Section 2

CONCRETE GRAVITY DAMS

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CONTENTS

GRAVITY DAMS A CENTURY AGO

Gravity dams are dams that by their own weight resist the forces imposed on them with a desired factor of safety. The definition was as applicable a hundred years ago as it is today; all that has changed in the past century is that our understanding of the forces and of the factors of safety have improved greatly. A century ago, the design of gravity dams was based primarily on considerations of weight and water pressure, with some attention paid to uplift pressure, which was less well defined. The forces due to earthquakes, ice pressure and temperature changes, as well as better definitions of uplift pressure, became the subject of intensive research beginning in the 1920s. Similarly, the properties of concrete were systematically explored, a large increase in knowledge of mass concrete coming with the design investigations for Hoover Dam.

Gravity dams are designed so that every unit of length is stable, independent of every other unit of length; hence, the dams can be straight, curved or arched, or even crooked. The typical gravity dam is straight, although many designers curve the axis upstream to gain added stability through arch action.

One hundred years ago, the typical gravity dam was constructed of masonry. Large stone blocks were shaped and fitted into the structure, and the joints were filled with cement and sand mortar. The shape of the cross section was greatly influenced by European engineers whose aim was to produce a section that was stable under reservoir and dead loads, with no tension anywhere, and with nearly constant stress at the upstream and downstream faces. In order to achieve the goal of zero tension anywhere in the cross section, the resultant of dead and water loads was made to lie in the kern of the section. For a straight gravity dam, the kern lay in the middle third of the section, and this one "middle third" criterion became the most important factor for judging the suitability of a gravity dam cross section. Allowable stresses were derived from a study of Almanza Dam, a 300-year-old Spanish masonry dam, with an ample safety factor. These considerations led to a subtly curved, roughly triangular cross section, which can be seen repeated in the dams of the next 40 years.

The materials for concrete gravity dams evolved gradually, starting with stone masonry, a descendant of the historic dams of Europe and Asia, and evolving into mass concrete. When dams constructed in this way became too expensive, in comparison with earthfill and rockfill dams, a new construction method evolved for concrete gravity dams, which placed and compacted concrete materials using earthfill construction techniques, resulting in the term roller compacted concrete. The gradual evolution of gravity dams is exemplified in the twenty-one landmark dams described in this section, listed in Table 2–1, and described in the following paragraphs.

Of the 67,451 dams that had been identified in the U.S. by 1978, about one-sixth were concrete gravity dams, of which 189 were over 100 feet high, as shown in Figure 1–1. Starting with the 154-ft high Crystal Springs Dam in 1888, the record height for gravity dams increased gradually until 1973, when a 717-ft height was reached with Dworshak Dam, as shown in Figure 2–1.

Lower Crystal Springs Dam

Against this background, it is interesting to study this section's first landmark dam, the 154-ft Lower Crystal Springs Dam[1] (Description No 2–1), completed in 1888. This dam, situated in San Mateo, California about 20 miles south of San Francisco, is parallel to and on the margin of the world-famed San Andreas fault. The foundation rock is a highly fractured, fresh to slightly altered graywacke of the

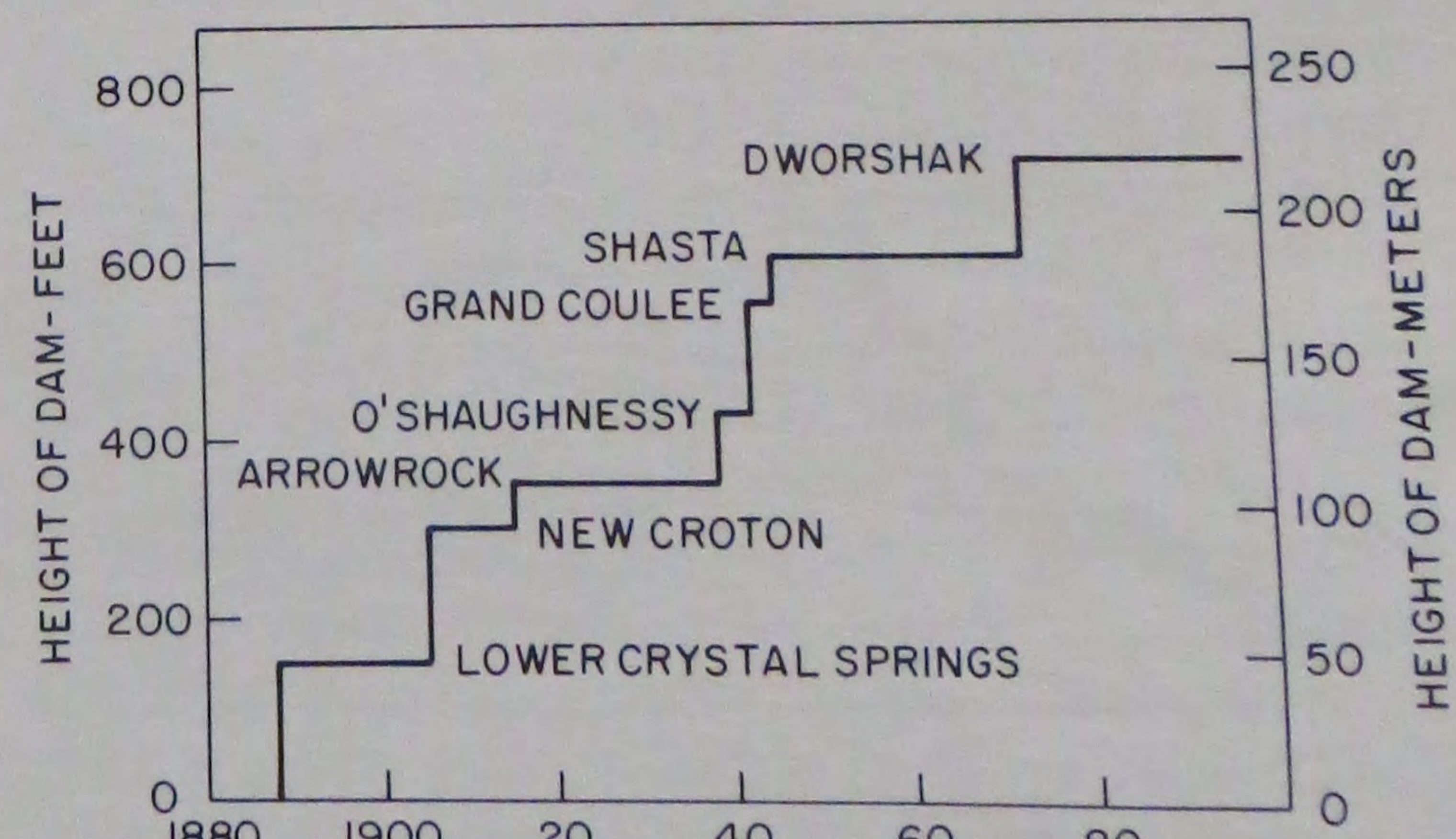

Figure 2–1 Record-high gravity dams

Franciscan Formation, a widely distributed Mesozoic unit with variable quality. At this site, on the fringes of the right lateral San Andreas Fault, the rock is divided by visible fracture surfaces and also by incipient planes of weakness that become apparent only during testing of cores. Drill cores typically have six to sixty fractures per meter, and it is rare to find an intact core larger than 4 inches. Nonetheless, a successful concrete dam was built on this untreated foundation, which was typical for the time.

Suitable rock for masonry could not be found in the vicinity, hence the dam is made of Portland cement concrete. Figure 2–2 shows the 170-ft high dam as originally designed, with a battered upstream face, and a curved downstream face, much like the cross section for the constant-stress dams of De Sazilly and other French engineers. The dam is curved upstream in plan on a radius of 632 feet. As shown in the figure, construction stopped when the dam reached a structural height of 154 feet so that the crest, instead of the designed 25 feet, now is 41 feet wide. This flattened profile undoubtedly contributed to its successful behavior during the San Francisco earthquake, a Richter magnitude 8.3 temblor on the San Andreas Fault, which occurred in 1906, 18 years after completion of the dam.

The problems of constructing a concrete dam in California, at a time when masonry dams were the state of the art, were immense. In the first place, the region had only begun to be settled 40 years previously, with the influx of the gold miners. In addition, transcontinental railroad service was in its infancy, since California had its first rail connection to the East in 1870. There was not yet a cement industry in California, hence the cement for Lower Crystal Springs Dam was imported from England.

