Hoover Dam: First Joint Venture and Construction Milestones in Excavation, Geology, Materials Handling, and Aggregates

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ABSTRACT: The size of the Boulder Canyon Project necessitated a broad array of innovations in construction engineering and management which had enormous impacts on all of the large scale projects that followed it. Foremost among these was the employment of a joint venture involving eight different firms, organized into six partners (Six Companies, Incorporated). Many of the techniques employed to construct of Hoover Dam were of a pioneering nature, designed to hasten the construction schedule and maximize profits. These were emulated and perfected by Six Companies and most of their competitors for several decades thereafter. Some of these included: multiple-level rail spurs; temporary trestles and suspension bridges of many sizes, employment of construction access adits to allow multiple headings of underground workings; fully automated concrete batch plants; staging of construction materials on the opposite river bank; government provision of all materials except the concrete aggregate (to minimize risk of construction claims and delays). Major achievements were also made in quality assurance and materials testing, despite the fact that the job proceeded round-the-clock.

FIRST LARGE JOINT VENTURE

Six Companies Incorporated

The Boulder Canyon Project approved by Congress had a budget of $165 million, making it the largest federal contract ever awarded up to that time (March 1931). It called for 4.4 million cubic yards (mcy) of concrete, which was more than all previous Bureau of Reclamation projects during the previous three decades, combined (4.3 mcy). The project was so large that no single company in America had the resources to bid the job alone. The government contract called for bidding of 119 separate items and allowed seven years for completion of the project, commencing on April 20, 1931 and running thru April 11, 1938, with a performance penalty of $3,000/day.

The joint venture of Six Companies, Incorporated was organized by Edmund O. and William H. Wattis of Utah Construction Company. There were actually eight firms that originally comprised the joint venture. Bechtel, Kaiser, and Warren Brothers intended to pool their resources to become the largest partner, but Warren was unable to come up with the half million in cash required to become a partner when Six Companies incorporated in February 1931 (Tassava, 2003; Wolf, 1996). The remaining seven firms pooled their financial resources to capitalize the new corporation with $5 million in capital stock, a government requirement to bid the job. A $2 million dollar bond was also required by Reclamation as part of their actual bid submittal. The seven firms were: W.A. Bechtel Co. of San Francisco, Kaiser Paving Co. Ltd., of Oakland, Utah Construction Co. of Ogden, MacDonald & Kahn Construction Co. of San Francisco, Morrison-Knudsen Co. of Boise, J. F. Shea Co. of Portland, and Pacific Bridge Co. of Portland. This was the first time a joint venture of more than three firms was used in public works construction.

On March 4, 1931 Reclamation opened the bids for the construction of Hoover Dam and Six Companies' bid for $48,890,955 was the lowest of any qualifying firm, nudging out Arundel-Atkinson Corporation of New York ($53.9 million) and Woods Brothers of Lincoln, Nebraska ($58.6 million), the only other serious bidders. The winning bid was just $24,000 more than the engineer's estimate by Reclamation, a difference of just 0.05%. The largest line items in Six Companies bid were: $13,285,000 for 1,563,000 yd^3 of tunnel excavation; $9,180,000 for placement of concrete for the dam; and $3,432,000 for lining the four diversion tunnels with 312,000 yd^3 of concrete. No other items exceeded $1,000,000.

Everyone with the Six Companies management agreed that Frank T. Crowe of Morrison-Knudsen (Figure 1) was the most qualified individual to serve as the General Superintendent for Hoover Dam because he had been Reclamation's General Superintendent of Construction. In June 1925 he left Reclamation to join Morrison & Knudsen (MK). MK had secured a subcontract with Utah Construction Company, the prime contractor building Guernsey Dam in eastern Wyoming. Crowe supervised the construction of Guernsey, followed by Combie Dam in California and Deadwood Dam in Idaho (also with Utah Construction).

Crowe possessed the most experience in concrete dam construction of anyone in the Six Companies consortium, and had won every bid he had prepared for Morrison-Knudsen during the previous five years. Known by the workmen as '*Hurry Up Crowe*,' he had an uncanny ability to attract "*reliable, competent, fast-thinking men*" to his job sites (Rocca, 2001). He also possessed superior skills in appreciating critical path management, which he brought to materials handling, processing, and delivery. Crowe was also a natural leader, although he preferred the moniker "*problem solver*" (Raphael, 1977).

Crowe's uncanny ability to solve problems quickly, around the clock, earned the respect of all who worked for him. Crowe gave much of the credit to the supervisors and foremen he hired, who he expected to solve such problems, not waste his time with complaints. Problem solving, after all, was *the* essential skill in heavy construction, where unforeseen delays can easily snowball into logistical, managerial, and financial catastrophe (Gerwick and Woolery, 1983). His generalship was never in question, and when it was all over (in mid-1935) he had managed to complete the most expensive and complicated engineering project 30 months ahead of schedule, netting record profits for the Six Companies partnership (Hiltzik, 2010).

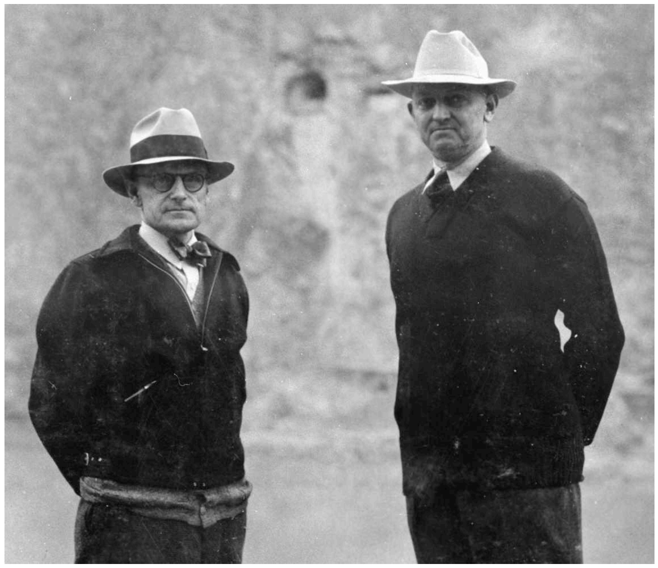


FIG. 1. Civil engineers Walker R. Young (left) and Frank T. Crowe (right). Young was the senior onsite representative (Construction Engineer) for the Bureau of Reclamation while Crowe was the General Superintendent for Six Companies (USBR photo). Everyone expected Young to succeed Elwood Mead as the next Commissioner of Reclamation, but his subordinate John C. Page was given the position because he was a Democrat. Crowe went on to manage construction of Parker and Shasta Dams before dying of a heart attack at age 63 in February 1946. Young went on to head up the Central Valley Project in California, returning to Reclamation headquarters in 1945, where he served as Assistant Chief and then Chief Engineer until retiring in 1948. He lived to be 97, passing away in 1982.

Frank Crowe's greatest impact on the construction industry was his penchant for crafting what came to be known as "unbalanced bids." The contractor's unit costs were manipulated to seek greater compensation for materials excavation, handling, and placement early in the job, to offset the cash bond that the winning contractor had to post to begin the job. At Hoover Dam Crowe sought compensation of $8.50 per cubic yard for rock excavation, a very high price, but just $2.70 per yard for mass concrete in-place. His concrete unit price was 20% below Reclamation estimates and 35% below their nearest competitor. With 4.4 million yd^3 of concrete, this might seem dangerous to an accountant, but Crowe knew exactly what he was doing; he was gathering the most cash possible at the "front end" (beginning) of the job, which offset the $2 million performance bond. By completing the four massive diversion tunnels a year ahead of schedule Six Companies was able to collect $13.285 million in the first 12 months on the job (May 1931 to May 1932). They received another $3.43 million for lining the diversion tunnels between March 1932 and February 1933.

In the end, Six Companies cleared about $13 million in profits (Hiltzik, 2010) on a $53 million job (including the extras), for a tidy profit of 25%, stellar by anyone's standards in the construction industry. Crowe received an annual salary of $18,000 and received performance bonuses in excess of $250,000 during the course of the job.

Between 1931 and 1935 Six Companies employed 21,000 men on the project, with the workforce averaging about 3,500 employees at any given time. Even with all the housing, there was so much commercial activity in the area the population of Las Vegas doubled between 1930 and 1934, while the dam was under construction. As many as 5,218 men were on the payroll during the height of construction, in June 1934. The average monthly payroll was roughly $500,000. Pay days were on the 10th and 25th of each month. Six Companies completed concrete placement on the dam on May 29, 1935, and all features were completed by March 1, 1936, more than two years ahead of schedule.

The official death toll eventually tallied 96 men. Most of these occurred during the first year and a half, while the diversion tunnels were being excavated. Six Companies also took preventive measures to provide water and emergency medical assistance, to placate the concerns of workmen. They were exempt from having to abide by mining safety ventilation standards in force at the time (1931-32), and by modern standards the paucity of forced ventilation in the massive diversion tunnels was shamefully low.

Site Access Secured by the Government

The greatest construction problem attendant to the construction of Hoover Dam was the difficult site access. The federal government contracted with the Union Pacific Railroad to construct a spur line 22.6 miles long from their Los Angeles & Salt Lake rail line in Las Vegas to Boulder City Summit. This contract was let in May 1930. From Boulder Junction Lewis Construction Co. built the U.S. Construction Railroad line that continued eastward for another 10 miles to a point overlooking the Nevada powerhouse, at an elevation of 1370 feet (138 vertical feet above the dam's crest).

Six Companies then constructed two additional rail lines, one down Hemenway Wash to the aggregate classification plant and across the Colorado River to the aggregate quarry on the Arizona side of the river and the second low level spur serving the lower concrete batch plant near river level, just upstream of the dam, within Black Canyon. These were known as the "Six Companies Railroad" lines and are shown in Figure 2.

Construction of the low level spur involved considerable hard rock tunneling in the andesite breccia, the costs of which had to be absorbed by Six Companies. Six Companies was obliged to use boats to access the dam site before temporary construction roads and the rail line could be extended into Black Canyon along the river.

The federal government hired General Construction Co. of Seattle to build 8.3 miles of highway leading from Boulder City to the steel fabrication plant. At the time General Construction was also building Owyhee Dam in Idaho, the Bureau of Reclamation's highest dam prior to Hoover. They became a Six Companies partner at Bonneville Dam in 1934, cementing a relationship that would continue into the 1950s (Wolf, 1996). All of the transportation links were brutally difficult, passing through extremely rough terrain.

On Kaiser's recommendation, General Construction subcontracted R.G. LeTourneau, Inc. of Stockton, California, an earthmoving firm that had worked with

Kaiser on highways and earth dams in California. They were given the task of grading a 22-foot-wide asphalt-surfaced highway from Boulder City to the staging area above the dam's Nevada abutment, known as the "government highway" (Figure 3). The timeframe for completion of this highway in the spring of 1931 was critical to Six Companies so they could move their workforce, equipment, and materials to the dam site.

