

ENGINEERING FIRSTS AT



J. David Rogers, Ph.D., P.E., P.G., M.ASCE
for the

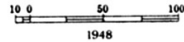
Hoover Dam 75th Anniversary Symposium
ASCE Annual Meeting Las Vegas, Nevada
October 22, 2010



UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER BASIN

MAP NO. 26380

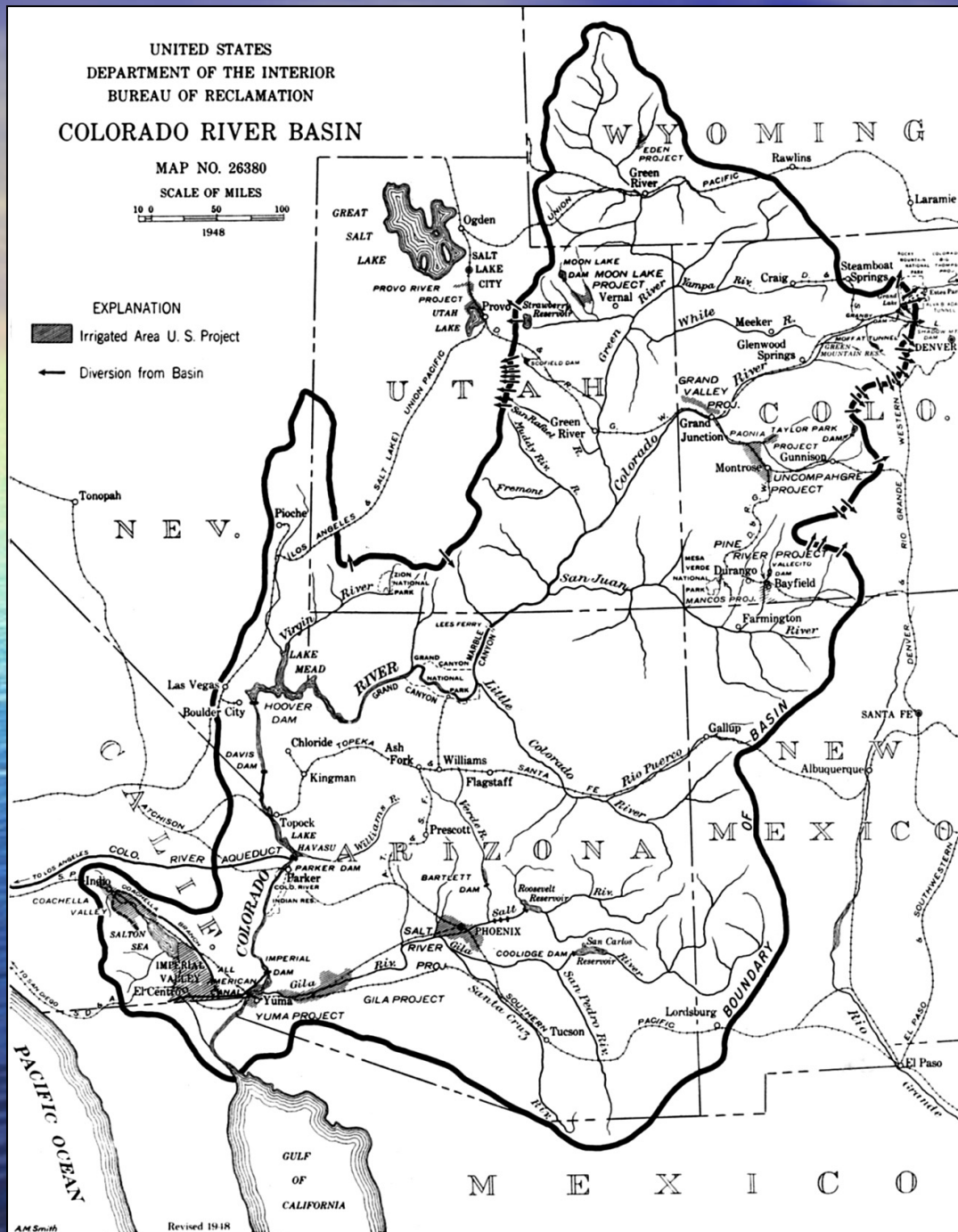
SCALE OF MILES



EXPLANATION

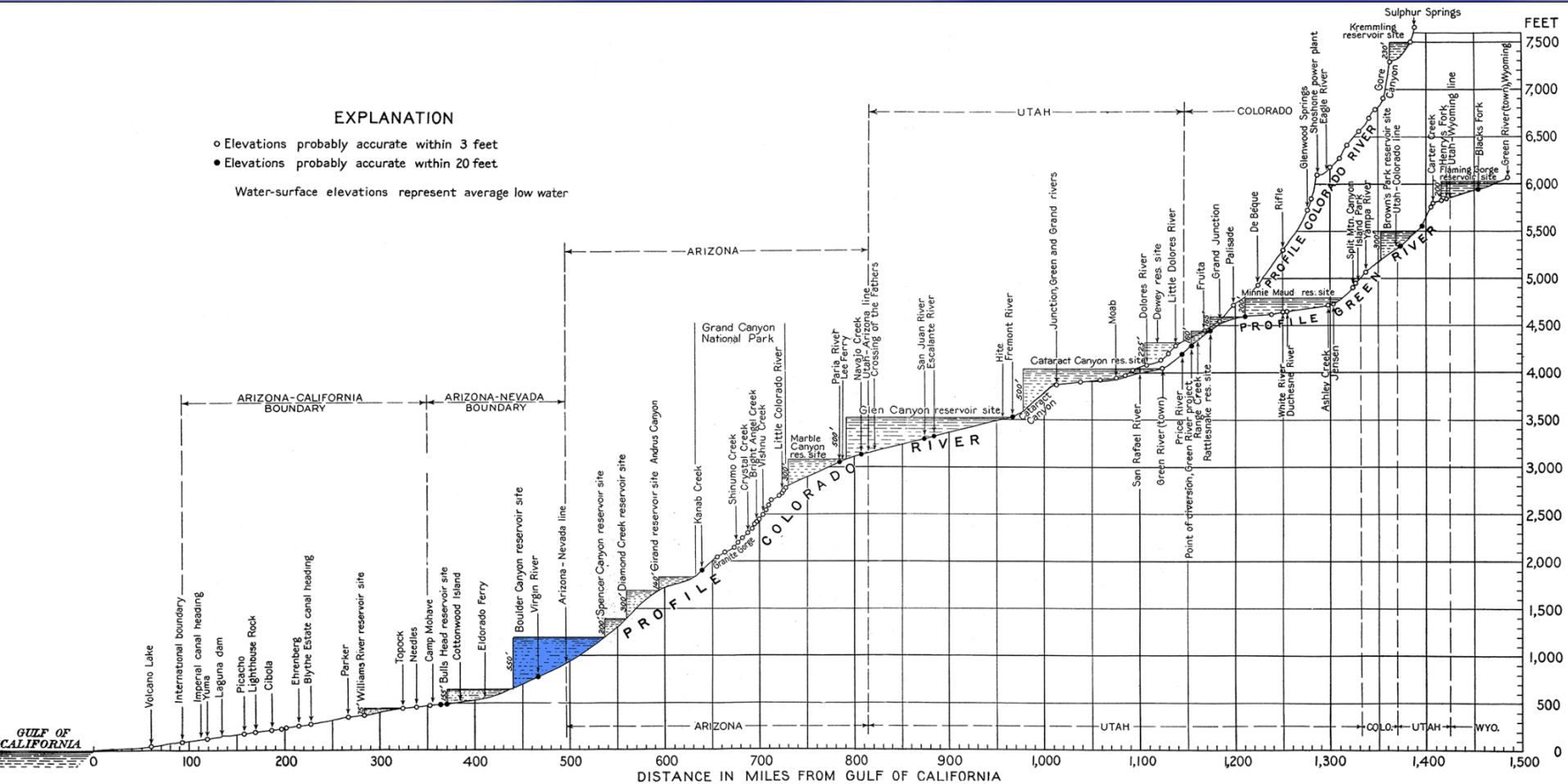
■ Irrigated Area U. S. Project

← Diversion from Basin

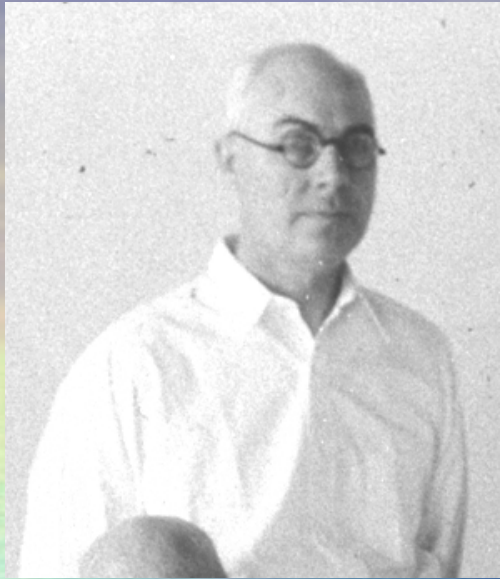


COLORADO RIVER BASIN

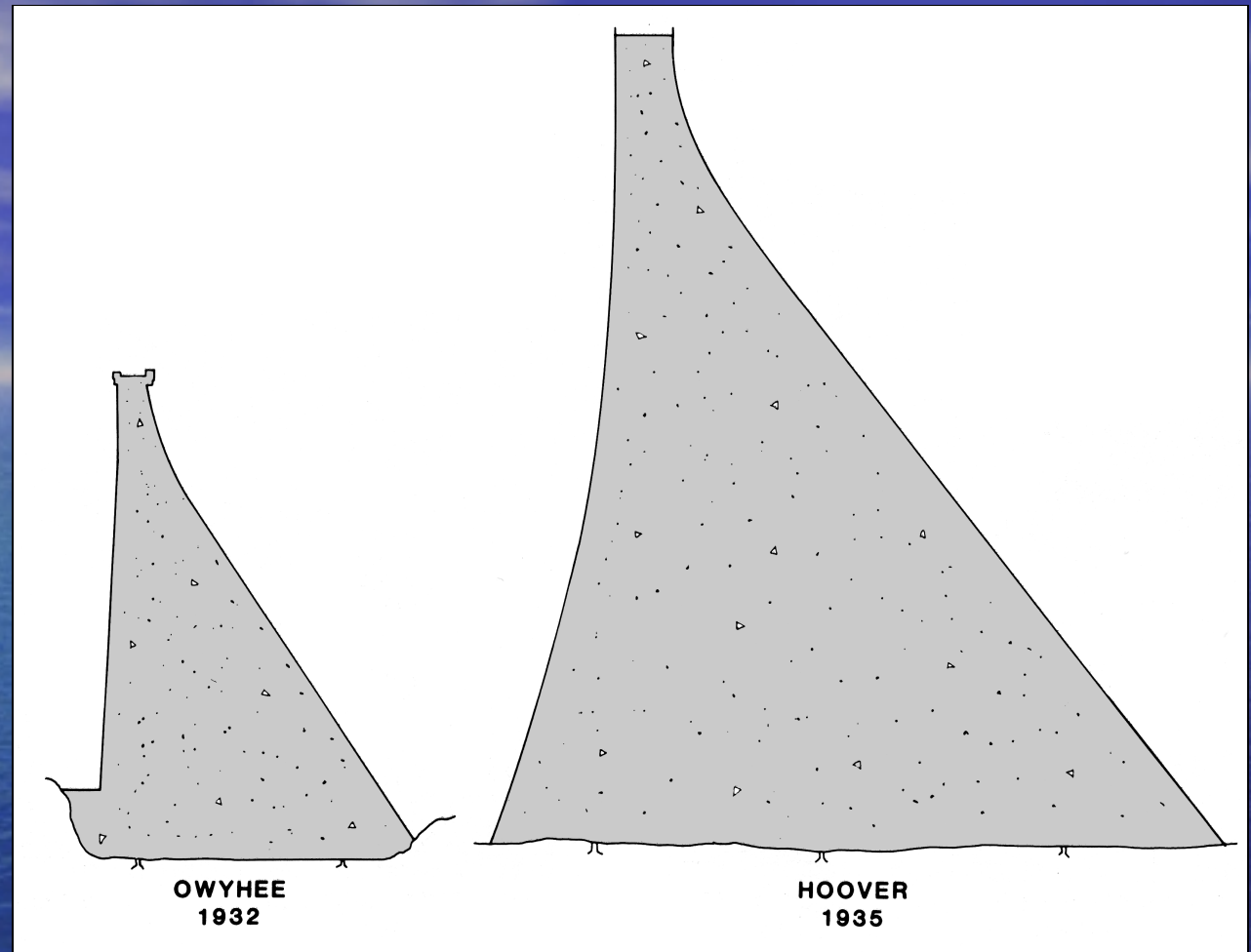
- Total watershed area of 246,000 square miles
- Shared by 7 states
- Only river in North America that flows through arid valleys



- In 1922 the Reclamation Service proposes a scheme by which the Colorado River's water and power can be utilized to transform deserts into gardens, for the benefit of mankind



Reclamation's Chief
Design Engineer
between 1924-44 was
Jack L. Savage



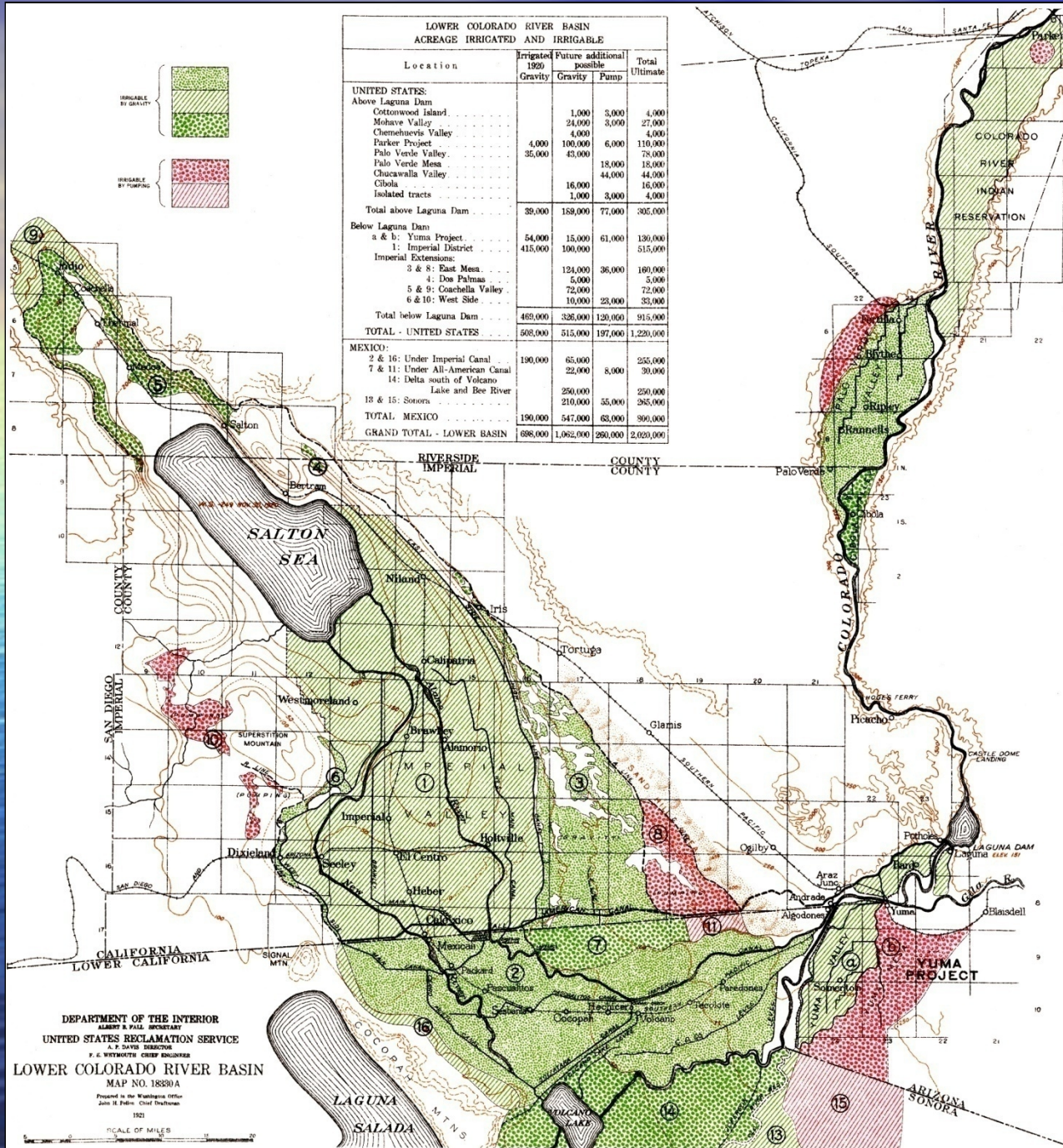
- **Unprecedented size:** Hoover Dam was almost twice as tall as the highest dam in the world, Owyhee, slated for completion in 1932!
- Owyhee Dam was designed by the same Reclamation design team, led by Jack Savage.

The Colorado was America's most fickle river

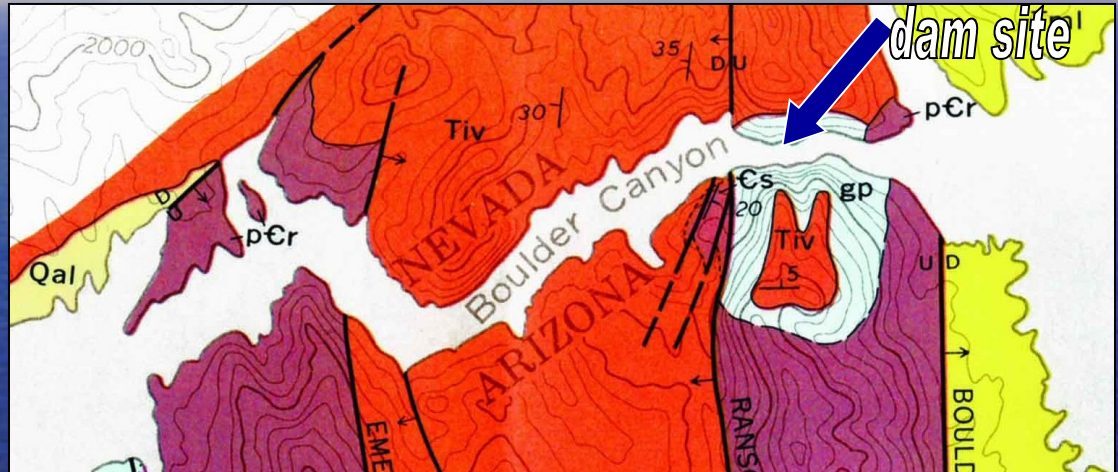
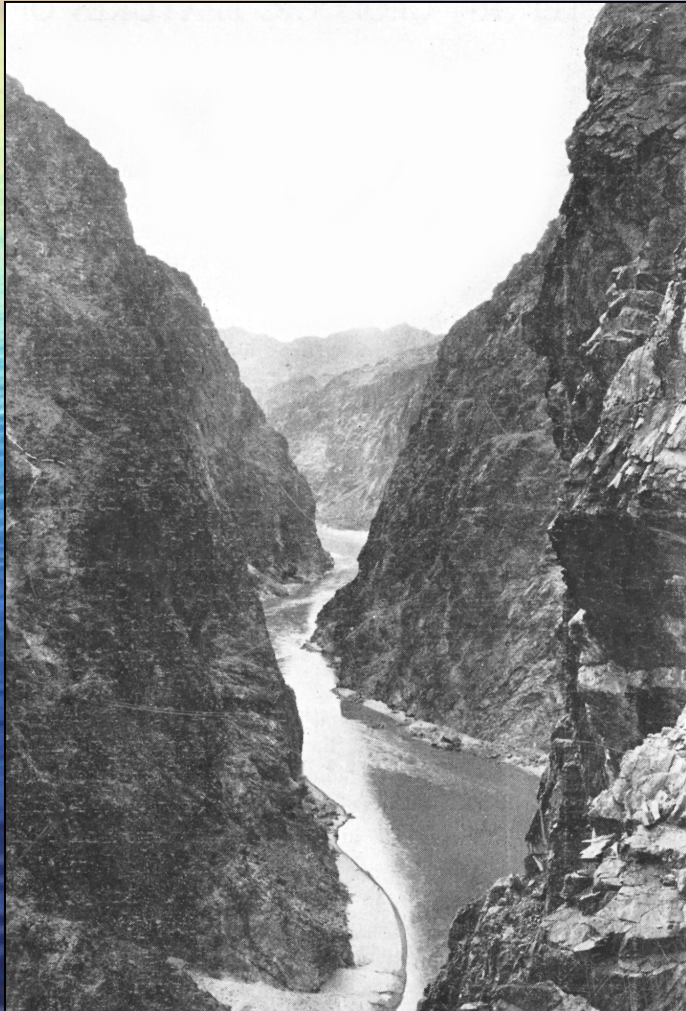
- Named *Rio Colorado* by Spanish because of red color of highly turbid flow
- **Fifth highest silt load** of any river in the then-known world (actually, 7th)
- Maximum recorded flow of **384,000 cfs** at Topock in 1884
- Minimum recorded flow of **500 cfs** in 1911
- High-low flow ratio of **768:1**

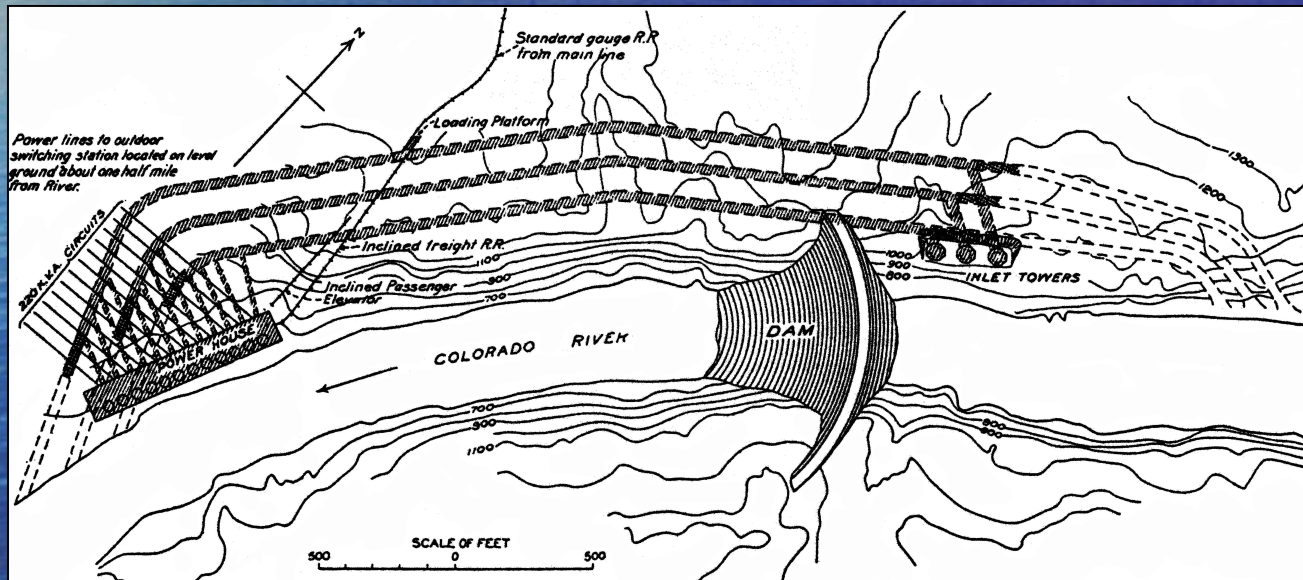
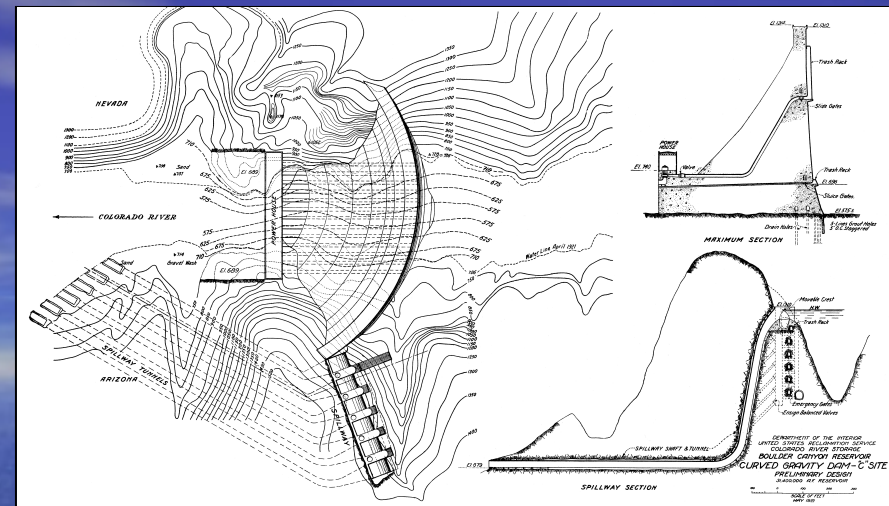
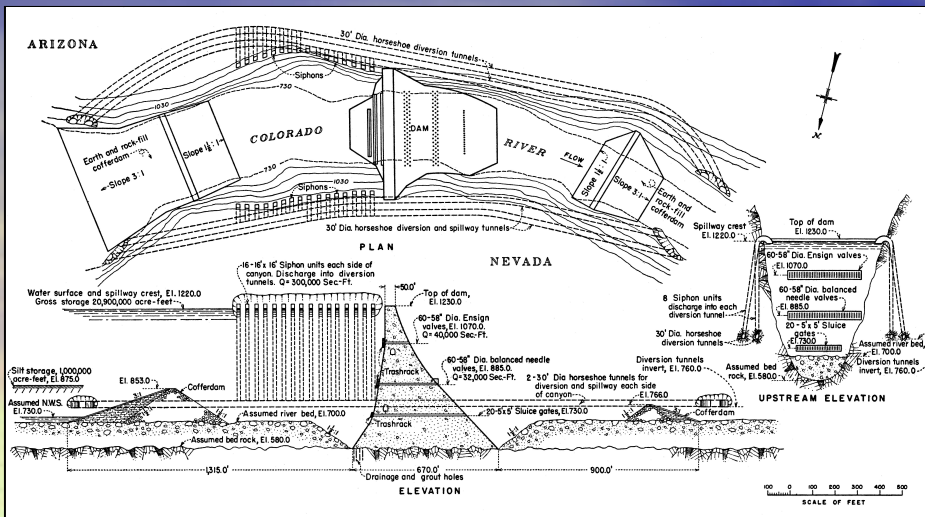
The Goal:

- 1.5 year supply of then entire Colorado River
- To Irrigate:
- Palo Verde Valley
- Yuma Valley
- Imperial Valley
- Coachella Valley



Initial studies in 1902 identified dam sites in **Boulder and Black Canyons**.
Boulder site favored because of **granite**





The design of **Boulder Dam** evolved throughout the 1920's; including a straight concrete gravity dam; various concrete arch dams; eventually, adding a powerhouse.

Surveys in Black Canyon



Engineer-geologist Homer Hamlin makes first survey of upper Black Canyon dam sites in the spring of 1920; marking axis of recommended site that is eventually chosen, 8-1/2 years later

PROBABLE FREQUENCY OF FLOOD DISCHARGES AT BLACK CANYON

Discharge, Second-Feet	Frequency With Which Discharge May be Equaled or Exceeded
130,000	Once in 5 years
160,000	Once in 10 years
190,000	Once in 20 years
230,000	Once in 50 years
260,000	Once in 100 years



The Colorado River Board expressed concern about how large the **maximum probable flood** might be after observing high water marks 80 feet above low water level at the head of Boulder Canyon (shown at left).

They concluded 320,000 cfs every 500 years and **450,000 cfs every 10,000 years**



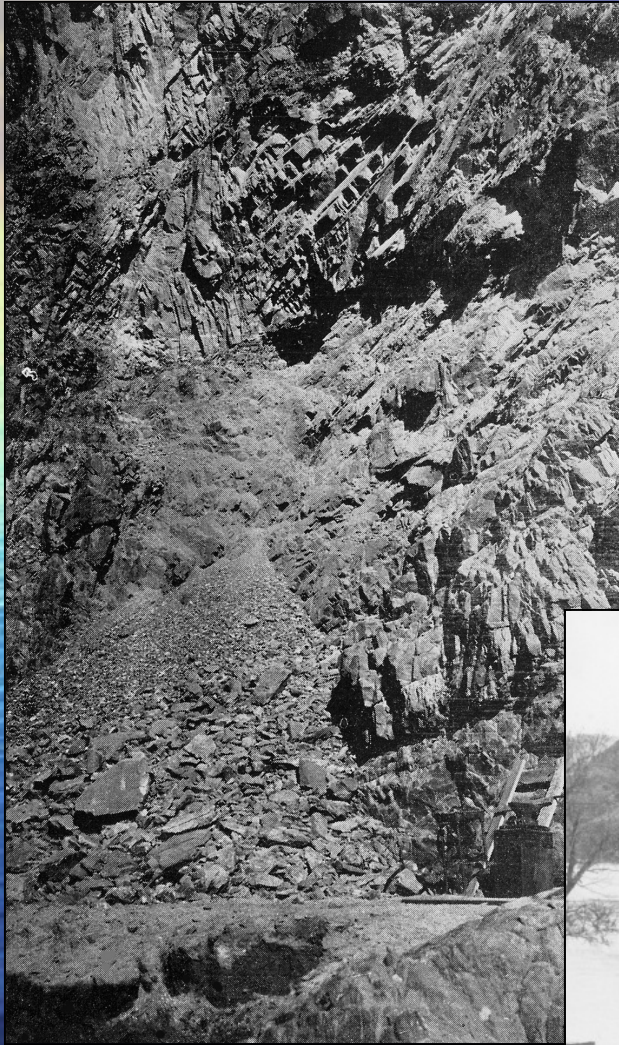
- The untimely failure of the **St. Francis Dam** 35 miles north of Los Angeles in March 1928 killed at least 435 people
- Public outcry and concern following the failure of a new concrete gravity-arch dam constructed by the same people pushing for passage of the Boulder Canyon Project prompted the appointment of an **independent panel of experts** to review the Bureau of Reclamation's plans for the Boulder Canyon Project and advise Congress on its feasibility and practicality.

Colorado River Board May 1928



MGEN William L. Siebert (Chair), Elwood Mead (advisor), and included geologists Charles P. Berkey (Secretary) and Warren J. Mead; and engineers Daniel W. Mead and Robert Ridgway. In those days geologist wore ties, just like engineers.