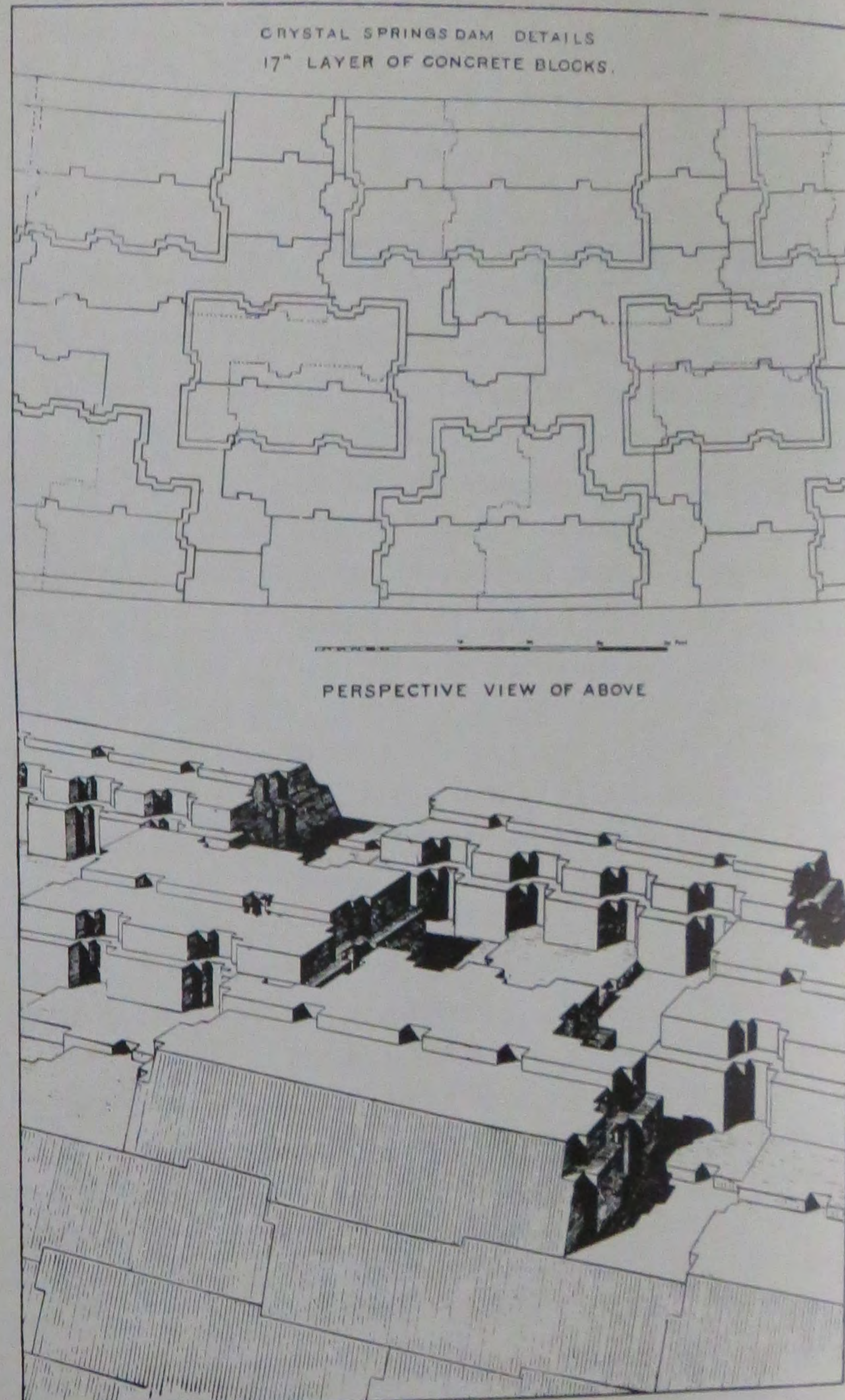

Figure 2–3 Block arrangement view—Lower Crystal Springs Dam

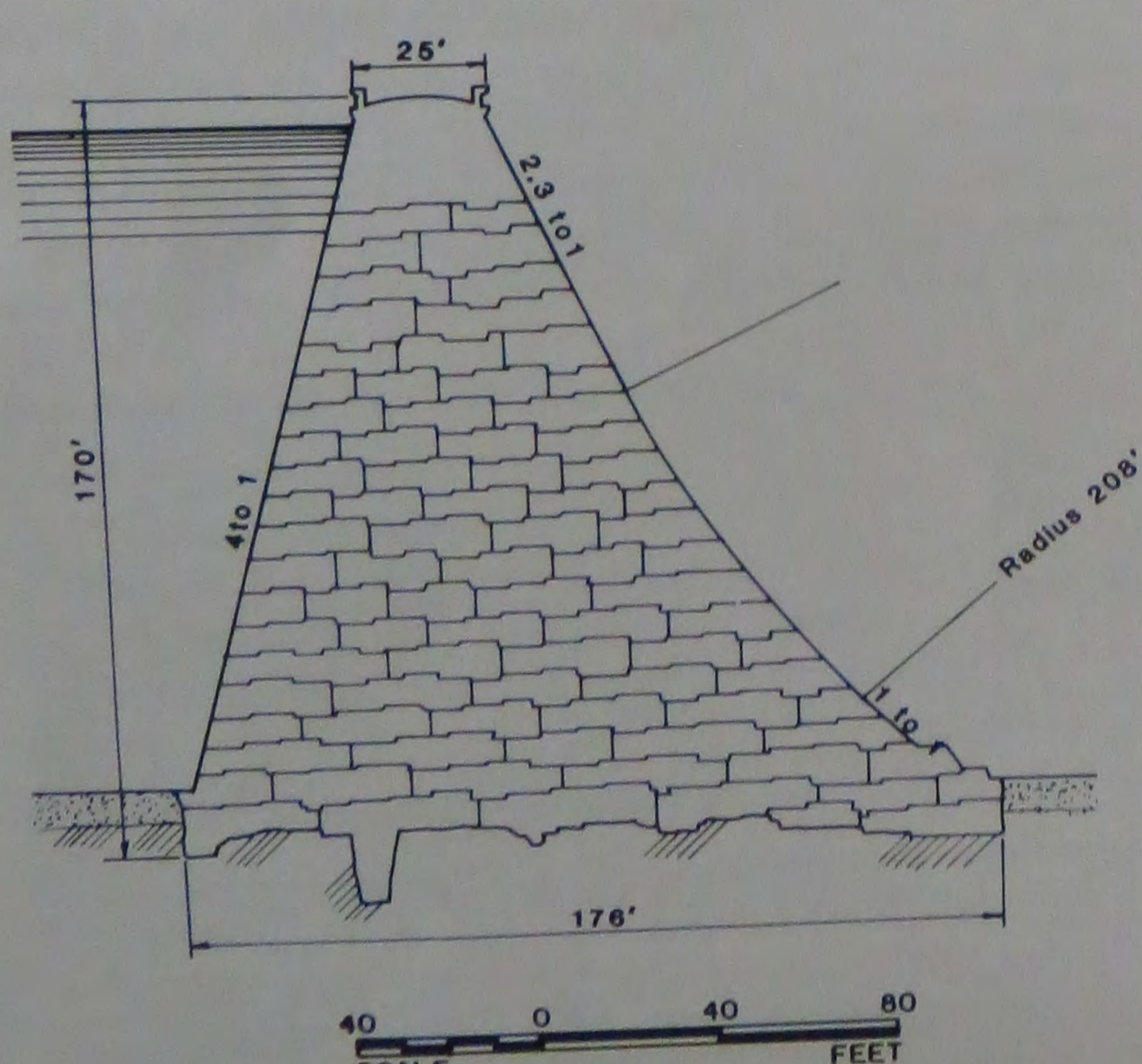

Figure 2–2 Cross section—Lower Crystal Springs Dam

The construction methods used for the dam, which were specified and rigidly enforced by Hermann Schusler, the Chief Engineer of the Spring Valley Water Company, were about a half-century ahead of their time, because they were devised at a time when masonry blocks were the usual building material, and concrete technology was in its infancy.

Lower Crystal Springs Dam seems to be the first dam in which the quantity of mixing water was specified. The imported cement was quite coarse, the specifications requiring that not more than 10 percent be retained on a No. 50 sieve. Fine aggregate

Figure 2–4 Photo of crest—Lower Crystal Springs Dam

was a natural sand to which crusher dust was added to increase fineness. Coarse aggregate was crushed rock, passing a 2.5-in sieve. The concrete mix was composed of one barrel of Portland cement, two barrels of sand, and two-thirds of a barrel of water, all thoroughly mixed with 22 cf of crushed stone, making 22 cf of first-class concrete in place in the dam[1]. This proportioning works out to a cement factor of about 470 lbs cement to the cubic yard of concrete.

Concrete for the dam was mixed in 4-ft cubical wrought iron boxes rotated by steam power, and transported and put in place in the dam within 15 minutes of mixing. The concrete was spread in 3-in layers and thoroughly tamped by hand until the new layer was completely consolidated with the underlying layer, and all interstices between the rock fragments were completely filled with cement mortar. The tale persists that Chief Engineer Schusler, when he visited the job, would reward the workman who seemed to be working the hardest by tossing him a silver dollar.

