Section 3

References

A. ASCE Transactions, Vol. XIX, November 1888, by James D. Schuyler

B. Section 3, "Concrete Arch Dams," 1988, Jan A. Veltrop, International Congress of Large Dams Commemorative Book (excerpt)

C. "100 Years of Sweetwater, 1888-1988," 1988, Sweetwater Authority
"THE CONSTRUCTION OF THE SWEETWATER DAM"
by
James D. Schuyler, 1888
(Photostatic Copy)
THE CONSTRUCTION OF THE SWEETWATER DAM.

By James D. Schuyler, M. Am. Soc. C. E.

Read October 17th, 1888.

WITH DISCUSSION.

The question of an adequate water supply for irrigation, as well as for the domestic use of cities and towns, is one which, in San Diego County, California, necessarily involves storage reservoirs. The streams of the county are of an intermittent character. The mountain ranges in which they head and from which they flow to the coast do not generally exceed 6,000 to 6,500 feet in elevation—an altitude too low in the latitude of San Diego to maintain perpetual snow upon their summits, or even to retain such proportion of the winter precipitation as comes in the form of snow (not usually more than ten per cent.) for more than a few days or weeks. As a result the streams are torrential in winter and carry large volumes of water, but in summer and fall, when most needed for irrigation, are almost dry for twenty or thirty miles of their lower course, with the exception of certain seasons of such unusual
rainfall that no irrigation is required—seasons that come at rare intervals. Ordinarily the streams in summer reverse the usual order of nature, and are largest at the small end, and to get a water supply the engineer must either go far back into the mountains and gather together a number of small living streams and springs, and pipe them out long distances, or construct dam and storage reservoirs to retain the winter floods. Fortunately nature has compensated for the existing conditions by providing numerous favorable sites for such constructions, and every stream of importance in the county has available sites for storage dams of large capacity. A number of water companies are engaged in preparing for extensive works of this character, which, when completed, will provide irrigation facilities for several hundred thousand acres of land otherwise unproductive.

This era of development was inaugurated but recently, and the first completed work of the character is the Sweetwater Dam and Reservoir and the extensive pipe system reaching out from it.

The circumstances which led to the building of the dam were that the San Diego Land and Town Company (a first cousin of the Atchison, Topeka and Santa Fé Railway), owned a large body of fertile and desirable mesa and valley lands bordering on San Diego Bay, adjacent to San Diego on the south, which were unsalable without water to irrigate them. These lands constitute the greater part of the "Rancho de la Nacion," including the town site of National City, which also languished with thirst. The Sweetwater River passes nearly through the center of the lands, and is of the nature described—intermittent in flow, at least for many miles above its mouth.

The first storm or two of the rainy season is absorbed by the thirsty earth, and the stream generally does not begin flowing into the bay until late in December, or in January. After each heavy storm thereafter its volume will reach 500 to 1,000 cubic feet per second, for a few days, and within a fortnight recede to 10 cubic feet per second.

The last severe storms of the rainy season are usually in March, and the flow of the stream will generally dwindle to one or two cubic feet per second by June 1st, which amount may be maintained through the remainder of the year, but not always. The large supply running to waste each year, followed by months of scarcity, naturally suggested storage, and the first section above the mouth of the stream was selected as the place to accomplish the object. This narrow gorge, 7 miles east
of the bay, is a deep and narrow cut, half a mile in length, through a dyke of trap rock or trachyte that intersected the valley of the Sweetwater, leaving above it a broad level valley some 8 miles long, 1 to 2 mile in width. This is the site of the reservoir formed by the dam built at the head of the gorge.