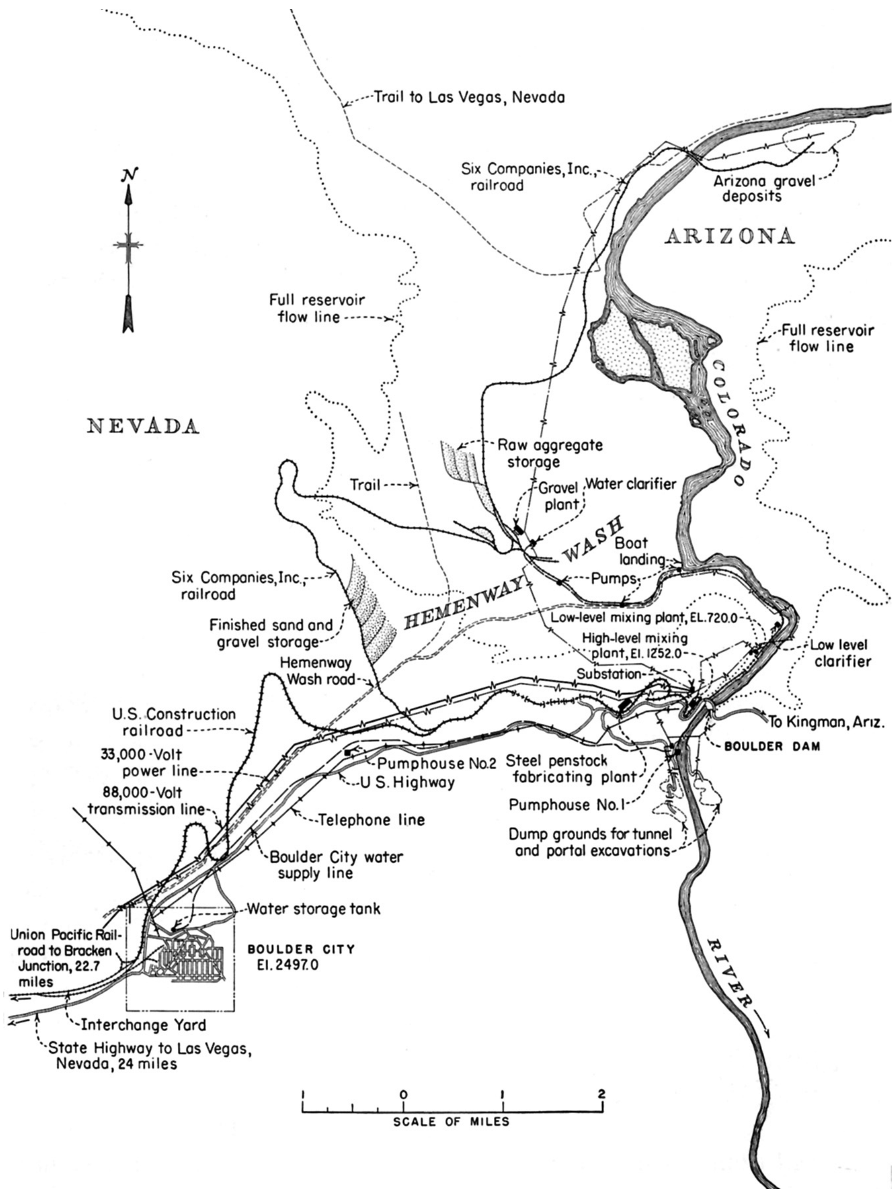


FIG. 2. Map showing Boulder City, the highway, rail spurs, and power lines serving the dam site during construction. The aggregate came from terrace gravels about 11 miles upstream of the dam, on the Arizona side of the river (USBR).

Robert G. "Bob" LeTourneau was respected as the inventor of the tracked bulldozer and the modern articulated scrapper, with a reputation for building the best earthmoving equipment on the planet (he registered over 400 patents and 70% of the

FIG. 3. Upper: The R.G. LeTourneau Co. lost close to $100,000 while grading the government highway between Boulder City and the dam staging area because they encountered resistant volcanic strata that proved much more troublesome than anything they had previously dealt with in California. The lower image shows the completed highway (costing $330,000) with the U.S. Construction Railroad in the background (costing $1 million). (USBR)

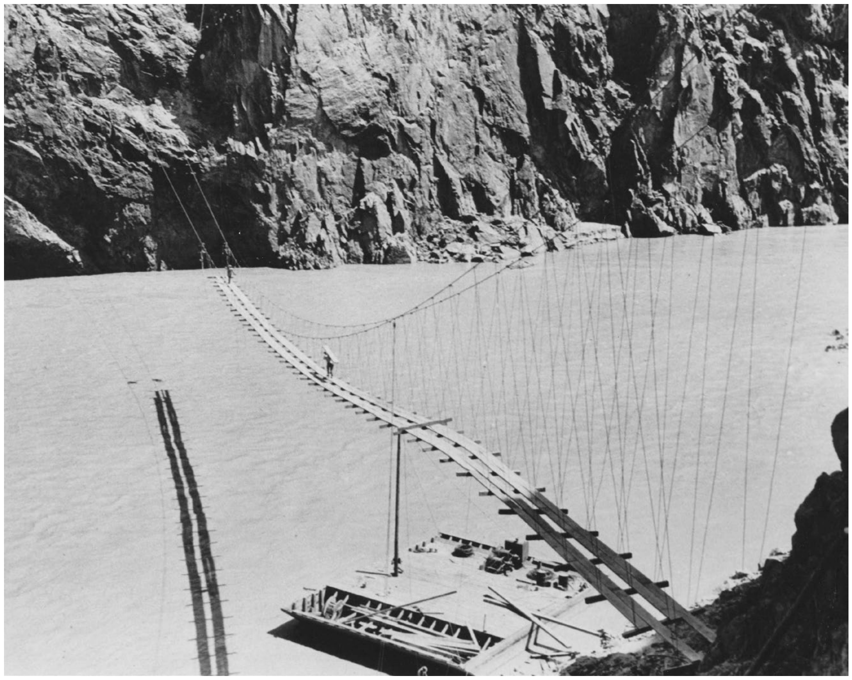


FIG. 4. Six Companies quickly built a series of suspended walkways like that shown here under construction to access the Arizona side of the river, to begin excavation of the two diversion tunnels underlying the dam's left abutment (USBR).

FIG. 5. Six Companies employed a variety of bridges to get workers and equipment across the channel. They began by driving timber piles to fashion simple timber trestle bridges such as that shown here, which replaced the span lost in the high water of February 10, 1932 (USBR).

earthmoving equipment used by the Allies during the Second World War were built at five different plants licensed by his firm). LeTourneau's crews battled the lava flows, sandwiched between softer, powdery strata. Every time they drilled holes, loaded them with dynamite, and shot them, the blast would simply shoot up the hole (called "cannon shots"), instead of "springing a pocket" of fractured rock at some depth. They adjusted their stemming and tried drilling deeper holes, but without success. In the end

LeTourneau fell back upon his previous experiences working in a gold mine and had his crews excavate a series of "coyote drifts," or adits, into the tough volcanic strata. These tunnels were then backfilled with "truck loads" of explosives and detonated. This succeeded in keeping the project on schedule, but LeTourneau lost about $100,000 on the contract, which came perilously close to bankrupting his firm (LeTourneau, 1960).

Satisfied that he was the best man for the job, Six Companies let an additional contract to LeTourneau to extend the government highway another 4,000 feet, down to the precipice for the inclined railway serving the main dam site in Black Canyon (seen in Figure 14). This proved tedious, but LeTourneau employed cable-winch-controlled bulldozers, which anchored by cables, were able to winch themselves up and down the precipitous cut slopes, just like the high scalers employed to pluck the loose rocks off the dam's abutments following each blast. This was the route that eventually became U.S. Highway 93, bringing millions of tourists to the dam, and crossed over the dam and continued on to Kingman, Arizona (the highway to Kingman was also graded in 1931, before the dam construction began in earnest).

Six Companies employed numerous subcontractors to help them establish site access throughout the summer and fall of 1931, establishing the roads, rail spurs, and electric power transmission lines crucial to excavating the four massive diversion tunnels around-the-clock. Two levels of access had to be provided; an upper level that serviced the cliffy area above the dam's right (Nevada) abutment, and another at river level, which allowed the river to be crossed by workers and vehicles (Figures 4 and 5). This transportation network extended many miles upstream to the aggregate quarries on the Arizona side, aggregate stockpiles and the main aggregate mixing plant on the alluvial fan in Hemenway Wash, connections to the diversion tunnels (to haul out tunnel muck) and to the two massive concrete batch plants on the Nevada side of Black Canyon.

EXCAVATION MILESTONES

Largest Diversion Tunnels

Reclamation's 1928 plans envisioned two partial excavations of the river bed to construct the upstream heel of the dam to a height of approximately 231 feet above the lowest point of foundation (to an elevation of 760 ft) during the first construction season of nine months, followed the next year by a downstream cofferdam about 153 ft high (to elevation 663 ft), incorporated into the downstream toe of the dam (shown in Weymouth, 1924). This scheme envisioned placement of 235,000 yd^3 of concrete

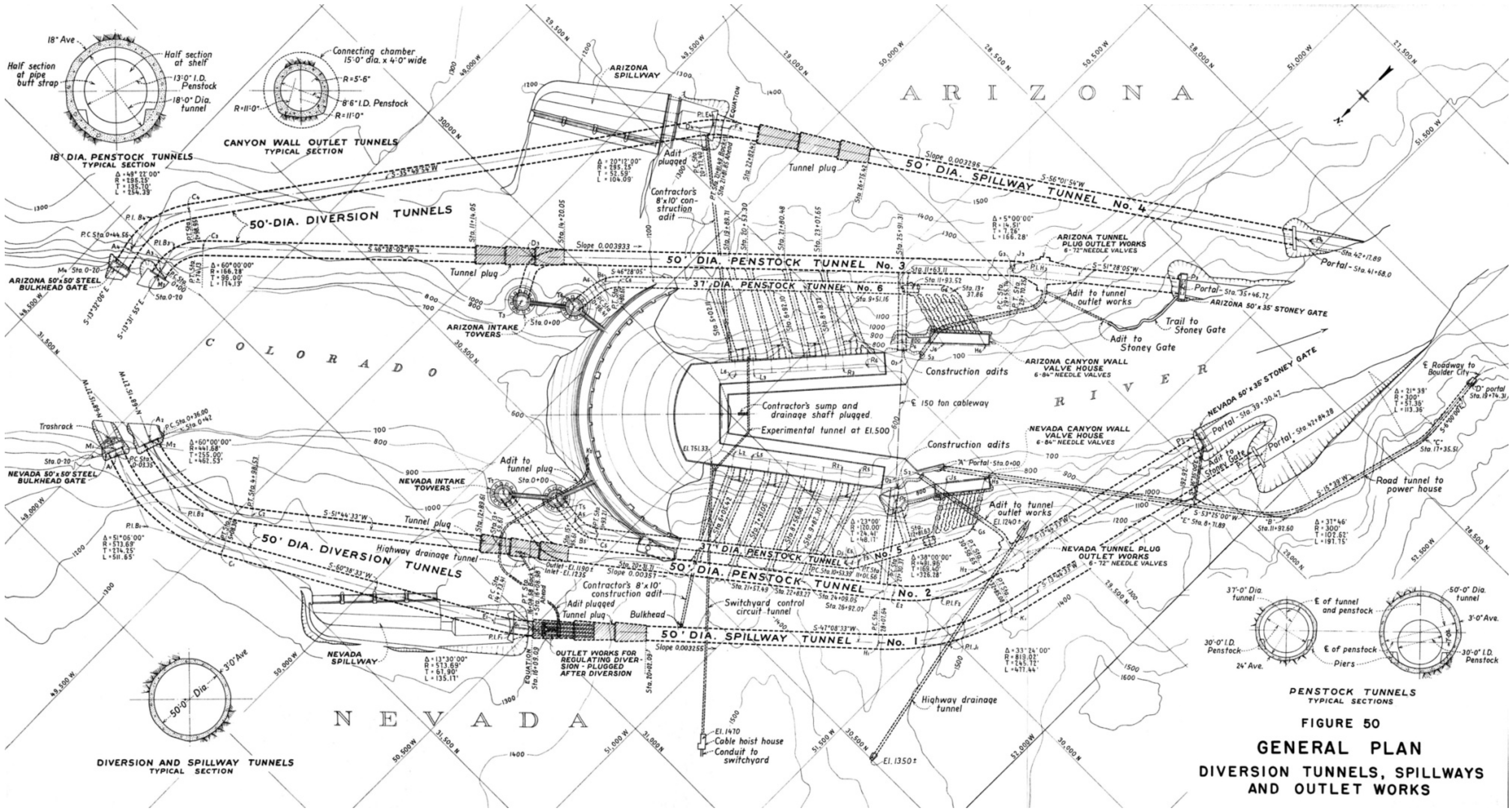


FIG. 6. Plan view of final layout employed for Hoover Dam, diversion tunnels, spillways, outlet works and powerplant. (USBR)

FIG. 7. Suspension bridge built by Six Companies just downstream of the dam site to allow access to 8 x 10 ft cross adits so they could drive multiple headings on the massive diversion tunnels. The portal on the Arizona side is clearly seen, about 50 feet above the bridge deck on the far side. Six Companies was not paid for constructing these additional tunnels, which greatly hastened the construction schedule (USBR).