All the favorable factors—the concrete mix, the small interlocking lifts, the great attention paid to batching, mixing and placing, and the truncated cross section—combined to account for the exemplary behavior of the dam over the past century, and in particular, as stated earlier, to its behavior on the margin of the San Andreas Fault during the great San Francisco earthquake of 1906, when so many structures up and down the state of California collapsed. As a matter of fact, dynamic analysis of the dam made recently showed that Lower Crystal Springs Dam can withstand an earthquake 10 percent stronger than the 1906 temblor with no structural distress. By all these criteria, this dam is cited here as the first landmark dam in this commemorative volume on notable dams in the United States.

THE END OF THE MASONRY DAM ERA

Lower Crystal Springs Dam was a concrete dam ahead of its time, a solution to the local geologic problem of rock unsuitable for quarrying masonry blocks. Masonry dams were the normal solution for the next quarter-century until overtaken by the expansion of the cement industry and the growth of concrete technology. Two large dams mark the end of the masonry dam era: New Croton Dam and Theodore Roosevelt Dam.

New Croton Dam

New Croton Dam (Description No. 2–2) is located in the state of New York, 3 miles above the junction of the Croton and Hudson Rivers and about 25 miles north of New York City. It is a straight gravity dam, 297 feet high, 1,080 feet long (excluding spillway), with a volume of 1,450,000 cy of masonry. Completed in 1905, it forms a principal reservoir for the water supply of New York City. The design of the cross section of the dam, which was almost twice as high as Lower Crystal Springs Dam, was based on very extensive studies and calculations made for the proposed Quaker Bridge Dam, a dam that was never built.[2] At the time of these studies (1884), there was only one high masonry dam in the United States, Boyd's Corners Dam, 78 feet high, constructed in 1872 in Putnam County, New York. The studies included methods for proportioning the profile of a masonry dam proposed by De Sazilly, Delocre, Rankine, Bouvier, Pelletreau, and De Beauve. As shown in Figure 2–5, which is reproduced from Wegmann profiles, the calculated dam sections varied somewhat, especially at the upstream face, depending on assumptions as to limits of vertical pressure.

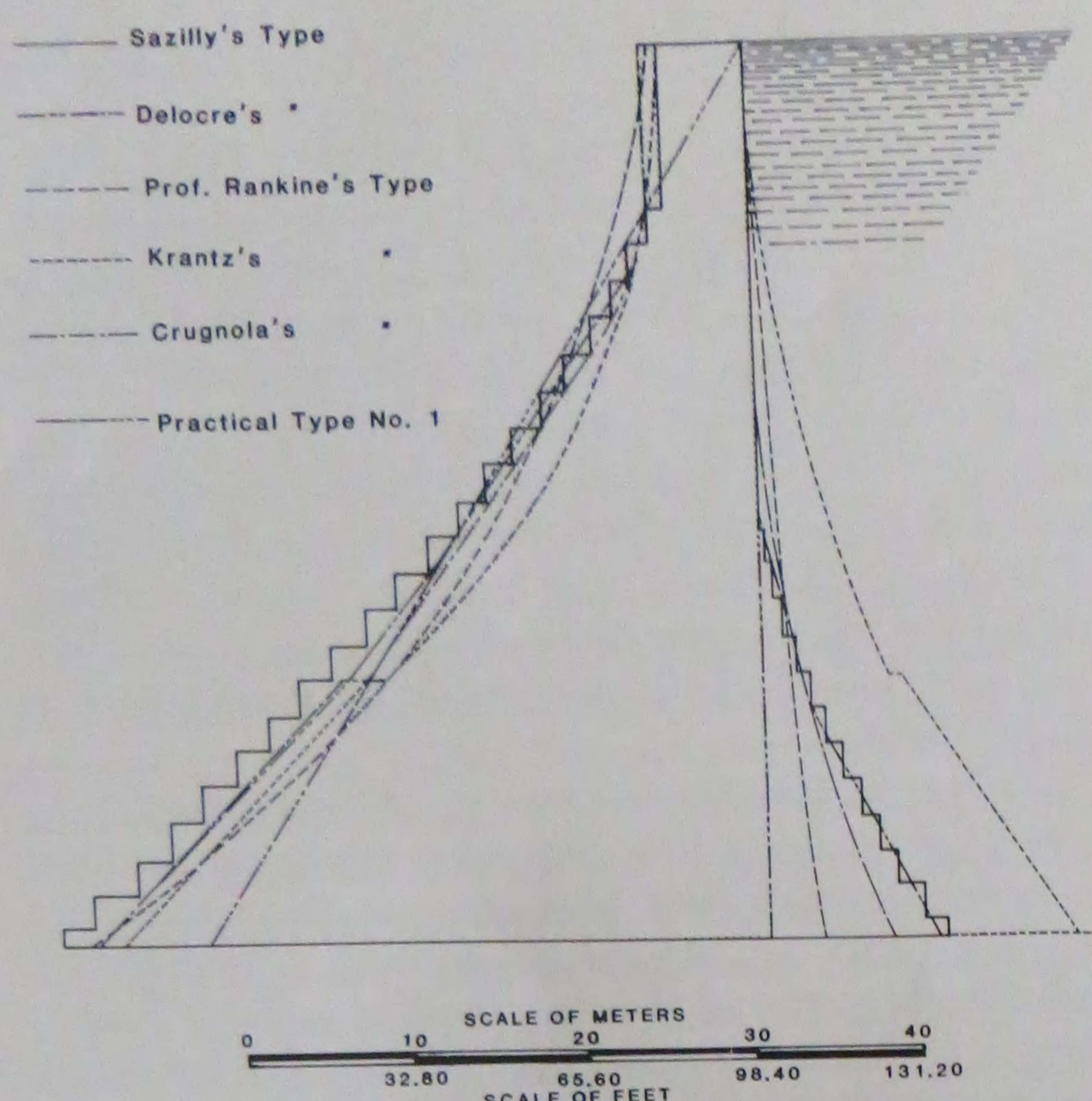

Figure 2–5 Comparison of profiles for gravity dams

A design for Quaker Bridge Dam was proposed by the engineers of the Aqueduct Commission and modified by its board of experts. After all this, difficulties arose in the purchase of the damsite, the whole project was moved a mile upstream to a new site, and the dam was renamed the New Croton Dam. The Quaker Bridge studies were adapted into the New Croton Dam with only slight modifications to the profile.

The change in site also changed the foundation geology from gneiss at the Quaker site to a combination of two metamorphic rocks at the New Croton site: gneiss at the right abutment and limestone at the center and left abutment of the valley, with the two kinds of rock joining on a line directly under the old riverbed. The limestone was quite fissured and full of seams. It was quite variable in hardness, had some caves, and contained water under heavy pressure, up to a head of 90 feet. To ensure a good foundation, the limestone was excavated to a maximum depth of 131 feet below the riverbed.

The stone for the masonry was gabbro, a dark-colored granite. The facing stone was laid in courses 20 to 30 inches thick, with every third stone being a header at least 4 feet deep. Joints at the face did not exceed ½ inch for 4 inches from the face, and not over 2 inches wide for the remaining depth. The interior was rubble masonry. Portland (England) cement mortar was used in the foundation courses and American cement mortar above the foundation. Where joints were very wide, rock chips were also placed in the mortar of the joints. The typical construction view was a forest of stiff-leg derricks for handling the heavy stones, with three cableways for delivering materials.

The original design of the dam consisted of three parts:

1. A central masonry dam about 600 feet long extending across the valley and well into the south slope.
2. A masonry waste weir about 1,000 feet long to be built along the rock-side hill forming the north slope of the valley.
3. An earth dam with a masonry core wall about 600 feet long, continuing the masonry dam at the south side of the valley.

After some cracks were found in the core wall of the earth dam, the earth dam and core wall were removed and replaced by a masonry dam similar to the remainder of the masonry dam. The interior of the earth dam replacement was made of cyclopean concrete: large stones bedded in concrete of a 1:2:4 mix, with the spaces between the stones also filled with concrete. About half the bulk of this masonry was concrete. The curved, stepped, waste weir, which today we would call the spillway, is a distinctive feature of New Croton Dam, the feature by which dam engineers recognize this dam instantly.

About 746,000 barrels of cement were required for the construction of the dam, half American cement and half Portland cement. These numbers give a good indication of the extent of the development of the cement industry in the United States at the turn of the century.

Roosevelt Dam

Roosevelt Dam, which today is thought of as an arch dam, was originally designed as a gravity dam, the arch plan being added to provide greater stability. It is located on the Salt River in Arizona, about 50 miles east of Phoenix. Completed in 1911, it was one of the first Bureau of Reclamation dams. It consists of a 723-ft long by 280-ft high curved central dam, flanked by a 201-ft long straight, gated spillway at each abutment. The reservoir formed by the dam supplies irrigation water to the Salt River Project.