The construction of this dam was decided upon and work begun in November, 1886. The original plan designed was a narrow wall of concrete masonry, 50 feet high, 10 feet wide at bottom, 8 feet on top, arched up stream. On the upper side an embankment of loose earth was to be filled in against the masonry wall to its fall height. After two months' work had developed the character of the design, the plan was disapproved by the management, and the writer was called upon to design a suitable structure and execute its construction. Some thirty-five thousand dollars had already been expended, and in order to utilize as much of the old work as possible, the new structure was planned to rest upon and encase the foundations already laid. This decision influenced to some extent the radius of the arch of the new dam, as well as its position relative to the axis of the cañon and the location of the anchorage on the sides. In other words, to avoid throwing away the work already done, the new work was adapted to the old in a way that ultimately increased the length of the dam on the crest somewhat more than would have been necessary by shifting the point of radius to one side of the central axis of the cañon, and making the radius somewhat shorter than it otherwise would have been. An engineer is sometimes driven to adaptations of this sort against his judgment, to save, or to give the appearance of saving, the pockets of his employers.

The modifications of the original plan were radical ones. The combination of earth and masonry was rejected, as it seemed to the writer that water alone was sufficiently heavy for the masonry wall to support without adding the last straw on the camel's back, of a mass of saturated earth. A gravity profile was adopted, and rubble masonry formed of blocks of stone up to four tons weight, was substituted for bastard concrete composed of cement mortar, with small stones rammed into it, which had been previously used. So much of the old plan was retained, however, as to form an embankment 50 feet wide on top, 10 to 15 feet high across the cañon, against the face of the wall, but clay, well rammed in layers, was substituted for the silt and quicksand loosely dumped, with which the dam was formerly being made. The object of
this clay-filling was to cut off possible seams in the bed rock underneath the dam, and reduce the pressure on the structure. The top of the embankment is 70 feet below the top of the dam.

The Foundation.—After the bowlders, sand and gravel had been stripped from the base of the dam on either side of the old work, the bed rock was found to be very irregular in surface, presenting the appearance of a number of pyramids and cones thrown heterogeneously together, but bound solidly in one mass, and well polished by attrition. The rock was very close in texture and exceedingly hard. No attempt was made to cut out the bed in level benches, as the unevenness of the bottom, as nature left it, gave the assurance that whatever movement might occur in the structure built on such a base, there could be no possibility of its slipping or sliding on the base. Wherever there were seams in the rock they were invariably occupied by roots, and the excavation was carried down till the seams pinched out and the roots disappeared. The rock was then thoroughly scrubbed by hand, and a thin grout of pure cement applied with brooms, filling the minutest crevices and angles in the rock, before starting the masonry.

The side walls of the cañon required more excavation to reach a satisfactory anchorage than the bottom. The north side was composed of shattered rock scored with innumerable seams, filled with red clay. In this material the excavation was carried to a depth (perpendicular to the slope) of 20 to 25 feet, before a solid ledge, free from seams, was encountered. This ledge lay with a slope nearly parallel with the surface slope, and in direction so nearly parallel to the radial line of the curve of the dam, that it could not have been better placed to receive the arch thrust, and formed a natural skewback. This was carefully stripped and treated with cement grout in the same manner as the base.

The abutment on the south side was against the end of a dyke of trap rock, crossing over the hills to the south in a direction nearly parallel to a line passing through the center of radius, and dipping westward at an angle of about 10 degrees from the vertical. After cutting into the face of this rock 5 to 10 feet, all seamy, loose material was stripped away, and a bedding that was deemed sufficiently good was obtained, although the rock was not as free from seams nor as solid in mass as the north abutment. However, the entire foundation is an admirable one, of rock in place throughout.
The Plan.—The original height of 50 feet was arbitrarily adopted at the beginning of the work, without any special investigation of the quantity of water to be stored by a dam of that height, but was "guessed" to be sufficient for present necessities, and the estimate of its cost was considered to be about the limit of the expenditure the company cared to make on an experimental scheme. There was an immediate and pressing need for water, the rainy season was passing, and it was desired to get up a part of the structure as rapidly as possible in order to catch a partial supply for the coming summer. Accordingly, in compliance with this desire, the foundation was rapidly laid and the structure hurriedly carried up to a point where it was safe to begin catchment. The base of the dam was laid with a width of 36 feet, and at a height of about 15 feet above the lowest course, it was drawn in to a thickness of 24 feet. At this level (whose elevation above tide is 140 feet) the lowest pipes pass through the dam. Above this level the structure was carried to a height of 45 feet, with a top width of 5 feet, base as stated of 24 feet, face better (upstream) of 1 to 6. In anticipation of a probable addition to the height of the dam in future, the back was built in three steps, to give an opportunity of bonding the new work to the old. The profile of this portion of the structure is shown in Plate XXX. It was a gravity profile, whose line of pressure passed within the inner third of the base. It was constructed in arch form, convex to the stream, on a radius of 225 feet on the face line at top.