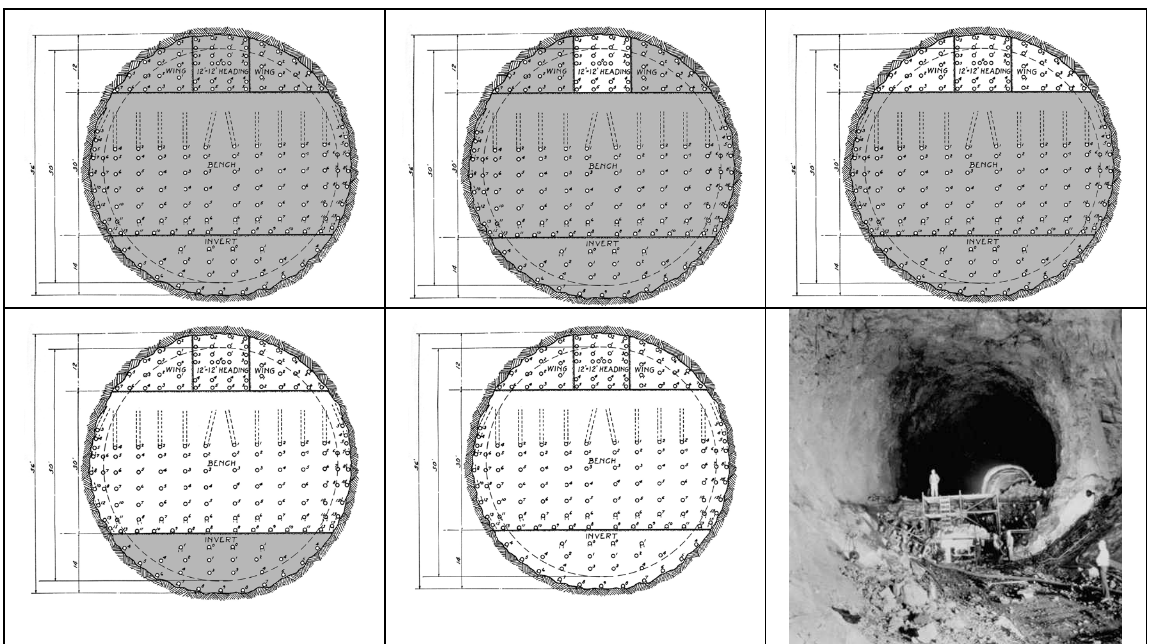
that would subsequently be incorporated into the main dam, which could retain up to 400,000 ac-ft of flood water. Similar schemes had been employed on several masonry gravity dams built during the previous decade in steep-walled canyons.

The 1928 design only provided sufficient river diversion (80,000 to 100,000 cfs) during the months of low to medium water stages, between the period of high flow, in May-June-July. The Colorado River Board overruled Reclamation on this diversion scheme, deeming it to be too risky to allow flood waters to run over the dam and damage the powerhouse excavations, immediately downstream of the dam (Clark, 1930). They favored the use of separate upstream and downstream embankment cofferdams which would allow the powerhouse excavations to be made "in-the-dry" at the same time as the main dam.

The CRB told Reclamation to double their bypass tunnel capacity from 100,000 to 200,000 cfs. They were therefore obliged to construct four diversion tunnels in lieu of the proposed two. This was the most significant design change proposed by the board, which resulted in significant increased costs and an additional year of anticipated construction (the Board anticipated that the diversion tunnels would have to be at least one mile long; but they averaged 4,000 ft upon completion).

From the project's inception Frank Crowe realized that the most important milestone in constructing Hoover Dam would be how long it took Six Companies to excavate the project's four massive diversion tunnels, which, at 56 ft, were the largest diameter hard rock tunnels ever constructed up to that time. The dam site couldn't be excavated until the Colorado River was safely diverted through these tunnels.

That the Colorado was a fickle river everyone knew. Over the previous half century its flow had ranged between a low value of just 500 cubic feet per second (cfs) in January 1912 to a peak flow of 384,000 cfs in February 1884 (USBR, 1950); a high-to-low ratio of 768:1. The Colorado River is unusual in that almost no accretiary flow joins the stream over its last 400 miles, 80% of the annual flow being derived from the Wind River and Rocky Mountains, far upstream. Late summer thunderstorms in the Colorado Plateau bring occasional flash floods, but these flows mollify rather quickly, downstream.



(USBR)

FIG. 8. Sequence employed to excavate the 56-foot-diameter diversion tunnels. Upper left: full face before drilling. Upper middle: 12 x 12 ft pilot bore in tunnel crown. Upper right: Excavation of crown wings. Lower left: seven rows of drill holes were employed with top row drilled upward. Lower middle: Four levels of holes in the invert. 173 drill holes were loaded with each round of blasting. Lower right image shows the completed full-face excavation.

The circular tunnels were to be excavated to a diameter of no less than 56 feet, and then lined with reinforced concrete to a finished diameter of exactly 50 feet. The falsework to support forms for a 3-foot thick-concrete lining 50 feet above the tunnel invert were just one of several unprecedented challenges faced Six Companies.

The tunnels were numbered 1 through 4, beginning with the outboard Nevada tunnel (No. 1) and ending with the outboard Arizona Tunnel (No.4). The tunnels' average length was about 4,000 feet. Their general layout is shown in Figure 6. The contractors would not be able to employ cross-cut adits or additional access shafts to accommodate multiple headings upstream of the dam's axis because these additional openings would lie beneath up to 600 feet of water when the reservoir filled. Multiple headings had been employed since the mid-1860s while driving railroad or highway tunnels of any significant length in order to reduce the duration of excavation.

It was of the utmost importance to divert the river in late fall, or early winter, before spring floods, which were estimated to be about 120,000 cfs every 2.5 years, based on the available records. The aggregate capacity of the four 50 foot diameter tunnels was intended to be 200,000 cfs. If Six Companies could succeed in diverting the river's flow before May 1st, they could accelerate the project by an entire year and thereby save millions of dollars by being able to excavate the channel bed beneath the dam and powerhouses.

FIG. 9. Suspension bridges, roads, and rail spurs accessed the diversion tunnels and dam site at river level. Tunnel muck on the Nevada side was removed by rail while that from the Arizona tunnels was removed by truck. The Arizona tunnels were completed first and lined in late October 1932 (USBR).

On May 21, 1931 Six Companies detonated their first blasts of dynamite on the diversion tunnels. Six Companies began the diversion tunnels by excavating a series of 8 by 10-foot cross adits from just downstream of the dam site (Six Companies was not compensated for these excavations because they were not required by the Reclamation contract). These exploratory adits extended 826 feet in on the Arizona side and 607 feet in on the Nevada side (Figure 7). These allowed access to employ double heading of the 12 by 12 ft pioneer headings at the crown of all four 56-foot-diameter bores (four faces would be worked simultaneously, from the upstream end, the downstream end, and in both ends of the exploratory adits).

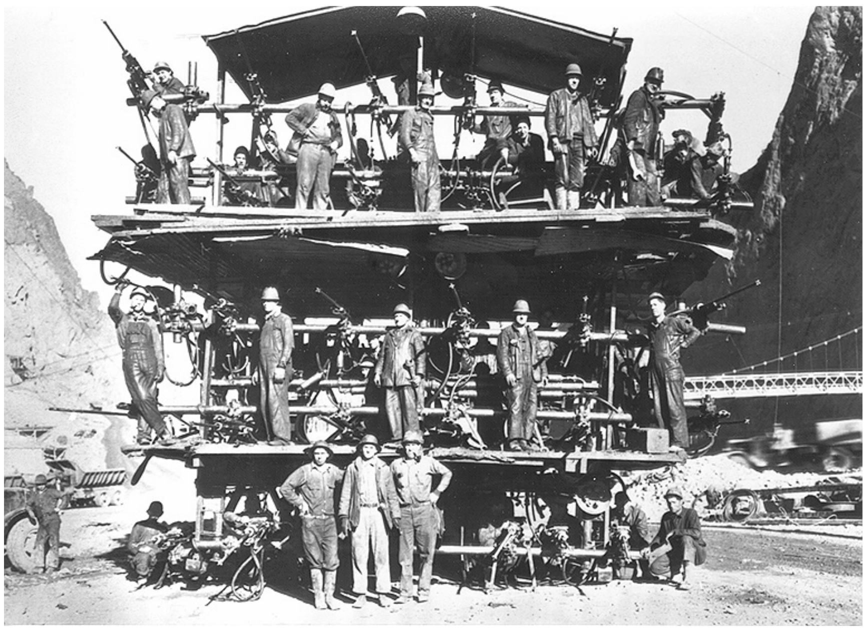
The tunnels were then enlarged from the upstream and downstream portals because the drilling jumbo could not fit through the cross adits. The single exception was the outboard Arizona Tunnel No. 4, which employed a full crown heading excavation (12 x 30 ft) proceeding upstream from the downstream portal (because of access problems at the upstream portal and the ease of wasting tunnel muck in side canyons adjacent to both of the downstream portals (see Figure 8). Six Companies erected a suspension work bridge to allow their crews to work on the Arizona diversion tunnels, as shown in Figure 9. During that first summer of 1931 average temperatures reached 120º F in the shade, and 14 workers died of complications of dehydration. Crowe responded proactively by hiring orderlies to deliver ice water to men while they were working, encouraging them to drink, but other hazards manifest themselves as the job progressed (described later).

First Use of Drilling Jumbos

The single greatest problem in excavating such large diameter tunnels was "reach," the slang term used to describe how far a driller could reach with a pneumatically-powered but hand-operated jackhammer, which was referred to as a "jack leg." The maximum reach of a jack leg was something between 6 and 12 feet. Up to that time the only way to accommodate such a large excavation face would have been to employ a pilot bore in the tunnel crown, which would be expanded outward, bit by bit, then dropping down in multiple benches, each about 8 feet high. The problem was how to pass the tunnel muck backward, out of the tunnel, without dropping it on the men working the lower benches.

One of the tunnel shift superintendents named C. T. Hargroves came up with a novel scheme that allowed four levels of drilling to be undertaken simultaneously, which allowed 2/3 of the tunnel face to be drilled by 24 to 30 jack-legs simultaneously. He took an International 10-ton freight truck, stripped it down to its chassis and welded on a semi-circular frame that would support four working platforms, each of which was equipped with two levels of jackhammers. This allowed seven different levels of the tunnel face to be drilled simultaneously, as shown in Figure 10.

By October 1931 Six Companies was employing their first full-face excavations on Diversion Tunnel No 4. By January 1932 they were employing eight Marion 100-ton electric shovels using modified 3.5 cubic yard buckets, removing an astonishing 16,000 cubic yards of rock per day from the four tunnels. The tunnel muck shed by the rapid excavations was removed using gas-powered International 10-ton dump trucks. The trucks were instructed to move as quickly as possible between the tunnel face and the railroad hopper cars lined up just outside the upstream portals, which hauled the muck away. Drivers were required to make a finite number of round-trips during each 8-hr shift, depending on the length of the tunnel in which they were working. The exhaust from the dump trucks caused increasingly poor air quality as the tunnels extended further into the canyon walls, bereft of any forced air ventilation. It's a wonder more weren't killed (96 men were officially recognized as having died during construction of the dam). Six Companies managed to complete excavation of all four diversion tunnels by May 1932, 14 months ahead of schedule.