Being first conceived as a gravity dam, Roosevelt Dam is described here for two reasons: to mark the end of the masonry dam era, and to show how local conditions affected the construction of a major dam.

Complete details of the project are found in Description No. 3–8 in Section 3.

The damsite is in a mountainous region, 63 miles from the nearest railroad point, at Mesa, Arizona. Some 38 miles of the access road were a rough mountain road called the Apache Trail. At the time the contract was awarded, freight was generally transported by horse-drawn equipment. If purchased on the open market and hauled to the job, Portland cement for a masonry dam would have been prohibitively expensive. However, there was a plentiful supply of dolomitic limestone and clay near the damsite, so a cement mill was purchased and erected at the job. Fuel for the mill was oil, shipped from California. The total output of the cement mill during construction was about 338,000 barrels.

The rock in the vicinity of the dam is a tough, fine-grained sandstone which made an excellent foundation, as well as being a source of stone for masonry. Accordingly, the dam is made up principally of cyclopean sandstone concrete, faced with ashlar sandstone masonry. Sand for the project was produced in a sand-crushing plant using a mixture of half dolomitic limestone and half sandstone.

The mixing plant was placed on the left abutment. Materials were transported from the top of the canyon on two 1,200-ft cableways and were placed in the dam by stiff-leg derricks.

SAND-CEMENT EXPERIMENTS

Increasing concern over the build-up of heat of hydration of cement in massive concrete dams led the Bureau of Reclamation to try a pair of experiments in 1916. Since the temperature rise in the interior of the mass was nearly adiabatic, a reduction of the quantity of cement would decrease the quantity of heat proportionately. Accordingly, for two dams, Arrowrock and Elephant Butte, the quantity of cement was reduced by replacing half the cement with ground sand, a forerunner of the pozzolan replacements of the 1950s. The resulting mass concrete was as workable as the all-cement mass concrete, but had lessened resistance to weathering, as described below.

Arrowrock Dam

Arrowrock Dam (Description No. 2–3), completed in 1916 by the U.S. Bureau of Reclamation, again established a world's record with its height of 350 feet. It[3,4] is located on the Boise River in Idaho, about 22 miles upstream from Boise, the capital city. The Arrowrock Reservoir impounds surplus winter and flood waters for irrigation and water supply of the 110,000-ac Boise Irrigation Project. The dam is a curved gravity type, with a volume of 585,000 cy of sand-cement concrete. It is 1,150 feet long and 223 feet thick at the base and has a radius of 672 feet. It has a gated side-channel spillway which extends 402 feet along the right bank, designed for a capacity of 40,000 cfs. Flow through the spillway is controlled by six drum gates, each 62 feet long and 6 feet high, separated by 6-ft thick piers containing the control mechanisms. There are twenty-five outlets through the dam, in three tiers. Ten 52-in outlets are set 110 feet below the crest, seven 52-in and three 72-in outlets are set 197 feet below the crest, and five 60-in sluicing outlets are set at riverbed elevation, 248 feet below the top of the dam.

The foundation is good quality hard granite, overlain in the riverbed with 65 to 90 feet of sand, gravel, and boulders. The excavated material, which proved suitable for use in concrete, was carefully stockpiled for later use.

As noted earlier, engineers were just beginning to become aware of the temperature rise in massive concrete structures at the time Arrowrock Dam was being planned. At the same time, the cost of cement represented a major fraction of the cost of the dam. A few attempts had been made to combine Portland cement with natural pozzolanic materials, such as tufa, to reduce cost without loss of strength. It was generally recognized that richer concrete mixes heated up more than leaner mixes. For all these reasons, a decision was made to intergrind sand with Portland cement for the mass concrete of Arrowrock Dam.

The cement was a blend of 55 percent normal Portland cement and 45 percent crushed granite. The granite, taken from the spillway excavation, was dried, crushed, and reduced to about 20-mesh size in a ball mill. This sand was then interground with the Portland cement in tube mills until 90 percent of the mixture would pass a No. 200 screen. In preliminary tests, the strength of the sand-cemen mortar was only fractionally lower than that of Portland cement mortar for ages up to 6 months, and comparable in strength for ages greater than 1 year. It is now thought that a good part of this favorable behavior was due to the extra fineness of the cement from the intergrinding, since ground granite sand is not a very efficient pozzolanic admixture.

In any case, the sand-cement was used throughout the mass concrete of the dam. The interior concrete was made of the 45/55 mix of sand-cement, and the outside 5 to 6 feet at each face was made with 76 percent sand-cement and 24 percent Portland cement, in effect yielding a 34/66 sand-cement. This yielded concrete with a 1-year strength of about 1,500 psi in the interior and 2,000 psi in the face of the dam.

The construction was modified in several ways in efforts to control heating and cooling of the mass concrete. For this reason the dam was a pioneer in instrumentation, ten electric resistance thermometers being installed in strategic locations to determine the thermal behavior. Radial contraction joints were provided at distances varying with the thickness of the mass: at 25-ft spaces for the top 70 feet of the dam, at 50-ft spaces for the next 60 feet, and at 150-ft spaces for the remainder of the base of the dam. The measured average temperature rise after placement was 30°F, significantly less than what it could have been with a straight Portland cement mix.

While the strength of the concrete was adequate for a dam with stresses computed to be 418 psi, the concrete proved to be inadequate in resisting the local climatic conditions. Weather conditions at the Arrowrock site are quite rigorous, with a yearly average temperature of 50°F, a lowest mean monthly temperature of 20°F, and a highest mean monthly temperature of 87°F. Daily extreme temperatures of course exceed these monthly means. Also, the concrete proved very porous, absorbing water readily. The outlets at the downstream face sprayed the concrete so that it began to spall off due to freezing-thawing action during the first 20 years of life. Accordingly, in 1936, the downstream face of the dam was repaired by adding an 18-in reinforced concrete slab which was thoroughly drained by a network of porous concrete drain tiles.

The dam, computed as a straight gravity dam, was originally designed for a maximum allowable stress of 30 tons per square ft (418 psi). No dependence was placed on arch action, and no allowance was made for uplift, tailwater, earthquakes, or ice pressure. In 1935, the dam was analyzed as an arch dam by the trial-load method, taking into account earthquakes, temperature changes, cantilever and arch action, and shear and twist, and also taking into account raising the dam by an additional 5 feet. The stresses in the heightened dam were found to be only slightly higher than those assumed in the original design, 35 tons per square foot (487 psi).

Elephant Butte Dam

At the same time that the U.S. Bureau of Reclamation was building Arrowrock Dam, it was constructing another sand-cement concrete dam, Elephant Butte Dam[5] (Description No. 2–4), which is located on the Rio Grande River about 60 miles northwest of Las Cruces, New Mexico. Completed in 1916, it provides a reservoir of 2,110,200 ac-ft capacity for the Rio Grande Irrigation Project. It is a straight gravity dam, 301 feet high, 1,674 feet long, including a 295-ft spillway, and contains 618,800 cy of rubble concrete. The upstream face has a batter of 1 to 16, and the downstream face a batter of 2 to 3 to the riverbed, and 1 to 1 for the 100 feet below the riverbed. Contraction joints extend transversely across the dam at 50-ft spacings in the upper 100 feet, and at 100 feet at lower elevations. The foundation rock consists of thick layers of excellent sandstone dipping upstream, separated by comparatively thin layers of shale rock of varying hardness. The foundation was grouted and drained to a depth of 45 feet. Outlet works through the dam consist of two sluicing conduits, each fitted with a pair of 47-in by 60-in sluice gates.

The sand-cement was manufactured to about the same specifications as that of the contemporary Arrowrock Dam. Sandstone from a nearby quarry was dried, crushed and ground to pass a No. 20 sieve. It was then interground with Portland cement in the proportion 52:48 by weight of sand and cement so that 90 percent of the mixture passed a No. 200 sieve. Coarse aggregate for the concrete was crushed sandstone; the sand was a mixture of river sand and crusher screenings. The maximum size of the aggregate was 3½ inches. The concrete mix for the interior mass of the dam was 1:2.8:5.45 by weight with a water-cement ratio of 0.8. A richer mix was used at the upstream face, varying from 11 feet thick at the base to as little as 4 feet thick at the top. The proportions of this concrete were 1:1.7:3.85 by weight, with a water-cement ratio of 0.65. At the age of 2 years, compressive strength of cylinders made of concrete from the body of the dam was 2,230 psi. About 15 percent of the masonry of the dam consisted of large plum stones embedded in the concrete.

The exposure conditions at Elephant Butte were somewhat more benign than those at Arrowrock Dam. Mean annual temperature was 60°F, lowest mean monthly temperature was 26°F, and highest mean monthly temperature was 92°F. Thus, there was no scaling of the concrete at the downstream face, even though it too received spray from the outlet works. However, the mortar face became somewhat chalky after prolonged exposure.