Board investigates the dam sites

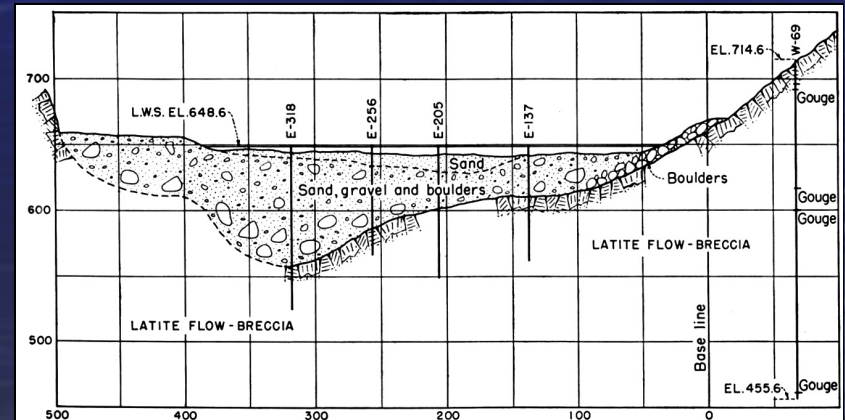
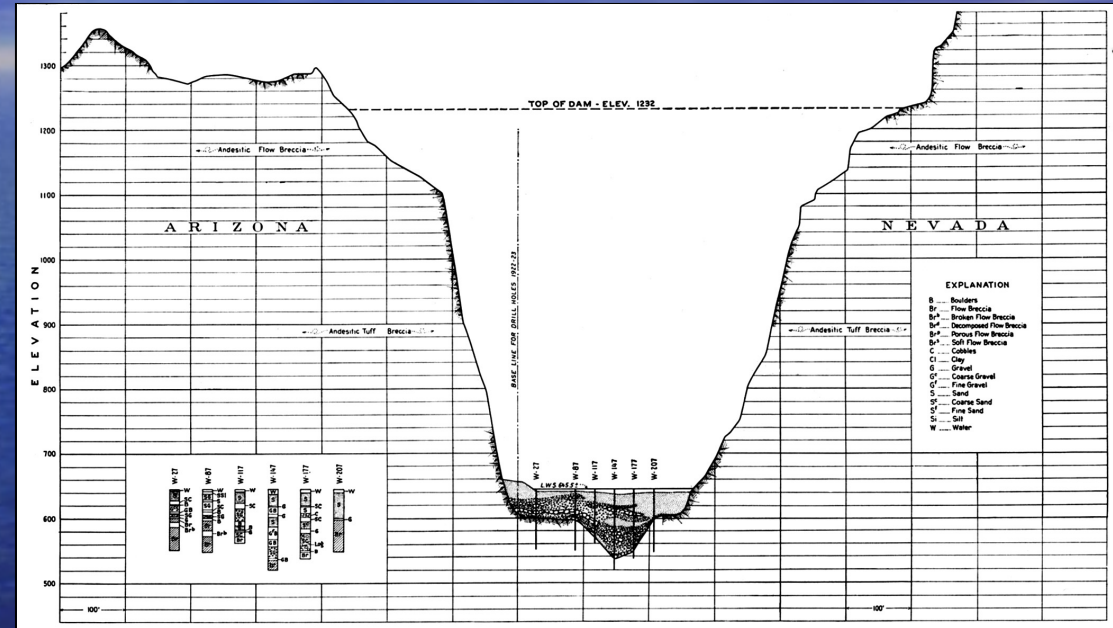


Fractured granite at one of the three Boulder Canyon dam sites



The Board's geologists raised a number of concerns that had not been addressed previously.

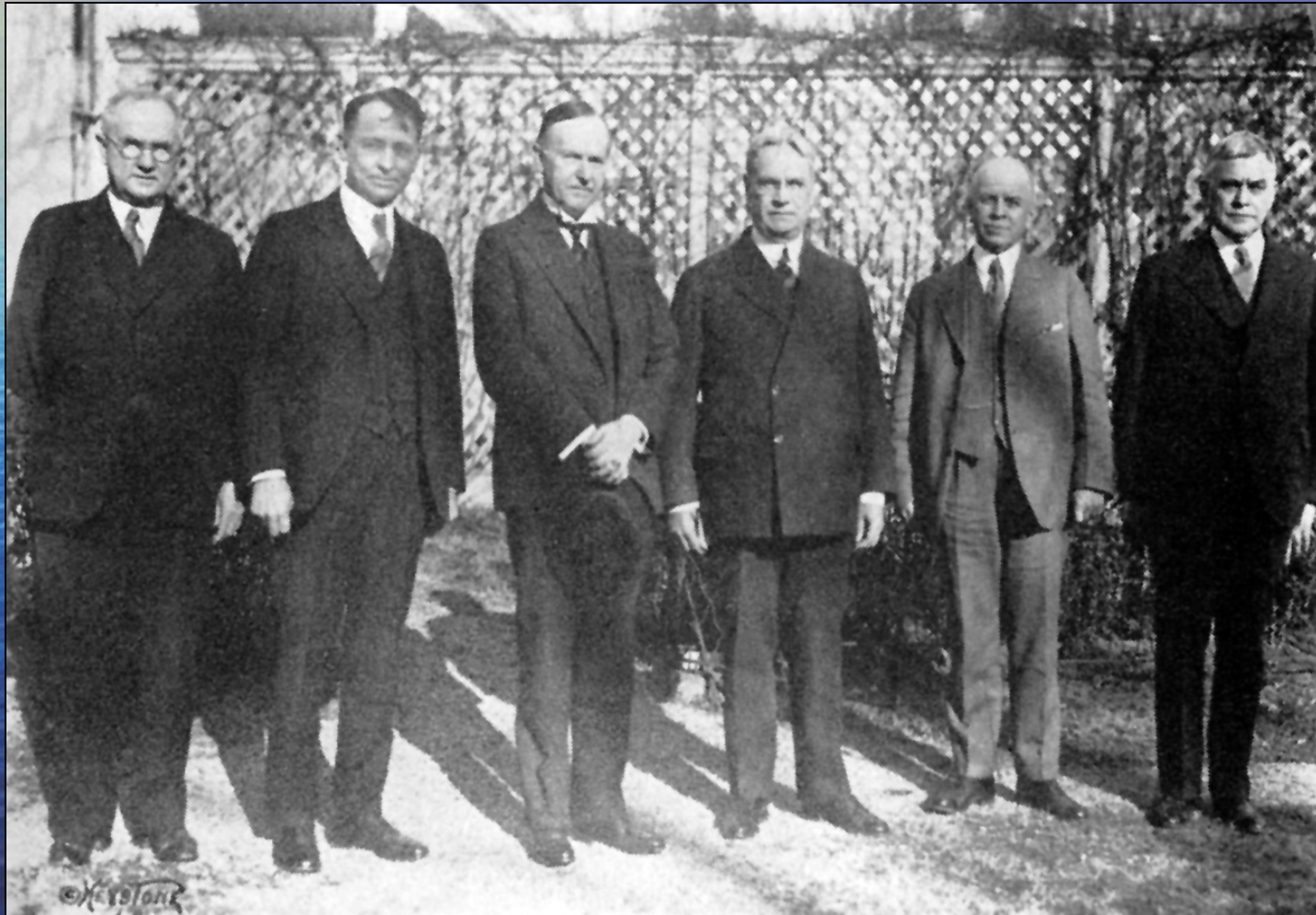
Colorado River Board recommends the upper Black Canyon site in Dec 1928



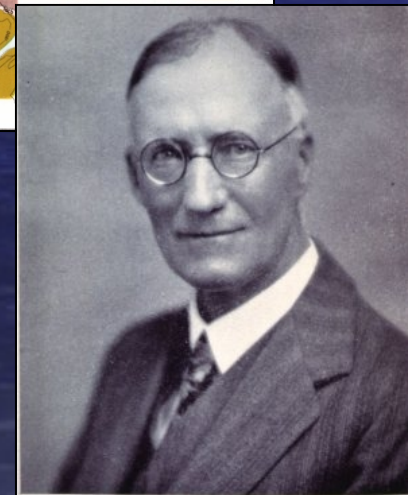
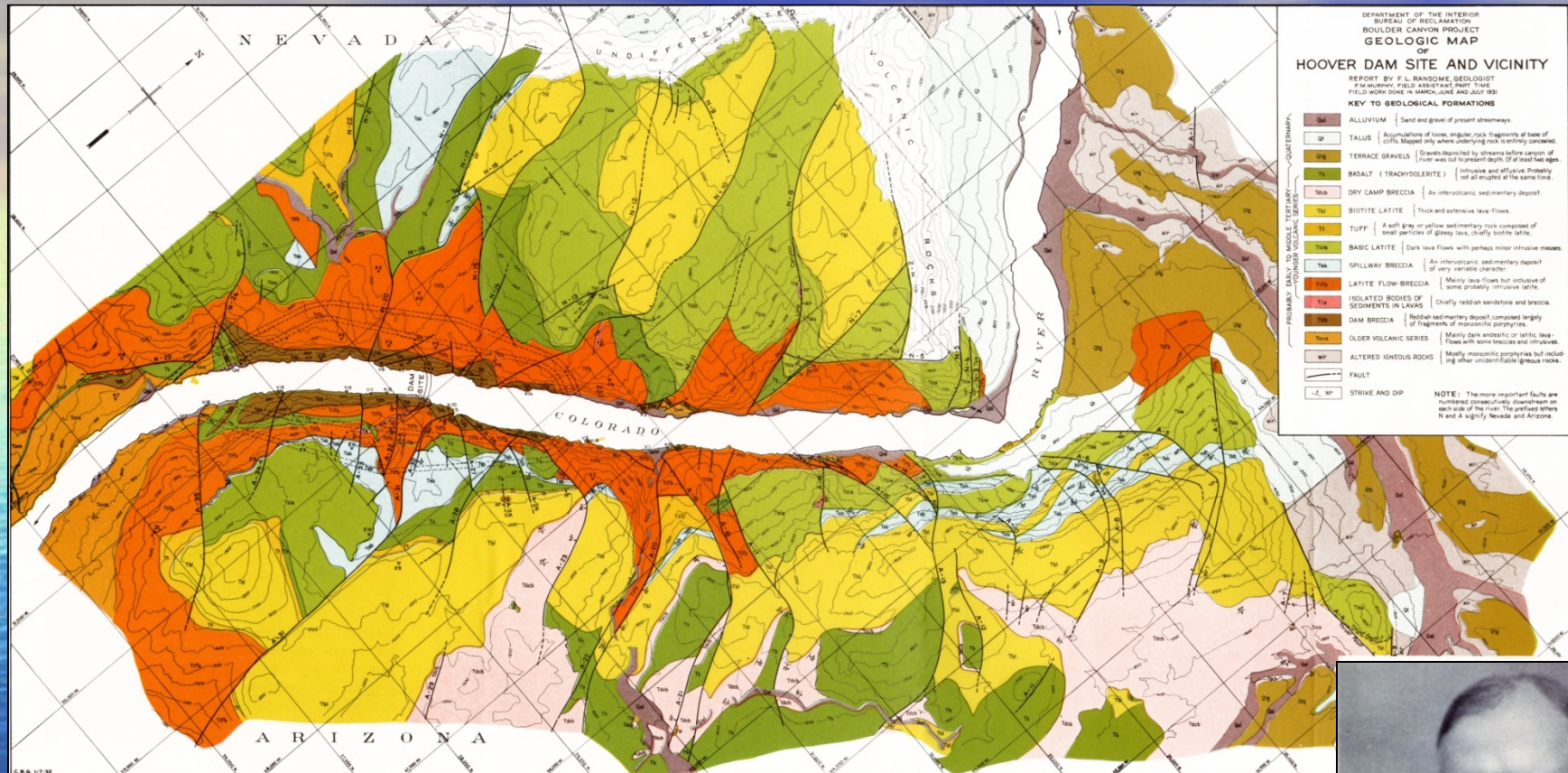
In December 1928, the CRB recommends design changes:

- **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.**

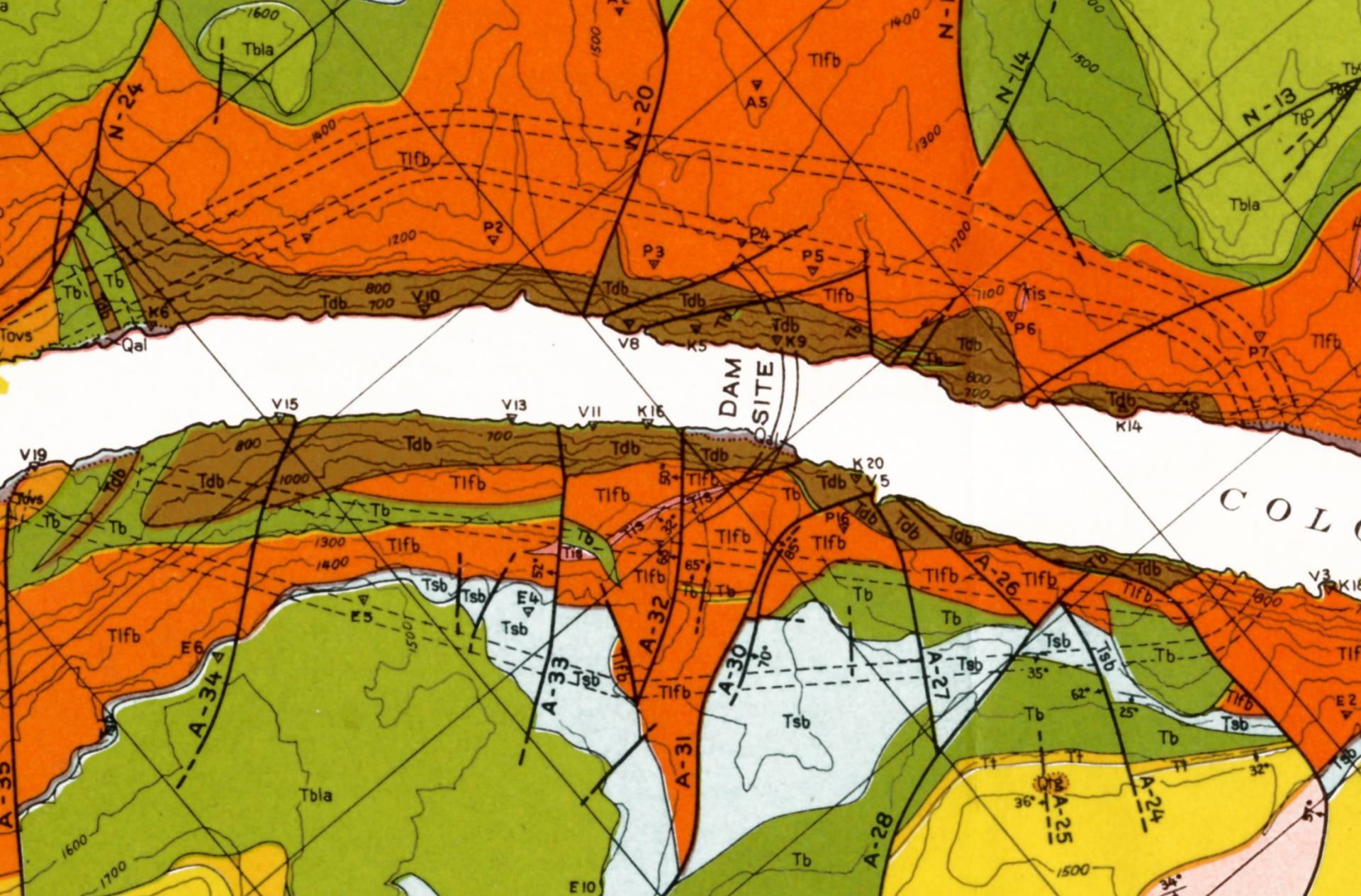
The **Boulder Canyon Act** introduced by California delegation in Congress as twice-annual ritual between 1922-28. The fourth version finally passes both houses in December 1928, and is approved by President Coolidge, shown here



Leslie Ransome maps both dam sites in 1921; returns to Black Canyon site in 1931



The dam was founded on a unit he called the **dam breccia**, a dense reddish unit composed of fragments of monzonitic porphyry; covered by a **latite flow breccia**. The deepest boring encountered dam breccia to a depth of 545 feet below river level.



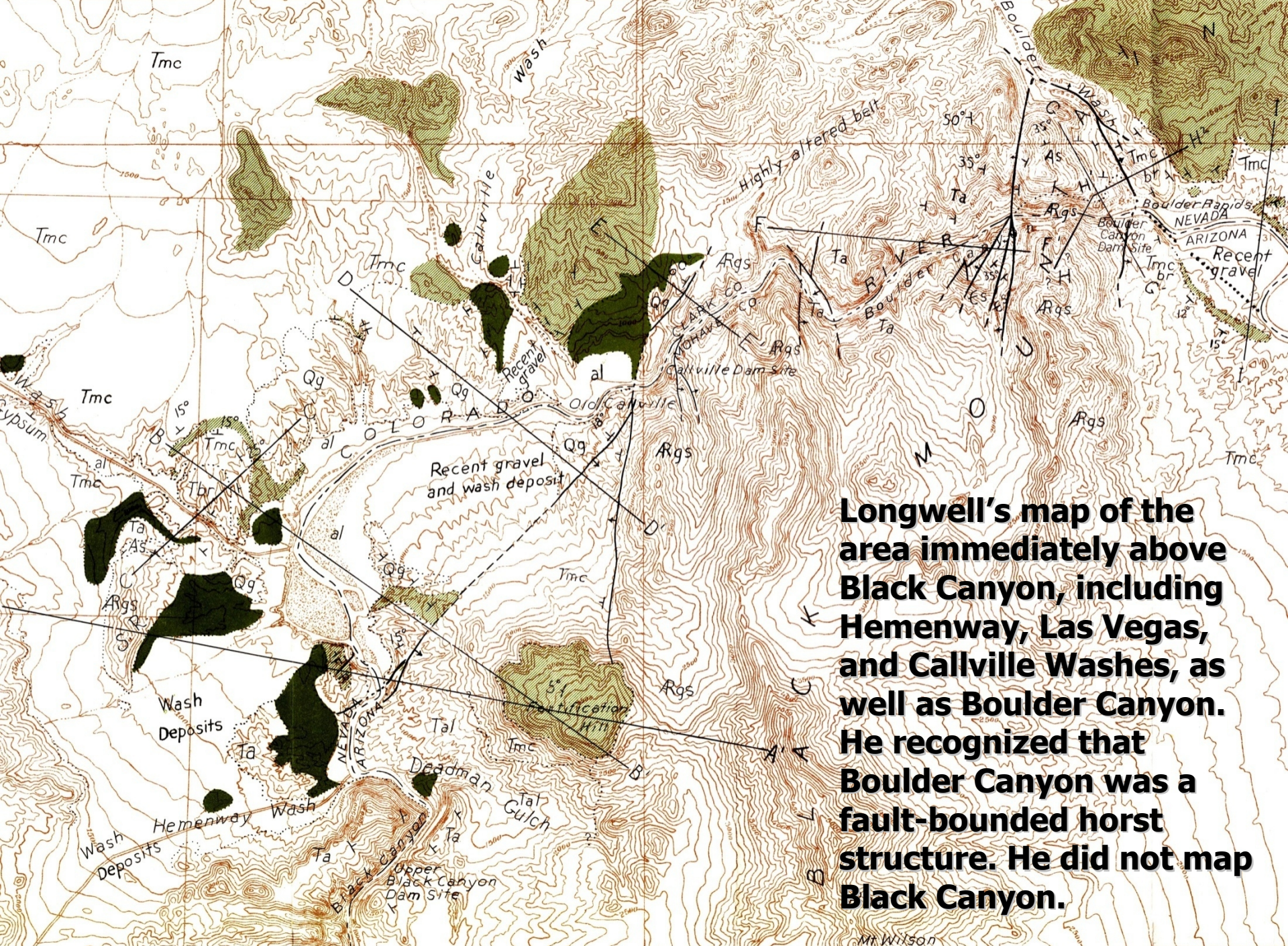
Ransome's geologic map controlled the position of the dam's axis, to wedge the dam in between the two prominent faults on the right abutment

Professor Chester Longwell mapped the reservoir area

Numerous salt mines dotted the lower Virgin River Valley

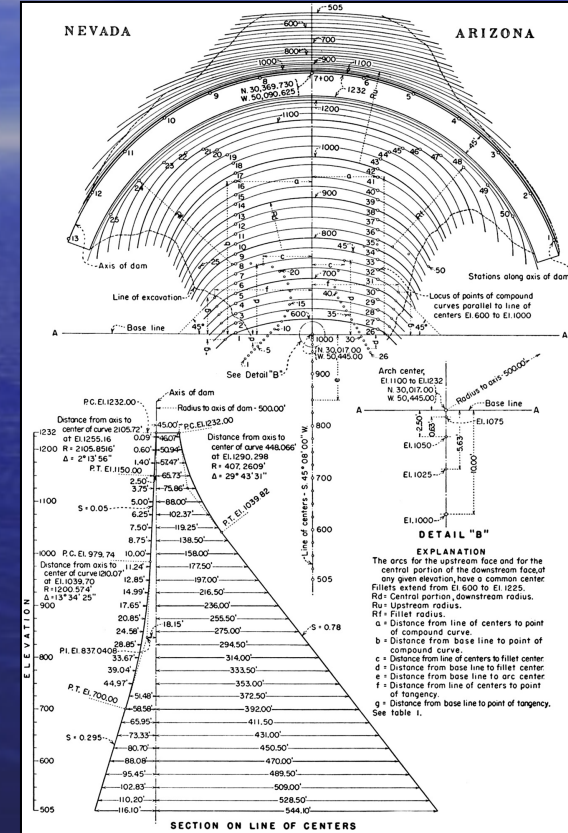
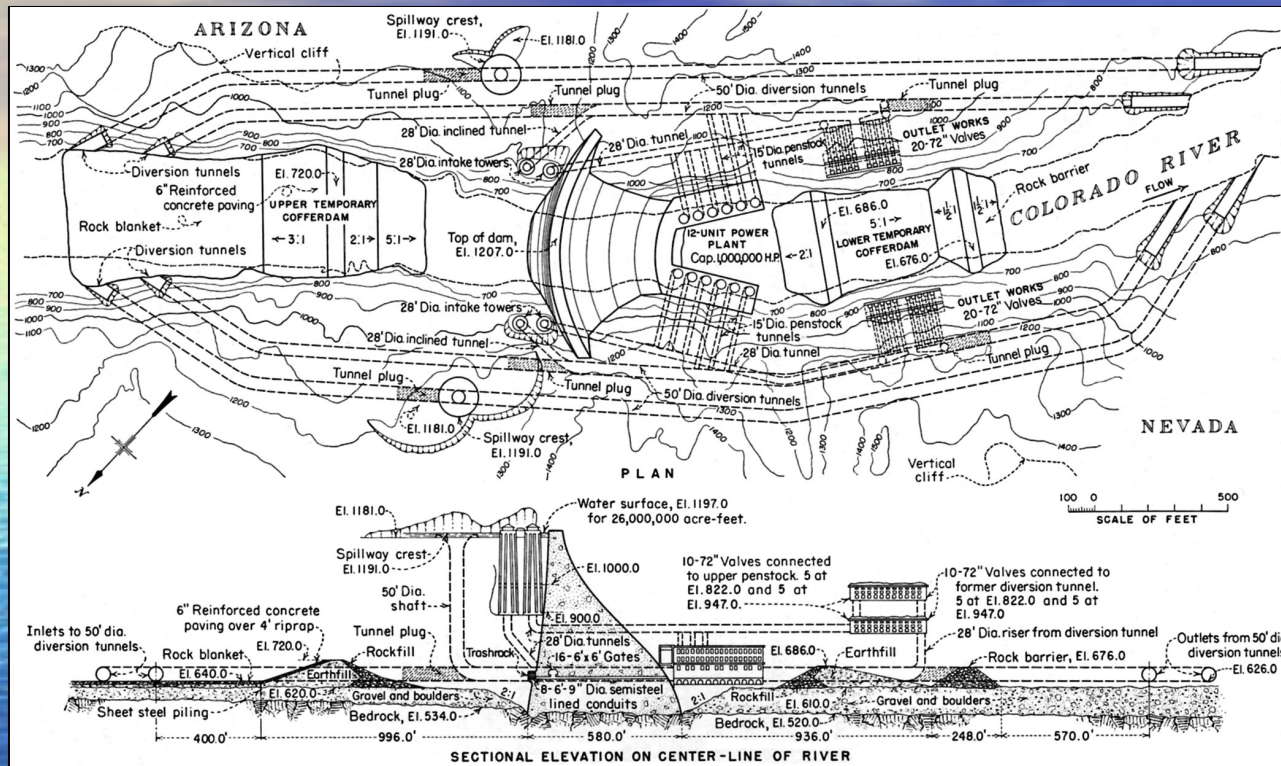


- The Colorado River Board felt that the geology of the reservoir area should be mapped in detail before impoundment.



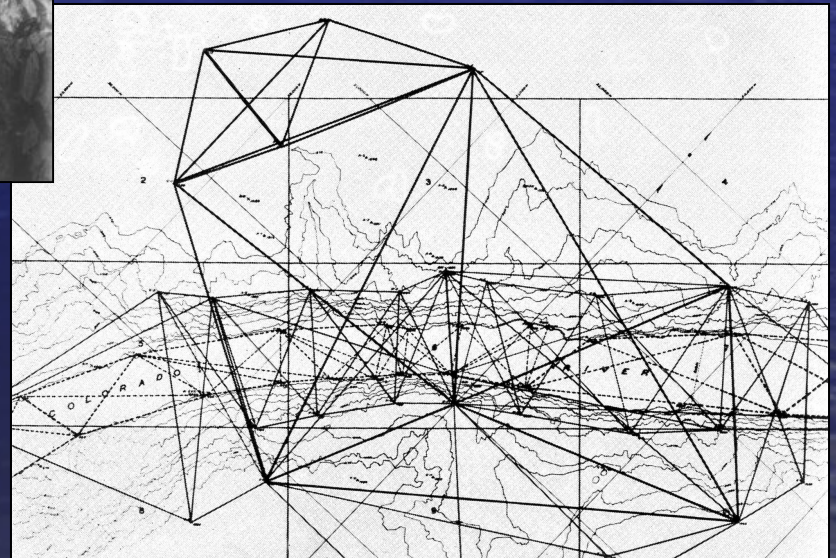
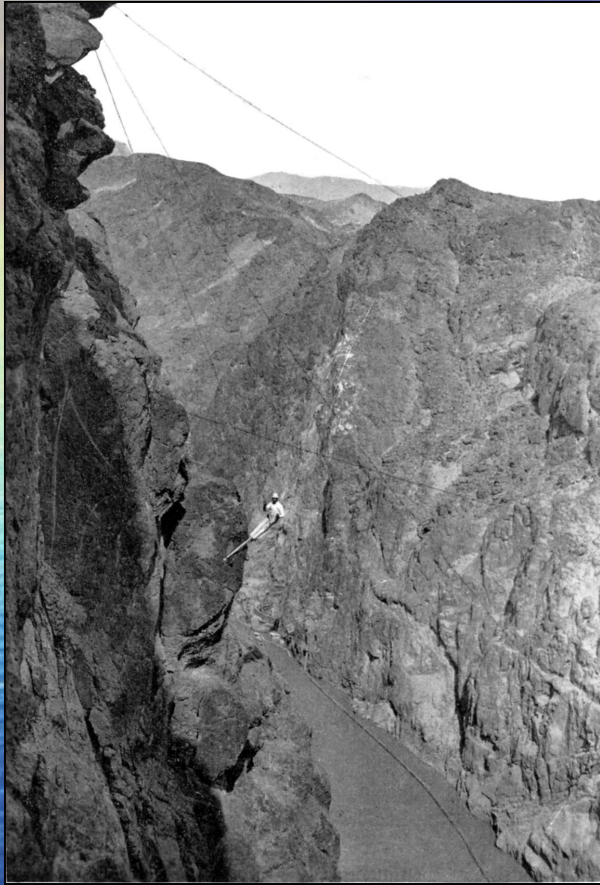
Longwell's map of the area immediately above Black Canyon, including Hemenway, Las Vegas, and Callville Washes, as well as Boulder Canyon. He recognized that Boulder Canyon was a fault-bounded horst structure. He did not map Black Canyon.

In April 1930 the decision is made to raise the dam 25 additional feet to increase flood storage



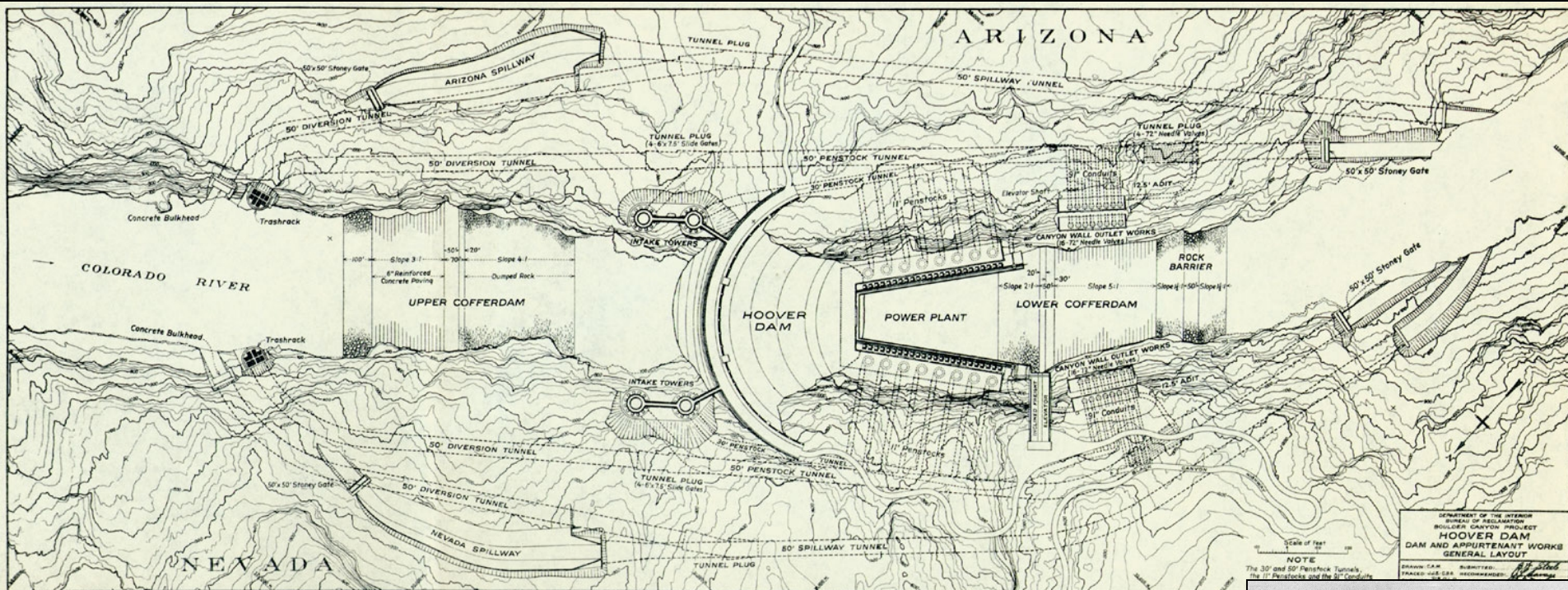
- Dam height now 726 ft; Crest elevation raised to 1232 ft; 30,500,00 ac-ft storage for maximum 9,500,000 ac-ft flood storage
- Curvature tightened from crest radius of 740 to 505 feet

Terrestrial photogrammetry

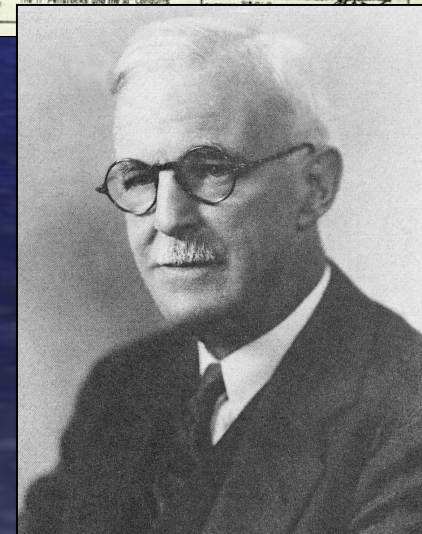


Making an accurate topographic map was a major obstacle before construction could begin.