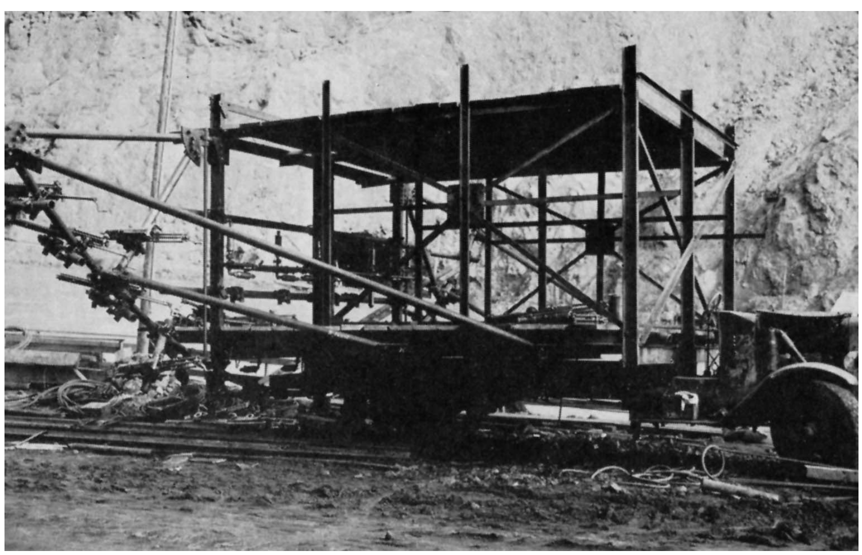


FIG. 10. Upper: Drilling jumbo fashioned upon a 10-ton International freight truck supported 24 to 30 jackhammers to drill 48 holes from four to 20 feet deep on seven levels. Lower: Smaller drilling jumbo designed to drill 24 holes in the semi-circular tunnel invert, on four levels. All of the drills were pneumatically-powered by Ingersoll-Rand compressors (USBR).

Dozens of tunnel muckers and dump truck drivers working inside the tunnels experienced the debilitating effects of what was likely carbon monoxide poisoning. About 50 of these workers brought suit against Six Companies seeking compensation for the loss of their health. The first trials began in late 1932 in Las Vegas courts and Six Companies brought their considerable influence to bear and was able to fend off defense judgments, although several jurors admitted to accepting bribes after one of the trails. In January 1936 an out-of-court settlement was reached by Six Companies with approximately 50 remaining gas-suit plaintiffs and the amounts of their payments were undisclosed.

Largest Traveling Slip-forms

The diversion tunnels were lined with concrete, beginning with their inverts (Figure 11). The tunnel invert was then filled with 15 feet of gravel to serve as a road bed for removing muck at the tunnel face and support the traveling slip-form used for lining the tunnel shoulders, shown in Figure 12.

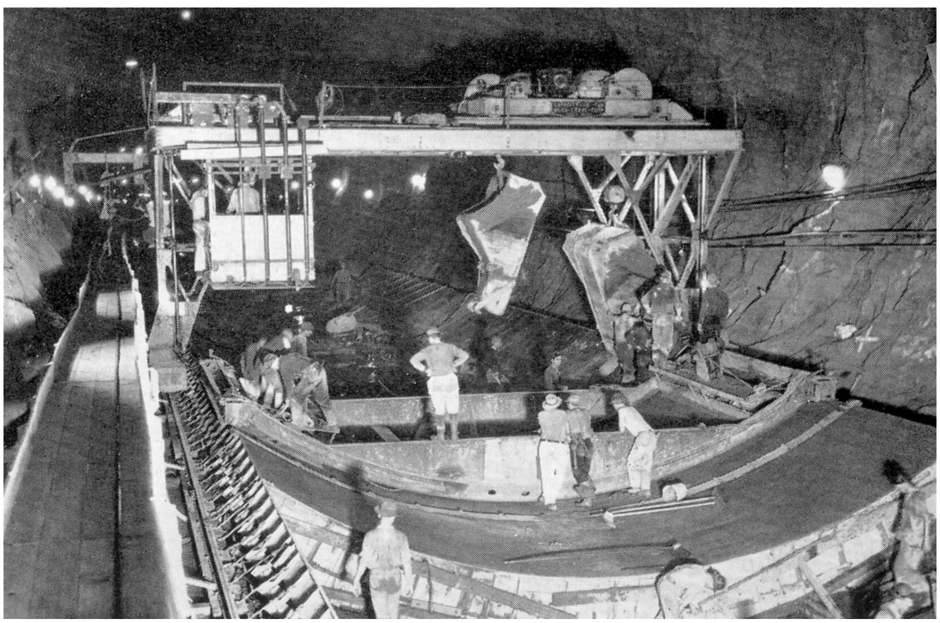


FIG. 11. Traveling slip-forms were used to pour the concrete invert section of the four diversion tunnels, as shown here (USBR).

The government contract required that the diversions tunnels be completed by October 1, 1933, subject to a $3,000/day fine if they were not finished on time (Figure 13). For 15 continuous hours on November 12-13, 1932 dump trucks bombarded the river channel with load after load of rock riprap; one dump truck dropping its load every 15 seconds. At 11:30 AM on the 13th the outboard Arizona diversion tunnel cofferdam was detonated, allowing the Colorado River to spill into the tunnel. Within 24 hrs entire flow of the Colorado River was diverted through this tunnel, which was running between 3,000 and 6,000 cfs over the next few weeks. The largest river

FIG. 12. Traveling slip-form used to line the crown of the diversion tunnels after pouring the invert and filling it with 15 feet of gravel, to serve as a road bed. This was the largest traveling slip form ever fabricated at the time (USBR).

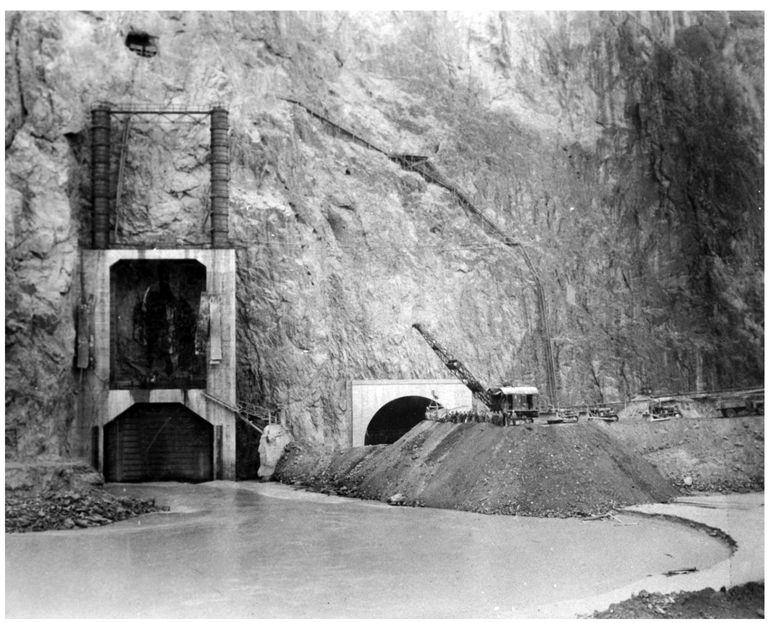


FIG. 13. Initial diversion of the Colorado River through Diversion Tunnel No. 4 on the Arizona side on November 14, 1932, a full year ahead of schedule. Note the scale of operations by the height of several hundred workers standing at the brow of the fill pile at right center, in front of the dragline (USBR).

diversion in history had been accomplished in just 13 months. The maximum capacity of the four diversion tunnels was 200,000 cfs, about a once-in-25-years event. The government assumed responsibility for flood damage after the cofferdams and diversion tunnels were completed. This opened the way for Six Companies to begin building the cofferdams and start excavating the channel at the dam site.

Abutment Excavations

The most celebrated aspect of the project's early years was the abutment excavations, typified by loud production blasts and swarms of high scalers rappelling from the cliffs, prying off the loose rocks using scaling bars, which looked like 8-ft long javelins with a tapered head, similar to an old Blacksmith's nail (Figure 14). High scalers were the highest paid and the most photographed laborers, earning \$3.50/day. High scaling was an art built on teamwork and close coordination, lest a block might fall on another high scaler. High scalers were thus obliged to descend newly blasted faces in a line-abreast fashion, as shown in Figure 15. This allowed ample space between the men, and used adjacent climbers to help pry off the larger blocks, often using wood wedges.

FIG. 14. Noontime production blasts on the Arizona abutment upstream of the dam. Tourists flocked to view the small blasts that accompanied the lunchtime breaks, when workers were cleared from the canyon floor.

FIG. 15. Upper: High scalers working the lower portion of the dam's left abutment, on the Arizona side. Note the raw loose character of the freshly blasted rock and the sheer scale of the operation. Lower: Enlargement of the same image, showing the high scalers worked line abreast of one another (USBR).

High scalers also drilled the shot holes using air-powered jackhammers. These men could be recognized by their bosun's chairs, which were fashioned of a rope wrapped around a small wooden seat, which sailors used to support themselves while painting a ship's hull (Figure 16). Behind these came "powder monkeys," the men who loaded the drill holes with dynamite, stemming, and blasting caps. There were three principal "blasting windows" each day, usually during mealtimes. The greatest audience of gawkers always occurred during the noon hour, when the lunchtime blasts were detonated.

The techniques developed to scale the precipitous cliffs at Hoover Dam became the standard practices employ." Scaling hasn't been improved with time or by employing advanced technologies. High scalers tapped the rock with their scaling bars to listen and feel its "ring." Solid rock tends to elicit a numbing thud, but rock that has separated from the parent cliff reverberates with a sort of hollow clang, alerting the high scaler that it has become loosened or dislodged, even slightly. These same scaling techniques were employed 34 years later, at Glen Canyon Dam.

FIG. 16. High Scalers in Bosun's Chairs operating jackhammers to drill holes for production blasting. This was hot, dirty, rough work, without any chance for rest. On the very steep slopes, like that shown here, scalers would have to stop and help one another 'set up' their 'jacklegs' on a hole and drill it a sufficient distance so that a man could safely control it (USBR).

FIG. 17. A group of 'powder monkeys' loading drill holes with dynamite, stemming, and blasting caps, photographed on August 15, 1932. Note the thin steel tamping bars, which were typically 10 ft long. These were used to tamp the sticks of dynamite and pack the stemming in the upper part of the holes, to force the blast energy into the rock mass (Bechtel Collection, USBR).

ENGINEEERING GEOLOGIC MILESTONES

Geology of Black Canyon Revealed in Excavations

According to Jerome M. Raphael, a Reclamation engineer who worked closely with Frank Crowe at Shasta Dam, Crowe described Hoover Dam as "*nothing more than a three-pronged job; the prongs were just bigger, that's all.*" First was dealing with site access, equipment mobilization, and materials delivery (aggregate, cement, steel, and fuel); Second was excavation of the bypass tunnels, the river channel, and the dam and powerhouse abutments; Third was concrete batching and placement, using an intricate system of overlapping cross-canyon cableways that were Crowe's trademark (Raphael, 1977, 1988; Rocca, 2001). Of these the greatest uncertainties lay in the excavation work because nobody really knew what they would find once they began excavating; that was simply "the nature of subsurface work."

In the end more than 5,500,000 cubic yards of sand, gravel, and rock material were excavated, and another 1,000,000 cubic yards of earth and rockfill were placed (Figure 18). By feature, this included: 1,912,000 yd^3 for the tunnels and shafts; 150,000 yd^3 for the dam's abutments; 1,300,000 yd^3 for the foundation of the dam and powerplants; 750,000 yd^3 for the spillways and inclined tunnels; 410,000 yd^3 for the valve houses and intake towers; 732,000 yd^3 earth and rockfill for the upstream cofferdam; 500,000 yd^3 earth and rockfill for the downstream cofferdam (about 2,000,000 total cubic yards excavated from channel excavations); and 2,300,000 yd^3 for other excavations.

A major limitation was that no tunnel muck or excavation spoil could be dumped in the Colorado River; the channel needed clear for operation of what would soon become the world's largest hydroelectric facility (eclipsing the Vemork hydroelectric power plant at Rjukan, Norway).

The contractor was expected to dispose of six million yd^3 of spoil in the steep ravines lining Black Canyon above and below the dam site. The contractor constructed a network of temporary construction roads to gain access to the diversion tunnel portals and to the dumping spots. These spoil slopes were to be neatly dressed and compacted so as to present a 'neat appearance' and resist surficial rill erosion.