During construction the stream was carried in a conduit 30 inches square through the masonry near the bottom of the original creek bed. But one storm of the season of 1886-87 (a dry one) swelled the creek sufficiently to exceed the capacity of this conduit, and then it rose and ran over the top of the masonry for two days only, without injury. This occurred February 14th and 15th, 1887, when the flow reached a maximum of about 500 cubic feet per second. The gate at the upper end of the conduit was finally closed April 20th, 1887, and the conduit was filled solid with masonry from below. From that time until June 1st, the catchment was about 80,000,000 gallons.

By the 1st of June the structure, as planned, was completed to the height of 60 feet above the bottom, 10 feet higher than the height originally contemplated. It contained about 7,500 cubic yards of masonry and had cost all told (including the preliminary experiments) about
$100,000. Meantime, surveys of the reservoir basin and watershed had developed the fact that the 60-foot dam would impound 1,221 million gallons, whereas, its extension to 90 feet in height would give a capacity of nearly five times that quantity, or 5,882 million gallons. Also that the area of the watershed tributary to the dam is about 186 square miles, of which one-third is above an elevation of 3,000 feet, and between that elevation and 6,500 feet. The watershed was evidently ample to justify the hope that the greater reservoir would be filled almost every year of ordinary rainfall. The increased volume of water stored would so largely extend the utility of the works, and give so considerable increase in security against the disasters following a severe drought, that the increased expense of extending the height of the dam while the working force and plant were on the ground and fully organized, seemed to be immediately justifiable. These arguments were embodied in a report, which was favorably considered by the directors of the company, and orders were given, about a fortnight before the 60-foot dam was completed, to extend the structure to a height of 90 feet.

This somewhat extended account of the growth of the enterprise from small beginnings is necessary to an understanding of the causes that led to the building of the structure in two sections rather than as a mass. The fact is that the work was nearly half done before all the conditions were thoroughly understood—conditions which ordinarily in works of such magnitude and importance are known, studied and exhaustively discussed preliminary to the beginning of any work whatever.

In designing the plan of the higher structure, greater reliance was placed upon the arched form than in the lower dam, then approaching completion. The profile adopted was one which theoretically gave stability by its own gravity, but without as large a factor of safety. The line of pressure falls about the center of the lower third. It was reasoned that as the foundation was as near perfection as can be generally found, apprehension on that score was unnecessary—and the source of the failure of such of the great masonry dams of the world as have given way—insecure foundations—need not be regarded as a factor in this case. If one can imagine a monolith to be carved in the form of a true arch, of such weight and dimension that any section of it is capable of withstanding the pressure of quiet water against it to its full height, without sliding or overturning, and such a monolith be firmly wedged
between the rock-bound walls of a narrow cañon, the possibility of its being ruptured, displaced or destroyed from water pressure alone, cannot readily be conceived. Now, if by the use of rich cement mortar and the best of building stone a structure be formed of the same dimensions and in the same position, which in time becomes virtually a monolith, based on the firmest of bed rock, its stability must be equally assuring to the mind.

The dimensions adopted were the following: base, 46 feet; top thickness, 10 feet; height, 95 feet; radius of arch, 222 feet on line of face at top. The face batter of 1 to 6 was carried to within 6 feet of the top; thence to the top of the parapet wall, vertical. The batter on the back started at the top with 1 to 3 for 28 feet; thence 1 to 4 for 32 feet; thence 1 to 6 to the coping.