The finished product



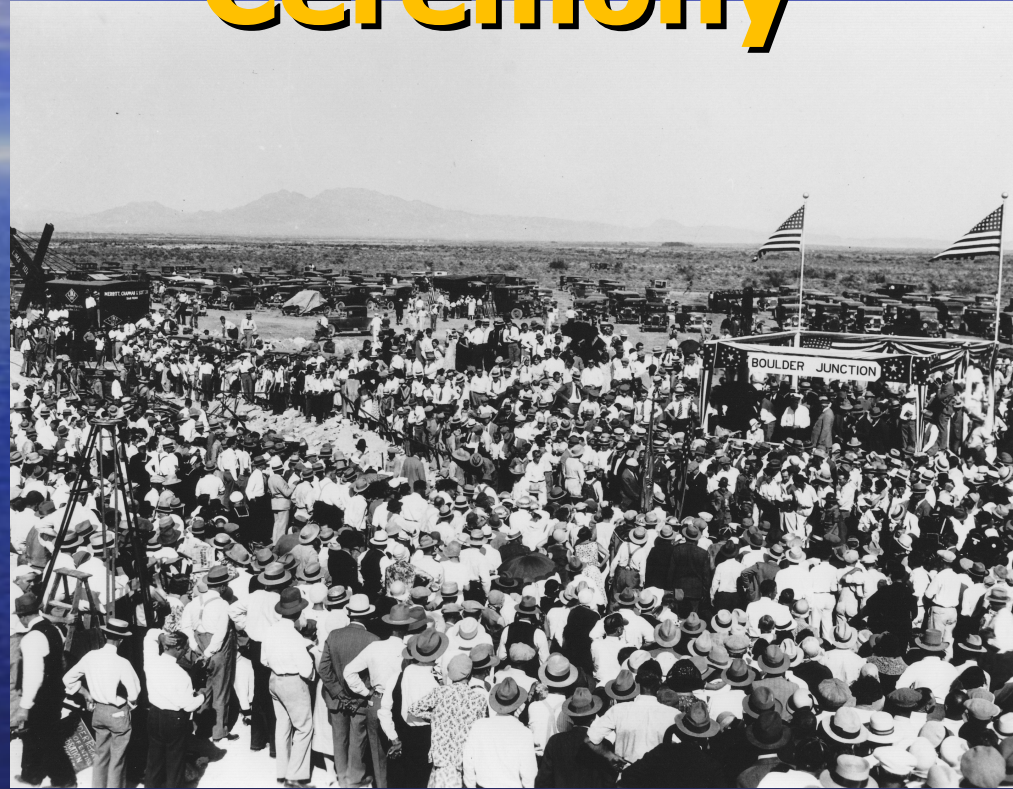
Terrestrial photogrammetry was employed using photo theodolites, directed by LtCol Claude Birdseye of the U.S. Geological Survey (inset), who had led the mapping expeditions of the Colorado River through the Grand Canyon in 1923.



Boulder Canyon Project:

- With a budget of \$165 million, it would be the **largest federal contract ever awarded up to that time**
- Funds were to be appropriated over a period of eight years, beginning in 1930
- It would require **more concrete** (4.5 mcy) than all previous Bureau of Reclamation projects combined (4.4 mcy)
- **No single contractor** was large enough to bid the project; the dam itself being around \$50 million

Silver Spike Ceremony



- On September 17, 1930 Interior Secretary Dr. Ray Lyman Wilbur presided over the ceremony at Boulder Junction, where a 26-mile spur would be laid by the Union Pacific Railroad to Boulder City.
- Thus began construction of the Boulder Canyon Project, and Lyman took the opportunity to christen the kingpin structure as the "**Hoover Dam**," in honor of President Herbert Hoover.

Government would provide:

- ALL MATERIALS, except concrete aggregate
- Railroad spur and highway to crest of gorge
- Construction of Boulder City, providing housing for 80% of workers
- Assumed flood damage liability after cofferdams accepted
- Government to **emplace turbines** and **machinery** for hydro powerhouses (cont'd till 1961)



- **Earthmoving pioneer R.G. Letourneau lost \$100K on a \$330K contract constructing the government highway between Boulder Junction and the dam site, because the andesite proved so difficult to excavate**
- **The feds also paid \$1 million for an extension of the U.S. Construction Railroad, along the highway, to the plateau above the Nevada, where the Babcock & Wilcox fabrication plant was later built.**

The massive job was split into numerous parts, with performance timelines:

- 1) River Division works – cofferdams and four 56 ft diameter tunnels no later than **October 1, 1933**
- 2) Completion of spillways by **November 1, 1933**, which may be postponed for up to one year or more, depending on other factors
- 3) Cofferdams to be completed by **May 1, 1934**
- 4) Place first mass concrete for dam no later than **December 1, 1934**
- 5) Bulkheads for inlets of outboard diversion tunnels must be lowered into position no later than **September 1, 1935**
- 6) Stoney Gates for outlet gates in inboard diversion tunnels; placement of upstream tunnel plugs, with high pressure slide gates by the **fall of 1935**
- 7) Begin storing reservoir water no later than **June 15, 1936**
- 8) Completion of the four intake towers and appurtenant works, except the bridges, by **July 1, 1936**
- 9) Completion of canyon wall outlet works by **September 1, 1936**
- 10) Completion of power house, ready for 6 generators by **September 1, 1936** (with reservoir pool at elevation of 935 ft)
- 11) Completion of power house for 12 generators by **April 23, 1938**

Opening the bids in Denver



Reclamation's Chief Engineer **Ray Walter** opening the five bids on Wednesday March 4, 1931 in Denver

- Bids for the dam construction contract with 119 items were solicited on January 10, 1931, and 107 firms requested packages.
- By the submittal deadline of March 4th only five bids had been received in Denver
- Six Companies won with a bid of \$48,890,995.50; just 0.05% above the government estimate, but \$5 million below their closest rival, Arundel Corporation of Baltimore



- Congressman **Phil Swing** (R-CA) at left, and Reclamation Commissioner **Elwood Mead** (at right) witness Interior Secretary **Ray Lyman Wilbur** signing the **largest single contract ever let by the federal government**, for the construction of Hoover Dam and powerhouse on March 11, 1931, in Washington, DC.
- The construction contract was to commence on Wednesday April 15, 1931, and that all work would be completed in 2,565 days, or just over seven years, by Saturday April 23, 1938.

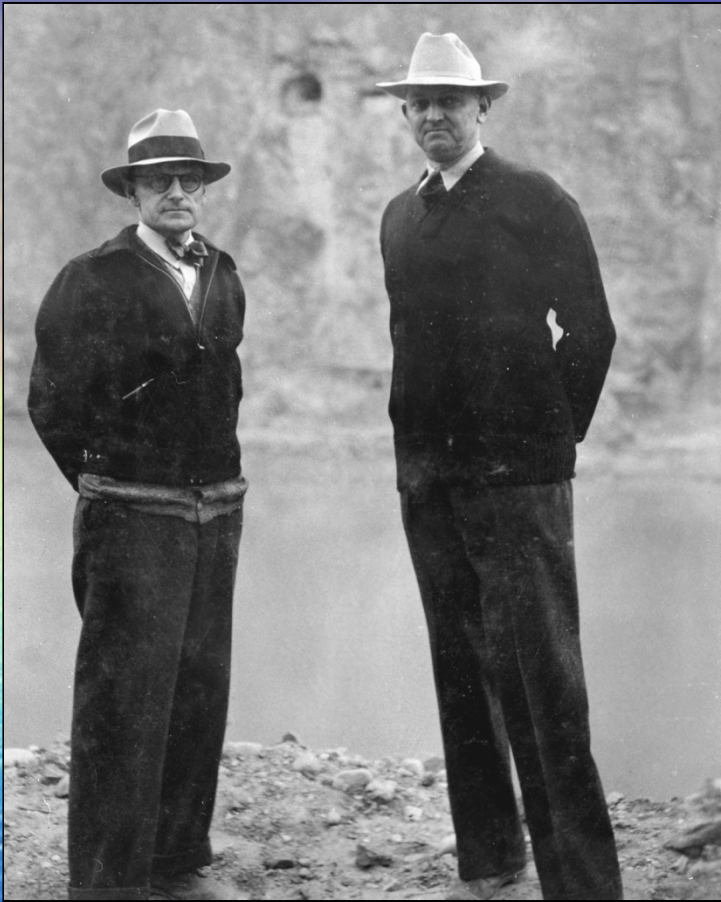
Six Companies Incorporated (actually seven)

- **W. A. Bechtel and Henry J. Kaiser 30%**
- **Utah Construction Co. 20%**
- **MacDonald & Kahn Co. 20%**
- **Morrison-Knudsen Co. 10%**
- **J. F. Shea Co. 10%**
- **Pacific Bridge Co. 10%**



**Six Companies Board of Directors
visits the dam site. Three of the
principals passed away during the
construction**

Frank Crowe and Walker R. Young



Everyone's choice for Construction Superintendent was **Frank Crowe**, Reclamation's former Construction Engineer, employed by Morrison-Knudsen. Crowe was 6'-4" tall. He is shown here with **Walker R. Young**, the Bureau's onsite Construction Manager.



Reclamation's three principal representatives at the dam during its construction were, left to right: **Walker R. "Brig" Young**, **John C. Page**, and **Ralph Lowry**.

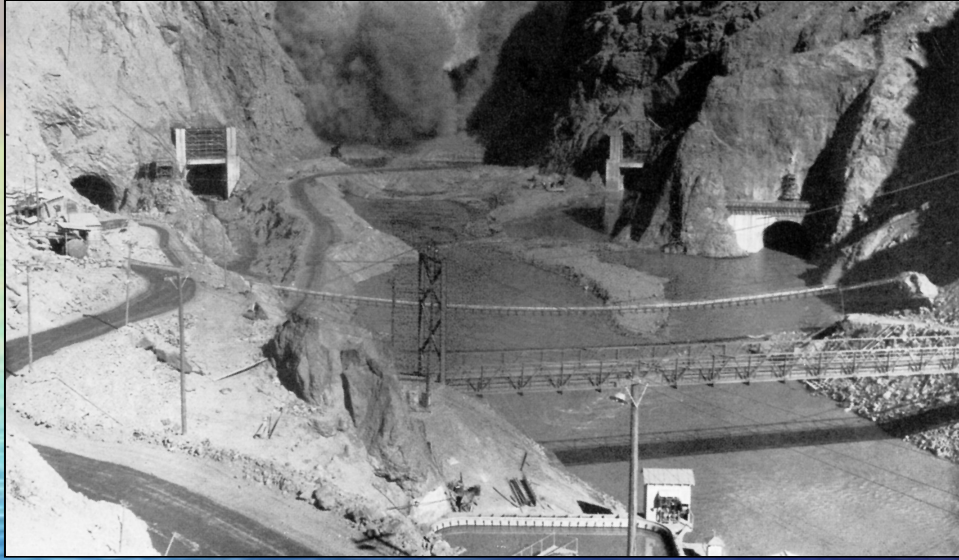


The Crowe's Nest

Frank Crowe received a salary of \$18,000 per annum plus 2.5% of the gross profit, which amounted to \$300,000. The most lavish villa in Boulder City was his residence, nicknamed "The Crowe's Nest," because of its unimpeded 360-degree view (below)



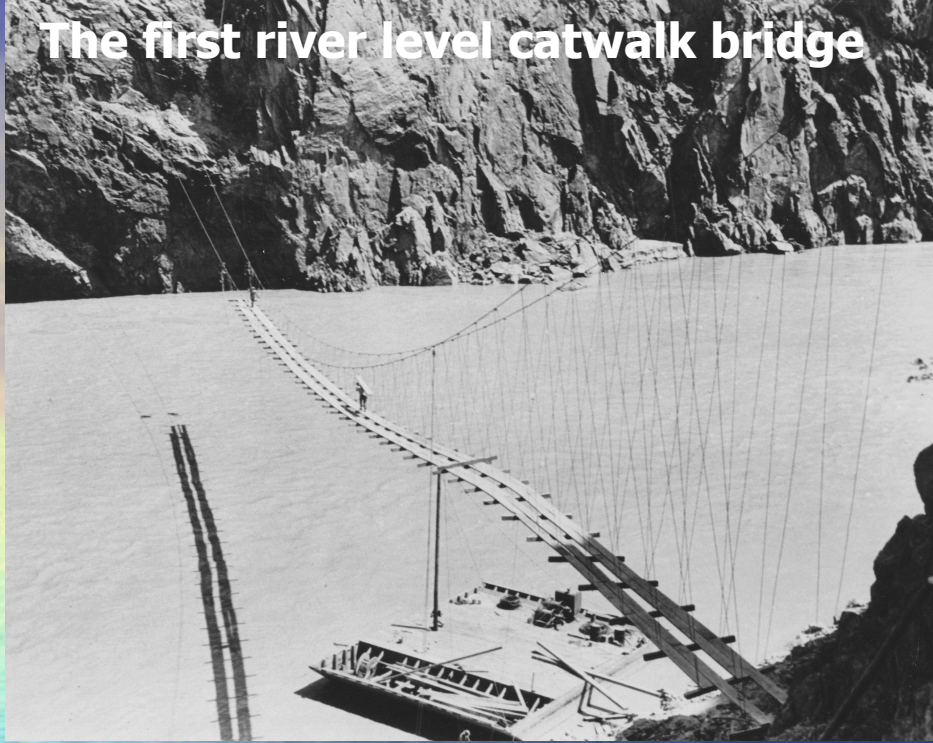
Site Access was the most difficult obstacle to overcome





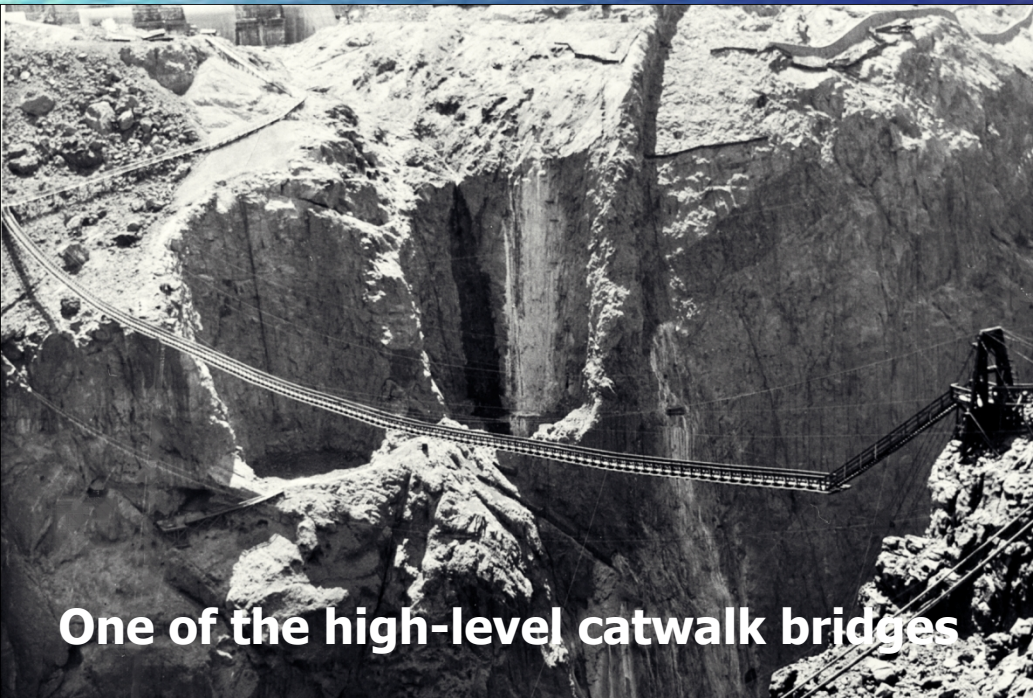
- **Tracked shovels were busily engaged whittling out switchbacks for temporary construction access, and creating valuable fill wedges along the channel**

The first river level catwalk bridge



Catwalk wire bridges

- **Six Companies built a series of increasingly sophisticated catwalk bridges which allowed shifters to work on the Arizona intake towers and spillways, without clogging the river trestles, which conveyed dump and concrete trucks, around the clock.**



One of the high-level catwalk bridges

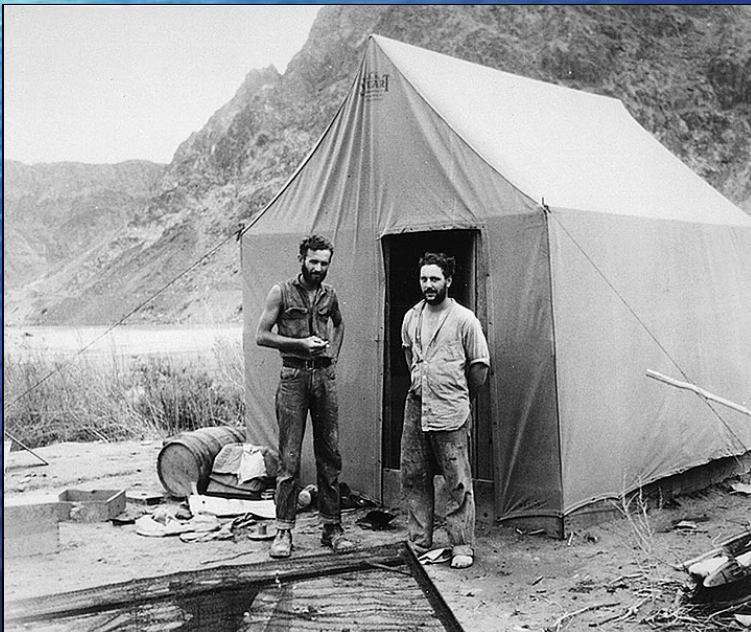
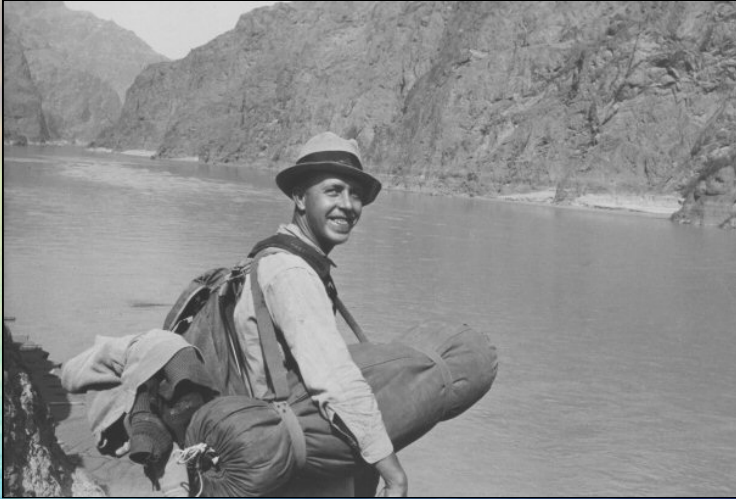
Construction Adits

- The first thing Frank Crowe did was to excavate construction adits in both abutments near the dam's downstream face, so he could effect multiple headings of the diversion tunnels, working 16 faces simultaneously in the four tunnels.



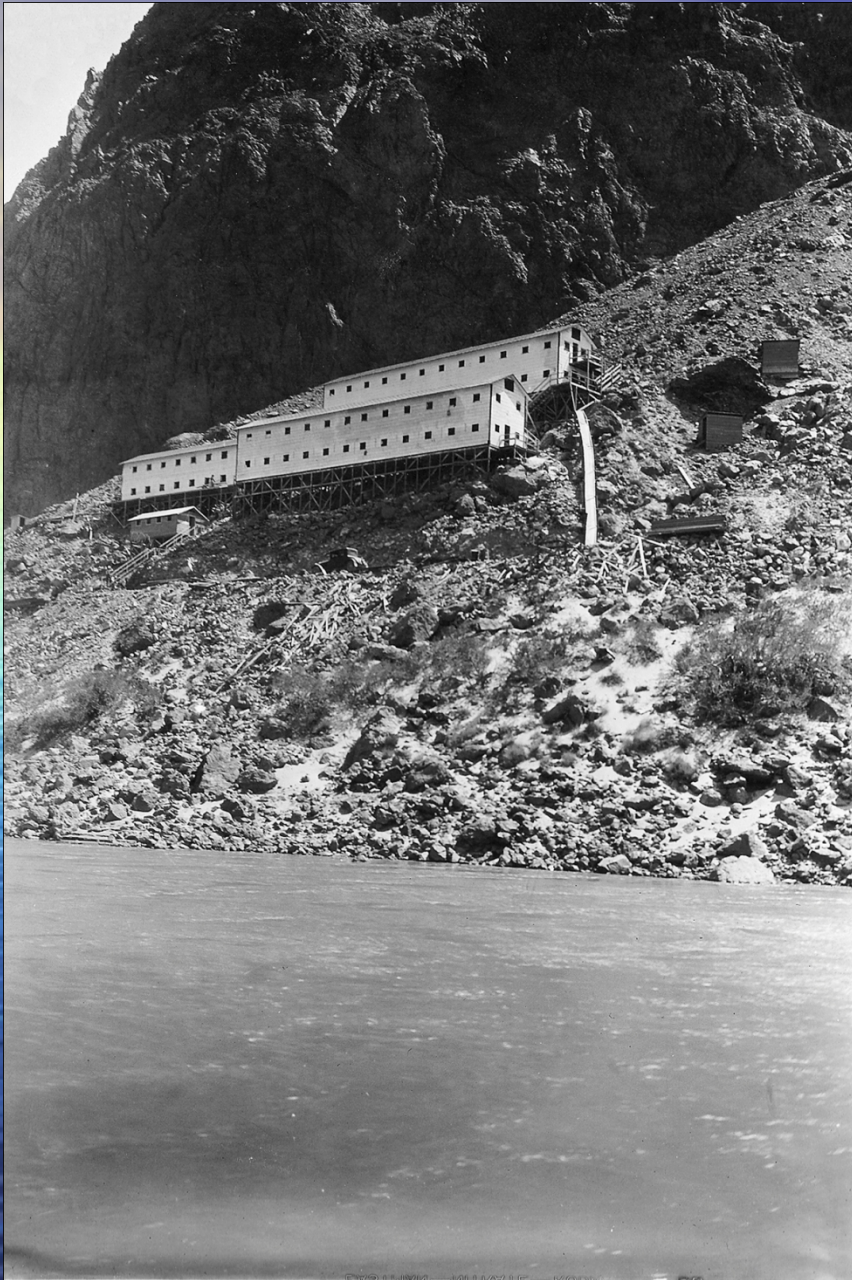
Wire suspension bridge serving the construction adit (dark hole in background) for the Arizona diversion tunnels.

Ragtown – Summer 1931



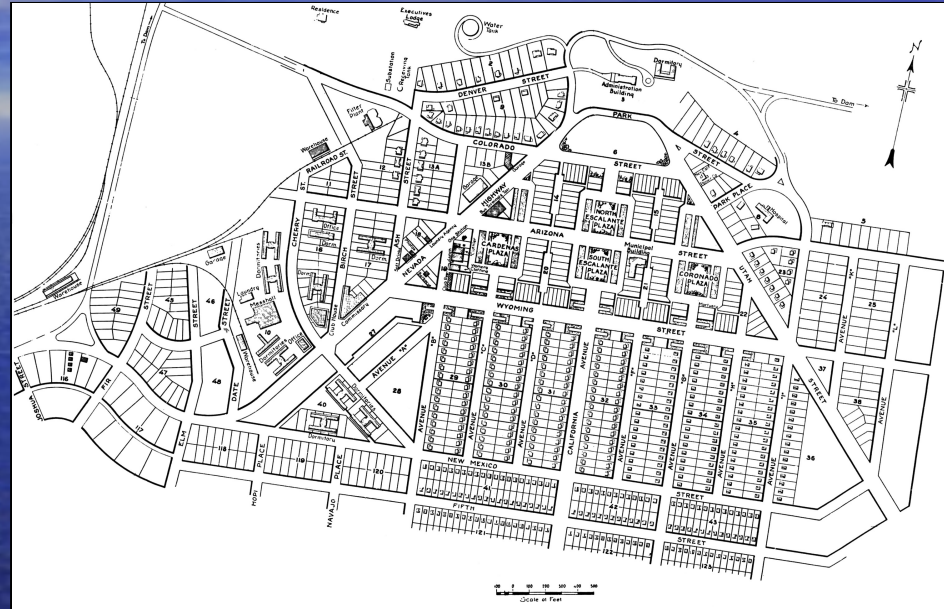
Several thousand workers and their families descended on the banks of the Colorado River in the spring and summer of 1931, hoping to find work. It was officially closed down on August 13, 1931, after several inhabitants succumbed to the heat.

Accommodating workers



21,000 men worked on the dam, with the average work force numbering **3,500 per month**, reaching a maximum of **5,218 in June 1934**. Average monthly payroll was \$500,000, disbursed on 10th and 25th of each month.

Boulder City - A model town owned by the Government



Boulder City was constructed by the Interior Department to house 5,000 workers and their families. No drinking or gambling allowed; remained a government town till 1961.

Un-balanced bid

- **Six Companies purposefully bid the rock excavation work high, at \$8.50 per yard, asking \$13,285,000 for 1,563,000 yds of tunnel excavation**
- **To compensate, Six Companies bid the concrete placement well below market price; at just \$2.70/yd: requesting \$9,180,000 for the dam's mass concrete and \$3,432,000 for lining the diversion tunnels, with high strength reinforced concrete**
- **The term of the contract was for seven years, with a \$3000/day performance penalty**

Largest Diversion Tunnels



At 56 feet in diameter and averaging 4,000 feet long; these were the largest diversion tunnels ever constructed at the time; under intense heat and air pollution. **Major obstacles were heat and air quality.** The contractor employed electric shovels inside the tunnels, but used gas-powered dump trucks.



Emergency room built on job site

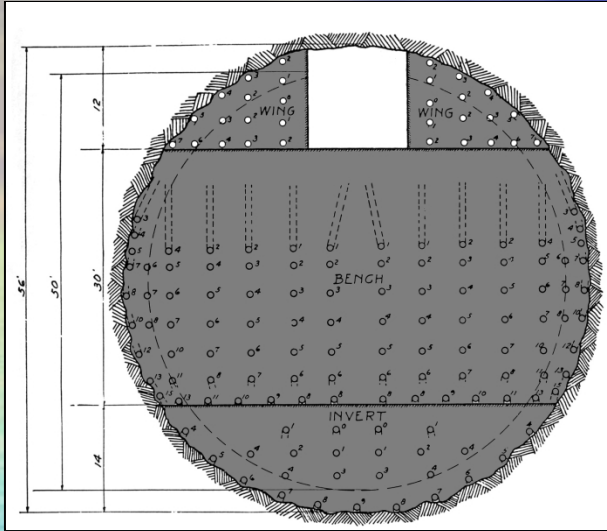
Death Toll



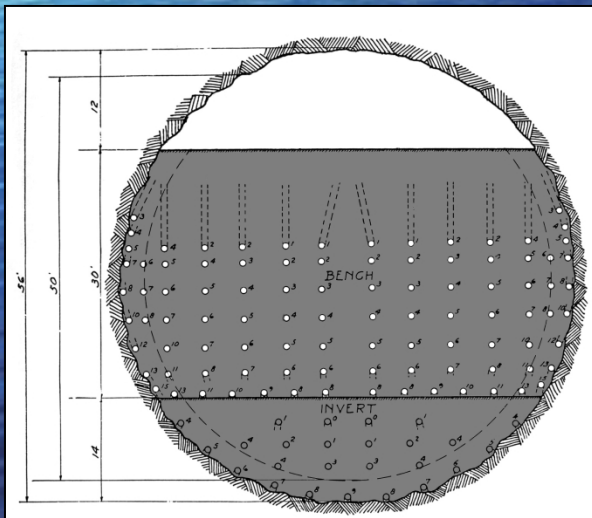
Water carriers added late summer 1931

During July 1931 14 men died working in the overheated and under-ventilated tunnels; necessitating changes in safety precautions. The official death toll for the entire job was 96; the unofficial total was 112.

Staged Excavations



Pilot bore in tunnel crown

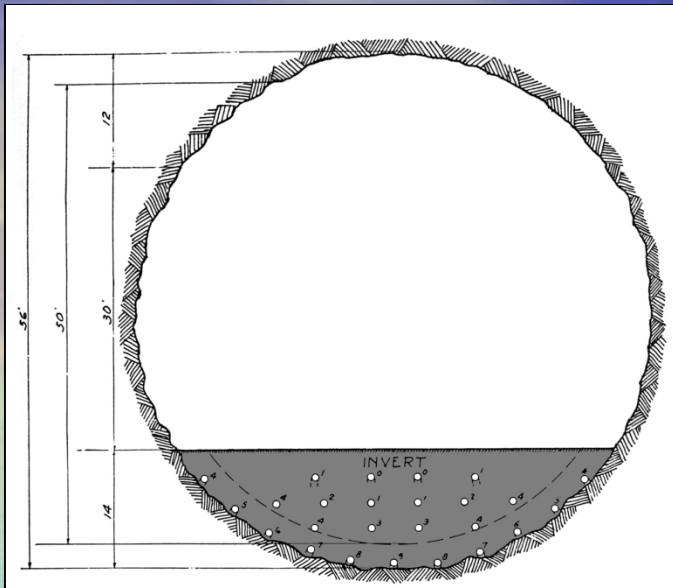


Jumbo drilled holes shown in white

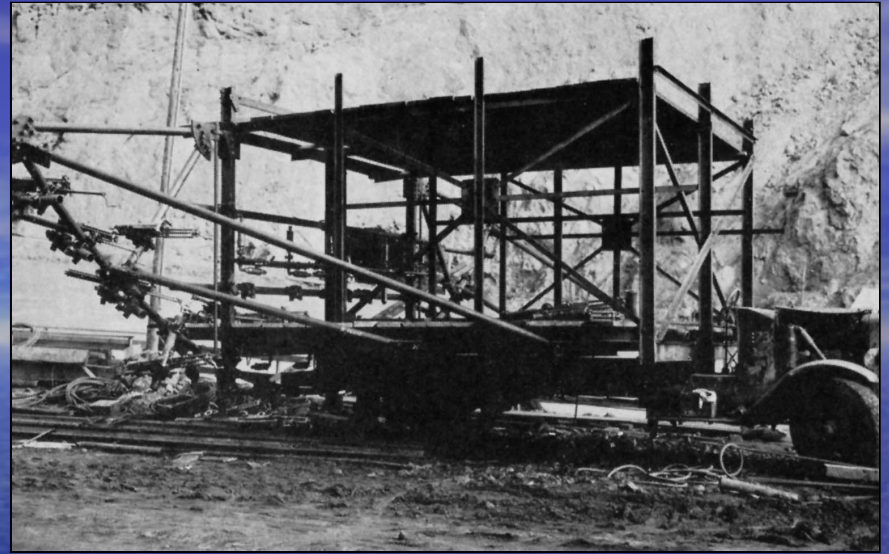


World's first drilling jumbo

Frank Crowe appreciated what later came to be known as **critical path management**. The biggest challenge was completing the four diversion tunnels by May 1, 1934, before the spring runoff arrived.