The average depth of channel excavation was between 110 and 130 feet below mean low water level. The deepest excavation was in the upstream cutoff trench, which extended 139 feet. A sawn 2 x 6-inch plank was discovered 50 feet below the low water surface during foundation excavation (Figure 19). This surprised everyone. It was thought to have come from either the June 1921 high flows (170,000 cfs) or during the winter of 1921-22 when a local downpour triggered a debris flow that swept through the old Mormon settlement at the mouth of Callville Wash, about 15 miles upstream of the dam site. A third alternative may have been the high flows of June 1928, which reached 137,000 cfs.

The 'Inner Gorge' of the channel beneath the dam and powerhouses was revealed in borings made ahead of construction, but its physical character was altogether unusual and the subject of considerable fascination with geologists at the time (Ransome, 1931; USBR, 1950).

First Use of Paleoseismology

In his geologic report to Reclamation, California Institute of Technology (Caltech) Geology Professor Leslie Ransome described curious pothole and rill structures in the uppermost reaches of Black Canyon around elevation 1550, about 900 ft above the low flow surface of the river! These potholes were filled with fresh water-rounded cobbles from upper Precambrian and Paleozoic units that outcrop in the Grand Canyon, well east of the Grand Wash Cliffs.

FIG. 18. View looking upstream from the Nevada abutment at the excavation work in December 1932 as the abutments were being trimmed back. The downstream cofferdam is taking shape in the foreground. The cofferdams had to be completed before they could begin excavating the channel gravels. All of the excavated materials had to be transported to disposal sites in steep side canyons upstream or downstream of the dam (USBR).

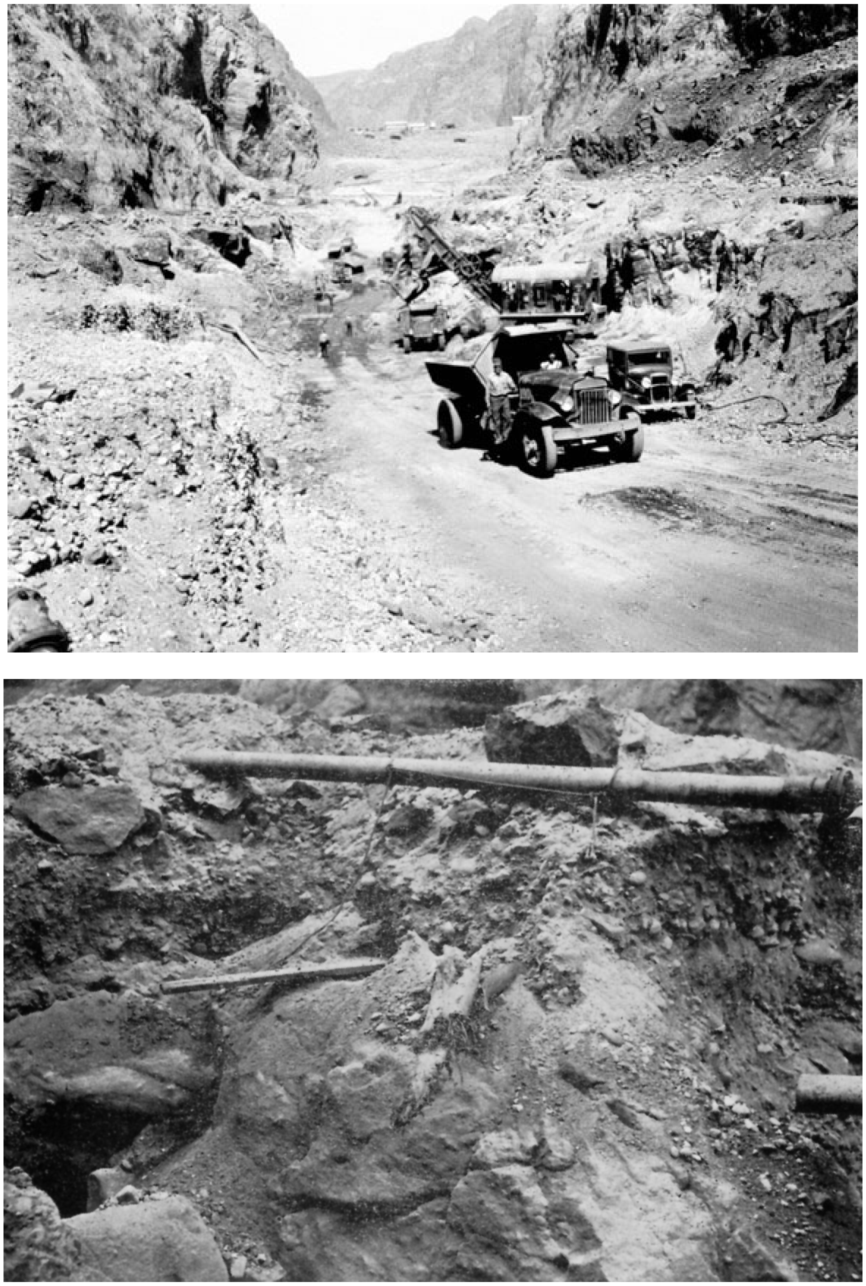


FIG. 19. Upper image shows excavation of the cobbles, boulders, sand, and gravels of the Colorado River on April 3, 1933 when crews began excavating the "inner gorge," which extended much deeper into the andesite bedrock. This narrow trough was filled with boulders up to 12 feet in diameter. Lower image shows the 2 x 6 inch plank unearthed at a depth of 50 feet below the river bed, thought to have been deposited during the peak flows of June 1921, which reached 170,000 cfs (from USBR, 1950).

FIG. 20. View of the excavated 'inner gorge' of Black Canyon as it appeared on June 3, 1933. This inner gorge was filled with enormous subangular boulders, which had fooled drillers in thinking they had encountered 'bedrock' during the first two seasons of drilling, in 1922-23 (USBR).

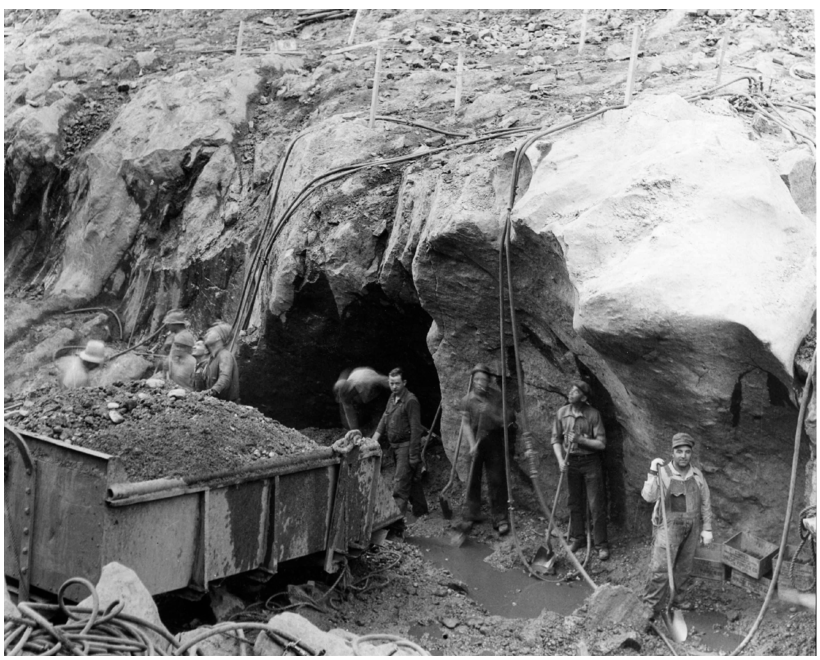


FIG. 21. The sides of the inner gorge were carved out into giant pothole-and-rill structures, on a scale not previously observed. These suggested an intensely turbid flow had rapidly cut the channel. These overhangs were chipped off to avoid the problems with bearing and arching over irregularities (USBR).

The potholes were locally surrounded and intermittently filled with older terrace gravels, which Ransome (1931) mapped as “Qtg.” Ransome recognized that that these gravels were from a much older river channel, approximately 950 feet above the present level of the Colorado River. One of the potholes was cut by mapped fault A-25, which clearly cuts the biotite latite bedrock, but without any apparent offset of the pothole.

Leslie Ransome correctly deduced that the absence of offset of the old potholes cut by the canyon’s faults suggested that they had been inactive since before the Colorado River had excavated the 900 ft deep gorge through Black Canyon. He then reasoned that the other faults, of similar style and inclination, most likely predated the incision of Black Canyon. The concern over state-of-activity of these faults was one of the prime reasons Reclamation had engaged Ransome’s services (in 1923 he had been an employee of the USGS, but was teaching at Caltech when he prepared his second report in 1931). Ransome’s reasoning appears to have been one of the first applications of in assessing seismic risk to critical engineering structures; the field we now refer to as paleoseismology (McAlpine, 1996).

80 years would pass before the puzzle of the paleochannel 950 ft above Black Canyon was more or less solved. Howard et al. (2008) have assembled data from numerous outcrops between the Grand Wash Cliffs (mouth of Grand Canyon) and the Gulf of California which consistently record major swings in river elevation over the last five million years (5 Ma), since the last basalt flow congealed along the margins of what is now Black Canyon (Howard and Bohannon, 2000). These sediments infilling more than 20 stranded paleovalleys of the ancestral Colorado River record alternating periods of aggradation (filling) and degradation (erosive downcutting). These cycles appear to have resulted in channel incisions of as much as 1,150 ft. 80 years later House, Pearthree and Perkins (2008) examined the Quaternary sediments preserved in proximity to the bedrock narrows of the lower Colorado River and made a convincing case for periodic breakout floods that carved the bedrock narrows that formed favorable dam sites for by Hoover, Davis, and Parker Dams.

MILESTONES IN COFFERDAM DESIGN

Largest Cofferdams

To isolate the dam and powerhouses foundation excavations and prevent their being flooded during construction cofferdams of unprecedented scale were constructed upstream and downstream of the dam site. As mentioned previously, the design capacity of river diversion was a once-in-25-years event. The government assumed responsibility for flood damage after the cofferdams and diversion tunnels were completed. The specifications for the cofferdams were for them to be at least 100 feet high (above the low flow level of the river), which required 732,000 cubic yards in the upstream embankment and 500,000 cubic yards in the downstream embankment. The upstream cofferdam was located about 600 feet downstream of the diversion tunnel inlets. The general layout of the cofferdams and protective rock dikes with respect to other project works are summarized in Figure 22.