The Construction.—When the new work was begun at the base of the completed structure, special care was taken to secure a perfect footing for the toe. When the foundation was stripped it was found that there was a slight leakage at various points along the bottom of the masonry, amounting altogether to about 10,000 gallons daily. The only perceptible leakage through the masonry was along the sides of the waste conduit, which had been recently filled in, although there were moist spots all along near the bottom.

All the leakage was entirely cut off by the new work, although it was necessary to carry up small wells alongside the old masonry to within about 15 feet of the level of the water surface in the reservoir, and keep them pumped out, before it was safe to close them entirely. Water was standing in the reservoir at a height of about 25 feet above the base of the dam, and the small quantity of leakage, and the ease with which it was stopped, was considered a favorable test of the superior quality of the masonry.

The stone used was of two grades, a dark blue and a gray metamorphic rock, impregnated with iron. The gray stone is full of minute quartz crystals, and is of slightly less specific gravity than the blue stone, which carries more iron. It was obtained from a quarry opened in the face of a vertical cliff over 100 feet high, situated 800 feet below the dam. It has no well-defined cleavage, and broke out in irregular masses, although generally having one or more tolerably smooth faces. Numerous tests of its specific gravity gave its weight as 175 to 200 pounds per cubic foot. The average weight of the masonry in place was
estimated at 164 pounds per cubic foot, which was the value used in the calculation of stability and strains.

Portland cement of the best obtainable quality was used in the proportion of one part of cement to three parts of sharp river sand. For the upper 6 feet next to the water a richer mixture of one to two was used. The sand was clean, sharp, and of the most suitable degree of coarseness to make the best of mortar.

In all the later portion of the work, from May 1st till its final completion, the mortar was mixed in a machine invented and patented by Mr. E. L. Ransome, of San Francisco, consisting of a cubical dice-box suspended on bearings attached at two corners diagonally opposite, through the center of which passed a perforated tube for injecting water, the box being revolved by horse-power. The ordinary charge was three barrels of sand and one barrel of cement, which was dumped into a hopper from a platform above the mixer, and admitted into the box through a door. The box was generally given three or four revolutions after charging with sand and cement before the water was admitted. A cock from a small tank regulated the flow of water, which was turned in slowly, the whole supply required being admitted in the next three or four revolutions. Eight to ten revolutions were sufficient to thoroughly mix the mortar, requiring two to three minutes in all. The batch, when mixed, was dumped into a box with a hinged bottom, resting on a low car, and run out on a tramway within reach of the derrick standing on the wall. Four chains of equal length, attached to the corners of the box with rings at the end, served to hoist it from the car, and the derrick delivered it where required on the wall, the latches holding the bottom in place were tripped, and the load instantly dumped within reach of a group of three or four masons.

After the completion of the 60-feet structure the tramway for delivering mortar was carried entirely around the face of the dam on a bracket trestle suspended from bolts driven into holes drilled in the wall, the track being on a level with the top. A grade of 3 feet in 40 at the end next the mixer was sufficient to give impetus to the car and carry it to the farther end of the dam, and a brake was attached to stop it where required. This tramway did excellent service, and remained in the same position until the dam was carried to its ultimate height, 80 feet above the level of the tramway. Prior to adopting this device the mortar had been mixed by hand, and delivered by hod carriers. With
the mixer and tramway, five men and a horse performed the work formerly requiring sixteen to twenty men (four mixers and twelve to sixteen hod-carriers), more promptly and satisfactorily. The hoisting of the mortar by the derricks was performed without interference with their regular work.

The stone was hauled on wagons, rigged up with platforms on a level with the hind wheels. The derricks in the quarry were simple shear-legs, slightly inclined from the vertical. The stone was hoisted under the center of the shear-legs, the wagon driven underneath it, the load gently lowered, and the chain left in position for use in hoisting at the wall. Stones weighing 6,000 pounds were not infrequent—and even greater ones were readily handled on the wagons and hoisted into position. All stones smaller than 600 pounds weight, were loaded on stone-boats, 4 feet square, made of 3-inch plank with a bottom of boiler plate. These were provided with chains at the corners for hoisting. They cost $30 each; were made very strong, and yet the wear and tear was so great that several sets of them were worn out on the job.