Tunnel Invert excavated last



Invert drilling jumbo



Finished 56 foot diameter bore



Ready for lining

Flash flood



All of the diversion tunnel portals were inundated, filling them with fine silt.

- Despite the fact that there hadn't been a flash flood on the Colorado River during the month of February for over 20 years... a **flash flood** inundated the construction site on February 10-11, 1932, before any of the diversion tunnels were completed. The shutdown and clean-up lasted 5 days.



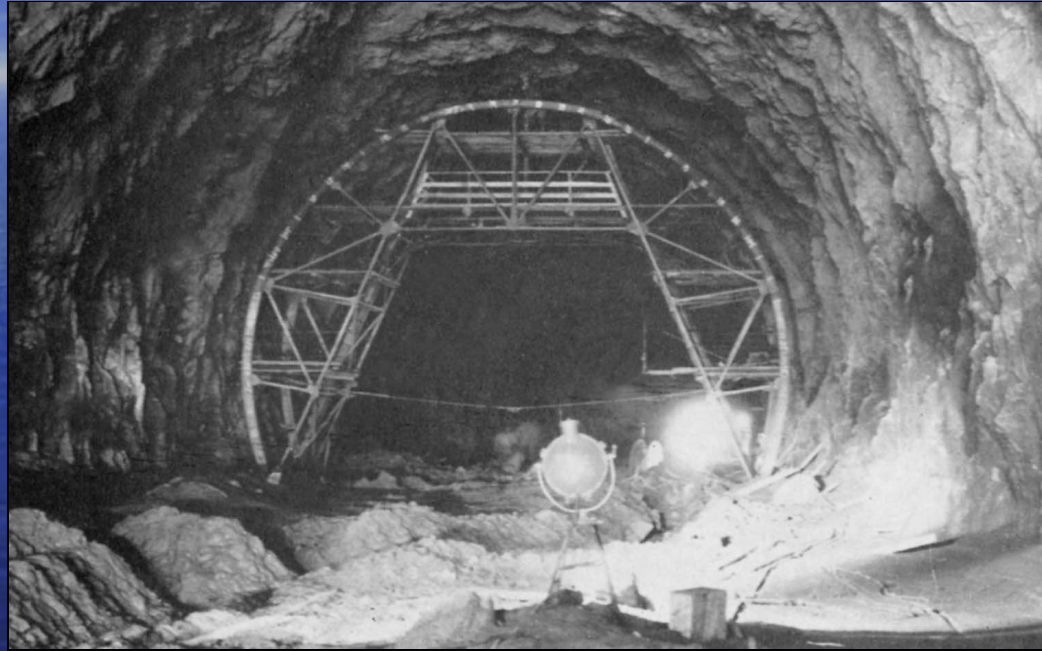
- The February 1932 flood and its associated clean-up reduced progress on excavating the diversion tunnels by 2/3 of what had been accomplished the previous month.
- These views show the reconstruction of one of the new temporary trestle bridges the contractor built at his own expense (note pile-driving derrick), and the completed structure, as viewed on March 7th, 1932.
- Note the extensive use of 'wing fills' along the channel (far right), which allowed vehicular access.



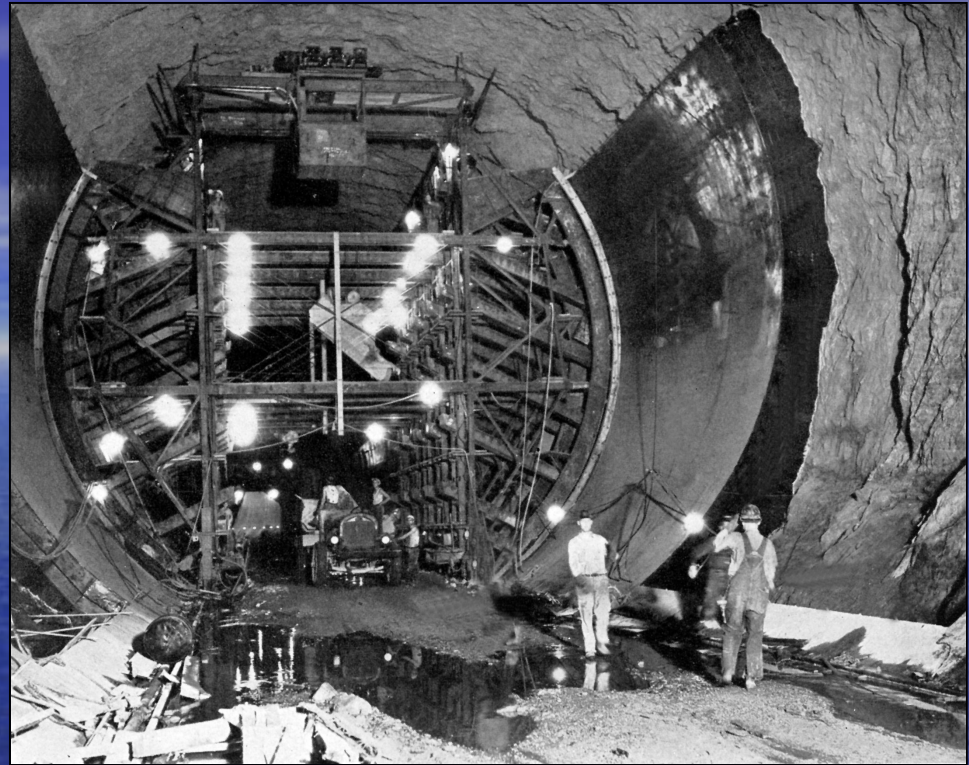
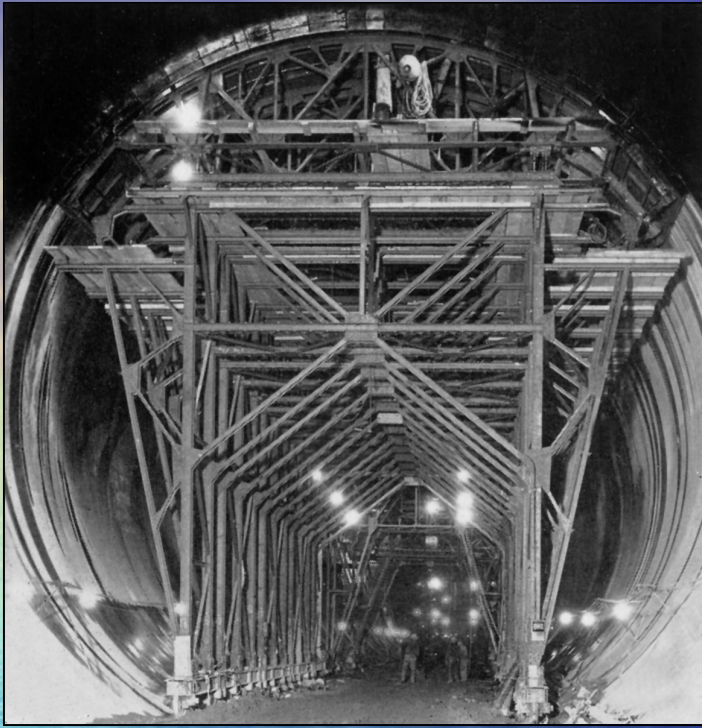
Wing, or channel fills

- The only way Six Companies could gain vehicular access to the dam site was by building temporary bridges, excavating tunnels, and placing enormous fills along the base of the cliffs, much of it at their own expense.
- They were paid to excavate 6 million cubic yards of rock and gravel on the job.

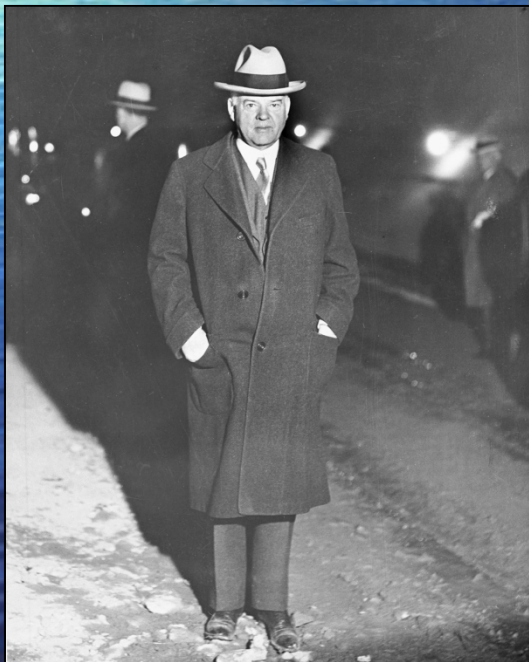
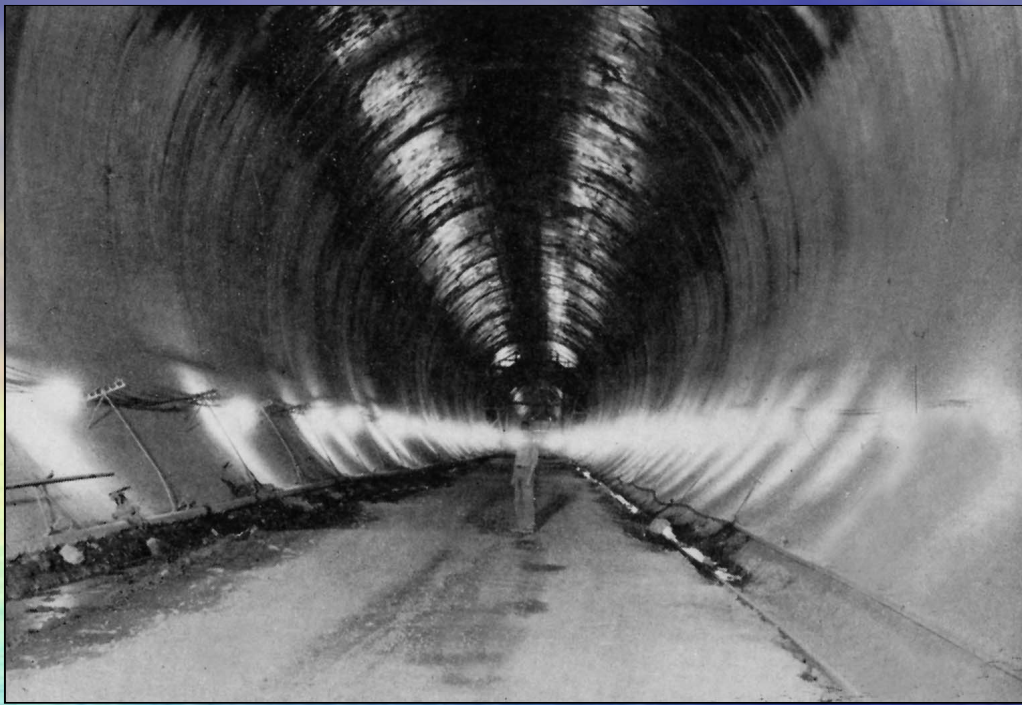
Concrete tunnel lining



The tunnel was lined with 3 feet of reinforced concrete, requiring 312,000 cubic yards of 5-sack per cubic yard structural concrete. Lining of the four diversion tunnels alone cost \$3,432,000, more than the cost of most dams prior to 1931.



The contractor employed steel slip forms, using diesel fuel as a form bond breaker. The most difficult pour was the crown, across the top of the tunnel.



After lining, the invert section was temporarily backfilled with a gravel bed to provide vehicular access until the tunnels were filled with water.

View at left shows President Hoover walking through one of the Nevada diversion tunnels during his only site visit, in December 1932

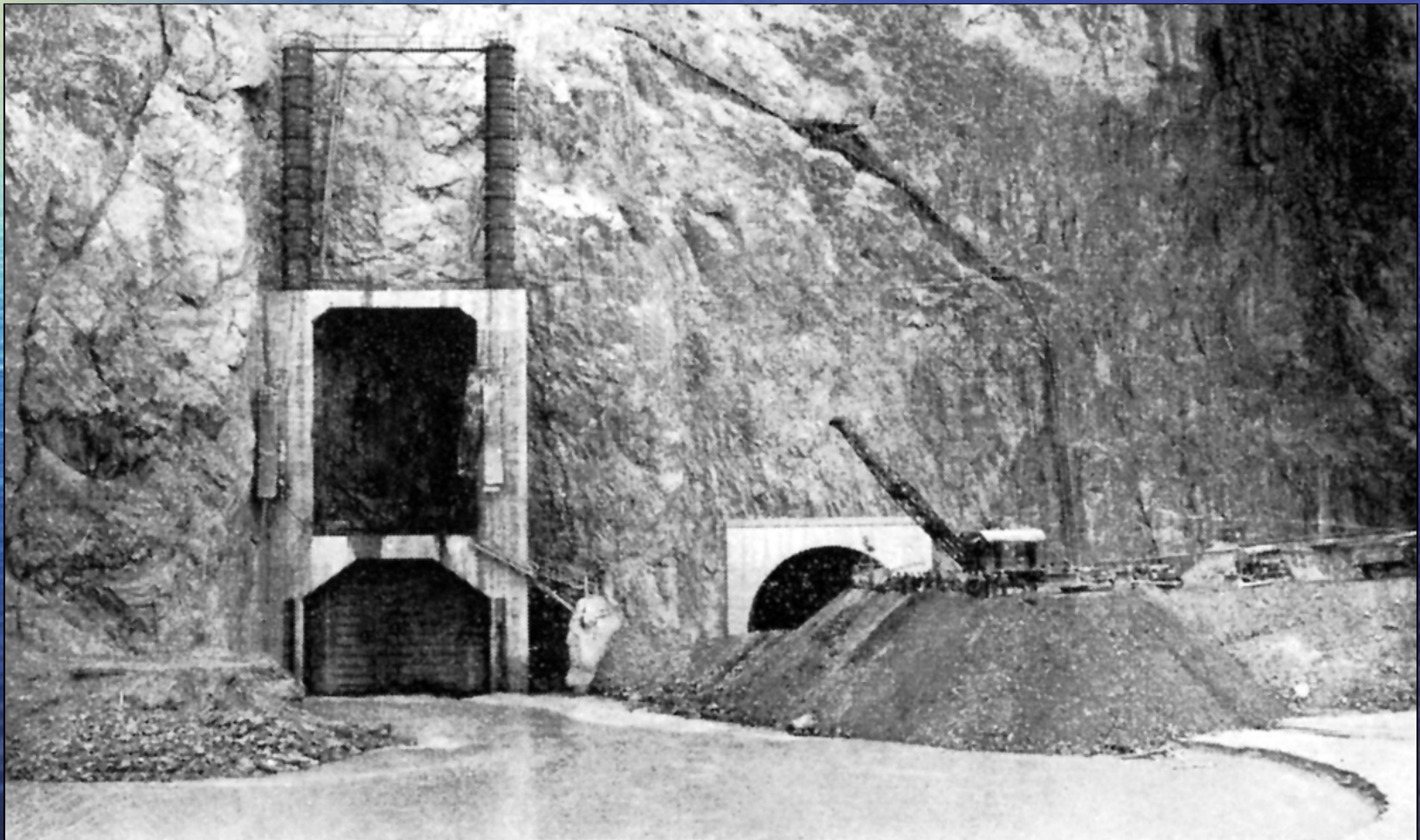
Diverting the river – Sept to Nov 1932



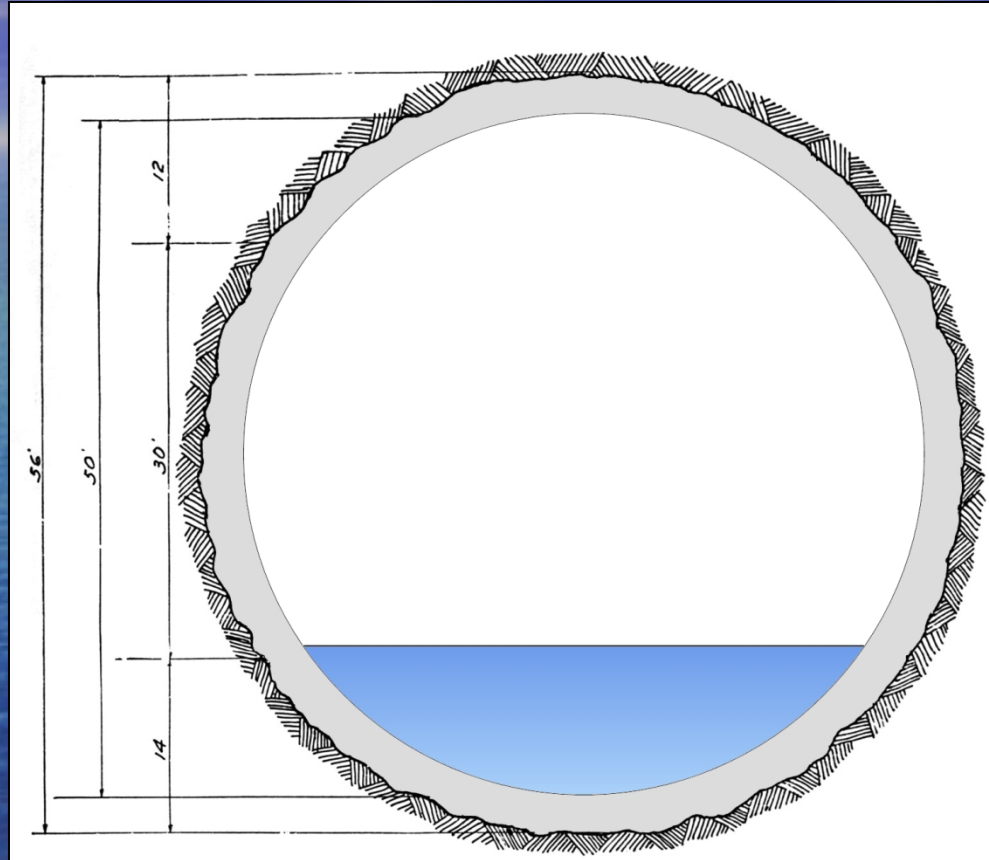
- When the Colorado River dropped to its seasonal low flow in September 1932, Six Companies began placing rockfill dikes, shown here.
- The river was turned into Tunnel No 4, the outboard Arizona tunnel, during the late evening of Sunday November 13, 1932



River flow was diverted through Tunnel No. 4 on Nov. 14, 1932; 1.5 years ahead of schedule; guaranteeing a profitable job

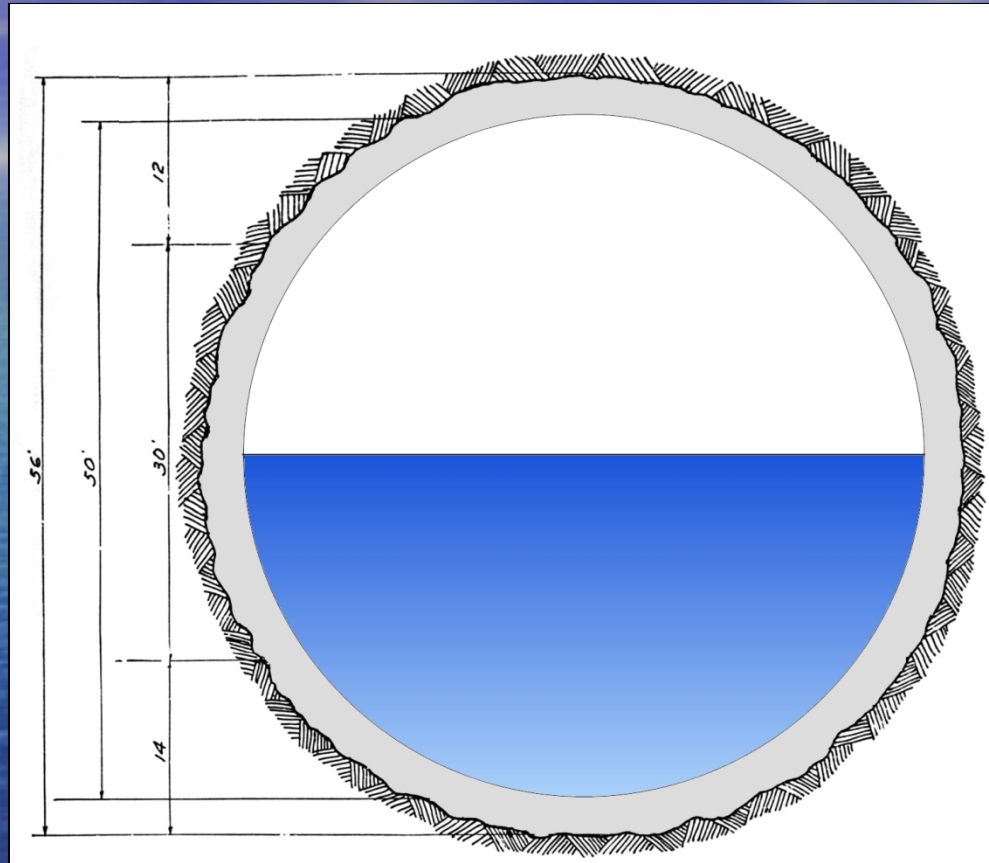


Massive diversion tunnels



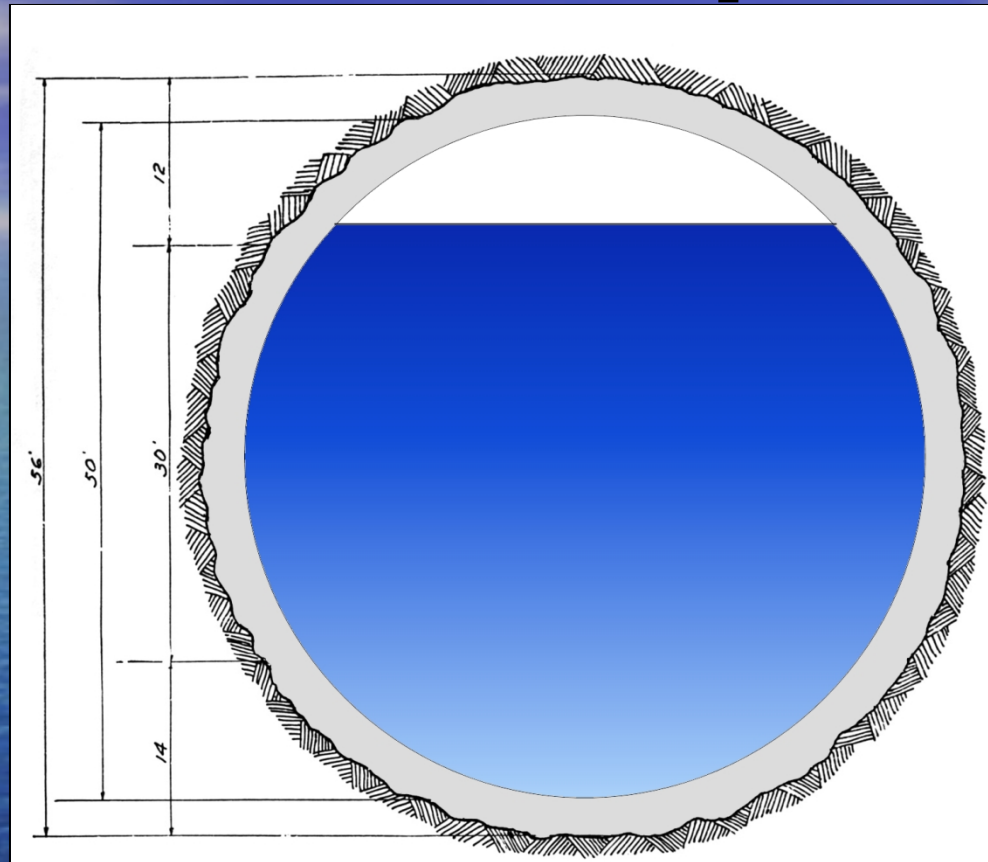
- The spring flood of the Colorado River averaged 120,000 cfs every 2-1/2 years, generally peaking between late May and late June. Prior to construction, great concern was expressed about the job site being flooded and disrupting the project's 6-year schedule.

Diversion scheme influenced by considerations of risk-consequence



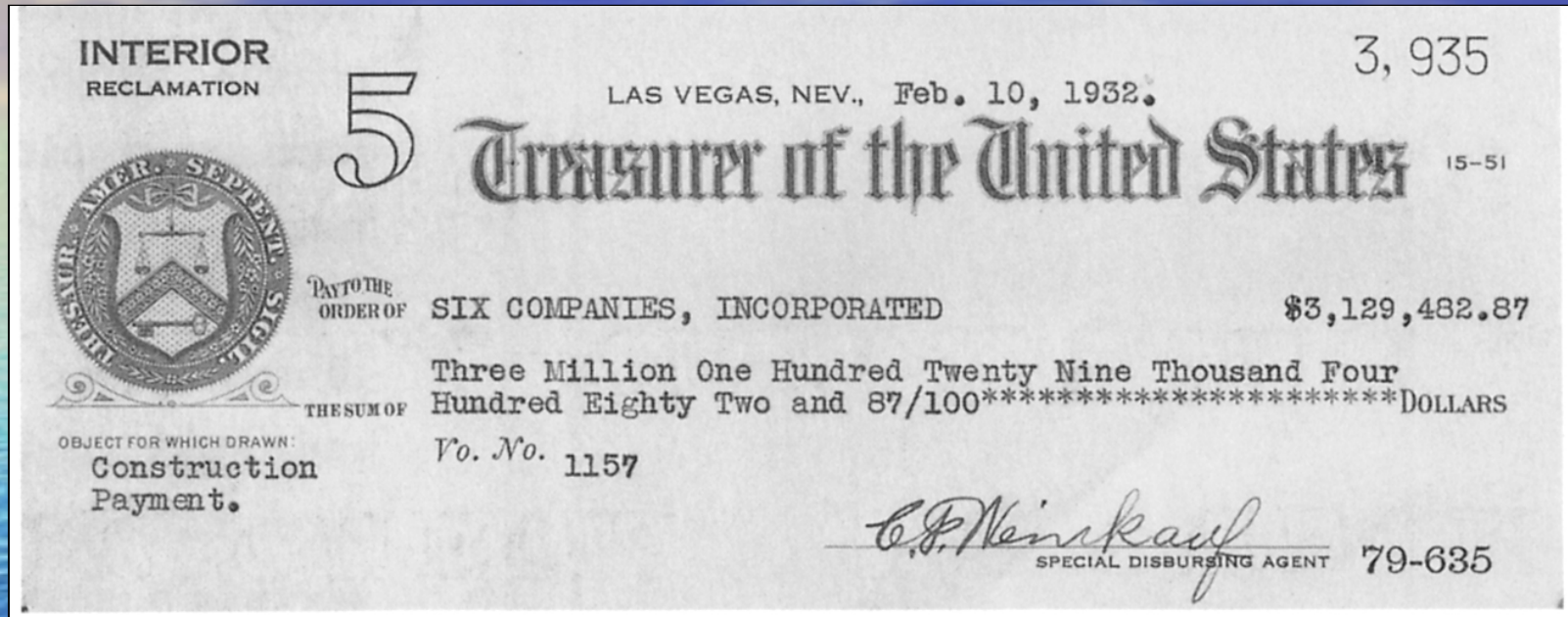
- Each of the four diversion tunnels were designed to convey 50,000 cubic feet of water per second (cfs); for an aggregate total of 200,000 cfs, during construction. This level of conservatism was unprecedented for a construction job of a few years duration.

Minimum versus peak flows



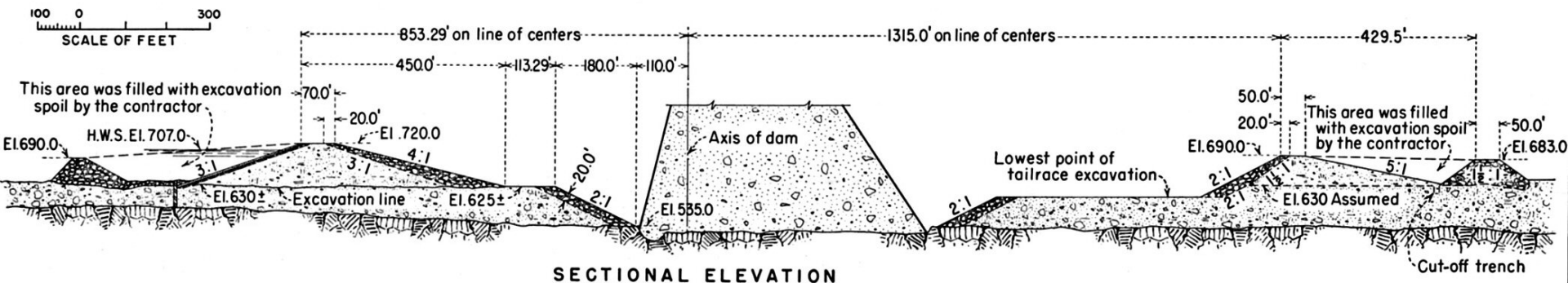
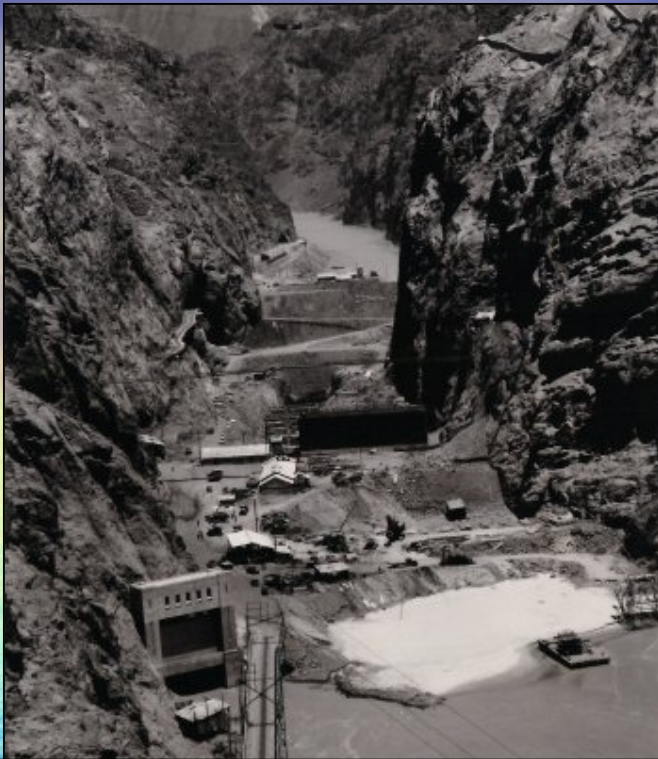
- The **biggest flow** the tunnels had to handle during construction occurred on June 16, 1933 when 73,000 cfs was safely conveyed around the dam site, while the **minimum flow** of 1,000 cfs was recorded on August 26, 1934.