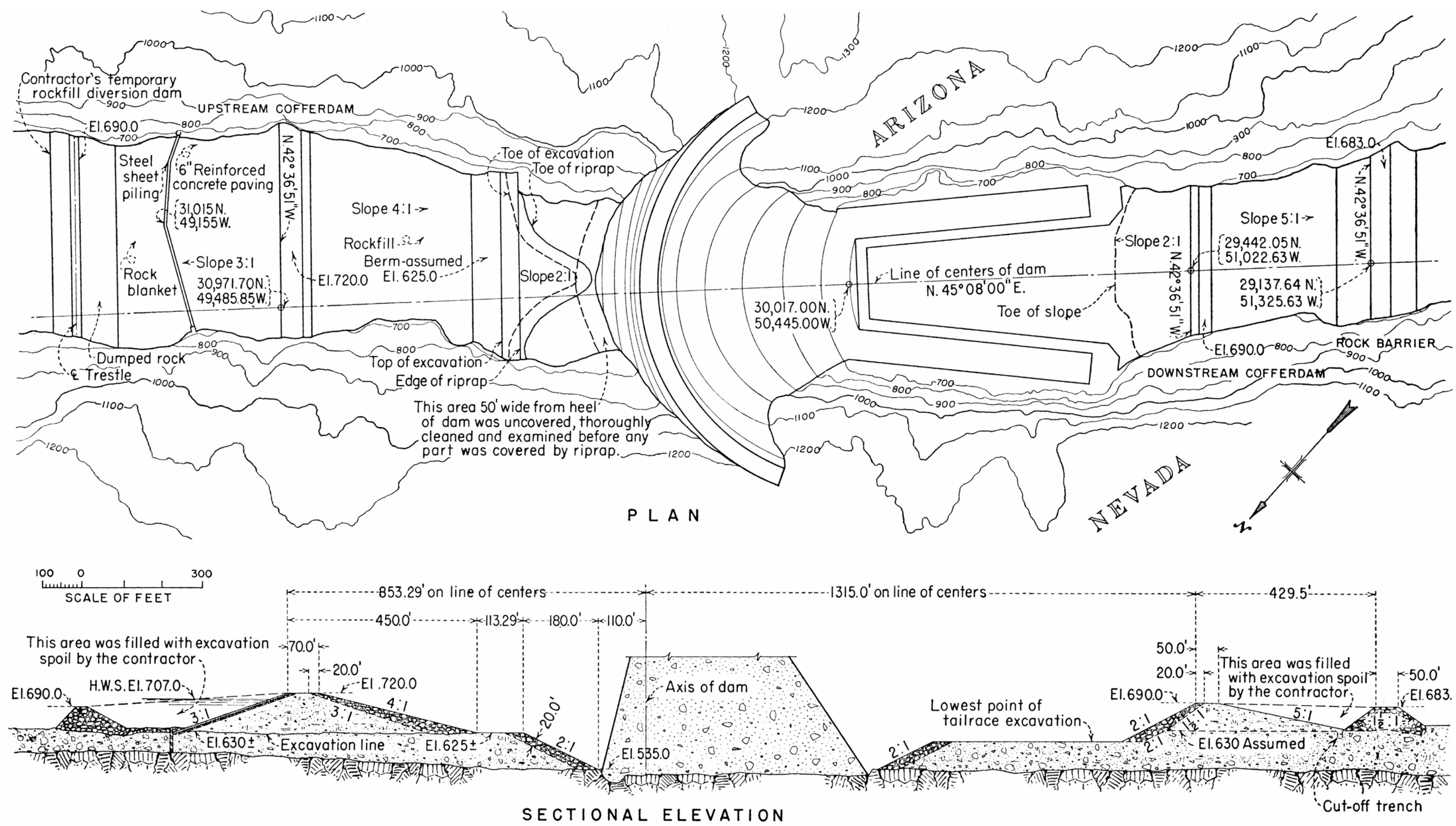


FIG. 22. Plan and section views through the dam site showing the up and downstream cofferdams, as well as the rock dikes added to these (USBR).

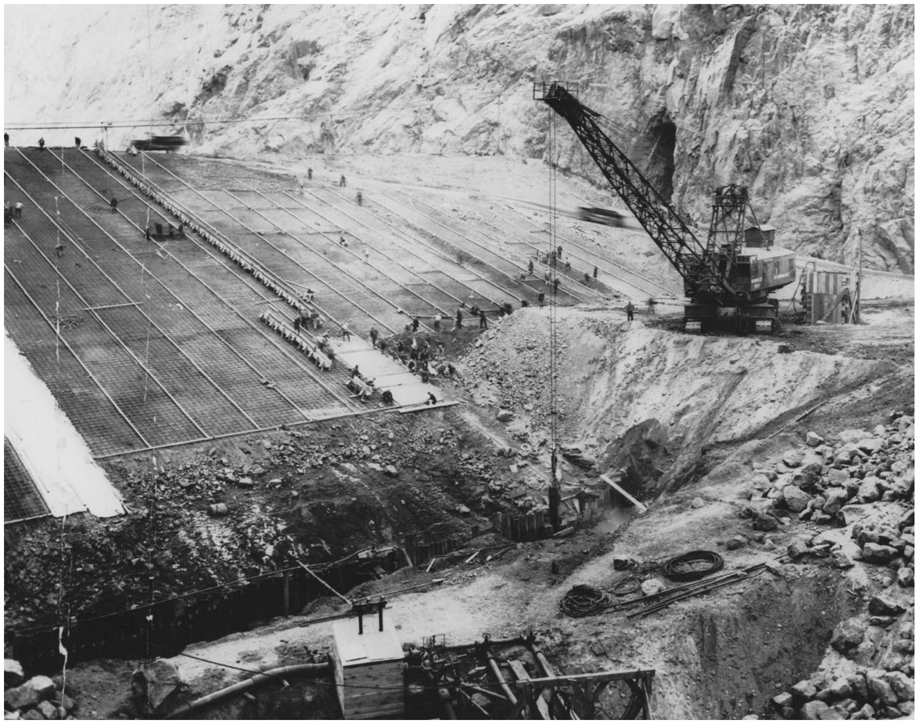


FIG. 23. Paving of the upstream face of the upstream cofferdam, as a protective layer and seepage barrier. The face was inclined at 3:1 (horizontal to vertical). Middle foreground shows the sheetpile cutoff wall being installed by a drag hammer attached to the tracked dragline. Note men for scale (USBR).

The Colorado River Board voiced some apprehension about the cofferdams because they were comprised of pervious channel gravels placed on channel gravels. Professor Mead worried that under 100 feet of pressure head during a flood, considerable seepage could be expected to percolate beneath and through these structures.

As an accommodation of this concern, Reclamation decided to require overexcavation of 250,000 yd^3 of channel fill to a depth of elevation 625 ft to provide a more stable and less pervious foundation for the cofferdam. This left 70 to 80 ft of channel gravel in-place beneath the embankment (Figure 22). Reclamation added a specification for installation of a sheetpile cutoff wall at the upstream toe of the cofferdam which extended 40 to 50 feet into the channel gravels, but they were unable to penetrate the boulders filling the inner gorge. They also required that the upstream face of the upstream cofferdam be covered with a 6-inch-thick reinforced-concrete mat (Figure 23), placed over a 3-foot-thick layer of tightly tamped rock, with sluiced fines brought in from Hemenway Wash (the only source of fine-grained material in the area).

To limit seepage along the abutments three rows of reinforced concrete "percolations stops" (cutoff walls) were constructed, which extended 30 feet into the embankment, along its axis. The upstream cofferdam had a crest elevation of 720 ft, about 30 feet above the crowns of the diversion tunnels. The maximum pool for the 25-yr flood (200,000 cfs) was assumed to reach elevation 707 ft, with a low water surface at 645 ft. This allowed 13 ft of freeboard beneath the crest of the upstream cofferdam. Another 77,000 yd^3 of rock was used to construct a rock dike above the upstream cofferdam (Figure 22).

Construction of the upstream cofferdam began in September, 1932, two months before the river diversion began. A horseshoe-shaped rockfill dike protected the cofferdam on the Nevada side of the river. After the Arizona tunnels were completed, and the river was diverted through them, the remaining work on the Nevada diversion tunnels was completed much faster because all of the mining resources could be concentrated upon them. The upstream cofferdam contained 516,000 yd^3 of re-worked channel fill (gravel and sand) and 157,000 $yd^3$of rockfill used on the facing shells (Figure 23), which came from the abutment excavations (Figure 18). During the month of December 1932 more than 400,000 cubic yards of material was placed in the upstream cofferdam, a record at the time.

Fill placement for the downstream cofferdam was delayed until the high-scaling of the canyon walls above the powerplant sites and outlet works was completed (Figure 9). The downstream cofferdam was built of rolled channel sands and gravels, with a crest elevation of 690 ft, 66 feet above the tailwater level and about 155 ft above the bedrock channel. The downstream cofferdam was originally designed for 230,000 yd^3 of channel fill and 63,000 $yd^3$of rock shell. The rock shells were placed on the upstream sides of the downstream cofferdams to retard hydraulic sluicing or piping of low cohesion fill materials into the dam and powerhouse excavations, the "wet" side being downstream of the "dry" side of the embankments (Figure 23).

To lessen the backpressure against the downstream cofferdam that might occur under maximum spillage (~200,000 cfs) during construction, 98,000 yd^3 of armor rock (> 18 inches in diameter) was placed to form an additional rock dike about 55 ft high, situated 350 feet downstream of the downstream cofferdam (shown on extreme right side of Figure 22). The area between this rock dike and the downstream cofferdam was eventually infilled with random rockfill, and the pay volume for the combination downstream cofferdam eventually reached 500,000 yd^3. Both cofferdams were completed by March 1933, 13 months ahead of the government schedule.

Handling Flash Floods

The annual average peak flow of the Colorado River before construction of the dam was normally around 85,000 cfs during the month of June. One local flash flood did succeed in inundating the construction site on February 10-11, 1932, before any of the diversion tunnels were completed. These waters came from the Virgin River Basin in southwestern Utah, and reached a peak flow of something around 50,000 cfs (Figure 24). The flooding overwhelmed the rock dikes protecting the diversion tunnels, filling them with mud, and washed out the trestle bridge Six Companies had constructed at the dam site, which they quickly re-built (Figure 5). The damage necessitated full shutdown of the job to accommodate clean-up that lasted five days. Another flash flood occurred on August 31, 1932 when a thunder storm striking the lower Grand Canyon-Grand Wash Cliffs area brought 60,000 cfs of water down Black Canyon, overwhelming the tunnel cofferdam dikes and flooding all of the equipment working adjacent to the channel. The main cofferdams were completed by June 1st, 1933 just before the season's annual spring floods. The biggest flow the tunnels had to handle during construction occurred two weeks later, on June 16th 1933. That day 73,000 cfs flow was safely conveyed around the dam site through the diversion tunnels. The minimum flow of 1,000 cfs was recorded late the following summer, on August 26, 1934 and the reservoir began filling on February 1, 1935.

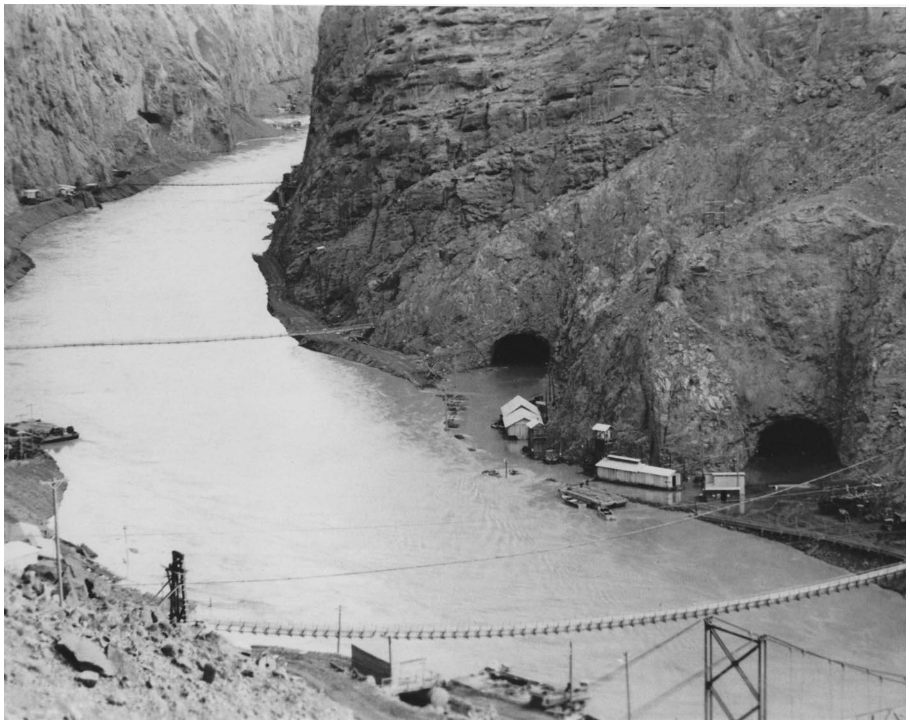


FIG. 24. The only flooding of the job site occurred in early February 1932, triggered by a local storm cell that hit the lower Grand Canyon area. This shows the flooded portals of Diversion Tunnels 3 and4 on the Nevada side. Several wooden trestle bridges were washout out, further downstream (USBR).

STRUCTURAL CONSTRUCTION MILESTONES

Low-heat cement was not available in sufficient quantities to use on the entire dam mass, as more than 5,000,000 barrels of cement were needed for the job (USBR, 1947). Of these, only 400,000 barrels were Modified Low Heat type. The aggregate and feed water were chilled, but an additional cooling process was needed to remove 700 BTUs of heat per cubic yard of concrete because of seasonal impacts caused by the warm summer weather (Figure 25). Cooling pipes had only been used on a trial basis; at Merwin Dam on the Lewis River in Oregon (for which there was no reliable data) and in one small test section of Reclamation's Owyhee Dam, then under construction.