Concrete for the dam was mixed in three 3-cy mixers, loaded for best results with only 1.63-cy batches. From these mixers, the concrete went to 3-cy hoppers, was loaded into 3-cy skips, and moved on flat cars to where three cableways could pick up the skips for transfer to the dam. This plant produced 2,651 cy of concrete in 16 hours on its best 16-hr day, and 380,200 cy in 1 year. The plant is described in detail because, by this time, concrete transport by chuting, a step backward, had begun to be used.

In addition to the cableways, the use of plum stones required twenty-one stiff-leg derricks. These required moving upward as the work progressed. Five percent of the cost of the dam was saved by the use of sand-cement instead of normal Portland cement, but the real advantage was in the decreased heat development with lessened volume change and lower temperature stress.

Eventually, it was perceived that masonry dam construction required two almost independent materials-handling systems: one for the large stones, and the other for concrete and mortar. When it was recognized that, except for details, the major task in constructing a large masonry dam was materials handling, efficiency demanded a single, smoothly functioning material flow system. With this basic need recognized, the masonry dam era ended.

FOUNDATION ENGINEERING BLOSSOMS

The quarter-century after 1916 must be considered as the period when foundation engineering for dams came of age in the United States. At the beginning of this period, engineers were making initial efforts at grouting to strengthen weak zones and reduce seepage. They were also just beginning to recognize the effects of uplift and were making some effort toward its reduction. In the middle of the period came a dam failure, blamed entirely on a foundation failure, an event that colored the thinking of the following generations of engineers. By the end of the period, foundation engineering was receiving as much attention as the engineering of the structure, with resident geologists, detailed mapping, curtain grouting and drainage, foundation shaping, consolidation grouting and successful efforts at reduction of uplift pressures.

Because the stability of gravity dams is provided by the weight of the dam, any force that reduces this weight has a negative effect on stability. Because uplift pressures can reduce the effective weight of a concrete dam by over 40 percent, great attention began to be paid to this force. The prevailing thinking on uplift at the start of this quarter-century of development can be found in a paper on dams by Davis and Henry, delivered at the International Engineering Congress in 1915:

> The San Mateo Dam, near San Francisco, was designed to resist uplift under its entire base, equal to the hydrostatic head, reservoir full. This involves the assumption that cleavage planes can exist in which there is no point of contact between the overlying and underlying strata, and yet these bodies are so close together as to confine the leakage and produce full uplift. This condition is, of course, impossible and can hardly be approached in practice. Various compromises have been proposed, all either involving some diminution of pressures near the downstream slope, or *making reduction for areas of contact.*

The phrase italicized by this writer was the usual expedient for producing a reduced uplift in line with the engineer's instinctive reaction that the gravity force had to be transmitted to the foundation by direct contact, usually expressed as specifying uplift to be "full hydrostatic pressure over some fraction of the contact area." While this criterion certainly reduced the total force, it usually did not reflect the way the force was distributed through the width of the dam. It took the entire quarter-century to resolve this conflict, which ended with a series of papers[6,7] showing that uplift pressure affected 100 percent of the contact area and uplift force could only be reduced by reducing uplift pressure.

Strangely enough, the same quarter-century was a period of retrogression in concrete construction, the era of chuted concrete. This method was marked by nonuniformity of concrete because it was easy to add water to make the concrete slide faster in the chutes. This period preceded a time when the effect of water-cement ratio on strength of concrete was appreciated.

This era will be characterized by discussing the following seven, among other contemporary, dams:

- O'Shaughnessy Dam, 1923, 1938
- Mulholland Dam, 1924
- Shaver Lake Dam, 1927
- St. Francis Dam, 1928
- Morris Dam, 1935
- Tygart Dam, 1938
- Hiwassee Dam, 1940

Pardee Dam 1929

O'Shaughnessy Dam

O'Shaughnessy Dam (Description No. 2–5) has two "completion" dates, 1923 and 1938, because it was designed to be constructed in two stages,[8,9,10] depending on the demand for its stored water. The dam, located on the Tuolumne River in California's Yosemite National Park, supplies water and power to the City of San Francisco, 150 miles away, via a series of tunnels and pipelines called collectively the Hetch Hetchy Project. The dam, like so many others of that time, is a curved gravity dam, with an ultimate height of 430 feet above bedrock and a length of 910 feet, curved on a radius of 700 feet.

The O'Shaughnessy damsite was at the terminal moraine of an ancient glacier, so that the river channel between the granite cliffs was occupied largely by boulders with thin intervening beds of sand to depths of 90 feet or more below river level. For construction, it was necessary to excavate 118 feet below riverbed level to the deepest point of the cutoff wall. The cross section is shown in Figure 2–6. Minimal shaping of the excavation was done, beyond removing all weakened material. This practice reflects the prevailing opinion that the irregularities provided additional shear resistance. A cutoff was constructed at the dam axis.

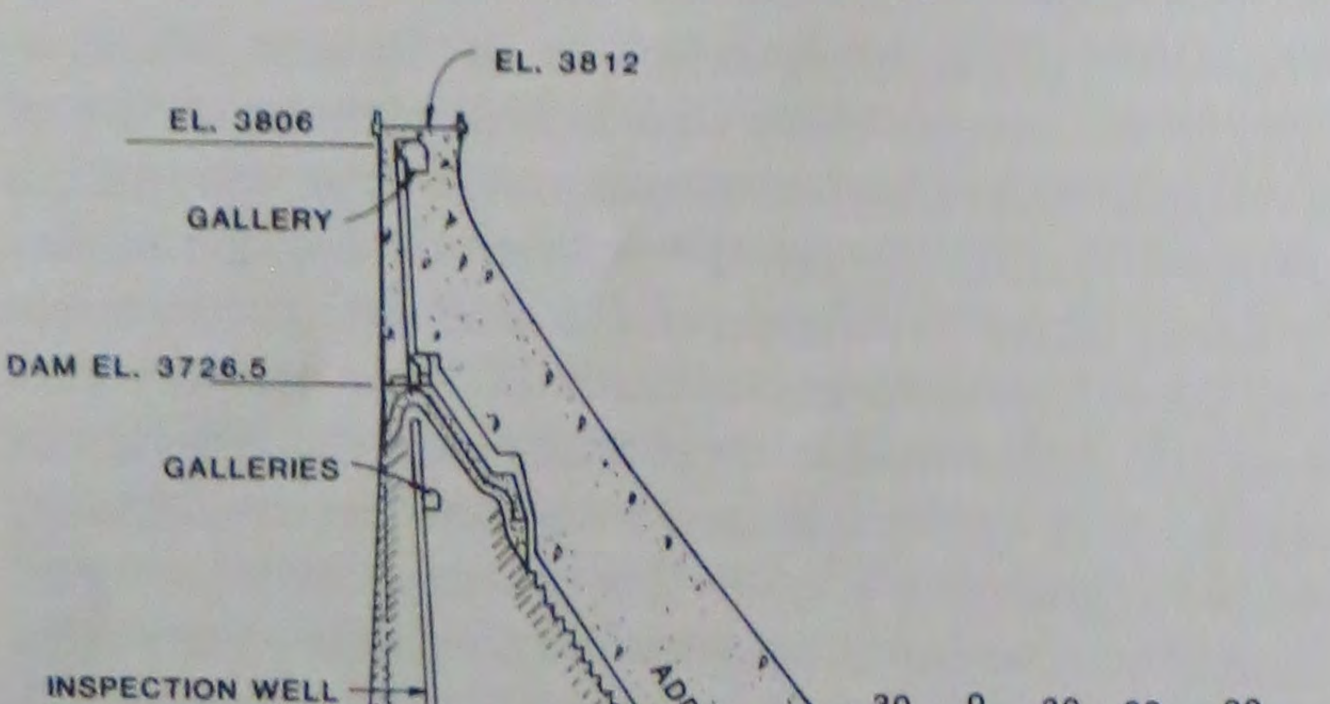

Figure 2–6 Section of O'Shaughnessy Dam

The upstream face of the original dam has a slope of 0.06, and the downstream face gradually steepens from a slope of 0.80 to a slope of 0.60 near the top of the dam, reflecting the practice for curved constant-strength dams earlier in the century. An 80-ft shelf forming the foundation for the final dam was constructed with the foundation of the original dam, to avoid later excavation near the downstream face of the dam. The first-stage dam, which had a height of 345 feet, had a stepped downstream face to increase bond to the eventual concrete addition.

Although only 12 years elapsed between the end of construction of the original dam and the beginning of construction of the addition, several features show how rapidly the technology of concrete dams was changing at that time. The original dam was constructed of cyclopean concrete, with granite plums or blocks of stone ranging in size from 1 cf to 6 cy embedded in the mass. The concrete contained 2.5-in maximum size aggregate (MSA) in a 1:3:6 mix, with a slightly richer mix using 2-in MSA adjacent to formed surfaces. Porous concrete drainage wells were provided to intercept seepage through the construction joints. Concrete was poured day and night in 5-ft lifts, a heating plant being used to prevent the concrete from freezing in very cold weather. A record of 2,000 cy was poured in 1 day, and 41,178 cy in 1 month. Concrete for the addition was a straightforward 4-sack mix with no plum stones, but with increased strength.