Advantage of an under balanced contract: cash up front



- The excavation of the four diversion tunnels cost \$13,285,000, 27% of the project cost. The concrete lining cost another \$3,432,000. This provided \$4.4 million in profit, allowing the partners to repay the \$2 million bid bond and \$5 million construction surety they put up when they signed the contract.
- With \$5.8 million in extras, Six Companies ended up charging \$54.7 million for the dam, netting \$10.4 million in profits, after taxes.

Cofferdams



The 100 foot high cofferdams required 732,000 cubic yards in the upstream dike and 500,000 yards in the downstream embankment.

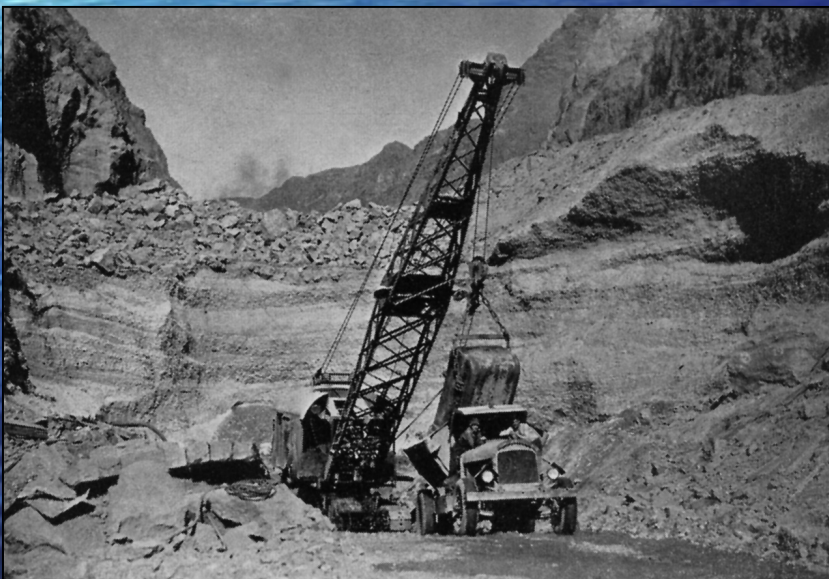
Lots of Surprises



A total of 6 million yards of material was excavated at the dam site.

A sawn 2 x 6 plank was found in the river bed buried 50 feet beneath the low water surface. Geologists suggested that it was deposited from a debris flow in Callville Wash during the high water of 1922.

Cleaning out the inner gorge

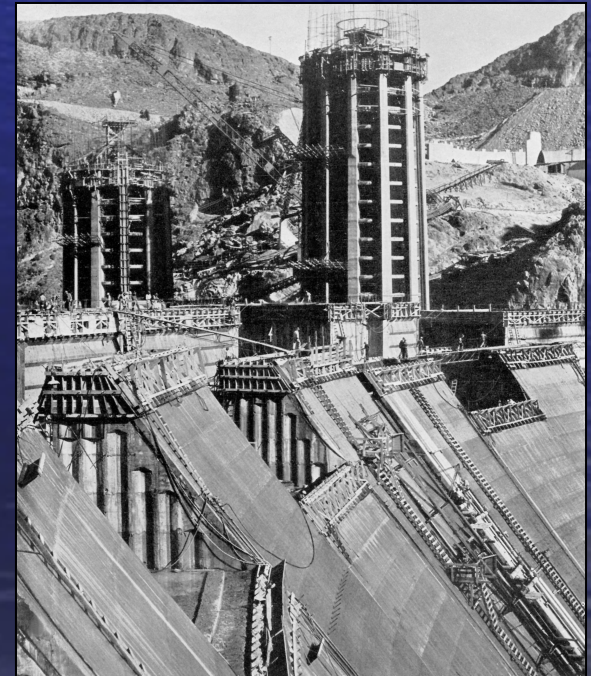
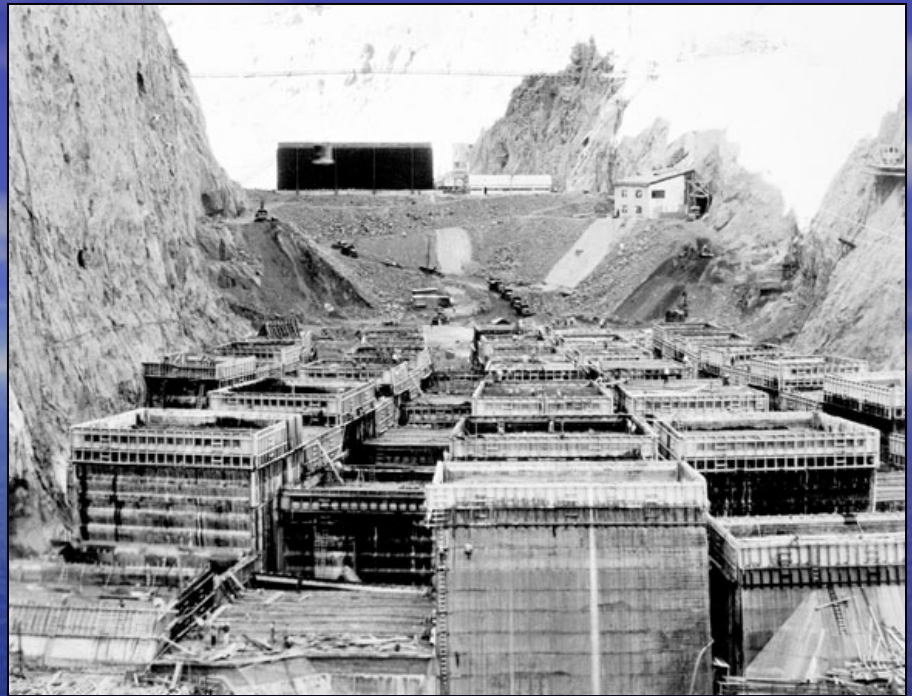


About 2 million cubic yards of material was excavated out of the river channel beneath the dam, revealing an incised inner gorge with fluting and boulders up to 12 feet across.

First concrete poured on June 6, 1933, 1.5 years ahead of schedule

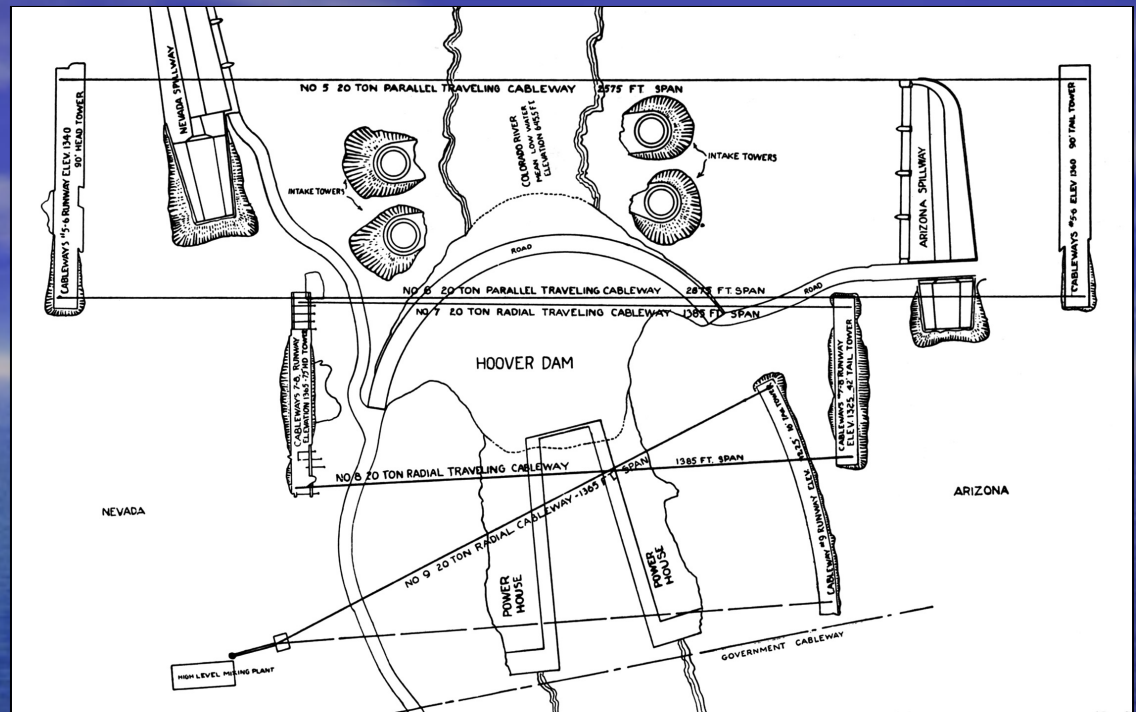


Most of the mass concrete was placed using 8 cubic yard hopper buckets, delivered via the overhead cableways. Each bucket carried 16.5 tons of concrete.

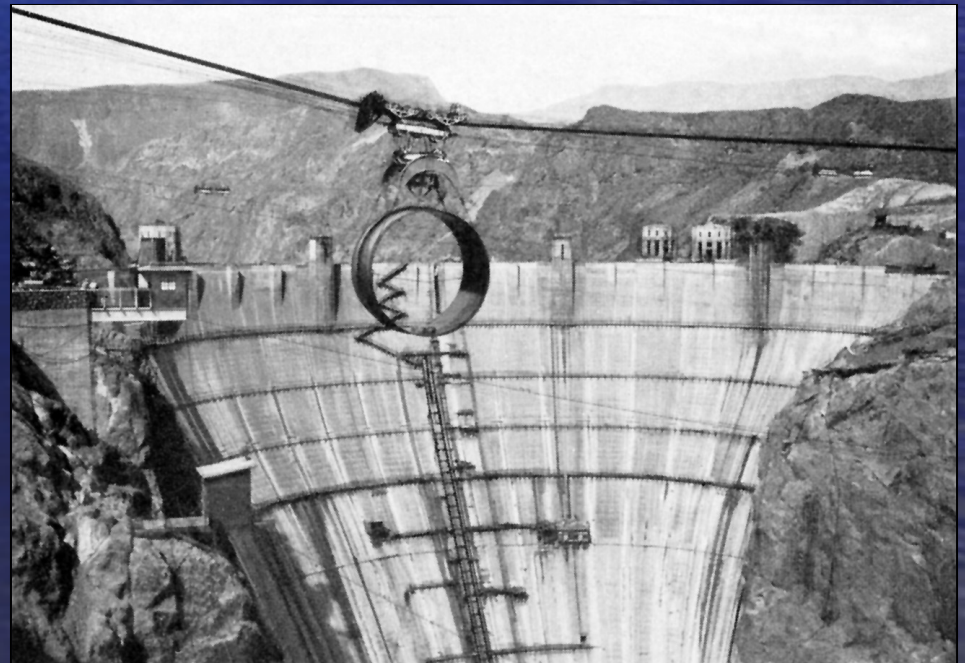


The dam required 3.25 of the project's 4.36 million cubic yards of mass concrete, at a cost of \$9,180,000. This was placed between June 6, 1933 and May 29, 1935; 2-1/2 years before the contract required completion.

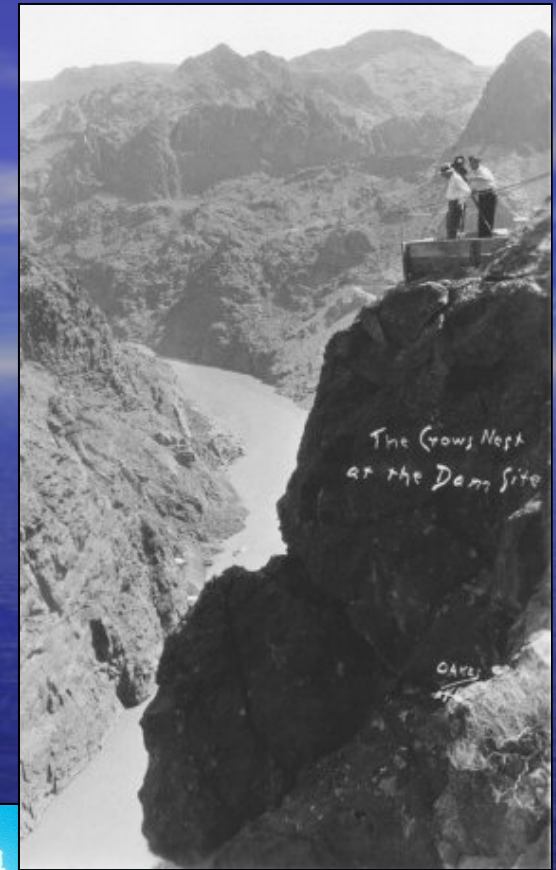
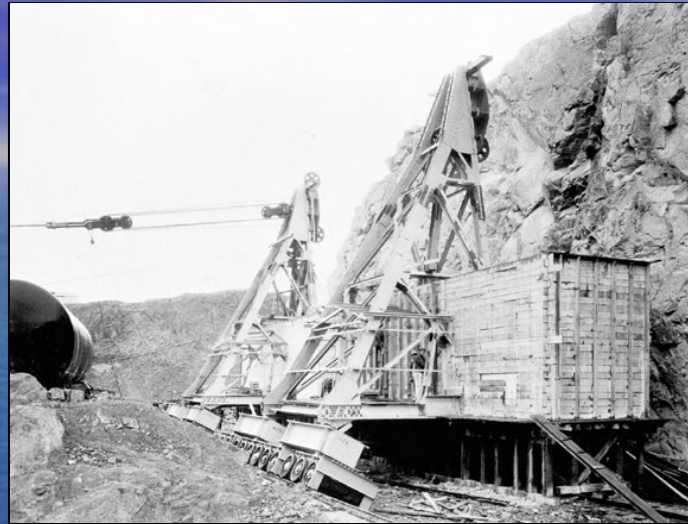
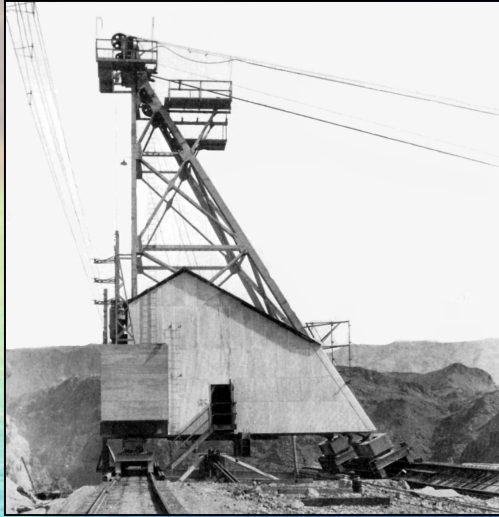
Cableway scheme



Frank Crowe was masterful in the use of overhead cableways to convey concrete and building materials with pinpoint accuracy. He had first used cableways at Arrowrock Dam back in 1911.



Cableways



Crow's Nest

**Permanent 150
ton cableway**

Gravel and sand for concrete only material items not supplied by government



Aggregate came from a site 6 miles upstream of Black Canyon on Arizona side. Aggregate up to 9 inches in diameter was used in concrete.

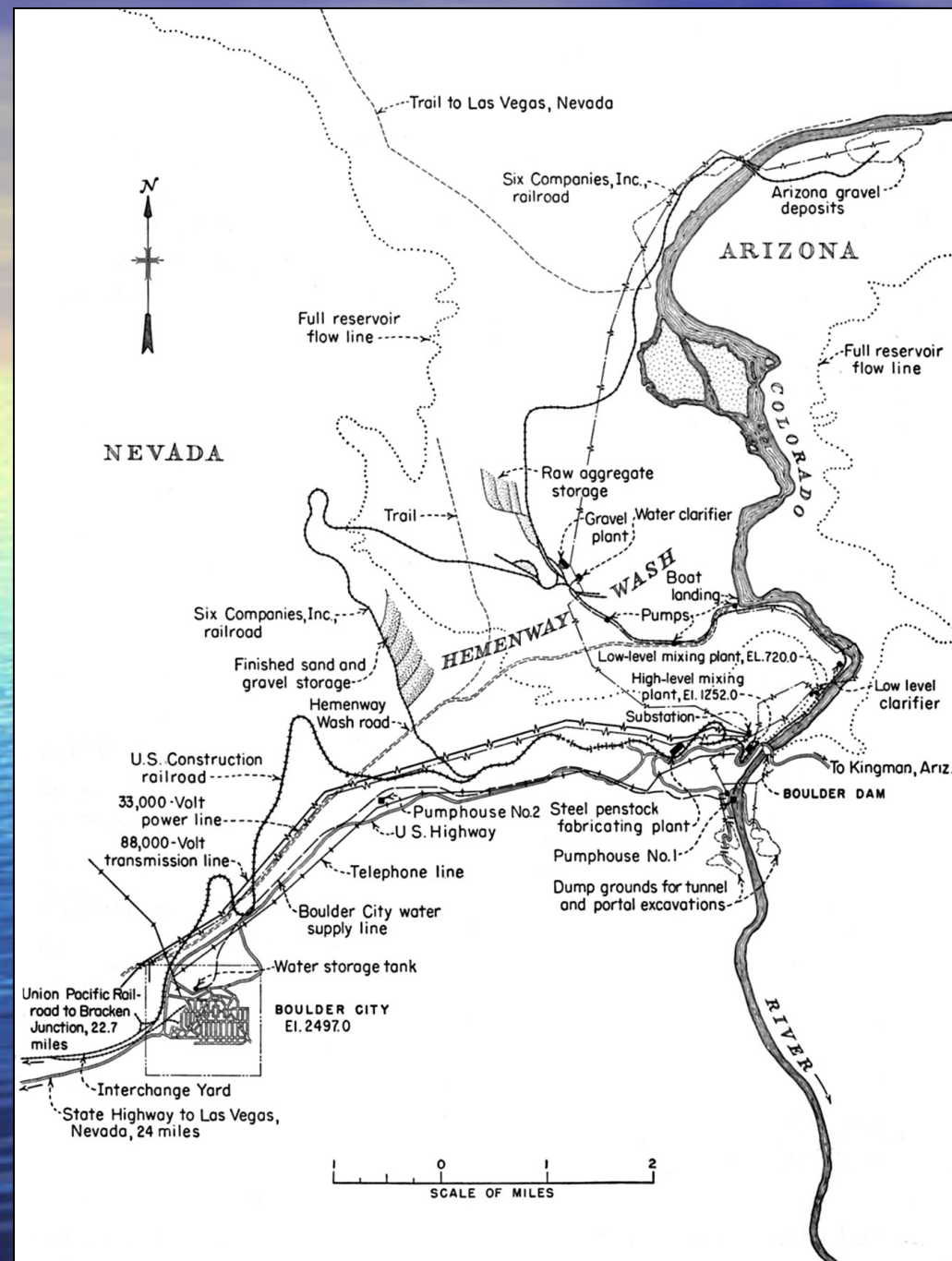


- **Left: Six Companies located a suitable aggregate quarry in the terrace gravels on the Arizona side of the river, about 12 miles upstream of the dam site.**
- **Right: They built a rail line with a trestle over the Colorado River to haul aggregate to Classification Plant in Hemenway Wash.**

Aggregate Classification Plant

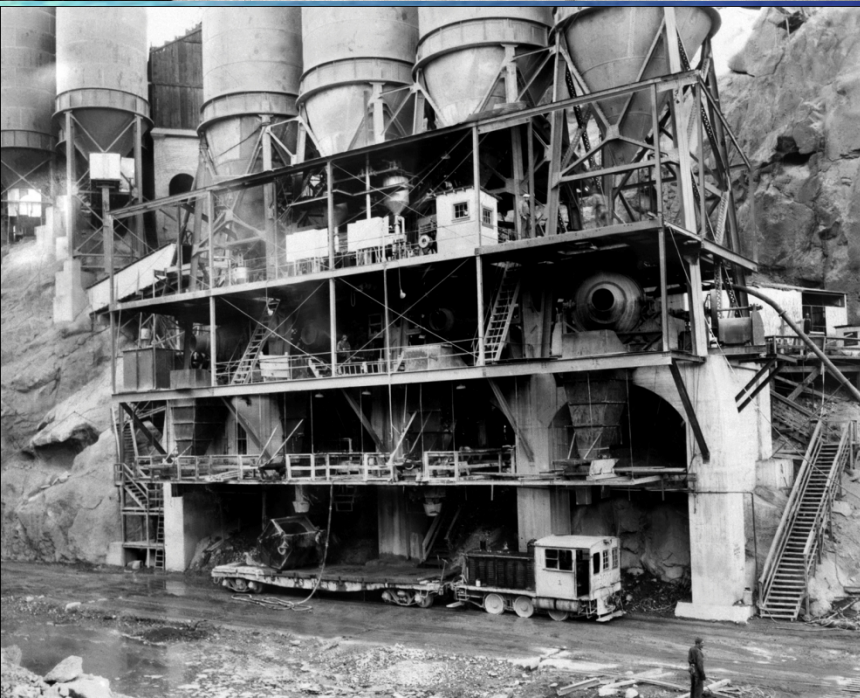


- A aggregate washing, classification and storage plant was constructed in Hemenway Wash, capable of classifying 20,000 tons/day





- The **Low-Level Mix Plant** was situated on a wing fill in the Colorado River on the Nevada side, about 4,000 ft upstream of the dam.
- The greatest concrete demand was below elevation 600, where the dam was widest.
- Production of the two batch plants peaked in March 1934, when they produced 262,000 cubic yards of concrete.
- This plant shut down in late October 1934 when the dam reached el. 800 ft and most of it was dismantled and moved to the Parker Dam site, Frank Crowe's next contract.



- **The Hi-Level Mixing plant** was highly automated, bearing the entire workload after November 1, 1934. It produced as many as 16 different types of mixes, depending on the needs for that day.

Concrete placement at Hoover Dam

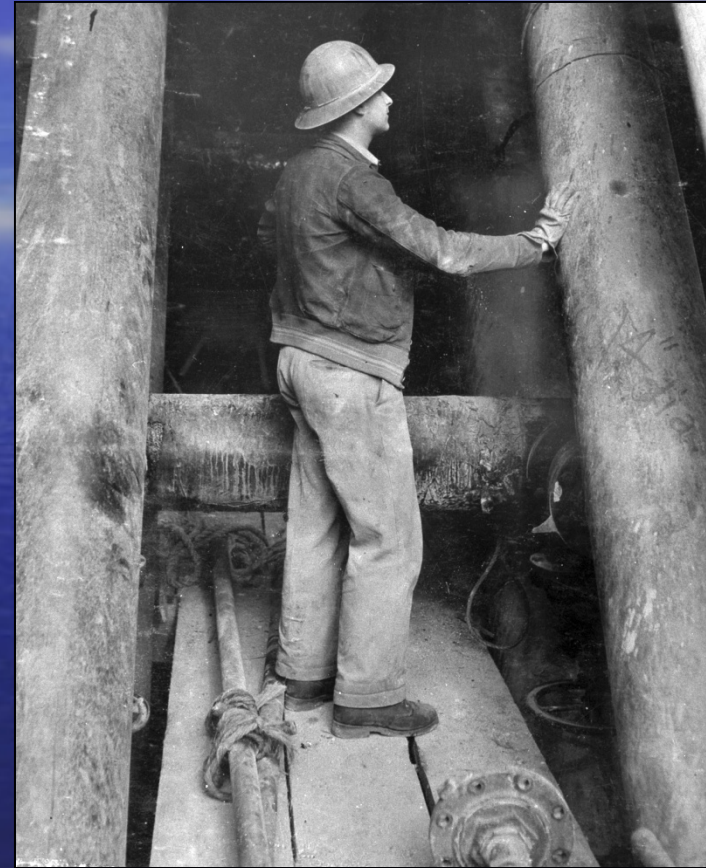
CONCRETE PLACED		PROGRAM AND PROGRESS																																																																							
PROJECT FEATURES	APPROXIMATE QUANTITY (See Note)	1932												1933												1934												1935												1936												1937											
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
DIVERSION WORKS																																																																									
Lining for tunnels	307,900 cu. yd.																																																																								
Eight portals and gate structures	20,800 " "																																																																								
Cofferdams, principally upstream face slab	3,500 " "																																																																								
DAM																																																																									
Dam proper	3,241,900 cu. yd.																																																																								
Parapets and towers	4,800 " "																																																																								
Abutment seals and safety island	4,500 " "																																																																								
SPILLWAYS																																																																									
Weir sections, channel linings, and highway bridge	127,600 cu. yd.																																																																								
Lining two inclined tunnels	25,400 " "																																																																								
Two tunnel plugs	66,300 " "																																																																								
OUTLET WORKS AND PENSTOCK SYSTEM																																																																									
Four intake towers and bridges	94,300 cu. yd.																																																																								
Lining tunnels from d.s. intake towers to valve houses	29,200 " "																																																																								
Lining tunnels from u.s. intake towers to diversion tunnels	4,000 " "																																																																								
Backfill in sloping sections of tunnels from intake towers	20,400 " "																																																																								
Backfill in 120-ft. radius curve, Nevada header tunnel	2,100 " "																																																																								
Piers and other supports for penstocks in tunnels	10,200 " "																																																																								
Two upstream plugs in inner diversion tunnels	49,800 " "																																																																								
Two downstream plugs in inner diversion tunnels	28,000 " "																																																																								
Two outlet valve houses	17,200 " "																																																																								
Lining 16 penstock tunnels	16,300 " "																																																																								
Lining shafts and adits, and miscellaneous items	6,400 " "																																																																								
POWER HOUSE																																																																									
Substructure and penstock anchors	195,300 cu. yd.																																																																								
Superstructure	47,400 " "																																																																								
Government cableway (150-ton)	14,600 " "																																																																								
Control circuit tunnel lining and switching station	6,500 " "																																																																								
Highway tunnel lining, sidewalks, etc.	3,300 " "																																																																								
TOTAL CONCRETE	4,347,700 cu. yd.																																																																								
PREPARATION OF CONCRETE																																																																									
Stripping at Arizona gravel deposit	490,000 cu. yd.																																																																								
Sand and gravel excavated	9,300,000 tons																																																																								
Aggregate processed	8,500,000 "																																																																								
Concrete production at low-level mixing plant	2,215,000 cu. yd.																																																																								
Concrete production at high-level mixing plant	2,285,000 " "																																																																								
Cement blended	4,265,000 bbl.																																																																								
Total cement	5,100,000 "																																																																								

Proposed program
 Construction progress as indicated in monthly estimates

Note: Concrete yardages for structures are based on pay quantities to March 1, 1936, for contract work, additional quantities to November 1, 1936, for work by Government forces on tunnel plugs and powerhouse.

- **Through amazing levels of production and placement coordination, Crowe picked up another year on the construction schedule, bringing the job to completion two years early.**

One of the first hard hat jobs

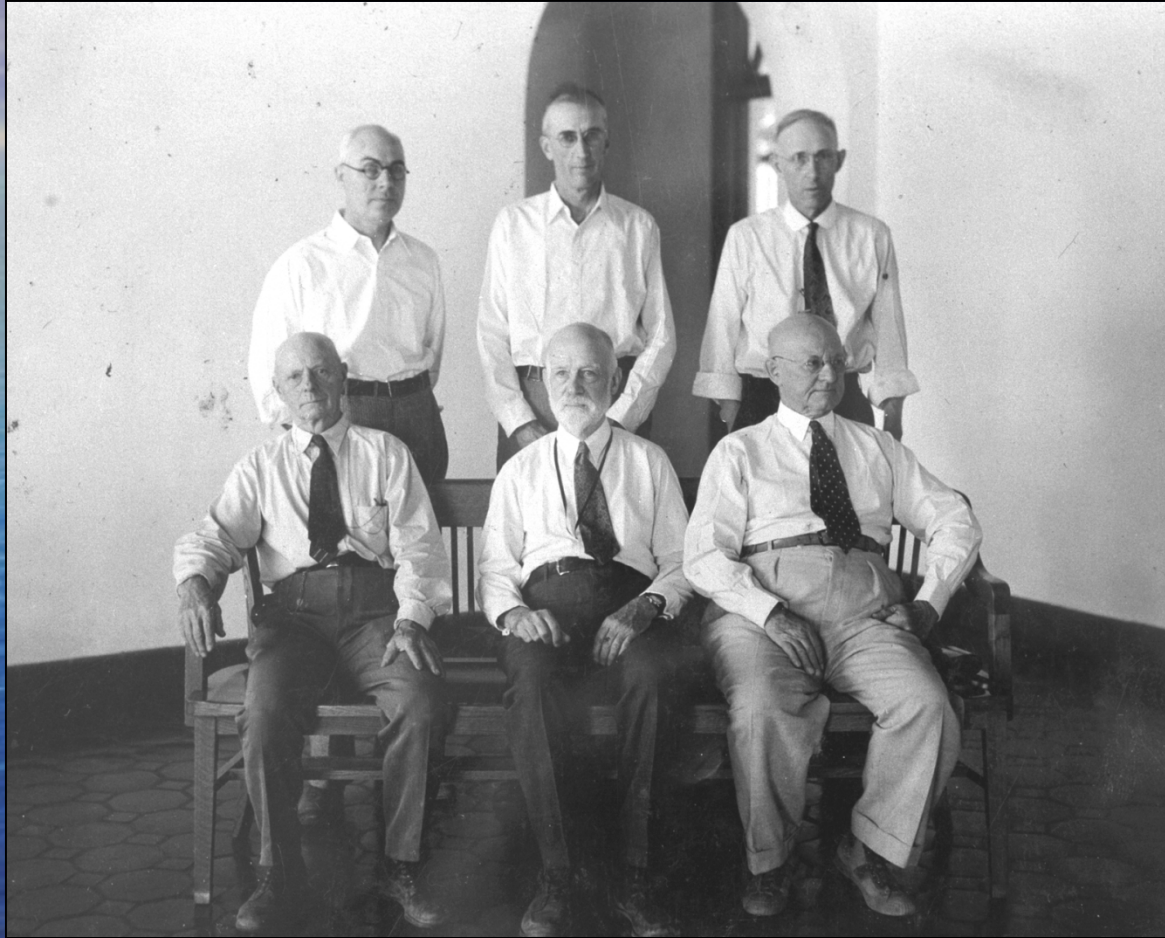


A number of workmen began fashioning their own safety hats by overlapping two baseball caps and dipping them in light tar to create a hardened shell for protection from falling debris (left image). Six Companies eventually supplied workmen with helmets, like those shown at middle and right.