All the hoisting was done with horse-power. This was frequently criticised as questionable economy, but taking into consideration the scarcity and high price of fuel, the cost of the number of hoisting engines that would have been required, the delays occasioned by breakages, the skilled labor required to do the work, etc., the advantage in cost and convenience was on the side of animal power. The writer had a previous experience during the construction of a section of the San Francisco sea-wall, which led to this preference. Steam and horse-power were there applied to the derricks in the quarry, side by side, in the handling of over 100,000 tons of rock, and the greater economy and convenience of horse-power was marked and decided.

Four derricks were in constant use on the wall, and at one time five. The masts of four of them were 20 to 28 feet in length, the booms 26 to 32 feet. A larger one with mast 50 feet, and boom 45 feet, was so superior in efficiency to the others, that it was a matter of regret that all had not been of larger size. All the work was done without serious accident or loss of life, although there were narrow escapes, and several horses were killed or injured. It was doubtless due to constant vigilance and inspection of apparatus, that no fatal casualties were recorded.

The work was completed April 7th, 1888, having occupied sixteen months in construction, including two months of delay on account of shortage of cement.
The total volume of masonry laid was as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Volume (cubic yards)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the dam proper</td>
<td>19,269.0</td>
</tr>
<tr>
<td>Wasteway</td>
<td>491.2</td>
</tr>
<tr>
<td>Inlet tower</td>
<td>376.8</td>
</tr>
<tr>
<td>Conduit from dam to tower</td>
<td>182.0</td>
</tr>
<tr>
<td>Gate houses</td>
<td>71.0</td>
</tr>
<tr>
<td>In various accessories</td>
<td>127.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>20,507.0</strong></td>
</tr>
</tbody>
</table>

In this work 17,562 barrels of cement were used, an average of 1.17 cubic yards of masonry per barrel of cement.

The total cost of the dam was $234,074.11, distributed as follows:

**PLANT.—Tools, etc.**
- $5,236.76

**MATERIALS.—Cement**
- $83,111.03
- Cement hauling: $8,614.18
- Lumber: $2,406.08
- Iron work: $4,915.99
- Pipes, gates, etc.: $5,152.58
- Miscellaneous materials, powder, etc.: $3,299.84
- **Total**: $87,431.70

**LABOR.—Common and skilled labor.**
- Foremen: $93,590.55
- Teams: $6,866.49
- Engineering, salaries and expenses: $10,555.20
- Clerical work: $653.88
- Earth work (contract): $7,666.51
- Miscellaneous expenses: $1,376.90
- **Total**: $149,405.65

**Total**: $234,074.11

The cost of the flowage tract for the reservoir is not included in the above. A little over one-half the land cost $16,426.93. The remainder is in litigation under an action of condemnation. A San Diego jury under the stimulus of "boom" prices awarded the owner $280 an acre, or a little over $100,000 for land, one-third of which was worthless, and the remainder unimproved. This judgment is being contested before the Supreme Court. The clearing and grubbing of about three hundred acres of the reservoir basin cost $10,806.46.
Measurements were taken weekly of the volume of masonry laid, and these measurements compared with the expense account, as a check upon the cost of each department of the work, and the system thus maintained throughout served to point out reforms needed from time to time. The average cost per cubic yard of 11,822 yards of masonry laid during the period from May 1st to December 31st, 1887, is shown in the following table:

<table>
<thead>
<tr>
<th>ITEMS</th>
<th>CONT.</th>
<th>COST PER YARD OF MASONRY</th>
<th>PERCENTAGE OF TOTAL CONT.</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone—Quarrying</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Loading</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Lining</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Holing</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Sand—Loading and laying</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Mortar—Mixing and delivering</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Masonry</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Helpes</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Excavations of foundations</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Making and repairing roads</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Blacksmithing (labor)</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Carpentry</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Rope</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Tools</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Blacksmith coal</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Blocks and sheaves</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Powder</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Foremen</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Engineering and superintendence</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Lumber</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td>Weaving masonry</td>
<td>4,817</td>
<td>4.255</td>
<td>4.820</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$99,736</td>
<td>$8,405</td>
<td>100.000</td>
<td></td>
</tr>
</tbody>
</table>