It was recognized that adding new concrete at the downstream face of an old dam would introduce problems because the new concrete, in undergoing volume change due to temperature drop, would overload the existing mass. Consequently, elaborate plans were made to forestall this contingency. The new concrete was not placed directly on the old, but was supported on 2-ft wide ribs at 22-ft spacings. The new concrete was artificially cooled to its final volume by circulating water in embedded pipes, a practice that had just been initiated for Hoover Dam. When the new concrete had reached a stable volume, the space between old and new concrete was filled with concrete, which was also artificially cooled. The contact surfaces between old and new concrete were thoroughly roughened, and 1.25-in square dowel bars were set at 2.5-ft spaces in each 5-ft lift, for further bond enhancement. In addition, the new concrete was designed to be stronger than the original concrete. This careful attention to

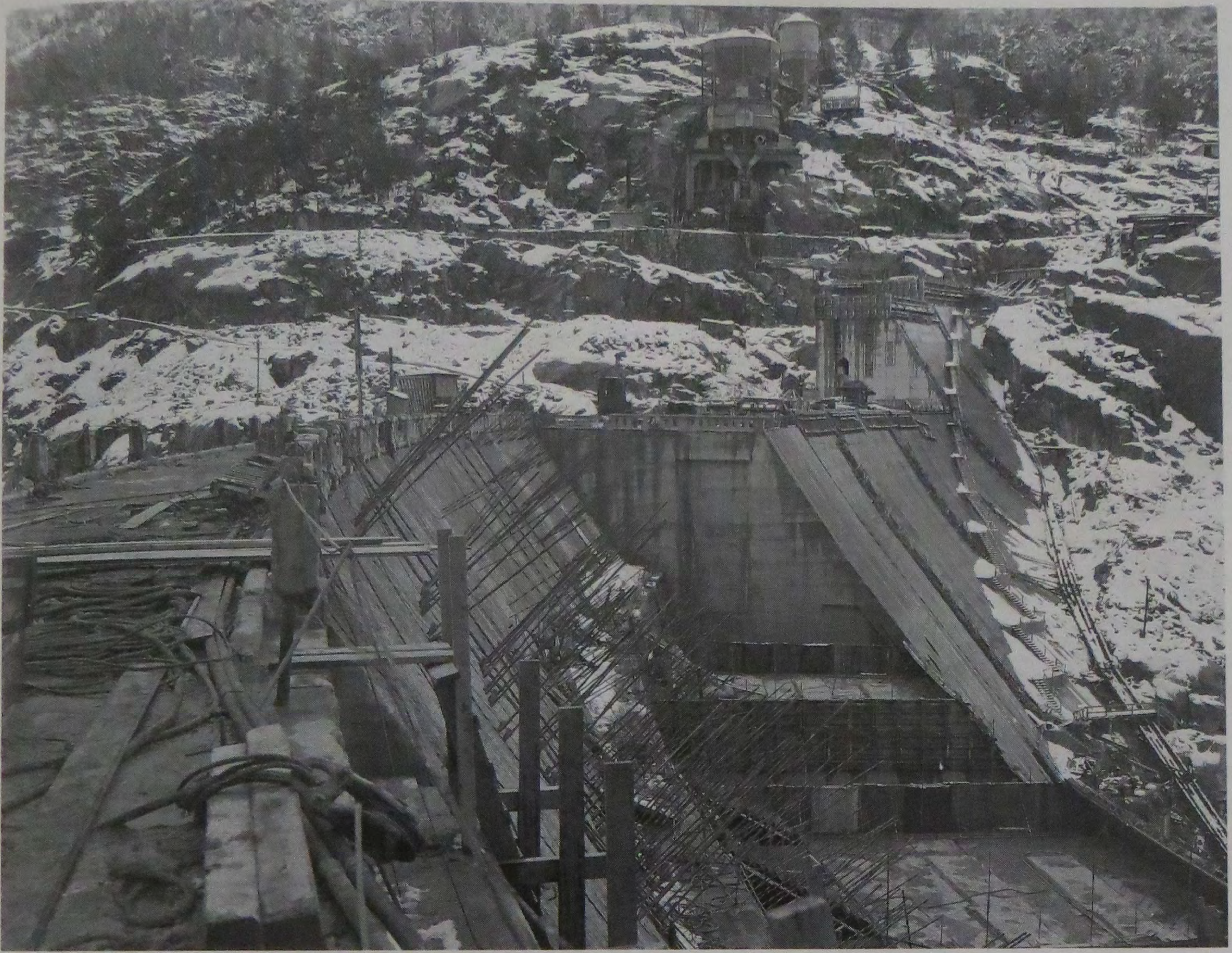

Figure 2–7 Raising O'Shaughnessy Dam

potential problems that could be caused by heating and cooling of two masses of concrete with differing temperature histories was notable for its time, and showed how quickly the new knowledge of the behavior of concrete had spread among engineers.

Mulholland Dam

Mulholland Dam (Description No. 2–6), sometimes locally called "Hollywood Dam," is a curved concrete gravity dam, completed in 1924. The dam is located in Hollywood Hills, a suburb of Los Angeles, California, and impounds Hollywood reservoir, a storage reservoir for the domestic water system of Los Angeles.

The foundation for the dam is a series of tilted massive sandstone strata, up to 4 feet thick, interlain with some thinner beds of sandstone, moderately weathered to a depth of 10 feet. This foundation received only minimum excavation, as shown by brown staining of recent foundation cores, but the foundation did have a system of twenty-three drainage wells drilled along the dam axis, leading by way of collector pipes to a weir box at the downstream toe of the dam. No drains were constructed in the dam itself. No significant leakage has ever been noted from beneath the dam.

The 195-ft high dam, which is 933 feet long, is curved on a radius of 550 feet. The profile is still in the general style of the constant-stress gravity dams of the early part of the century, with a slightly battered upstream face on a slope of 1:27, and a compound downstream slope, with the top 135 feet at a slope of 2:3 and the remainder at 1:1. The crest thickness is 16 feet and the volume of concrete in the dam is 173,462 cy.

The dam was constructed in 5-ft steps, each step poured monolithically for the entire length of the dam without contraction joints. The word "pour" is used here in its exact sense, since the concrete was chuted in place from concrete towers, using enough water to aid its movement down the chutes.

The dam is located in a highly seismic area, with the Santa Monica Fault zone approximately 2 miles south of the site, the Newport-Inglewood zone 10 miles south, and the most distant (and more active) San Andreas Fault zone 32 miles northeast. The concrete dam has recently been tested analytically for the maximum credible earthquake in this area, and found to be safe.

The dam was completed in 1924. Following the St. Francis Dam failure in 1928, local residents expressed concern over the safety of Mulholland, which had been designed by the same engineer, and in 1934 a 300,000-cy earth and rockfill buttress was placed against the downstream face.[11] A forest was planted on this earth surface. These measures seemed to satisfy public concern. It is interesting to note that in the seismic analysis described above, no element of added stability could be found in the earth embankment, due mostly to the quite dissimilar characteristics of the concrete and earth elements of the compound construction.

Shaver Lake Dam

Shaver Lake Dam[12,13] (Description No. 2–7), completed in 1927, had an interesting added feature to its foundation drainage system, reflecting increased concern in reducing the uplift force. The dam is located on Stevenson Creek about 40 miles northeast of Fresno, California, in the Sierra Nevada mountains at an elevation of about a mile above sea level.

Shaver Lake Dam might best be described as a bent concrete gravity dam, being made up of two almost equal straight segments with a change in alignment of the axis of 29° at about the midpoint, to take advantage of the topography of the site. The concrete dam has a maximum height of 185 feet, and a length of 1,760 feet, with a total volume of 281,300 cy of concrete. A 460-ft long earth dike extends from the left abutment. The cross section is thin for a gravity dam, with a vertical upstream face, and a compound downstream face at slopes of 0.63 and 0.67, with a 0.80 runout at the base. For a 185-ft high dam, the base is only 120 feet thick.

The foundation was the granitic rock typical of the Sierra Nevada batholith. Excavation removed all broken and weathered rock down to hard, firm rock, with no heavy shooting allowed that might have resulted in newly shattered rock or opened seams. As can be seen from the profile included with Dam Description No. 2–7, the final surface was quite irregular. The rock was very tight. A cutoff grout curtain comprising some 220 holes near the upstream face of the dam took a total of only 700 sacks of cement, half of which was taken in only five holes.

