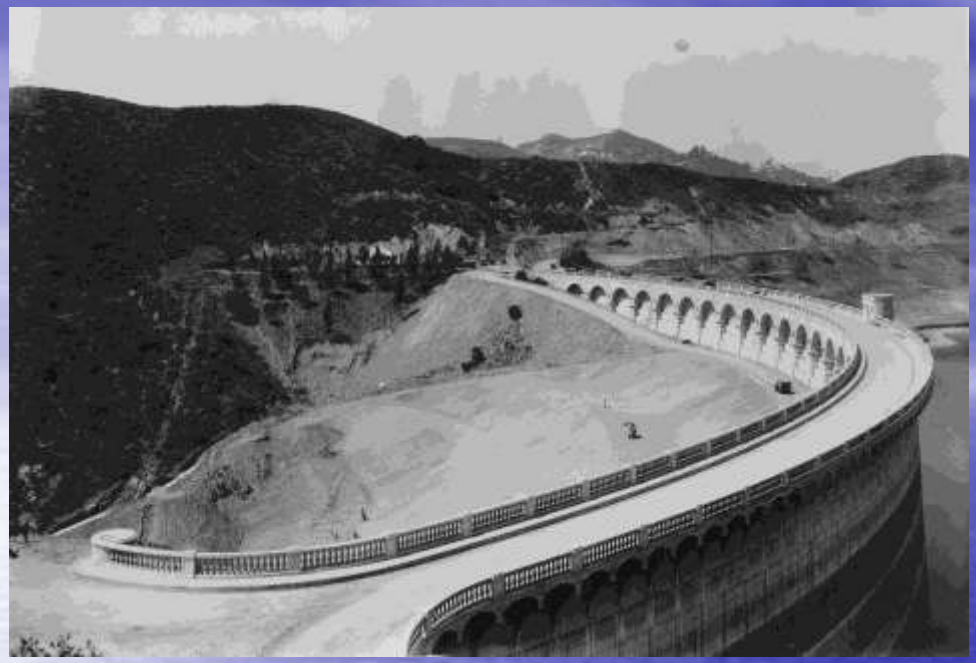


TYPICAL SECTION

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**

EXTERNAL PEER REVIEW

- **Bouquet Canyon Reservoir** was the replacement structure for St. Francis Dam. The city chose to construct a pair of earthfill embankment dams.
- The Bouquet Canyon plans were received external review from engineers **Charles T. Leeds, Louis C. Hill,** and **J. B. Lippincott**
- The City also considered input from a host of additional engineers and geologists external to DWP, including: geologists **Charles P. Berkey, Allen E. Sedgwick, Robert T. Hill, F. Leslie Ransome, and Rush T. Sill.** Other engineers providing input included **Thaddeus Merriman, R.E. McDonnell.**
- And, the **State Engineer** also reviewed the project and provided an on-site representative to inspect the construction as it progressed.

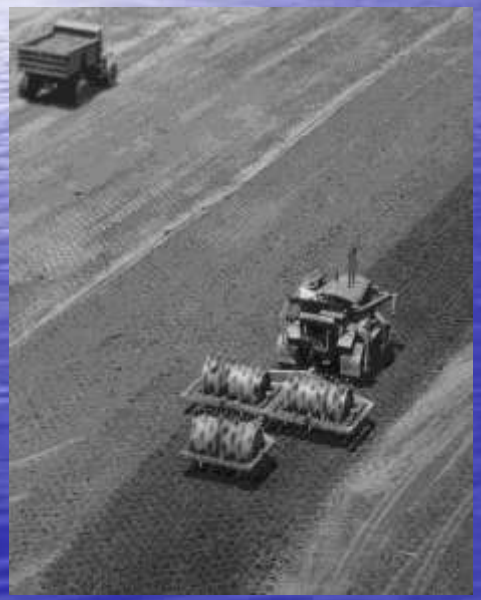


The external peer review panel appointed by the Los Angeles Department of Water & Power to review the Bouquet Canyon project included (left to right): Charles T. Leeds (1879-1960), a former Corps of Engineers officer and Los Angeles District Engineer; Louis C. Hill (1865-1938), a former CSM professor and Bureau of Reclamation supervising engineer, who was also on the Board of Consulting Engineers for Hoover Dam; and Joseph B. Lippincott (1864-1942), who had worked fro the U S Geological Survey, U S Reclamation Service, and had overseen design and construction aspects of the Los Angeles Aqueduct as a city employee in 1906-13.