The plumbing details for the concrete cooling pipes were not worked out in advance of letting the contract for Owyhee Dam in 1929, which was the largest dam Reclamation had designed up to that point. It was serving as something of a prototype test bed for the various for many of the innovations being incorporated into the designs for Hoover Dam. There had been considerable delay in circulating the cooling water to the lowest portions of Owyhee Dam, where many of the dam's joints were 100 feet apart. In this area the internal temperature reached a maximum of 150 degrees F, causing the joints to open as much as 0.25 inch, which exceeded the capacity of the few embedded electrical-resistance joint-meters (their design range was 0.22 inch) and they were rendered inoperative. These gaps were subsequently grouted (Carlson, 1977).

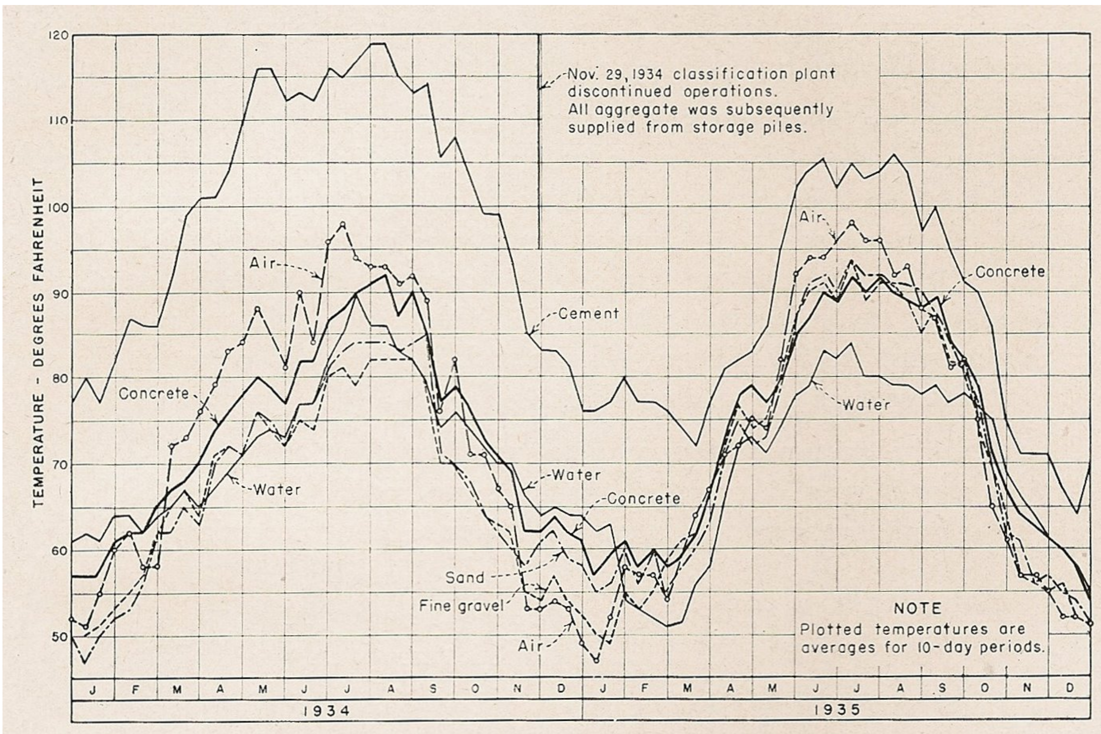


FIG. 25. Average temperatures of air, water, sand, gravel, and mass concrete as prepared at the High Level Mixing Plant throughout 1934-35. Note influence of warm summer temperatures (USBR, 1947).

By the time the contract for Hoover Dam was let in March 1931 Reclamation had opted to embed more than 582 miles of 1-inch diameter steel pipe in the concrete (Figure 26) and initially circulate river water through these, then shift to chilled water. The block temperatures were monitored, especially during the first 30 days. Chilled water came from a refrigeration plant that could produce up to 1,000 tons of ice every 24 hours. This water was chilled to between 35 and 40 degrees F, then pumped through the cooling pipes at a rate of 2,100 gallons per minute (gpm) with flow velocity of cooling water not less than 2 fps. The water temperature at exit was found to be between 42 and 65 degrees F, depending on the ambient temperature and time of year.

Cooling was completed in March 1935, allowing 125 years of curing to be completed in less than two years. A central slot 8 feet wide was left to provide access to the cooling pipes during construction (Figures 27 and 28).

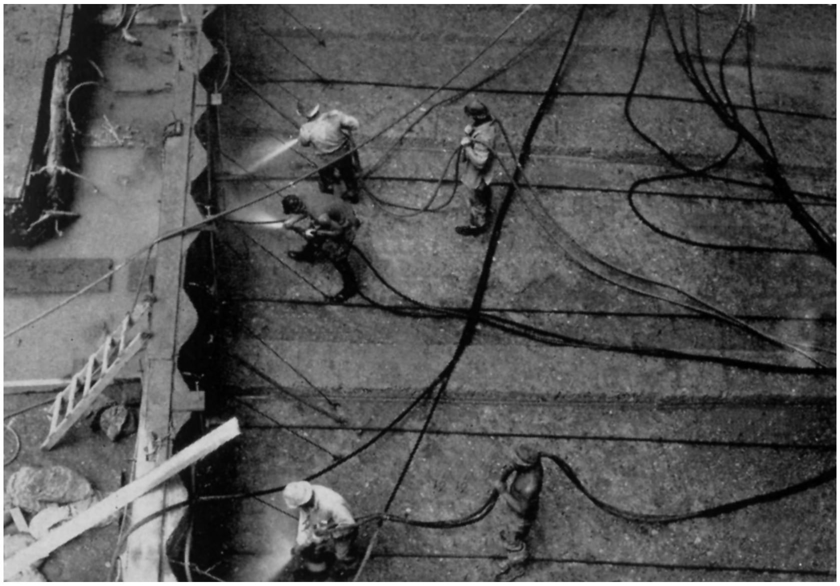


FIG. 26. Workers jetting off the laitance (scum) layer from freshly poured surface on one of the dam's internal blocks, in preparation for the next lift. These fine particles resulted from the tendency of free water to rise in response to aggregate separation, vibration, and agitation of the mix after placement (Troxell, Davis, and Kelly, 1968). Note one-inch-diameter cooling pipes spaced 5 ft apart (USBR, 1947).

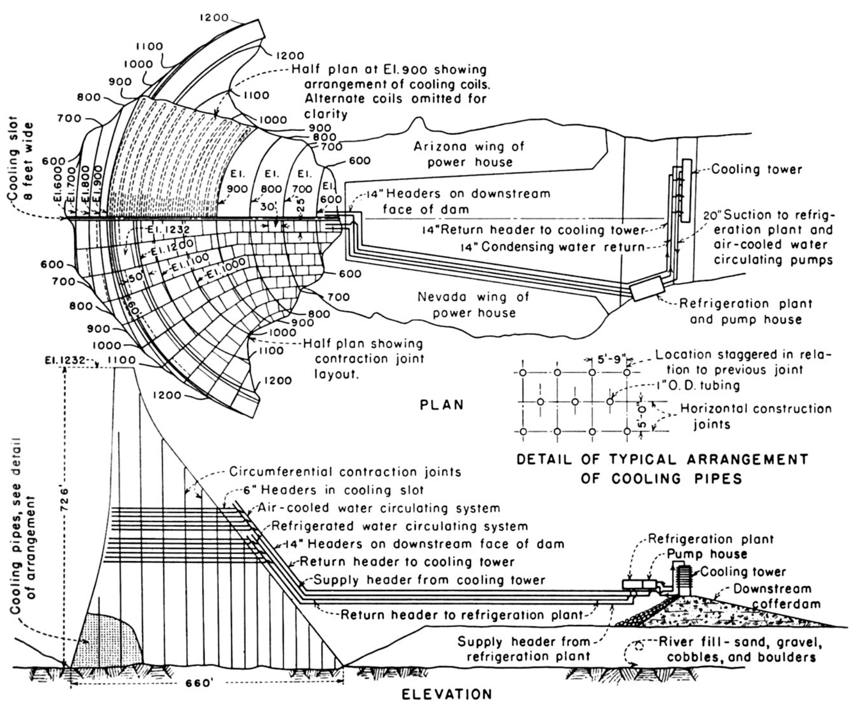


FIG. 27. Schematic of the cooling system installed in the dam as it was constructed. These pipes were subsequently grouted with cement prior to the dam's completion in June 1935 (USBR, 1941).

FIG. 28. 8-foot-wide "cooling slot" running vertically through the dam's axis afforded temporary access to the dam's cooling pipes until the concrete's heat of hydration was brought down to acceptable levels. This was grouted with a standard mix in 10 ft increments as the dam rose upward. (USBR)

Provision for Contraction Joints

In addition to using low-heat cement, two other measures were adopted to help alleviate problems with internal heating of the mass concrete during hydration. One was to cast the concrete in blocks small enough so that they would shrink as a monolithic block, and thereby avoid development of uncontrolled shrinkage cracks.

Dry mixes were specified to reduce shrinkage from moisture change. The dam was built in blocks or vertical columns varying in size from about 60 feet square at the upstream face of the dam to about 25 feet square at the downstream face, using steel forms. Adjacent columns were locked together by a system of vertical keys on the radial joints and horizontal keys on the circumferential joints (Figure 29). Lift heights in each block were limited to five feet in 72 hours, and 35 feet within 30 days. After the concrete was cooled, grout was forced into the spaces created between the columns by the contraction of the cooled concrete to form a monolithic (one piece) structure. Shrinkage was about 0.5%.

Water stops were employed near the up and downstream faces of block joints. Vertically serrated joints were used between blocks in the dam. These joints were grouted after the blocks had shrunk. Horizontally serrated joints used against the abutments. All joints between blocks were to be grouted in 100-foot lifts, after cooling occurred. All cooling pipes were grouted as well, after water circulation ceased.

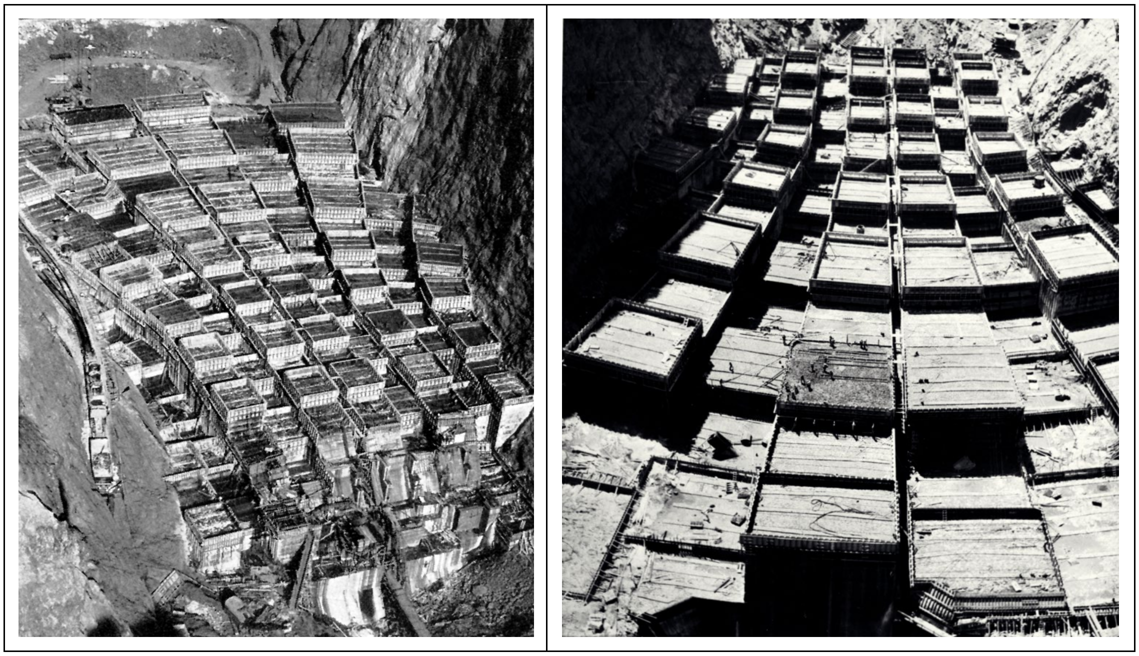


FIG. 29. Interlocking and convergent nature of the dam's basal blocks can be appreciated in these views, taken during construction. Left view looking upstream, while that at right looks downstream. The blocks were poured intermittently to enhance heat dissipation into the air immediately after placement, caused by the concrete's heat of hydration (USBR).