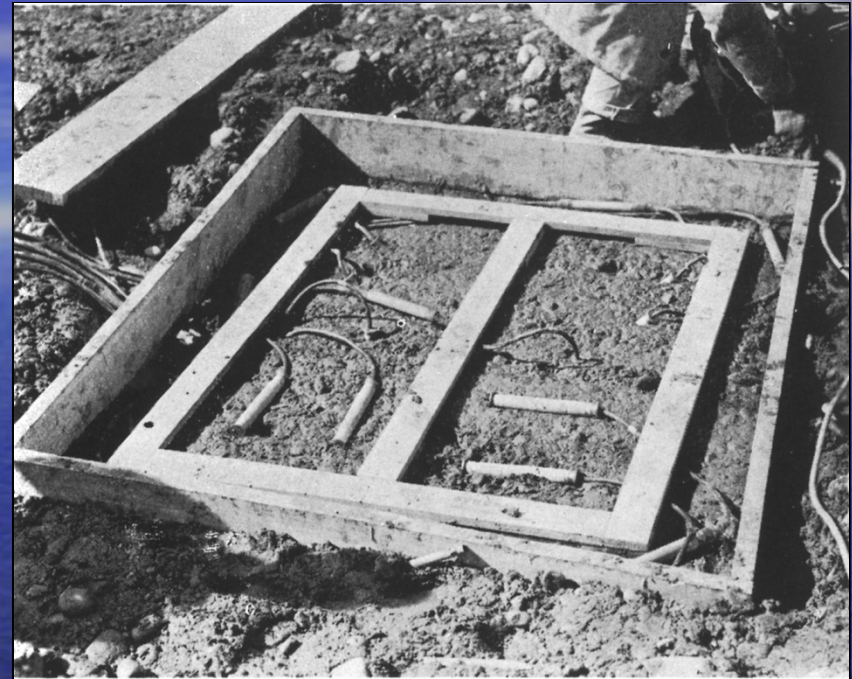
- Hoover Dam was the first **round-the-clock** federal public works project, using three shifts per day, seven days a week.

First Reclamation Use of External Board of Consulting Engineers on a dam

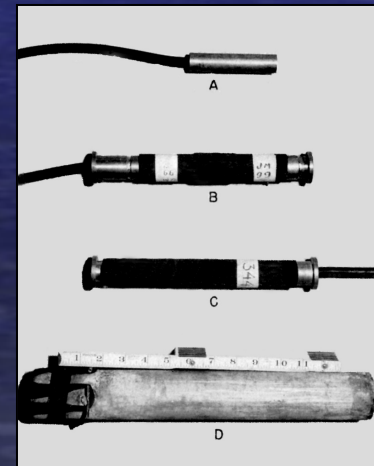
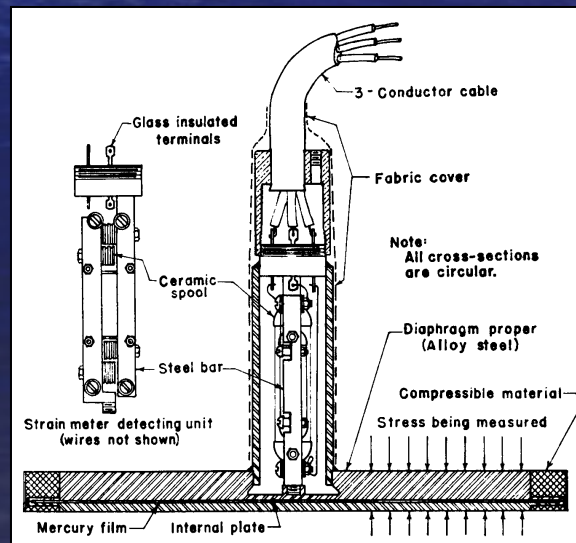


- **Standing: Reclamation engineers Jack Savage, Sydney O. Harper, B. W. Steele; Sitting: Consulting engineers D. C. Henny, W. F. Durand, and Louis C. Hill (September 1, 1933)**

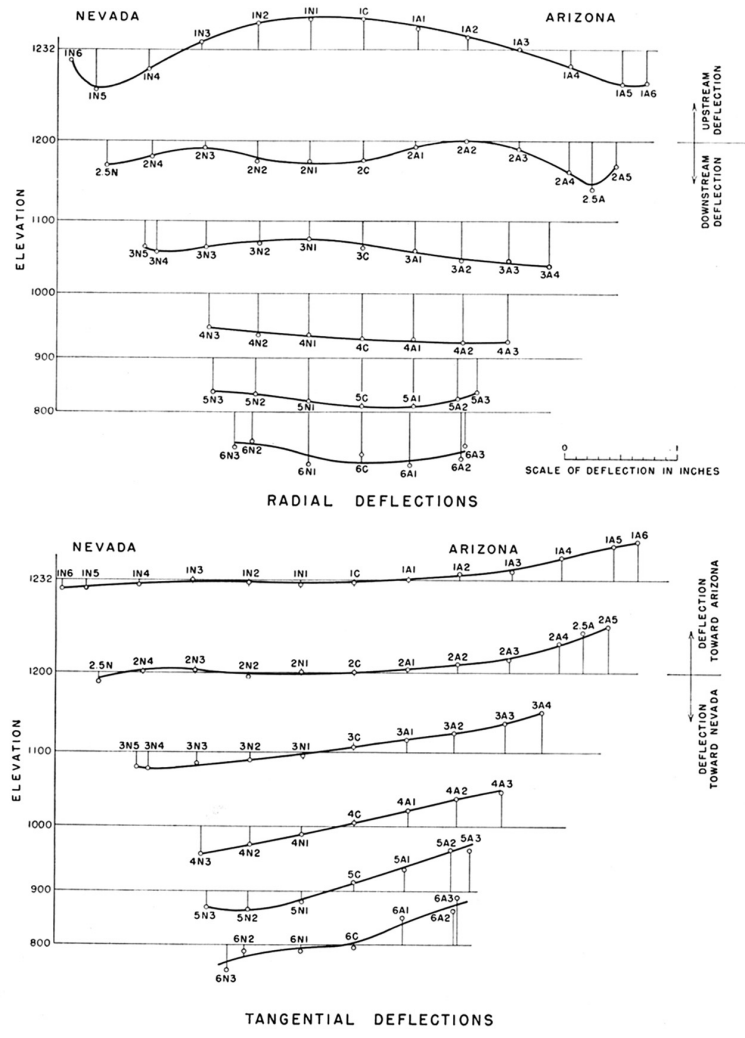
First Use of Embedded Instrumentation



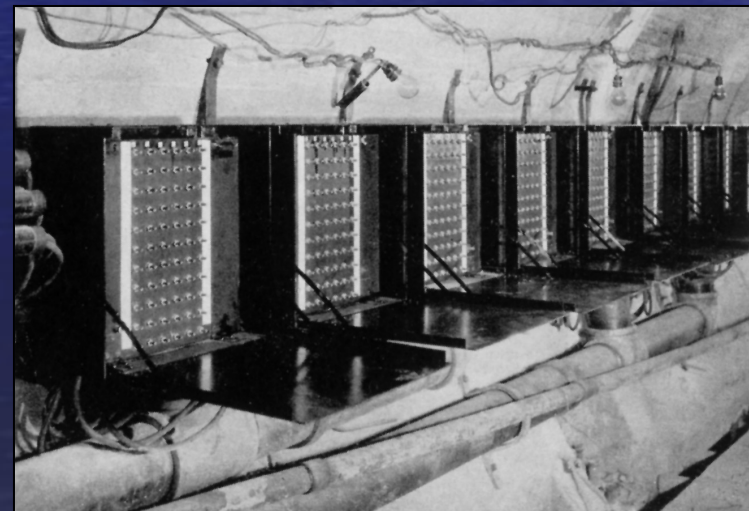
Carlson Stress meters and strain meters were embedded in the dam's mass concrete at various locations to record loads and strains as water rose against the dam.



Unprecedented Stress Analyses

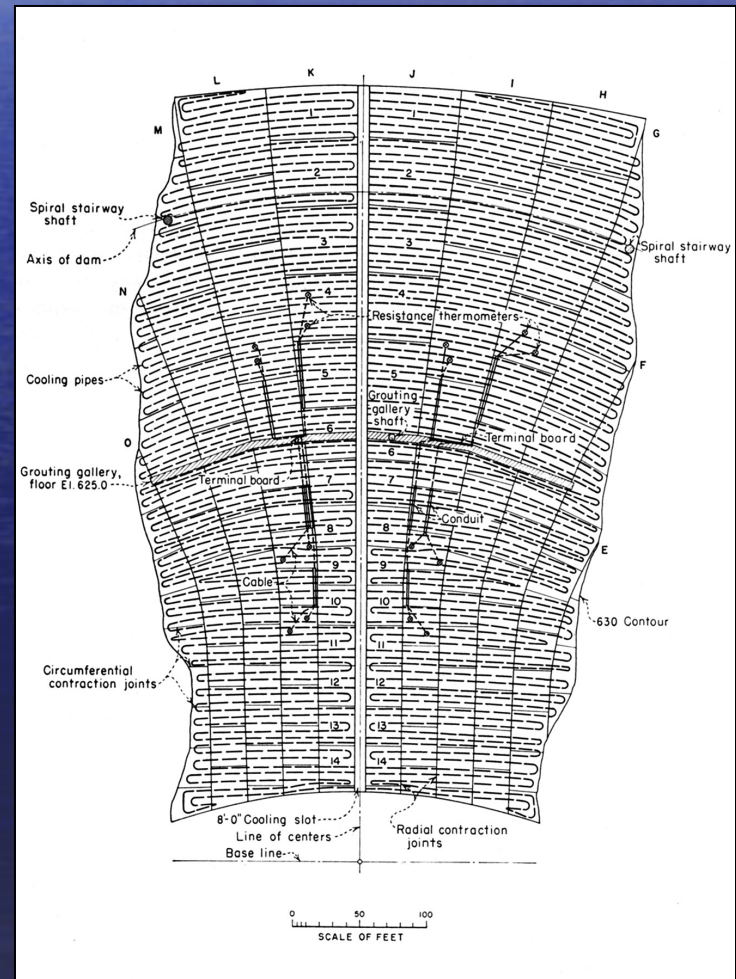
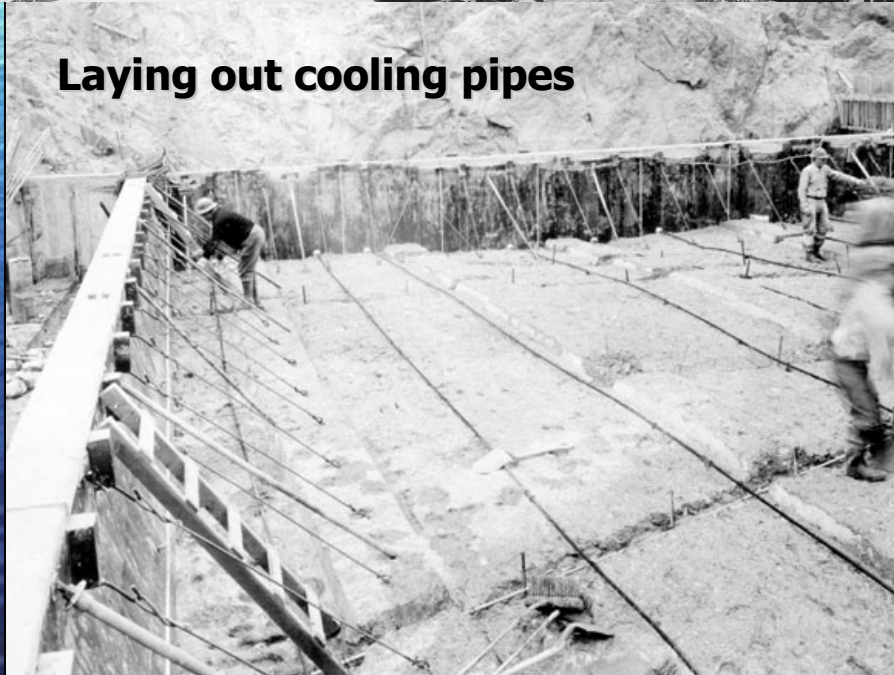


Roy W. Carlson



The structural performance data allowed validation of the **Trial Load Analysis** theory that had been developed in the late 1920s for arch dams.

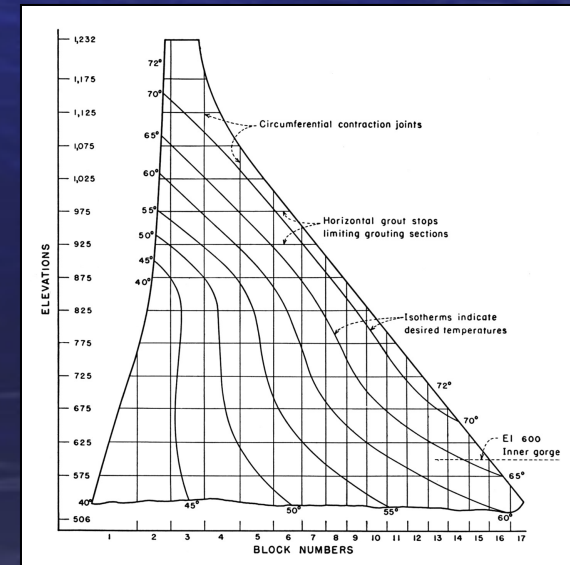
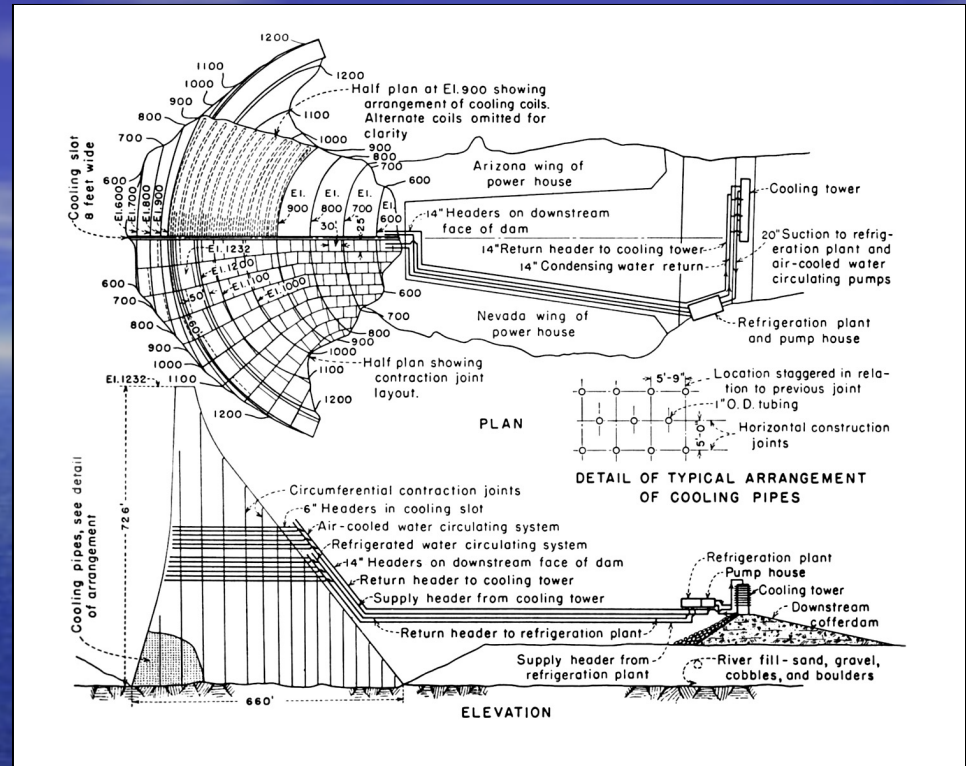
First Use of Aggregate chilling and Cooling of Mass Concrete



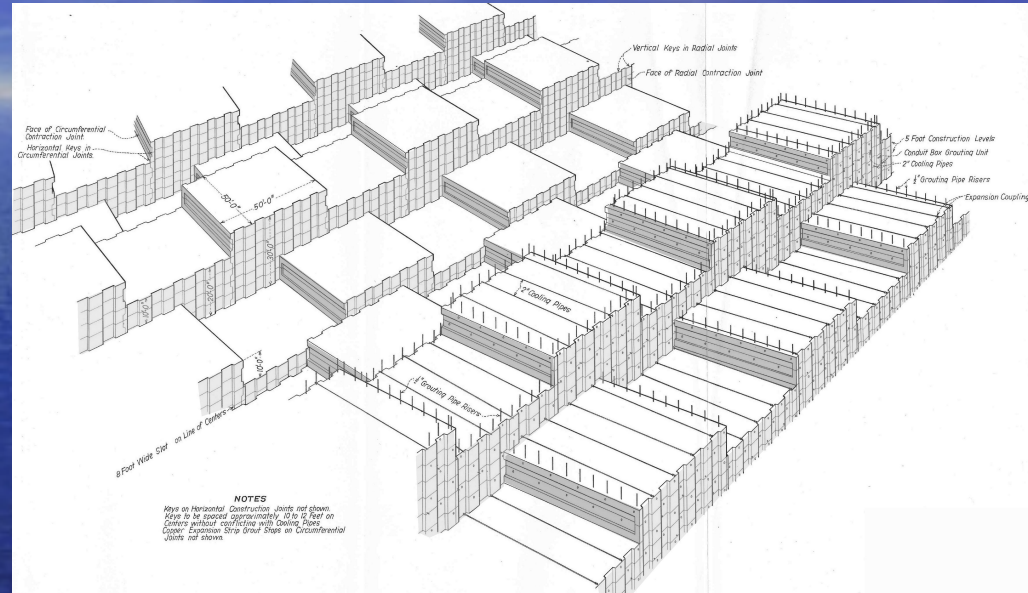
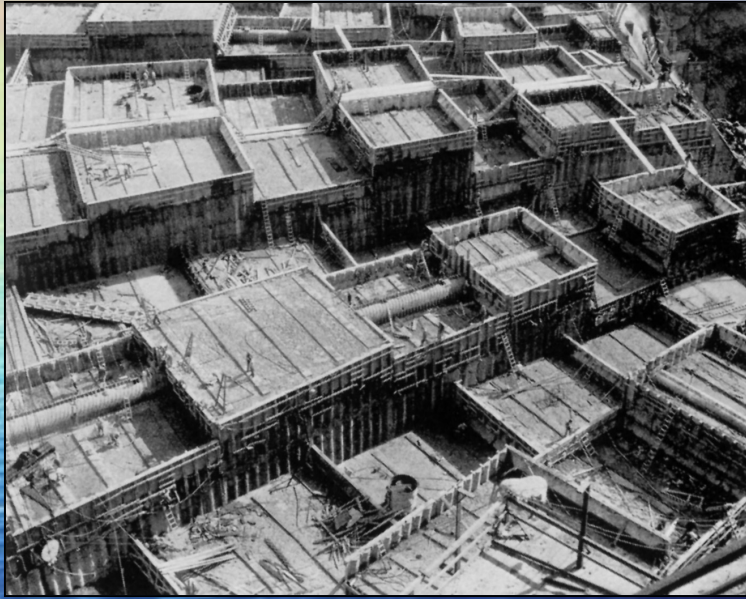
The "Big Slot"



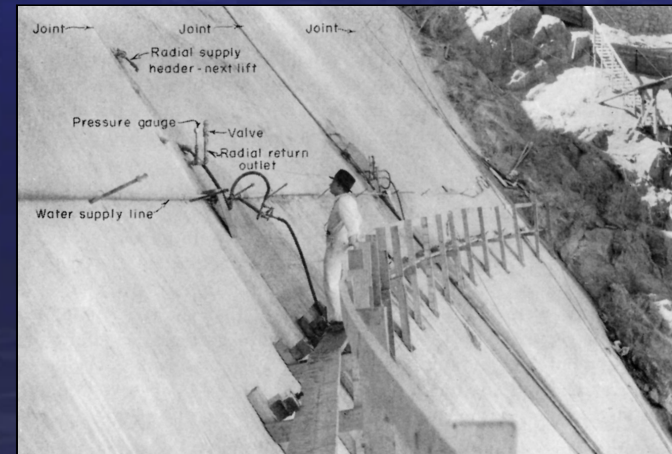
An 8-ft wide slot was left in dam axis to allow access to cooling pipes. River water was run thru the cooling pipes first, then water chilled to 42 F. This cool water removed the concrete heat of hydration, generated by chemical action as the concrete sets. Without artificial cooling the dam would have heated 40 F and taken 125 years to cure.



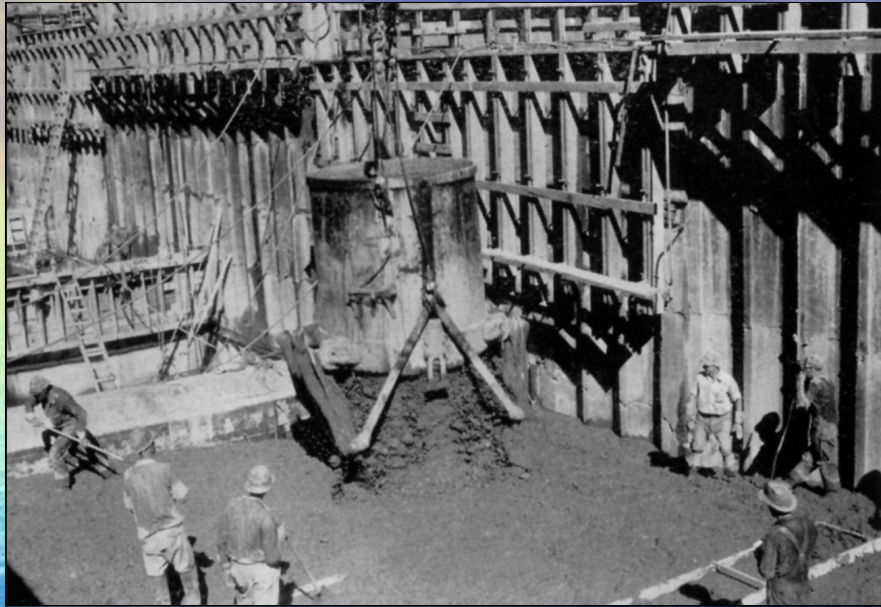
Monolithic blocks created to combat shrinkage; grouted in 100 foot increments



After the concrete heat of hydration was removed and the concrete shrank, the gaps between pour blocks and the cooling pipes were grouted under pressure to seal off any possibility of leakage. This became common practice on subsequent mass concrete dams.



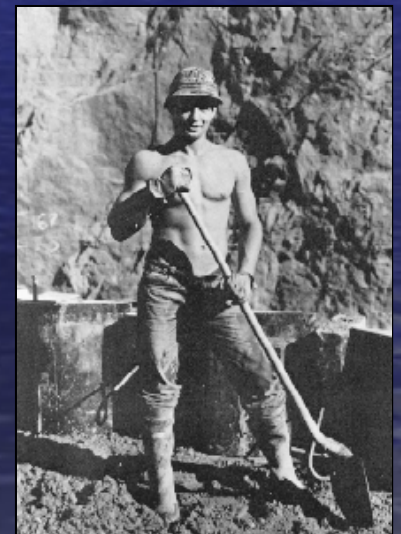
Myths about Entombed Bodies



The official death toll during construction was 96 men. None were buried in the dam's low slump concrete.....

Each bucket of concrete contained 8 cubic yards; if you divide that volume over a 50 x 50 ft pour block, the depth of wet concrete would be just over 1 inch!

As a practical joke, a night shift tunnel crew fashioned a fake body with shoes and hard hat which was revealed when the concrete forms were removed!



Dedication September 30, 1935



Reclamation Commissioner Elwood Mead referred to the project as "Hoover Dam"; while President Franklin Roosevelt christened it as "Boulder Dam"

Mead dies a few months later, and Walker R. Young was passed over as his replacement because he was a Republican

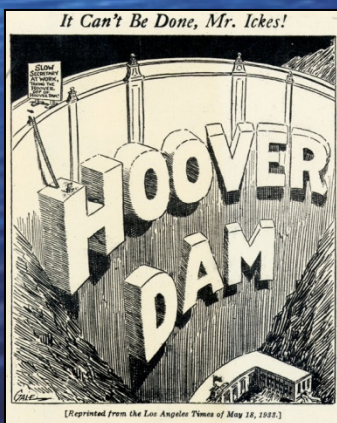
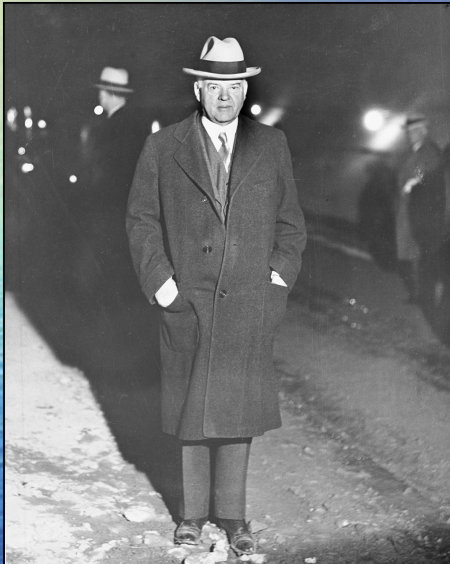
Name Controversy

Boulder Canyon Dam 1922-30: The Boulder Canyon Project was introduced in Congress in 1922; but not approved until December 1928.

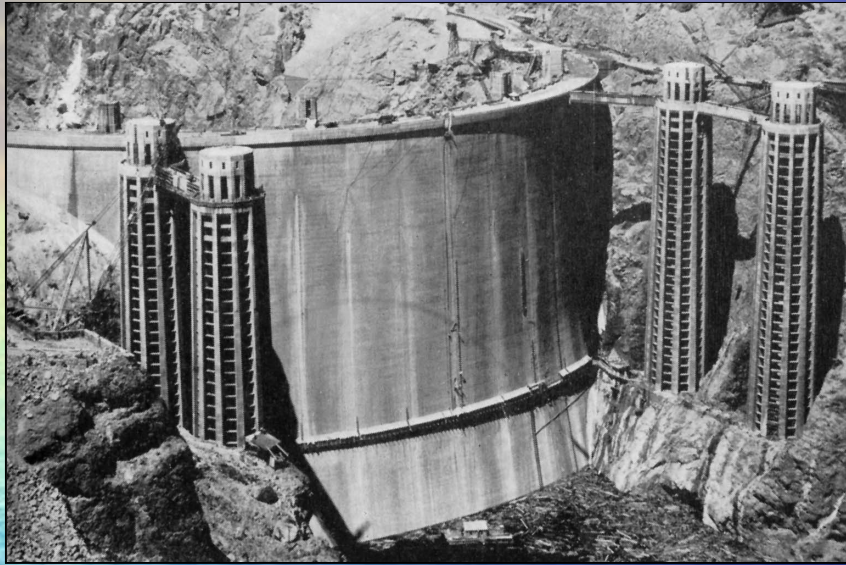
Hoover Dam 1930-33: On September 17, 1930 Interior Secretary Ray Wilbur (upper left) officially began the project in Las Vegas and announced that the dam to be built in Black Canyon would be named Hoover Dam, in honor of the President's long association with the project.

Boulder Dam 1933-47: On May 8, 1933, Roosevelt's new Interior Secretary Harold Ickes decides the name should revert to its original moniker, Boulder Dam.

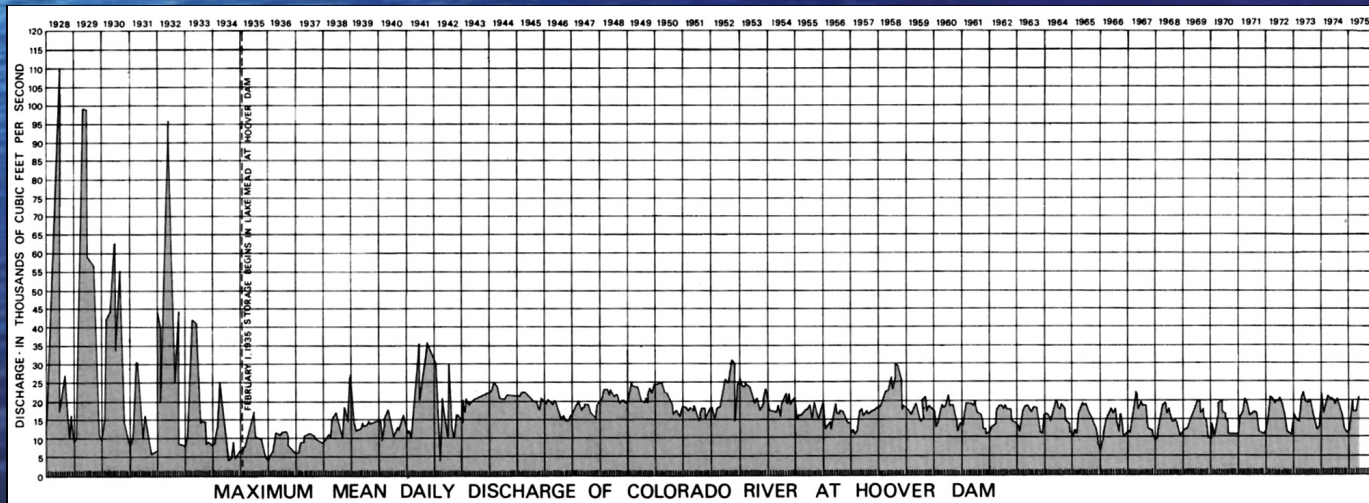
Hoover Dam: On April 30, 1947 the 80th Congress passed a resolution changing the name back to Hoover Dam, which is signed into law by President Truman