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 D698)

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

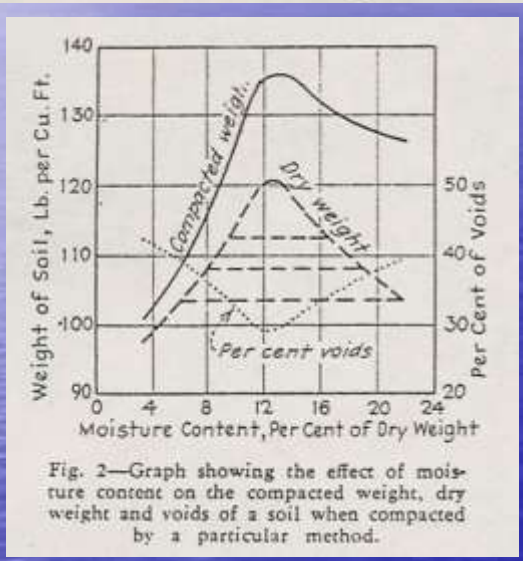
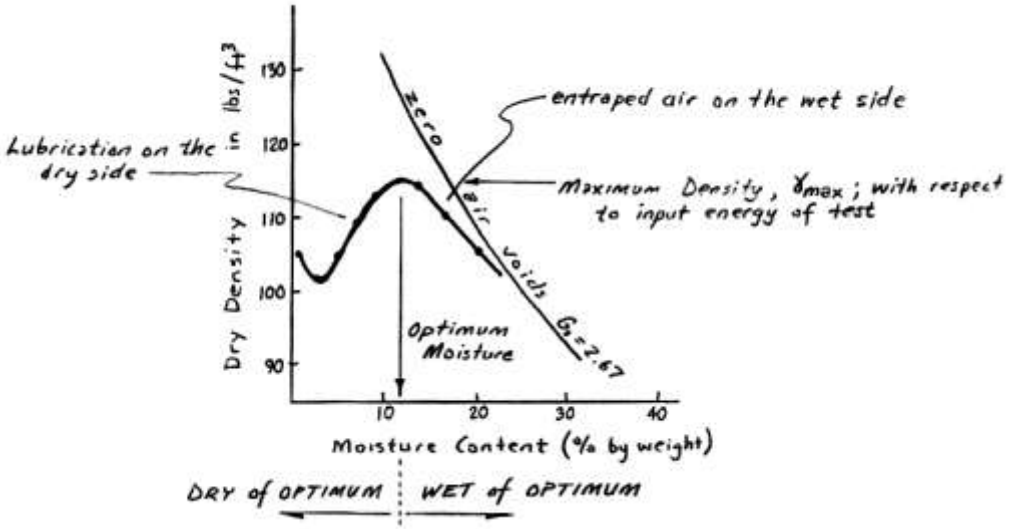
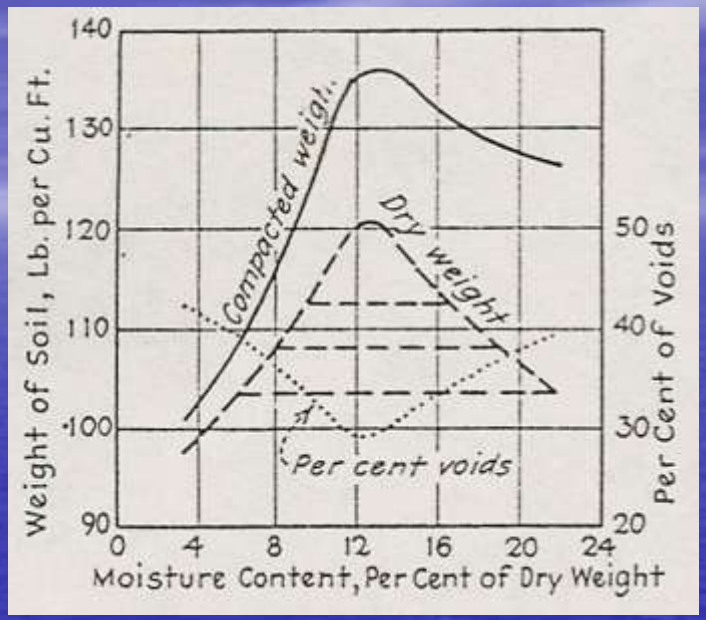


Fig. 2—Graph showing the effect of moisture content on the compacted weight, dry weight and voids of a soil when compacted by a particular method.