Aggregate Processing

The aggregate quarries were located 12 miles upstream on the Arizona side of the river, on land owned by the government. The mined aggregate was transported by rail (Figure 30) to an aggregate plant capable of processing 20,000 tons of aggregate every 24 hours. This facility was located in Hemenway Wash, on the Nevada side of river (Figure 31). Six Companies employed an ammonia water and aggregate chilling plant. Aggregate mining ceased on November 29, 1934 and the remaining concrete was batched using existing stockpiles.

FIG. 30. Six Companies Inc. railroad train hauling aggregate from the terrace gravel deposits in Arizona across the Colorado River on a temporary timber trestle. This trestle survived all of the high flows until it was dismantled in the fall of 1934 (Six Companies Collection, USBR-LCR).

FIG. 31. Six Companies Gravel Classification Plant in Hemenway Wash, beneath what is now Boulder Bay of Lake Mead. The mined aggregate was sieved and stockpiled here for shipment to the concrete batch plants at the dam site. (USBR)

Low and High Level Mixing Plants

Six Companies constructed two concrete batch plants. The Low-Level Mixing Plant was located on an enormous rockfill pad placed along the Colorado River, using muck from the diversion tunnels (Figure 32). The plant was situated about 4,000 feet upstream of the dam at elevation 720 ft (same elevation as the crest of the upstream cofferdam), about 80 ft above the normal low flow level of the river, about 2,200 ft upstream of the massive diversion tunnel inlets (Yates, 1932). It was serviced by the low level railway line as well as a gravel road. This plant produced 300,000 yd^3 of concrete to line the four diversion tunnels and over half of the mass concrete placed in the main dam. It was equipped with four 4-yd^3 tilting mixers capable of producing 17 batches per hour, giving the plant a capacity of 280 yd^3 per hour. Some of these mixers and batchers were subsequently transferred to the High-Level Mixing Plant to increase its capacity when the low plant was shut down.

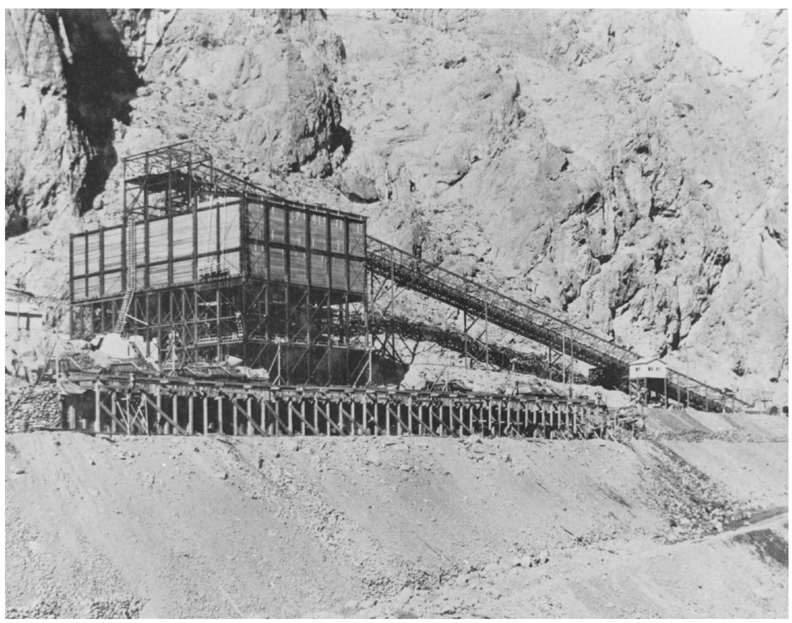


FIG. 52. Low-Level Mix Plant constructed by Six Companies about 4,000 ft upstream of the dam site, as seen in January 1932. Concrete was delivered to the dam site by rail, through tunnels 900 and 1,400 ft long on the Nevada side. This plant was shut down in November 1934 when the dam was 63% complete (USBR).

The High-Level Mixing Plant was assembled in a steep ravine about a 1,000 ft southwest of the dam's right abutment, at el. 1252 ft, 20 ft above the dam crest (Figures 33 and 34). The High-Level Mixing Plant produced almost half of the concrete used in the dam, as well as all of the concrete for the spillways, intake towers, and penstocks. It was placed in operation in March 1933, initially using just two batching and mixing units. The plant utilized conveyor-belt feeders with automatic batching and remote control of mixing using double screw feeders, which

FIG. 33. Classified aggregate being delivered to hoppers at the High-Level Mixing Plant by the Six Companies Inc. Railroad at an elevation of 1403 ft. The aggregate came from the classification plant in Hemenway Wash (USBR-LCR).

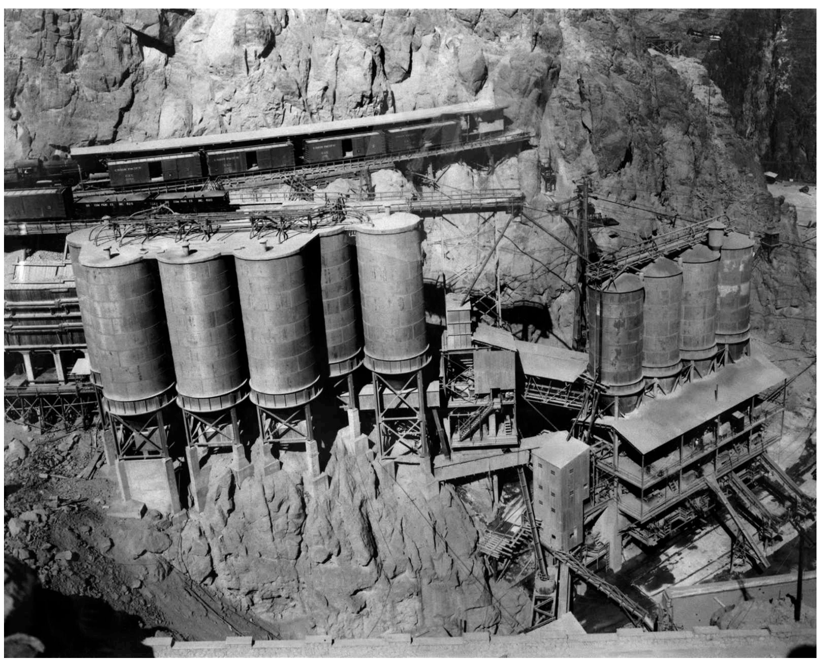


FIG. 34. High-Level Mix Plant constructed by Six Companies in a natural ravine about 700 ft downstream of the dam's right abutment crest. The lower silos were of 5,000 barrel capacity to store cement while the larger silos (at left) held aggregate. The plant's essential elements were 'stacked' vertically to take advantage of gravity in the material feed processing (USBR).

circumvented weighing the various batch components. Mix duration was controlled using consistency meters which operated by resistance feed-back. When both plants were operating they were capable of producing 24 yd^3 of concrete every 3.5 minutes, a record at the time (subsequently exceeded at Grand Coulee Dam). Two additional mixers were later brought in from Owyhee Dam and two more from the Low-Level Mixing Plant, when it shut down.

Most of the concrete was transferred to the dam in 8 yd^3 bottom dumping buckets carried on the overhead cableways, but smaller batches were also dispatched in mix trucks, which could reach all the locations on the job. When the dam reached about half of its design height (November 3, 1934) the Low-Level Mixing Plant was dismantled and shipped to the Parker Dam site downstream. From that time all concrete production shifted to the High-Level Mixing Plant (there was much less concrete volume in upper half of the dam).

CONCLUSIONS

The unprecedented size of Hoover Dam led to many innovations in construction, especially in scheduling and bidding of unit costs. Six Companies emerged as the model contracting organization for large complex jobs, leaving an indelible mark on heavy construction. Too large for a single contractor, the project required the formation of a joint venture of eight contractors, pooling their talents and resources, and sharing the risks. Six Companies also employed numerous innovations to avoid costly schedule delays, such as the use of construction access adits, to allow multiple headings to be advanced on underground excavations (at the contractor's expense), which forever shifted the manner by which underground jobs were designed or bid from thereafter. The complex geologic conditions were handled with what was state-of-the-art expertise at the time, with Reclamation hiring their first geologist. The project also set records for materials processing and handling, which proved of great value, and which figured prominently in the contractor being able to complete the project two years early.

ACKNOWLEDGMENTS

The author is most indebted to retired Reclamation engineer Richard Wiltshire, who appreciates civil engineering history and organized this symposium commemorating the 75th anniversary of Hoover Dam's completion. The author's interest in Hoover Dam was originally piqued by his initial viewing of the hour-long documentary film profiling the Boulder Dam project which he viewed in high school. A year later he visited the dams along the lower Colorado River and took an extended tour of Hoover Dam.

In 2009-10 the author was a Trent Dames Civil Engineering Heritage and Dibner Research Fellow at the Huntington Library in San Marino, California. This fellowship and the residency it afforded allowed the author to review of numerous serial publications, collections, archives, and ephemera that provide invaluable to understanding the engineering decisions and political pressures influencing those

decisions, not just during construction (1931-35) but during the decade preceding and following the dam's completion. Huntington Archivists Dan Lewis and Bill Frank proved to be particularly valuable in ferreting out rare or obscure accounts from the Huntington's civil engineering and scientist manuscript collections, as well as rare maps and historic photos.

Between 1976 and 1988 the author conducted interviews with Roy W. Carlson (1900-1990), Milos Polivka (1917-1987), Jerome M. Raphael (1912-1989), and George E. Troxell (1896-1984), all professors in the civil engineering program at U.C. Berkeley. Carlson had been an ex-officio member of the Hoover Dam Concrete Research Board. Troxell, Carlson, Polivka, and Raphael were all protégées of Professor Raymond E. Davis (1885-1970), who supervised the concrete research for Hoover Dam during its final design and construction, between 1930-1935.

The author also wishes to thank Shelley Erwin of the Archives of the California Institute of Technology for researching the files of Professor F. Leslie Ransome (1868-1935), who served as the principal geologic consultant on the Boulder Canyon Project to Reclamation from 1922 to 1935, and alumni newsletters and records relating to Dr. Frank A. Nickell, who received all his degrees from Caltech (in civil engineering and geology) and became Reclamation's first engineering geologist in 1931. Special thanks is also due to Allen W. Hatheway, Jeffrey Keaton, Richard Proctor, and William K. Smith of the AEG Foundation, who provided documents from Frank Nickell's files.

Sincere appreciation for assistance is also rendered to the following people and their respective organizations: Reclamation historians Brit Allan Storey and Christine Pfaff, Dianne Powell of the Bureau of Reclamation Library; Reclamation archivists and staff Bonnie Wilson, Andy Pernick, Bill Garrity, and Karen Cowan of Reclamation's Lower Colorado Region (LCR) office in Boulder City; Boulder City Library Special Collections; Eric Bittner at the National Archives and Records Service Rocky Mountain Region depository at Denver Federal Center; Paul Atwood and Linda Vida at the University of California Water Resources Center Archives in Berkeley; Su Kim Chung of the University of Nevada-Las Vegas Libraries; civil engineering historian Edward L. Butts; journalist and author Michael Hiltzik; and a special thanks to the author's best friend Steve Tetreault, who accompanied the author of his first tour of the dam in February 1973. Over the past several decades Mr. Tetreault has provided invaluable support and logistical connections in support of the author's numerous visits to the University of Nevada-Las Vegas, Boulder City, and Hoover Dam.

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