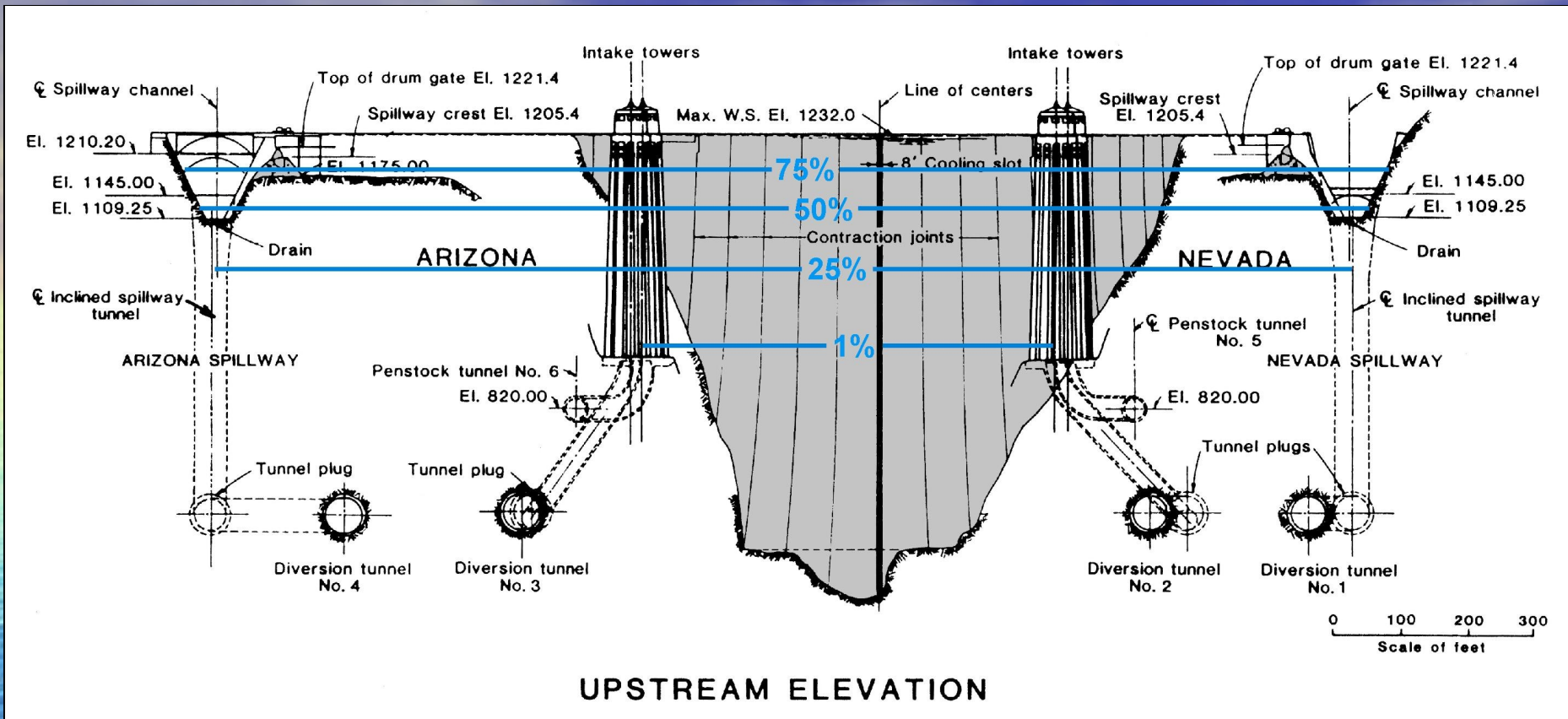


The Wild River Is Tamed



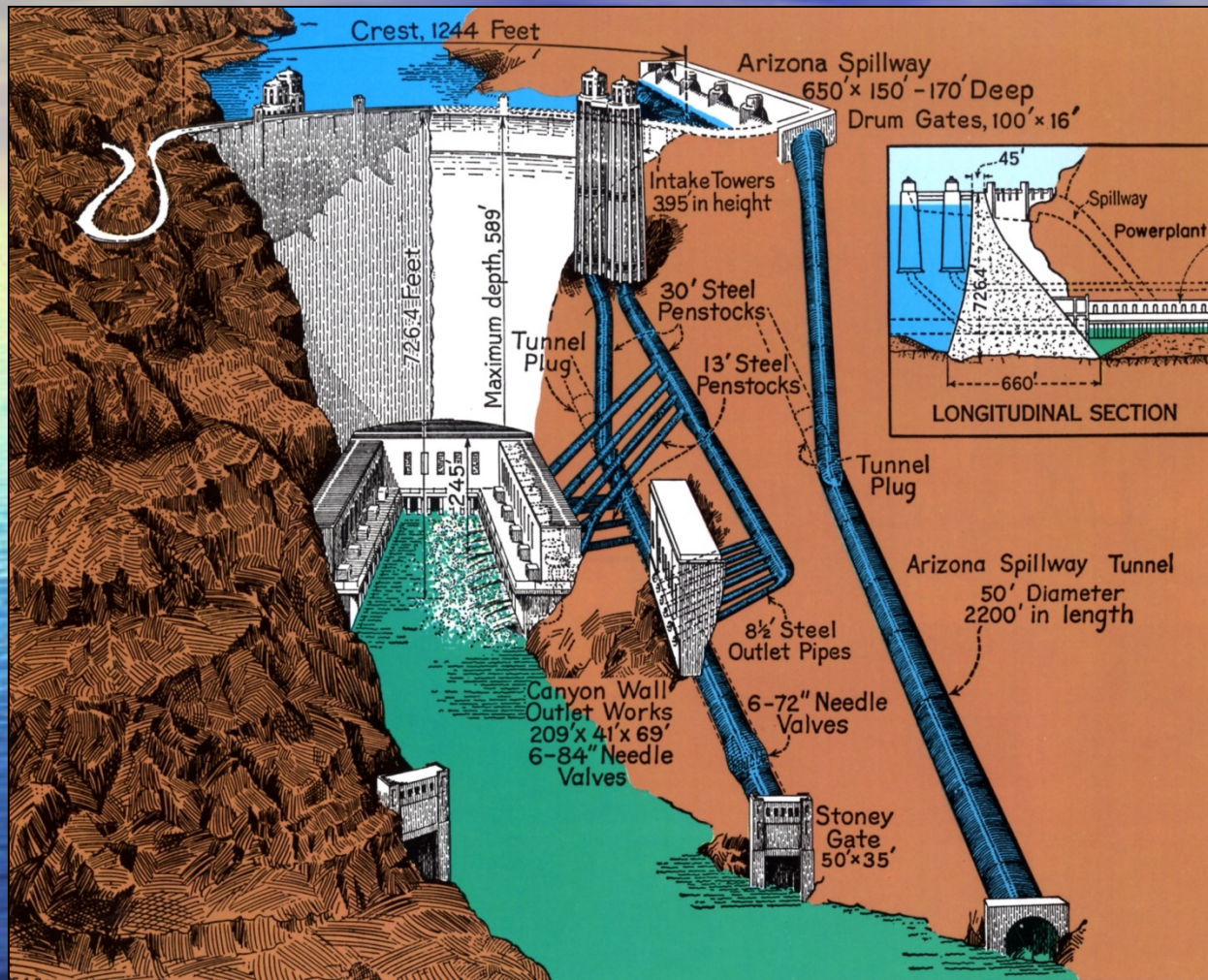
Storage of water behind the dam began on February 1, 1935





- The storage capacity of Lake Mead increases dramatically in the uppermost elevations of the dam. Note how the lower half of the dam only retains 1% of the lake's water!

World's Largest Spillways



The outer bypass tunnels were connected to enormous side channel spillways; giving the dam an aggregate spillage capacity of 520,000 cfs

Keeping spray downstream

- One of the CRB's comments concerned moving the valve houses and spillway outlets well downstream of the powerhouses to reduce transmission losses on the exposed lines leading from the transformers



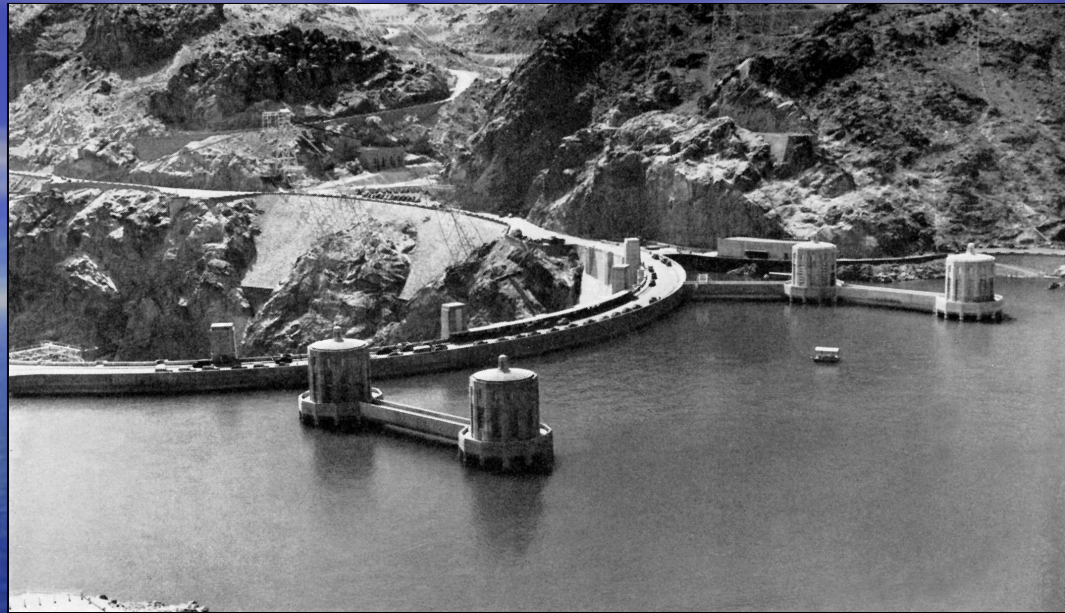
Corrective work was carried out on the Nevada spillway sill in 1945, to remove sediment deposited in the 1941 spillway tests

Original Spillage Capacity

- The two side channel spillways were designed to accommodate **400,000 cfs**
- The canyon wall outlet works could discharge an additional **48,000 cfs**;
- The tunnel plug outlet works could discharge up to **43,200 cfs**;
- The powerhouse turbines were assumed to pass **28,800 cfs**; but can pass **50,000 cfs** today.



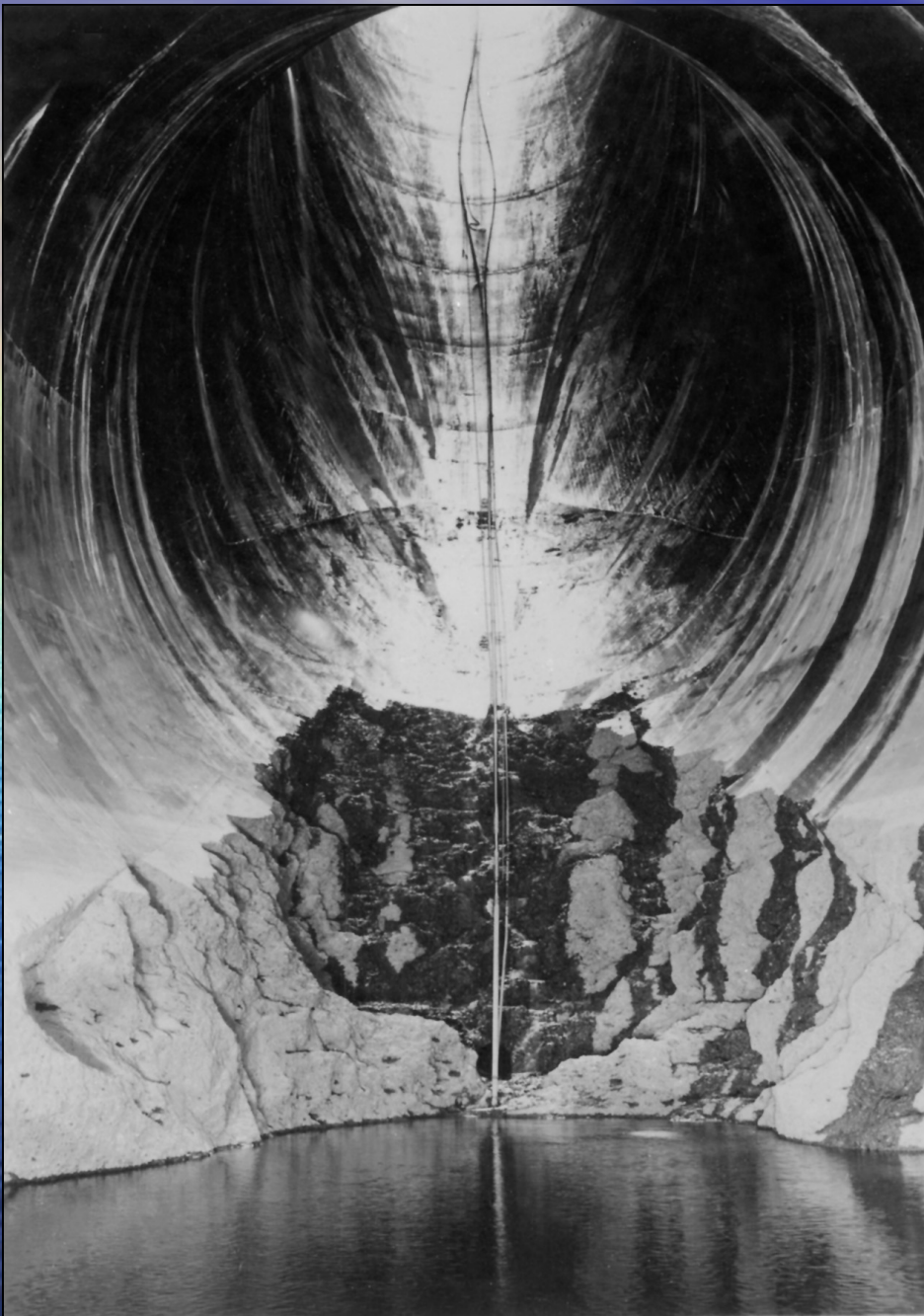
Spillway test August-October 1941



Lake Mead initially topped out in August 1941. The lowest water level occurred 15 years later, in 1956.

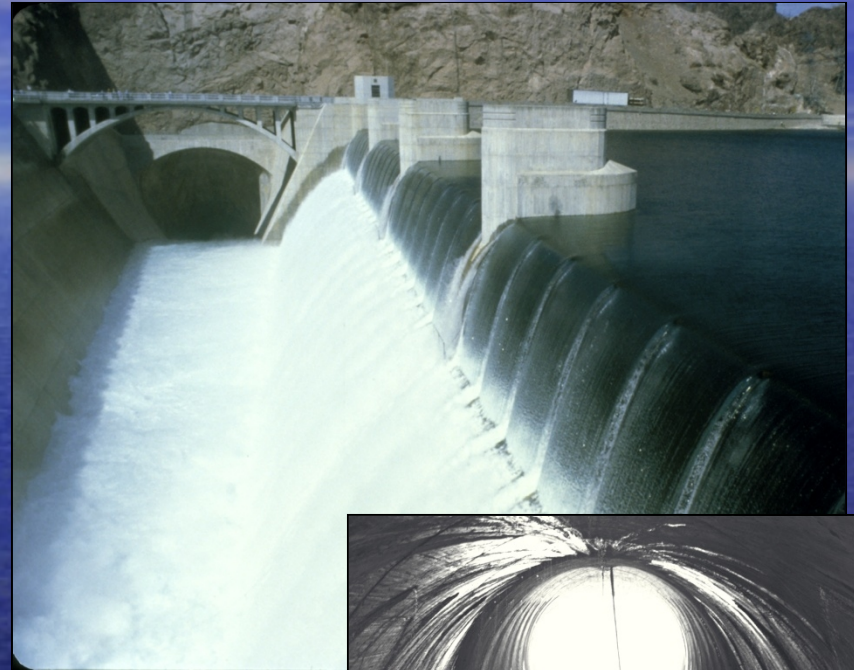
The Concrete Research Board sought confirmation of the design assumptions that had been employed, so the dam was fully instrumented. Lake Mead was brought to maximum pool level and the spillways were tested between August and October 1941.

Cavitation Damage in 1941

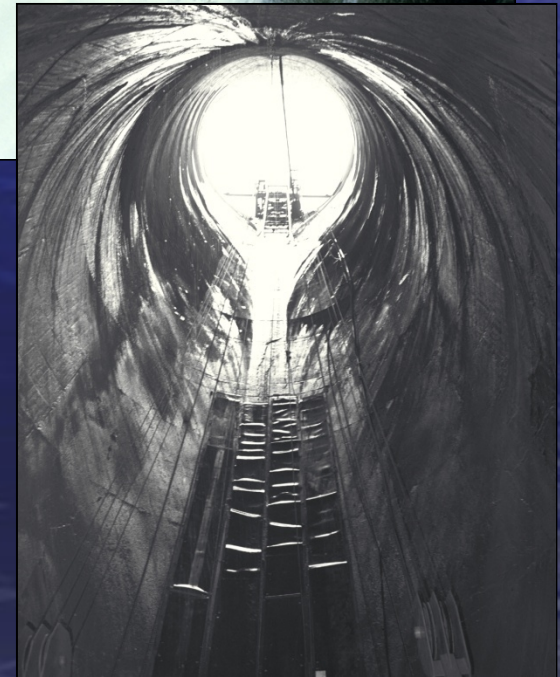


- Reclamation engineers were surprised to find severe cavitation of the spillway elbows
- They wrongly ascribed this to a $\frac{1}{2}$ inch variance in alignment of the tunnel lining; but continued studying cavitation

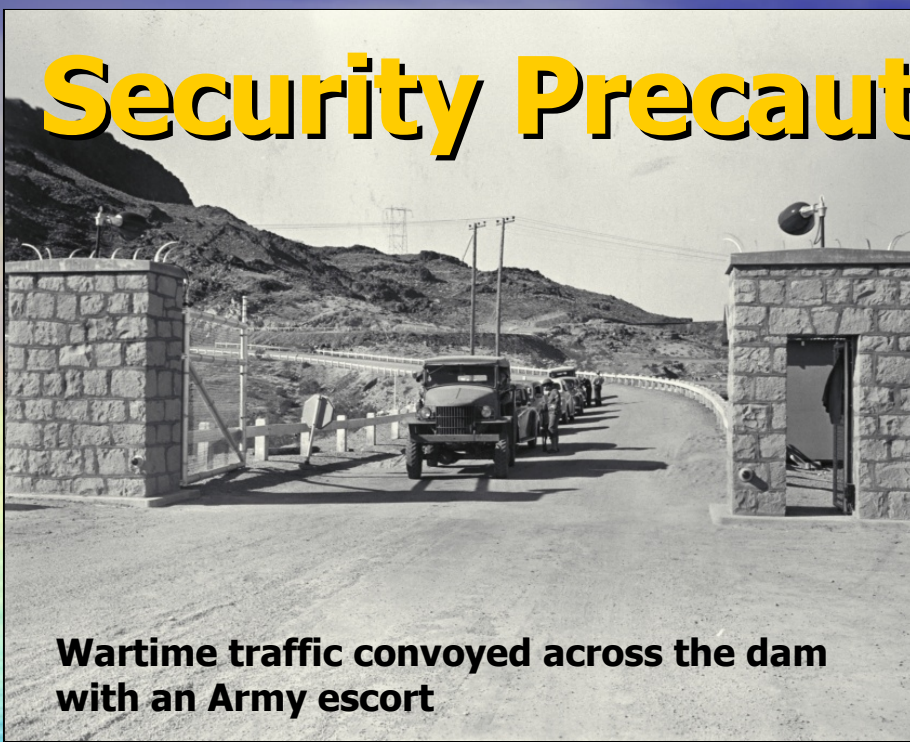
Spillway Cavitation in 1983



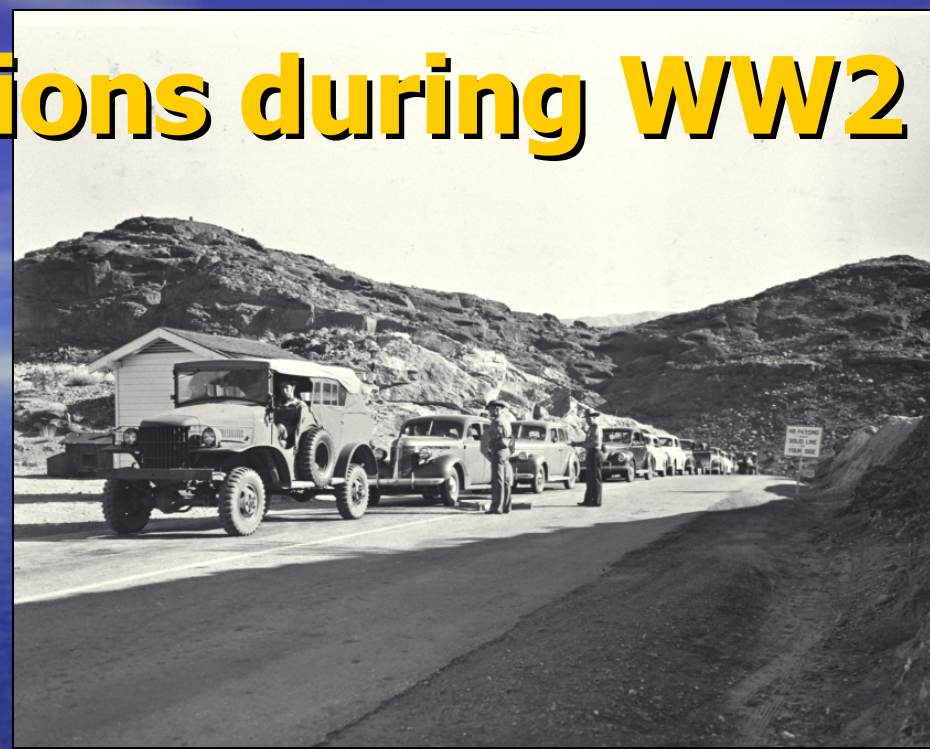
The spillways were next used in 1983 because of excessive runoff and a flawed computer program that was supposed to model runoff in the upper Colorado Basin. As in 1941, cavitation damage occurred at the heel transition with the old bypass tunnel. Reclamation undertook an emergency retrofit of aeration slots in the spillway tunnels at Hoover and Glen Canyon Dams later that year.



Security Precautions during WW2

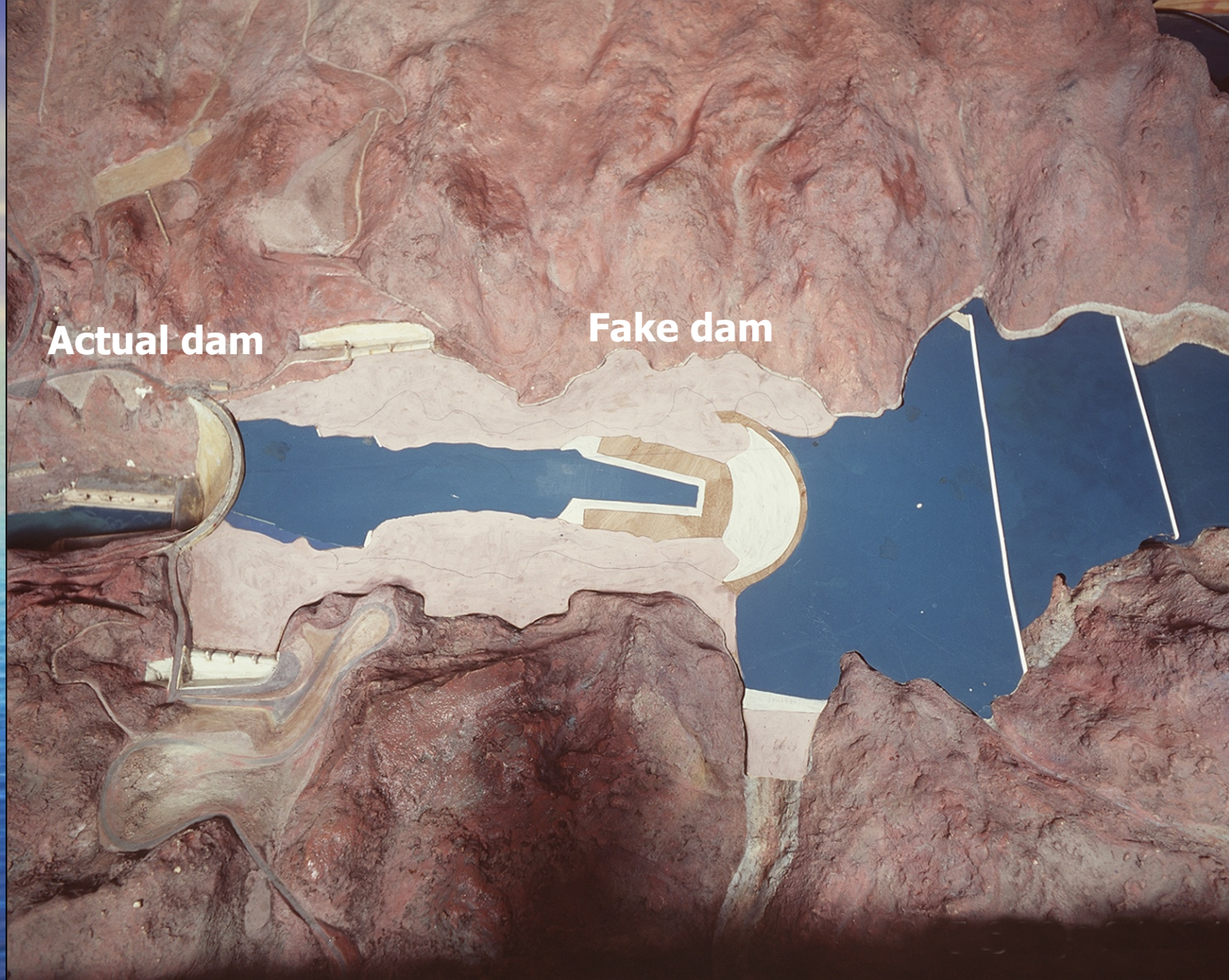


**Wartime traffic convoyed across the dam
with an Army escort**



German agents tried to sabotage the intake towers using satchel charges from a rented boat in Nov-Dec 1939; and concocted a scheme to sabotage the switch yard at Boulder City. Both of these attempts were foiled by the FBI, but security measures included Army guards, closing the dam to tours, installing checkpoints, and convoying traffic across the dam.





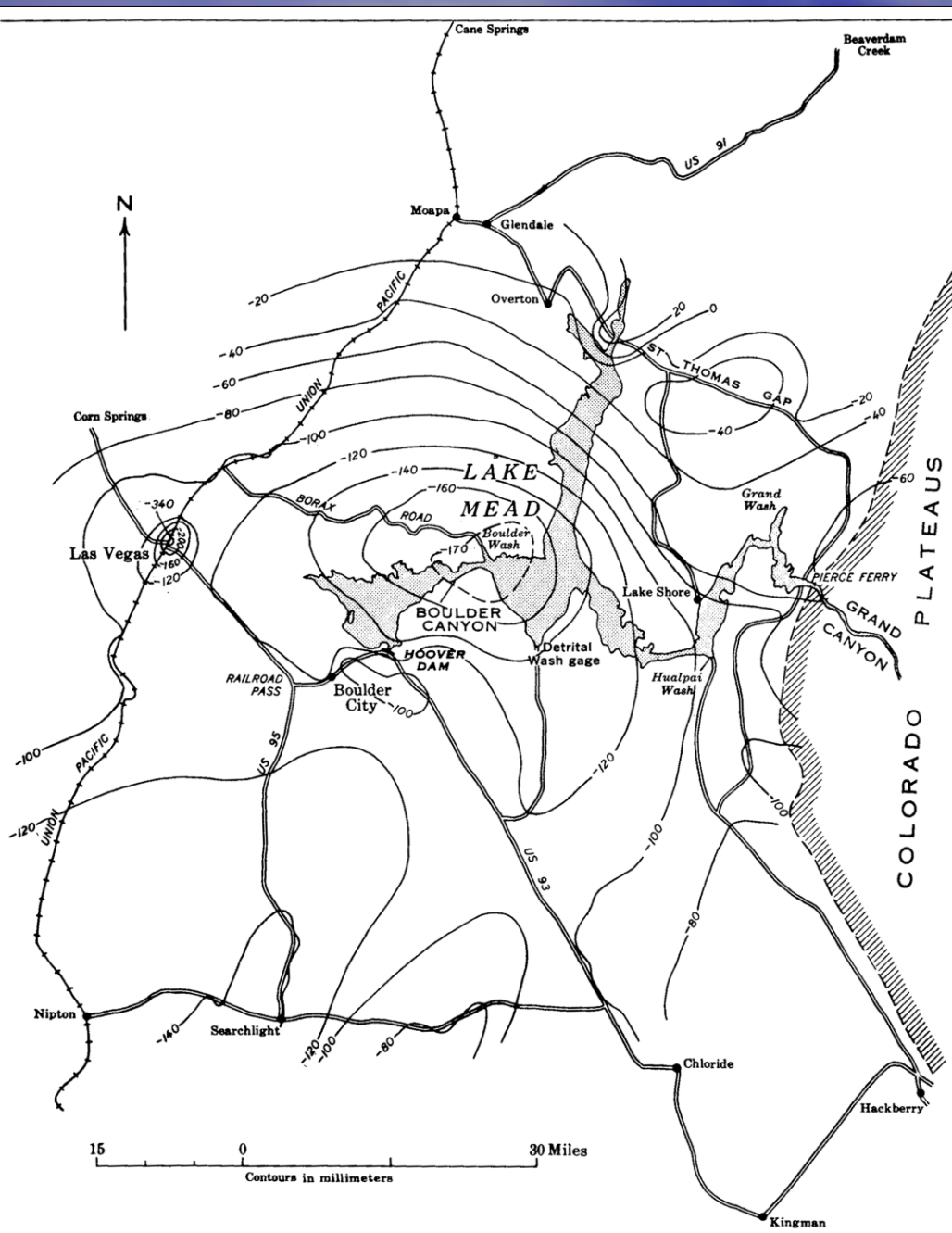
- **Plaster model of camouflage scheme designed by Alan True during World War II using camouflage nets suspended from cables.**



- The **Basic Magnesium Plant** and the community of Henderson were originally conceived under the Lend-Lease program in 1941, then enlarged during the war to supply this strategic metal for the aircraft industry

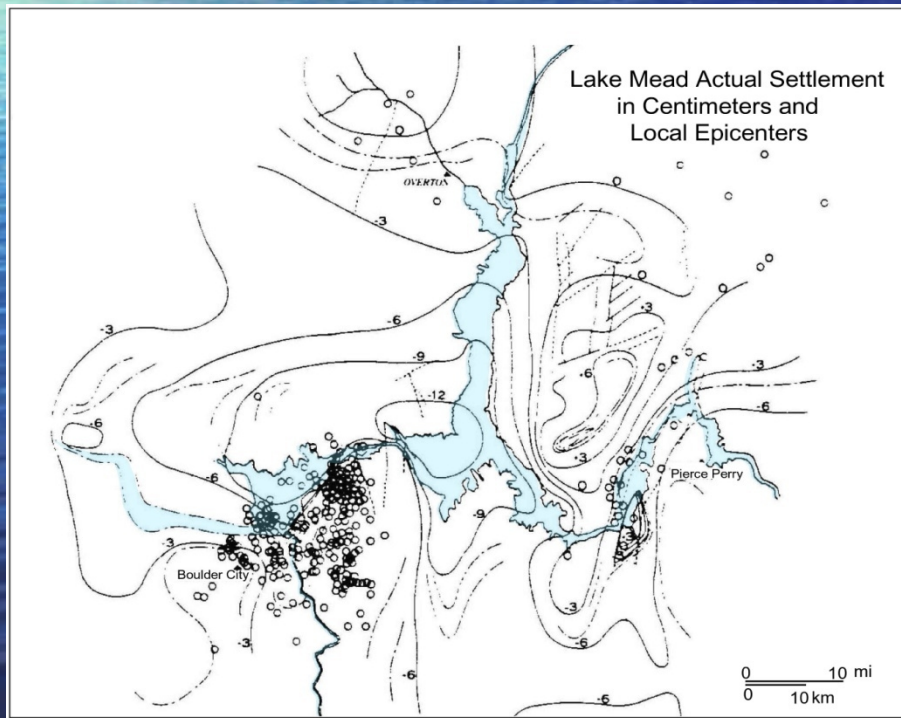
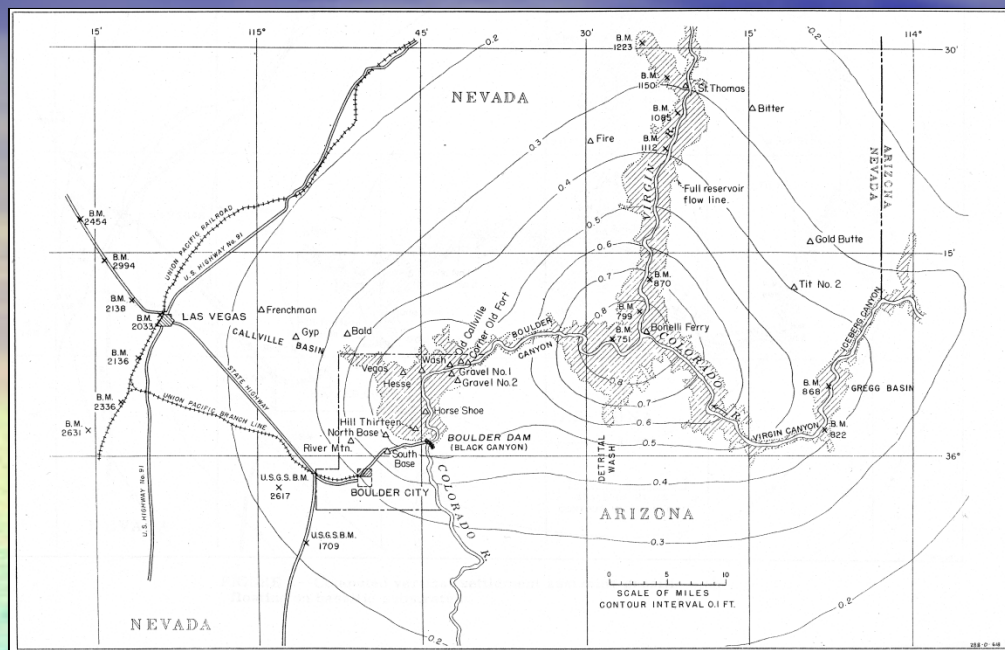
First Reservoir Induced Seismicity and Crustal Deflection Studies

Three precise leveling
surveys performed
1935, 1940-41, and
1949-50. A seismic
array was also
monitored.