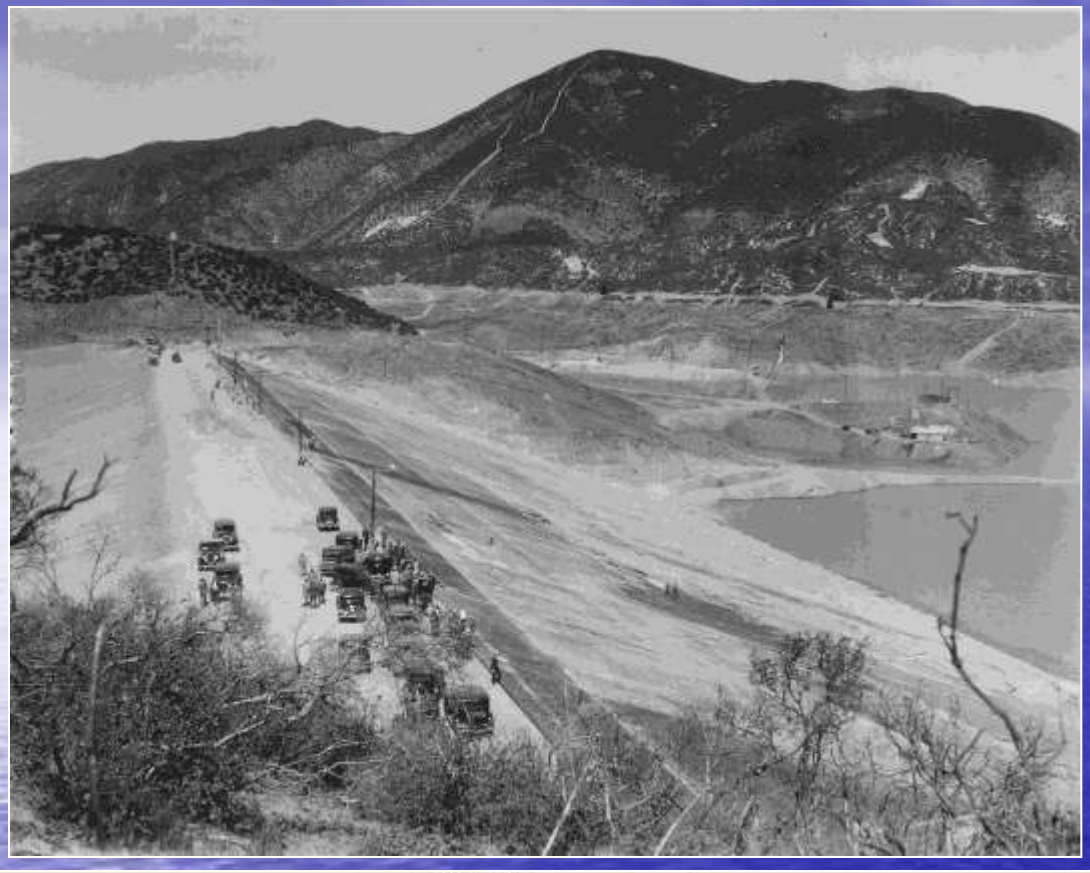
- **Ralph Proctor** devised an alternative method to California Test 216 introduced by the State Division of Highways in 1929, which measures the *maximum wet density* ('compacted weight,' shown above left), and controls the compactive effort based on the total weight, not the volume, of the test sample (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