The thin cross section meant that excessive uplift pressure could not be tolerated without encroaching excessively on the stability of the gravity dam. Accordingly, a system of drain holes was drilled from the inspection galleries, downward into the foundation, and upward into the body of the dam. Later, the foundation drains were made still more effective in reducing uplift pressure, by lowering the head about 18 feet by the introduction of sub-atmospheric pressure at the exit through the use of siphons. Following the failure of St. Francis Dam 2 years after the completion of Shaver Lake Dam, the owners became concerned about its slender profile and further reduced uplift pressure by hand-mining a drainage tunnel parallel to the axis of the dam at the granite/concrete contact for a distance of 277 feet, and draining this tunnel downstream by gravity. A monitoring system of piezometers ensures that the whole drainage system is working.

The 135,668-ac-ft reservoir impounded is an important storage reservoir in the Big Creek Hydroelectric Development, a major source of power for southern California. Hence, besides monitoring its instrumentation regularly, the dam is observed daily and examined by consulting engineers on a biennial basis. In its most recent examination, the seismicity of the site was re-examined, including analysis by dynamic finite element methods to check its safety. The location of Shaver Lake Dam was fortunate with regard to seismicity. While California is certainly a well known seismic region, all of California is not equally seismic. It turned out that while the damsite is in the vicinity of three earthquake-producing fault systems, it is sufficiently distant from all three of them that the energy from any earthquake would be reduced by long travel through rock to a fraction of the energy found close to the faults. Thus, the stress analysis was made for a Maximum Credible Earthquake with a time-history lasting 20 seconds and a peak horizontal acceleration of 0.15 g. The resulting stresses were compared with strength determined from testing cores taken from the concrete of the dam, with the result that, despite its thin cross section, the dam was considered to be amply safe.

St. Francis Dam

In 1928, an event occurred that changed forever the thinking about foundation engineering for dams: the failure of the St. Francis Dam[14]. This dam was located on San Francisquito Creek about 45 miles north of Los Angeles, California. It was a concrete gravity dam, 205 feet high, 175 feet thick at the base, 700 feet long, and curved on a radius of 500 feet. As shown in Figure 2–8, the cross section was typical for the period, with the upstream face on a series of batters at 1:27, 1:10 and 3.5:10. The downstream face was a series of 5-ft steps, with widths ranging from 5.5 feet at the base to 1.45 feet near the crest. The dam impounded a lake with a volume of 38,000 ac-ft.

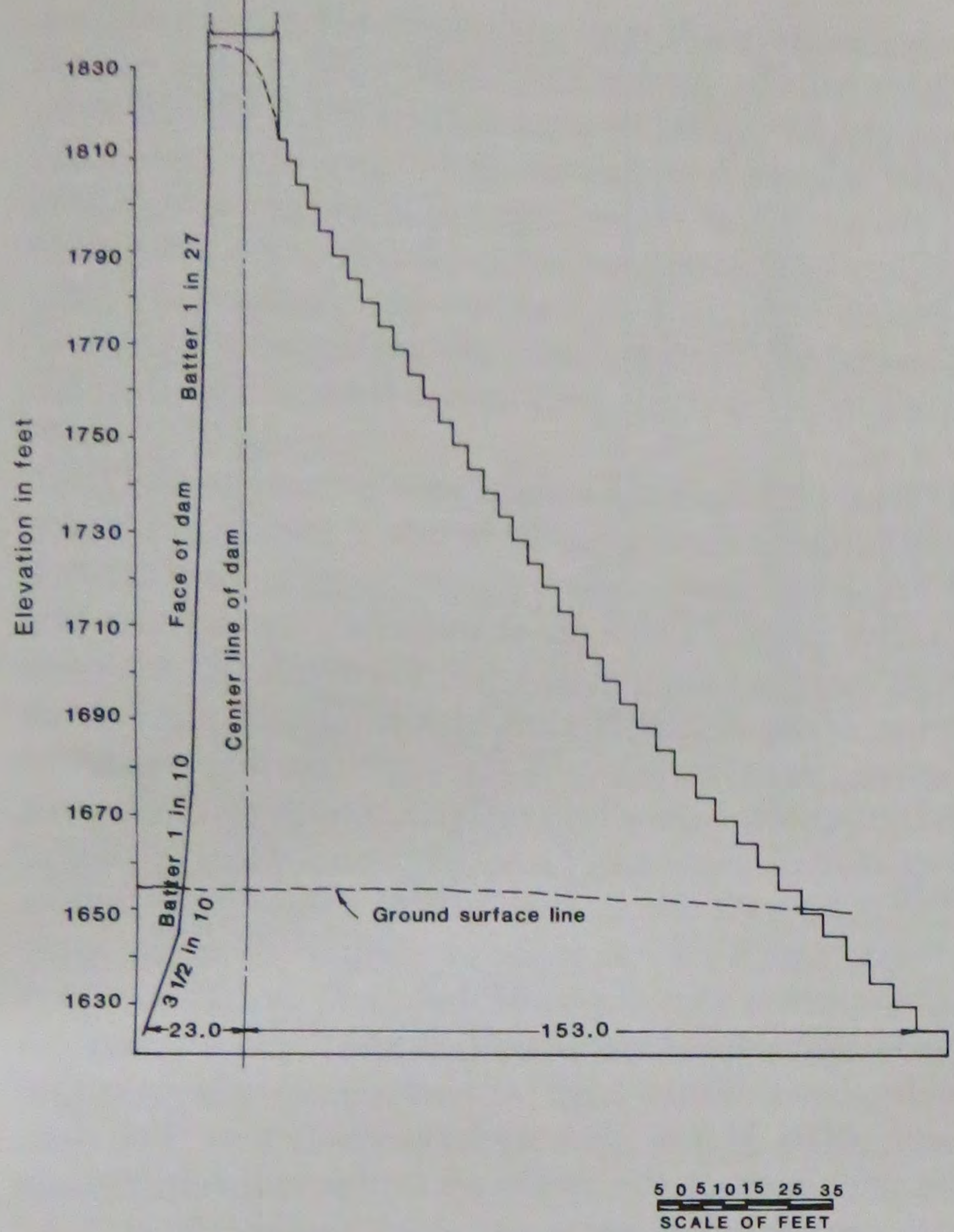

Figure 2–8 Section of St. Francis Dam

The geology of the foundation was quite simple. A fault line running down the creek bed divided the site into two distinct geologic formations. The steeply sloped left bank paralleled the laminations of a fairly uniform mica schist. The gentler, less regular slope on the right bank was a reddish conglomerate. The fault dipped 30° to 45° underneath the schist. The footwall of the schist was marked by a layer of gouge, which when wet became plastic clay. The conglomerate itself was traversed in various directions by intersecting fractures, some containing small seams of clay gouge, and others filled with gypsum.

Relief of uplift was provided only at the center of the dam, in the main channel, by one line of three holes at 20-ft centers at about the axis of the dam, and a second line of seven more holes 15 feet farther downstream from the first line, also at 20-ft centers, all drilled from 15 to 30 feet into rock, and all discharging into a common pipe which led downstream.

The concrete was a 6-in MSA mix with 4.5 sacks of cement per cubic yard of concrete. No inspection gallery was carried through the dam, and there was no pressure grouting under any part of the structure.

The construction of the dam was completed May 4, 1926. Storage of water began March 1, 1926, maximum storage capacity being reached on March 5, 1928. The dam failed at 11:58 P.M. on March 12, 1928. A water level recorder situated in the one remaining part of the dam recorded faithfully during the outflow, from which a maximum discharge of 438,000 cfs was deduced. Fragments of the dam up to 10,000 tons in weight were distributed downstream for a distance of several thousand feet.

The investigations following the collapse of the dam, without exception, pointed to deterioration of the strength of the foundation rock after it became saturated with water as the cause of the collapse. There was not much seepage through the dam itself, but seepage along the contact between dam and foundation was seen as soon as impoundment began. This seepage increased with the rise in reservoir level and had reached a maximum of 2 cfs on the afternoon before the failure.

Although the conglomerate appeared hard and sound when dry, it actually had very little strength, on the order of a quarter the strength of the concrete in the dam. Under the action of the seeping water, much of the cementing material of the conglomerate was dissolved, and the conglomerate reverted to a sandy gravel which collapsed under the forces imposed on it. Landslides occurred in the schist after the rapid drawdown of the reservoir, due to backpressure and to weakening from saturation.

The great lesson of the disaster was the necessity of thorough investigation of the geology of a proposed damsite and reservoir. In reviewing the physical evidence, it appeared that the dam began failing as soon as water storage began. Perhaps the most important judgment was that of the jury drawn by the Coroner of Los Angeles County[8]:

> A sound policy of public safety and business and engineering judgment demands that the construction and operation of a great dam should never be left to the sole judgment of one man, no matter how eminent, without . . . checking by independent experts.

One year after the failure, the State of California enacted legislation to this effect.