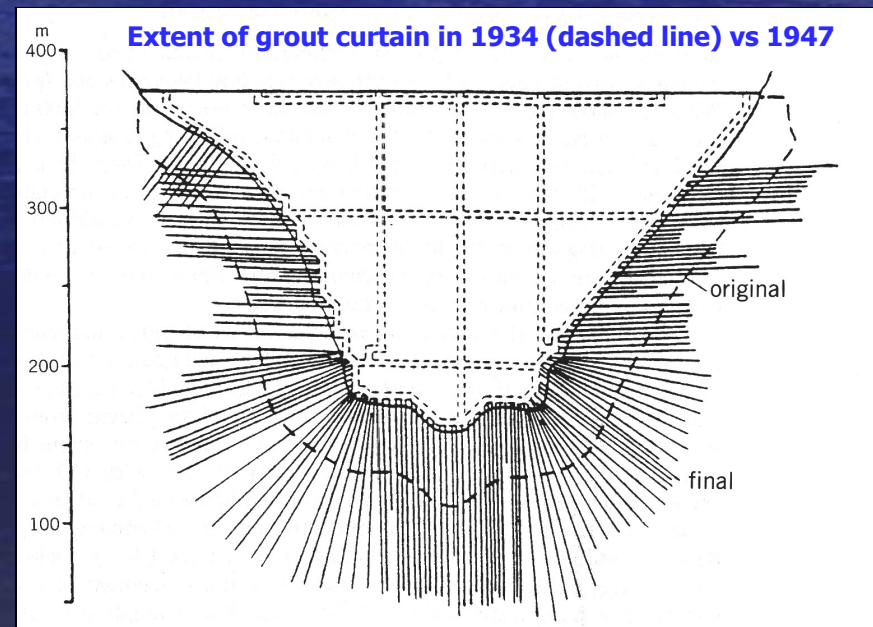
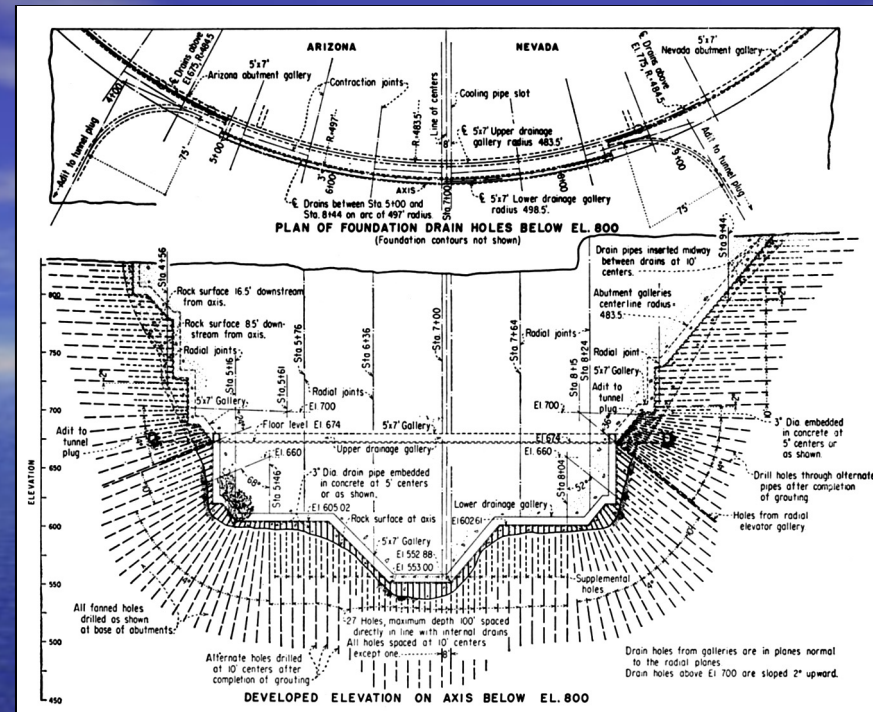
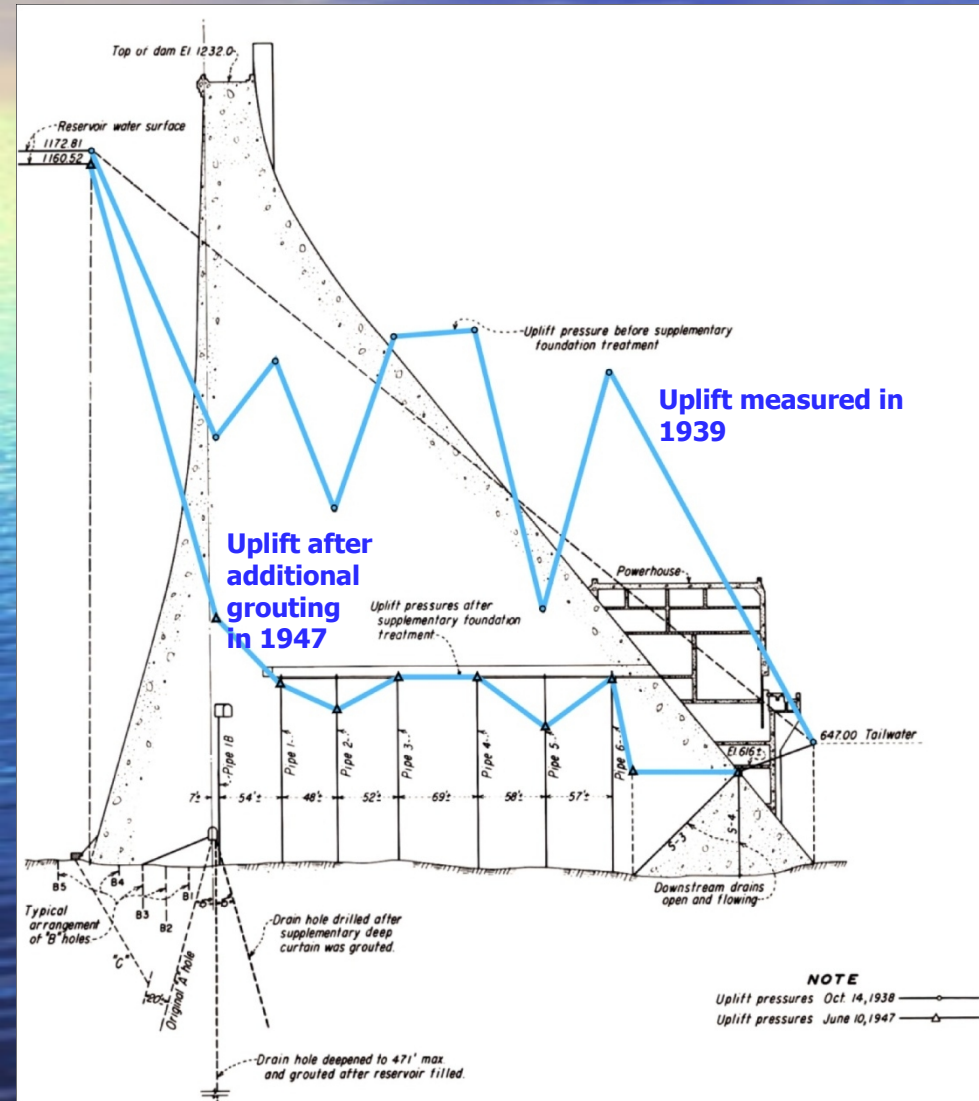


Credible estimates

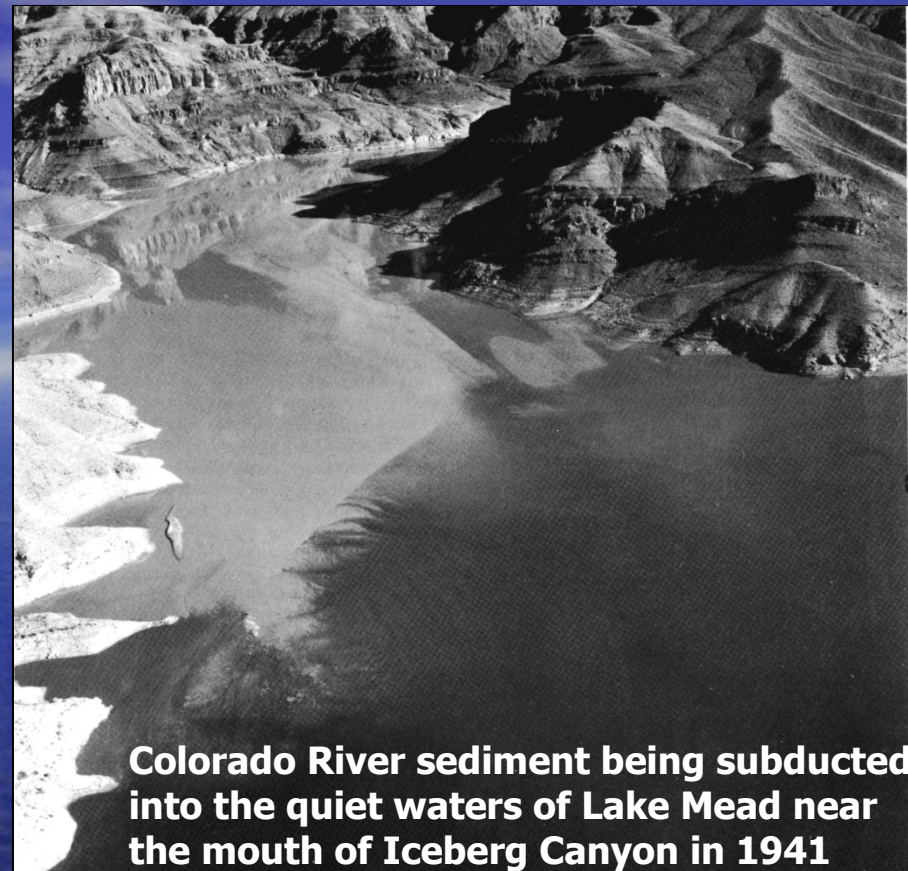
- **Crustal settlement** was very close to that predicted by Reclamation engineers, for an assumed mass of **granite crust** behaving elastically, under 41,500 million tons of water
- **Predicted deflections** up to 10 inches; actual deflections were up to 7.5 inches.



Failure of the Grout Curtain

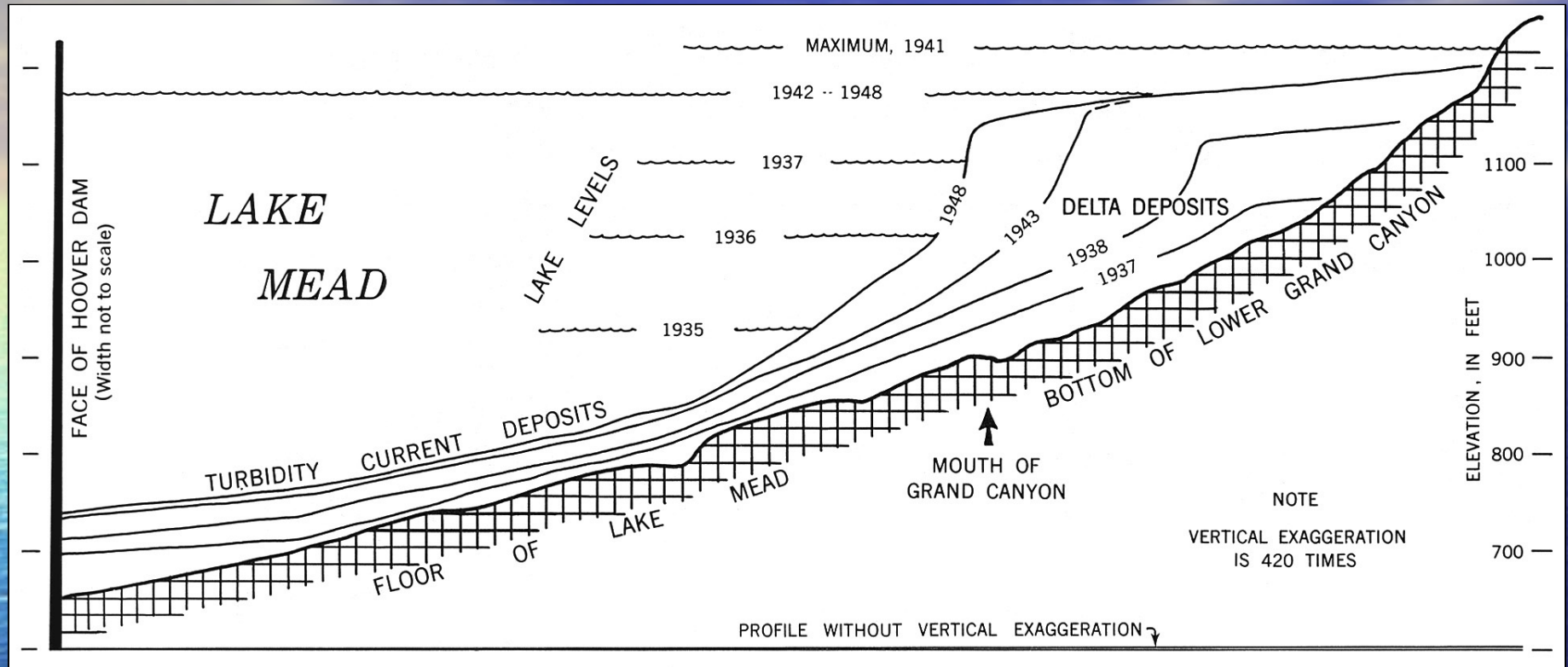


Siltation studies

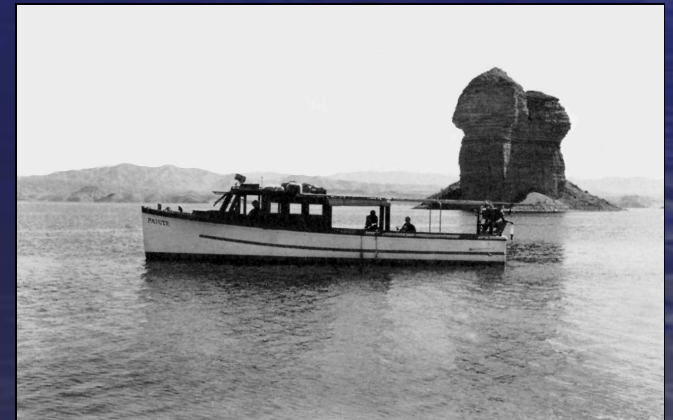


Lake Mead had a design life of just 150 years before it was expected to silt up, absent any upstream dams. One of the biggest mysteries concerned “missing sediment;” when it was learned that almost 50% more silt entered Lake Mead than passed Lee’s Ferry (360 miles upstream). The lion’s share of this silt was subsequently found to have emanated from the **San Juan** and **Little Colorado** River Basins.

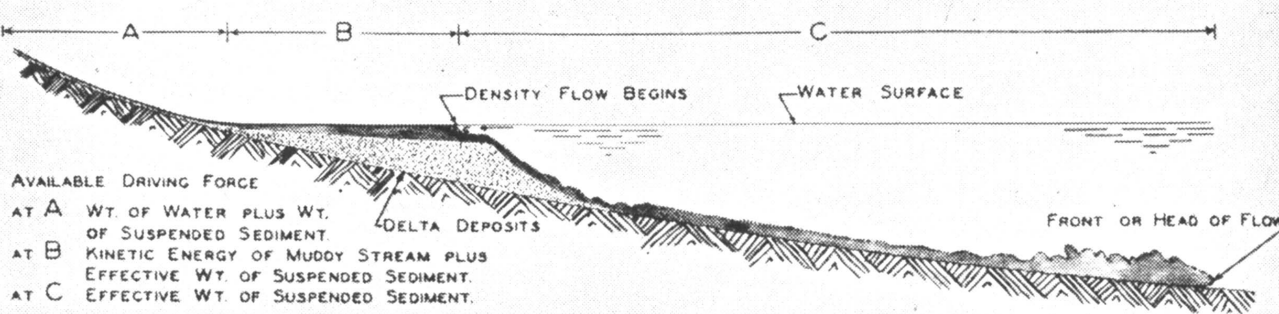
Sedimentation Studies



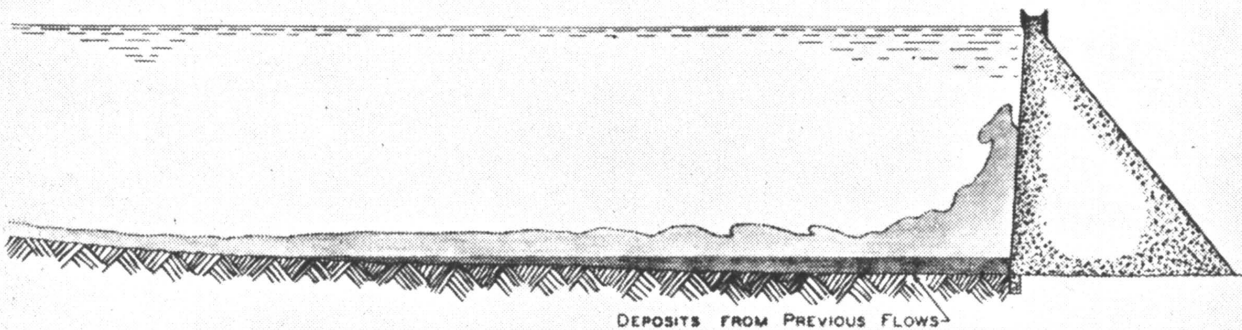
Bathythermography tests adjacent to the dam's upstream face revealed unusually high temperatures from **biologic reduction of nutrient rich silts** brought 115 miles across the sinuous course of the old river channel by **turbidity currents**.



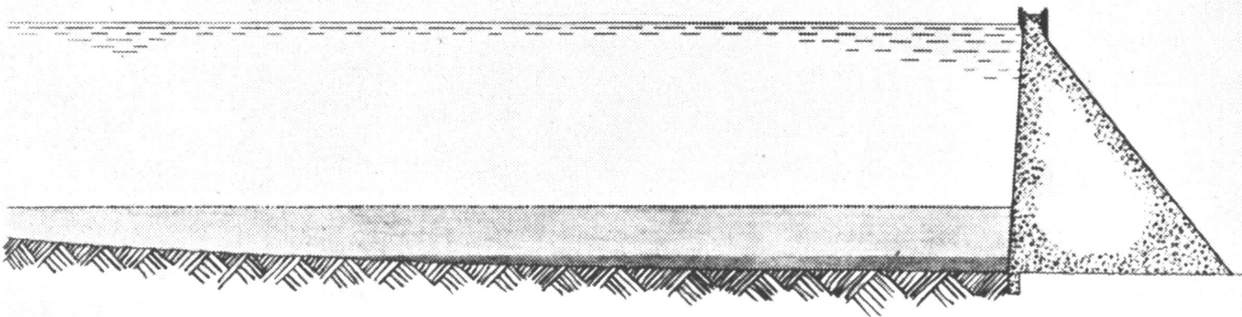
Turbidity Currents



1. A TURBID DENSITY FLOW RESULTS AS MUDDY STREAM ENTERS THE RESERVOIR



2. HEAD OF FLOW BREAKS ON DAM

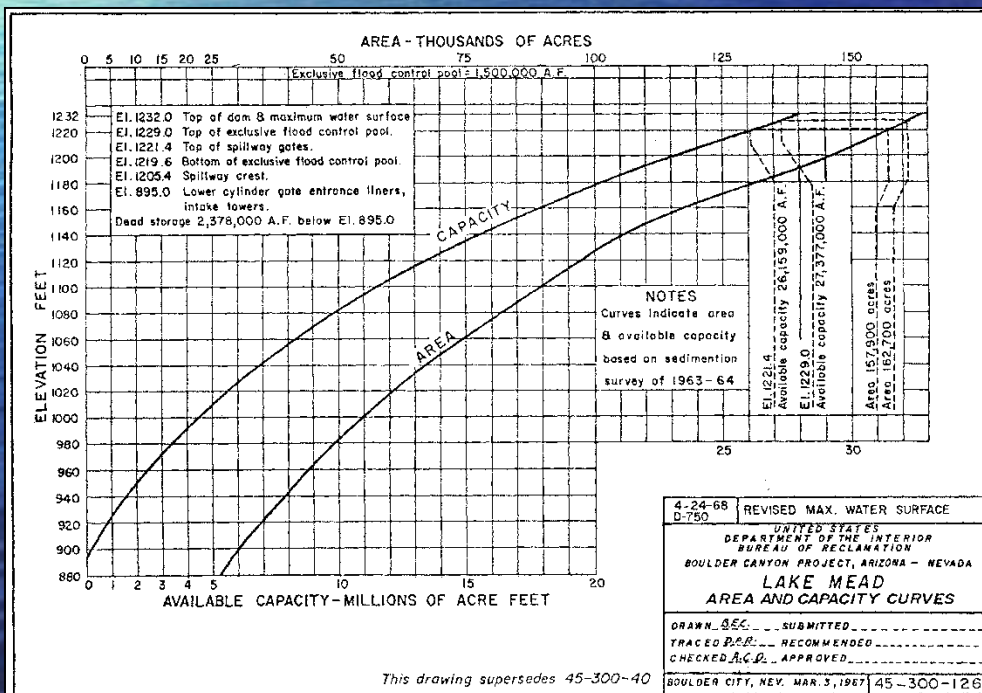
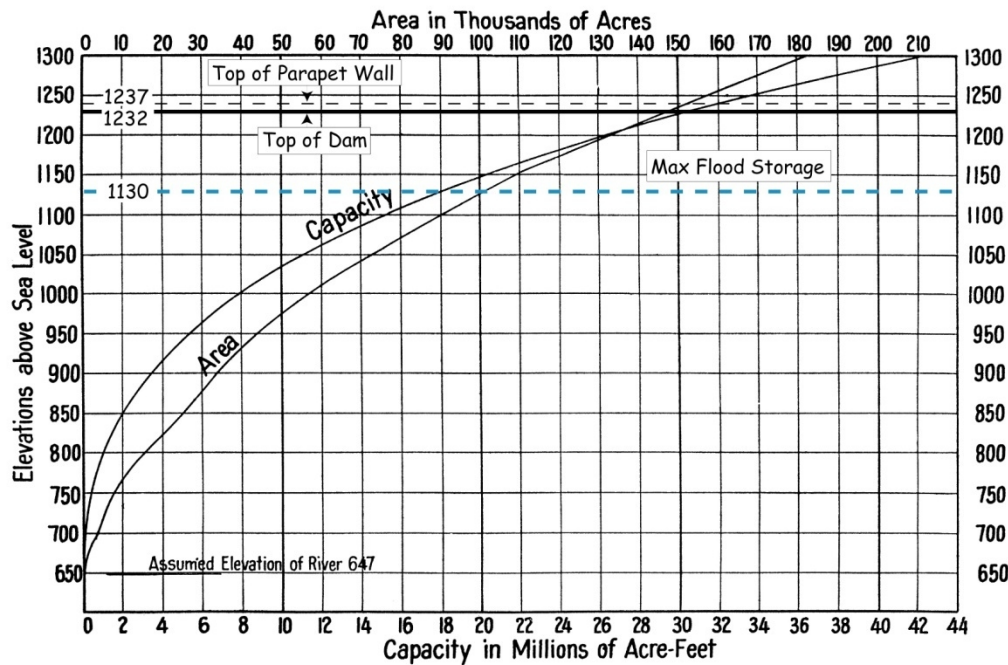


3. FLOW COMES TO REST AS SUBMERGED MUDDY LAKE

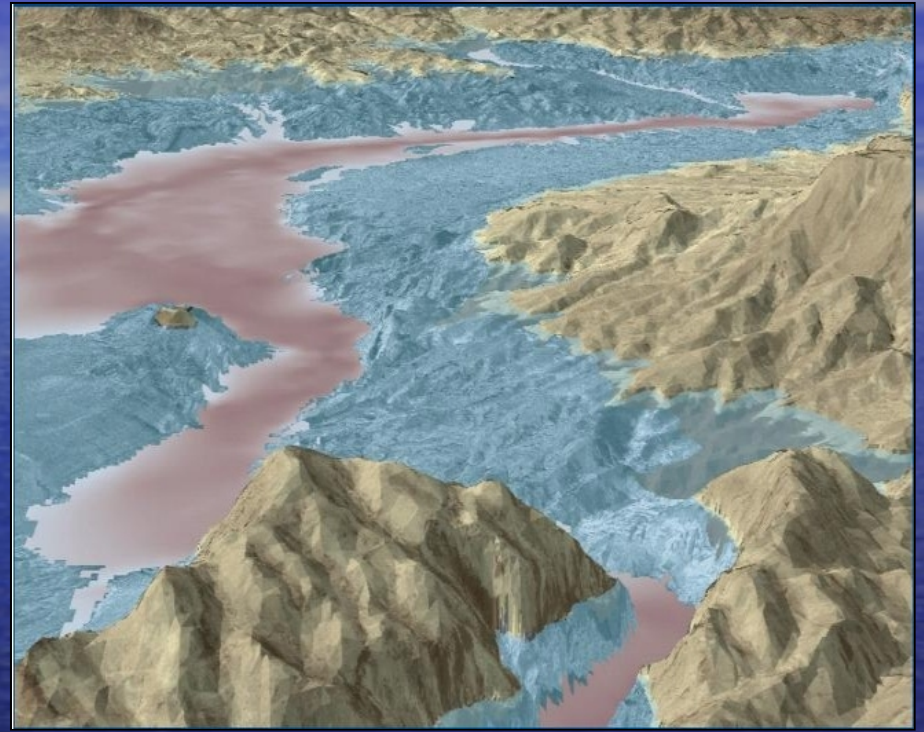
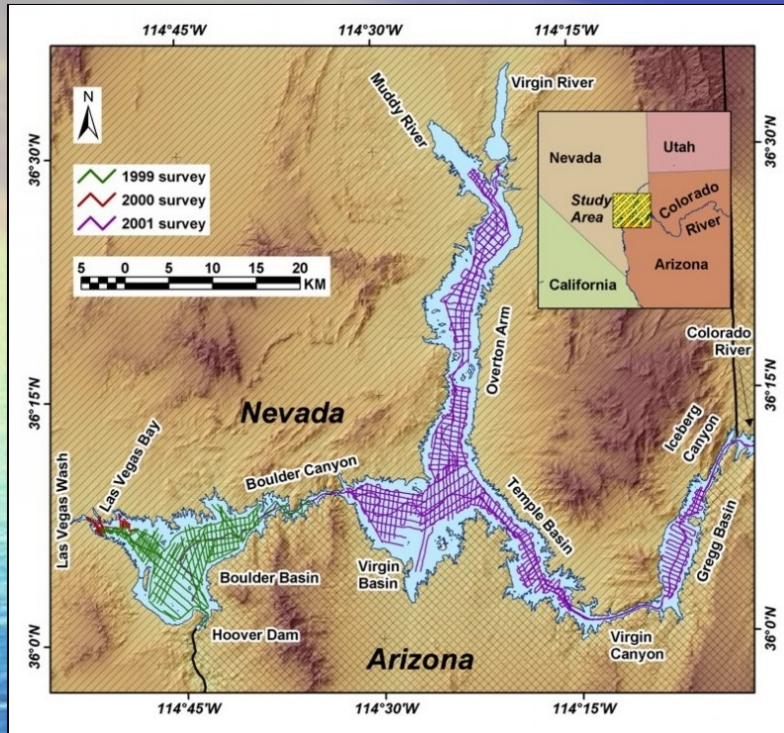
- The discovery of turbidity currents in the early 1940s triggered intense studies under the aegis of USGS, Caltech, and the AGU at Hoover, Elephant Butte, and Norris Dams.

Reservoir Area and Capacity Curves

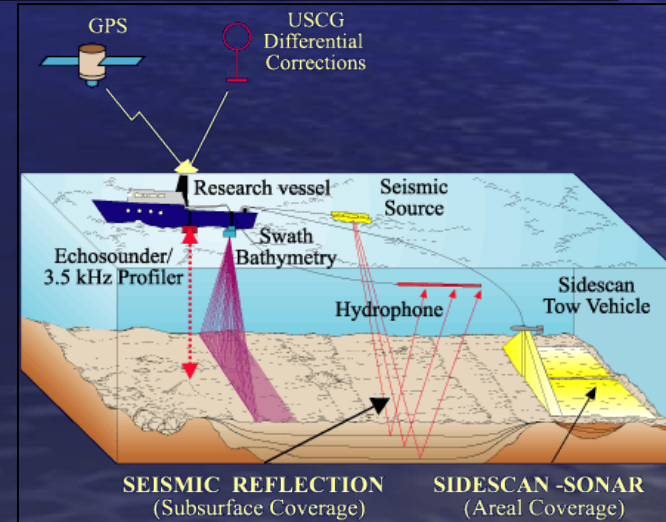
- Between 1935-64 Lake Mead lost about 3 million acre-feet of reservoir capacity by siltation
- That figure dropped dramatically after the completion of Glen Canyon Dam in 1964



Lake Mead sediment studies



The tailwater channel and deep basins of Lake Mead are being infilled with silt coming out of the Grand Canyon. The annual influx was reduced substantially when Glen Canyon Dam closed its gates in the fall of 1964.



Popularity as a Tourist Attraction Continues to Rise



- **Tourism feeds off Las Vegas as a major vacation destination**
- **750,000 visitors per year at the dam**
- **6 million people per year recreate on Lake Mead**
- **Boulder City survived transition; but still does not allow gambling**

Special thanks to:

**U.S. Bureau of Reclamation
National Archives and Records Service,
Rocky Mountain Region
Richard L. Wilshire, PE**

**ASCE History & Heritage Committee
Trent Dames Civil Engineering Heritage Fund
Dibner Research Fellowship of
The Huntington Library
AEG Foundation**

**Edward L. Butts, PE
U.C. Water Resources Center Archives, and
the late Roy W. Carlson, PE and Jerome M. Raphael, SE**

**This lecture will be posted at:
www.mst.edu/~rogersda/dams**

In .PDF format for easy downloading