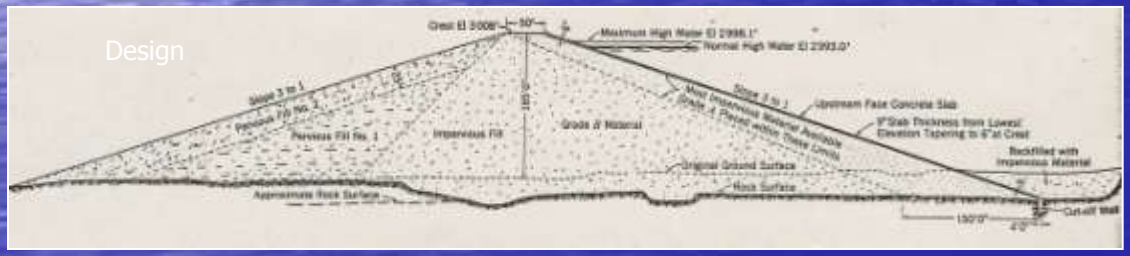


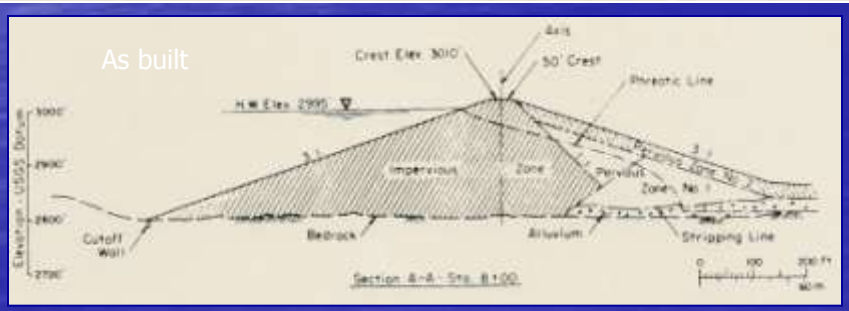
Ralph R. Proctor
(1894-1962)

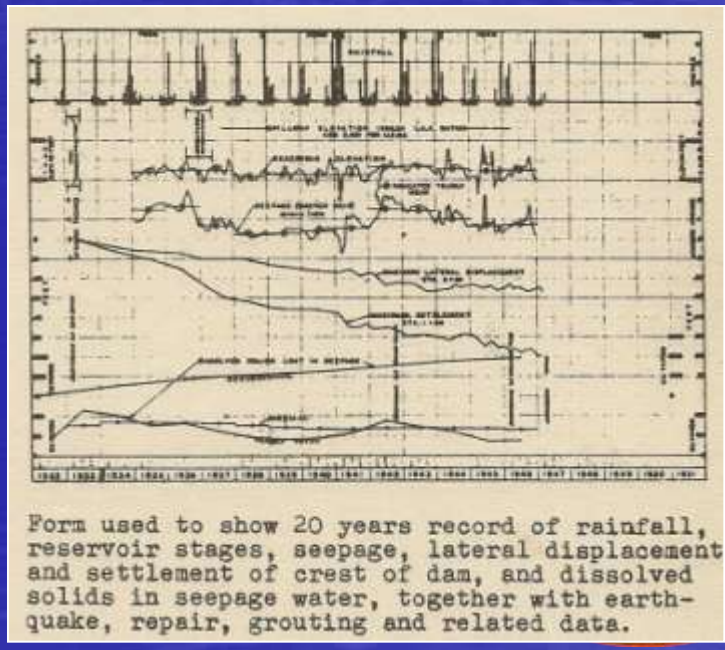
- **Ralph Proctor** was charged with developing a test scheme for the earth fills at Bouquet Canyon which would engender confidence in the City's ability to build safe dams in the wake of the St Francis disaster
- What he came up with has been known as the "Proctor Compaction Test," which remains in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





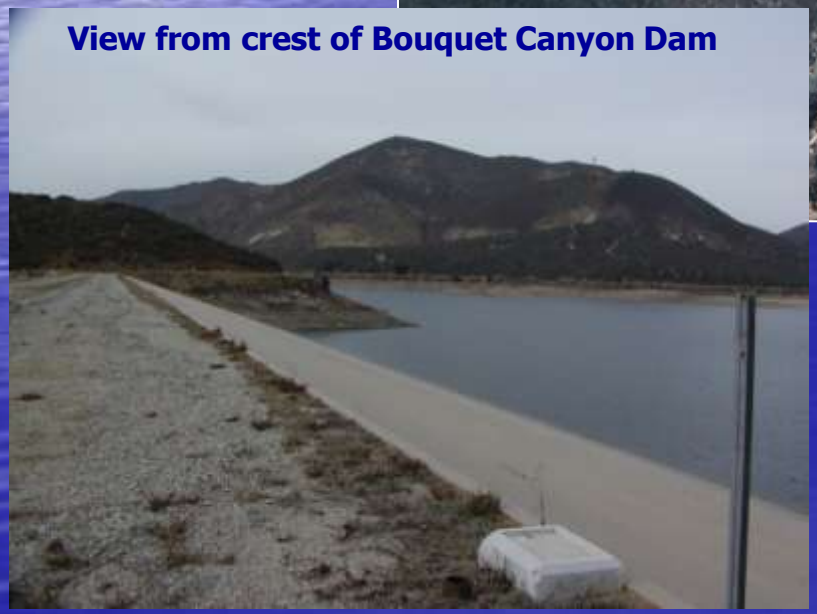


Form used to show 20 years record of rainfall, reservoir stages, seepage, lateral displacement and settlement of crest of dam, and dissolved solids in seepage water, together with earthquake, repair, grouting and related data.

West Saddle Dam

Main Dam – 224 ft high

View from crest of Bouquet Canyon Dam



- 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.