Morris Dam

Morris Dam (Description No. 2–8), completed i 1934, is a good example of a gravity dam designed t accommodate a known foundation weakness.[15,] The dam, which is now owned by the Los Angel County Flood Control District, is situated on th San Gabriel River, about 4 miles upstream of Azus

California. It is a 328-ft high straight gravity dam, with ends curved slightly to accommodate the topography. A 210-ft long chute spillway, controlled by three 18-ft by 70-ft drum gates, is situated in a saddle in the right abutment.

The foundation was mainly granodiorite and diorite gneisses, intruded by aplite and diabase dikes, with a number of faults. The region is extremely susceptible to seismic action, and the engineers and geologists considered that there could be movement on one particular fault during the life of the dam. Accordingly, one of the transverse joints of the dam was aligned with this fault and provided with sliding planes, gaps, and mastic filling to allow at least 3 feet of movement either way along this joint without affecting the stability of the dam. Figures 2–9 and 2–10 show the conceptual design of this joint.

The dam itself is typical, with a 0.05 : 1 batter on the upstream face and 0.81:1 batter on the downstream face in the straight section. In 1980 the crest of the dam, its abutments and downstream face were adapted for emergency outflow following a restudy by the State of California Division of Dam Safety of the adequacy of the spillway under estimated probable maximum flood.

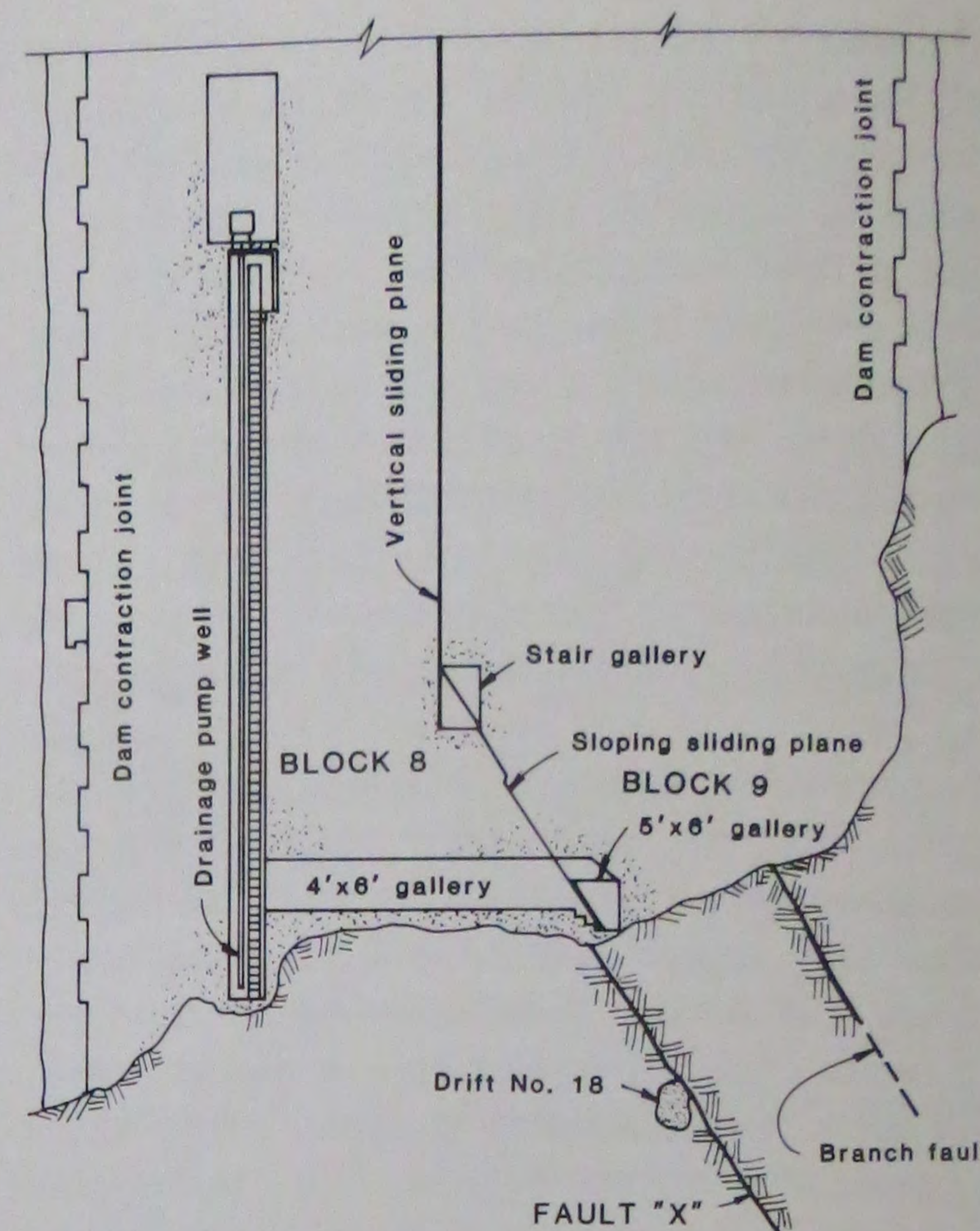

Figure 2–10 Morris Dam — profile of joint

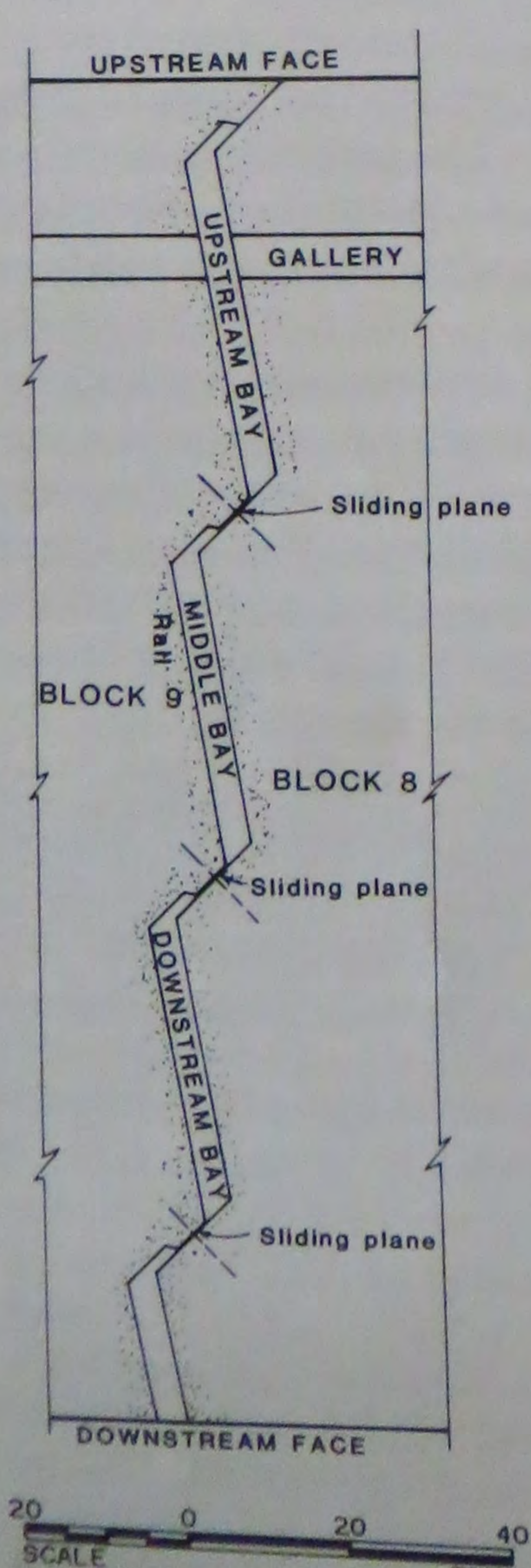

Figure 2–9 Morris Dam — sectional plan of joint

In its more than 50 years of history, the dam has had regular surveillance for movements and seepage and has undergone increasingly sophisticated analyses of its expected behavior under earthquake forces, all with a clean bill of health. Built shortly after St. Francis Dam, Morris Dam shows at once the greatly increased attention paid to local foundation conditions brought on by the failure of the St. Francis Dam.

Tygart Dam

While most of the large dam construction took place in the western part of the United States, there were a few massive dams constructed in the east. The first of these was Tygart Dam[17,18] (Description No. 2–9), a concrete gravity, flood control dam located 2 miles south of Grafton, West Virginia, on the Tygart River, a branch of the Monongahela River, which in turn is a branch of the Ohio River. Tygart Dam was the first of fourteen dams planned for flood protection of the upper Ohio River Valley. When completed in 1938, it was the largest and highest dam in the United States east of the Mississippi River.

Tygart Dam has a maximum height of 253 feet; is 1,921 feet long, including a 490-ft long centrally located uncontrolled overfall crest spillway; and