The Wasteway.—This important adjunct to the dam was carefully considered and proportioned to carry the probable maximum flow of the stream that may be presented for discharge, with a full reservoir. It is located at the south end of the structure, and is 40 feet in length by 5 feet in depth, divided into eight bays of 5 feet each. These bays are formed by piers of masonry, set at right angles to the flow, and provided with recesses on the upper face, in which loose flash-boards of 2-inch plank rest on an incline of 35 degrees from the vertical. Any set of boards may be removed from top to bottom, or the water may be held at successive levels from the top to the bottom of the weir by removing the top boards all the way across. The water falling over the weir drops
into a series of pools, 3 feet deep, which relieve the structure of shock, and pass down an inclined plane with a fall of 1 to 10, until it is carried away from the dam a distance of 50 feet, and then plunges into the cañon below. The capacity of the wastewater is about 1,500 cubic feet per second. This may be increased to about 1,800 cubic feet per second by opening a 30-inch blow-off gate in the main pipe below the dam.

The Inlet Tower.—This structure is located 50 feet above the dam, nearly opposite its center. It is built of masonry, with cement mortar mixed two to one, plastered outside and in with two coats of mortar mixed with one of sand to one of cement. It is 16 feet square at the base for a height of 10 feet, where its form is changed to a hexagon, with walls of a uniform thickness of 3 feet to the top. Each of the sides of the hexagon measure 3 feet on the interior face. Into the walls of the tower are built seven cast-iron elbows, at an elevation of 10 feet apart from bottom to top, the upper one being 10 feet below high-water line. The bell-mouths of the elbows open upward, and are ordinarily closed with a plain valve or cover of iron. The design is to draw water from the surface at whatever stage it may be. When any one cover is removed, a basket screen is lowered in its place, fitting closely into the mouth of the elbow. Three pipes pass through the dam and enter the tower at the bottom. The two lowest pipes are of cast iron, 14 and 18 inches in diameter respectively, and lie side by side. They are encased in concrete throughout, from the tower to the dam. On top of them is built a conduit of masonry with a circular orifice 40 inches in diameter, formed of walls 30 inches in diameter, in double arches. This conduit leads from the interior of the tower to the center of the dam, where it joins a pipe of 4-inch boiler-iron, 38 inches in diameter, leading to the main gate immediately below the dam, and from this gate is carried the main pipe line down the valley. The smaller pipes are not at present used, except to supply a hydraulic ram throwing water to the keeper's house on the hill, 150 feet above, and to drain the tower when all the valves are shut. They are intended to be used for supplying a turbine and pump to throw water to a higher level than the dam will now reach.

As an illustration of the fact that masonry laid in Portland cement in the proportion of two of sand to one of cement, may be made water-tight with care exercised in laying, this tower, and the conduit leading from it, may be cited. When they are empty the pressure from the outside at present is somewhat more than 20 pounds per square inch on the
conduit and at the bottom of the tower, and there is no leakage in either of them.

The Reservoir.—Red clay soil constitutes the bed of the reservoir basin, or the major portion, outside of the old river-bed and bottoms, and is of an impervious nature. The following table of area and contents of reservoir is presented:

<table>
<thead>
<tr>
<th>Contour elevation (feet)</th>
<th>Area in acres</th>
<th>Contents, Gallons</th>
</tr>
</thead>
<tbody>
<tr>
<td>145</td>
<td>3.51</td>
<td>11 640 000</td>
</tr>
<tr>
<td>160</td>
<td>10.72</td>
<td>30 577 000</td>
</tr>
<tr>
<td>165</td>
<td>17.12</td>
<td>79 631 000</td>
</tr>
<tr>
<td>170</td>
<td>43.10</td>
<td>175 819 000</td>
</tr>
<tr>
<td>175</td>
<td>75.21</td>
<td>329 546 000</td>
</tr>
<tr>
<td>180</td>
<td>113.40</td>
<td>547 069 000</td>
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<tr>
<td>185</td>
<td>153.75</td>
<td>835 851 000</td>
</tr>
<tr>
<td>190</td>
<td>200.77</td>
<td>1 221 355 000</td>
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<tr>
<td>195</td>
<td>272.22</td>
<td>1 710 583 000</td>
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<tr>
<td>200</td>
<td>326.96</td>
<td>2 302 261 000</td>
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<tr>
<td>205</td>
<td>397.85</td>
<td>3 005 642 000</td>
</tr>
<tr>
<td>210</td>
<td>463.80</td>
<td>3 824 197 000</td>
</tr>
<tr>
<td>215</td>
<td>536.94</td>
<td>4 778 549 000</td>
</tr>
</tbody>
</table>

The table shows that eighty per cent. of the capacity of the reservoir is within the upper 50 feet of height, and that forty per cent. is within the last 10 feet. This fact reduces within small limits the fluctuation of head on the mains after the reservoir is once filled, and constitutes one of the reasons for increasing the height of the structure, as it enables the establishment of the probable limit of irrigation on the lands below, at a line not lower than 25 to 35 feet from the top of the dam. The irrigable area was thus largely increased, by reason of the decrease in fluctuation of depth in the reservoir.

A line has been drawn upon the map, Plate XXXI, which represents approximately the limits of the irrigable land directly commanded by the reservoir.

The cement used in the construction of the dam was principally such as could be obtained in the market of San Francisco, at a time of extreme scarcity. White's, Gillingham, Knight, Bevan & Sturges and Kaufmann & Liefmann (German cement) were the brands chiefly used; but at times it was necessary to take inferior brands, and reduce the proportion of sand, to keep the work going. The average cost of the
cement laid down in San Diego was $3.66\frac{1}{2}$ per barrel; seventy cents per barrel was the price paid for hauling the greater portion from San Diego to the dam. Just as the work was nearing completion, a branch of the National City and Otay Railway was finished to the dam, and a part of the cement delivered by that means at less rates.

*Price of Labor.*—Masons were paid $4 to $5 per day; common labor, $2 to $3.50; foremen, $4 to $5; carpenters, $3.50 to $4; blacksmiths, $4; teams, including driver, $5; machinists, eighty cents to $1 per hour. The work was done in the midst of the "boom" in Southern California, when labor of all kinds was difficult to obtain, independent and restless on account of the general feverish excitement, and inclined to pick up at any moment and move on in search of better pay. All classes of supplies, tools and materials were correspondingly higher than the ordinary prices. These conditions increased the cost of the work twenty to twenty-five per cent. above the normal.

There has been no lack of wiseacres who predicted the failure of the enterprise as a permanent irrigation scheme; and some of the most intelligent citizens of the country criticised the location of the reservoir so near the mouth of the stream, on account of its presumed liability to obliteration as a reservoir by reason of the deposit of sand and silt. A careful examination of the water of the stream at flood time, when it was most heavily charged with sediment, convinced the writer that fears of this nature were groundless. An estimate made, within reasonable limits, indicated one thousand years as the time when it might be expected to fill. Samples taken by the State Engineer Department of California of the water of the Yuba, Bear, and American Rivers, immediately below the hydraulic mines, yielded an average of only about one half of one per cent. of sediment. Were the Sweetwater as heavily charged, it might fill the reservoir basin in one to two hundred years, but the voids would still contain a considerable volume of water that would drain out and be available, and the utility of the reservoir would not be destroyed if it were entirely filled with sand.

*The Distributing System.*—From the dam to the lower end of the cañon, 1,600 feet, the main pipe is 30 inches in diameter, and covered with masonry laid in lime mortar, plastered with cement. From this point it is reduced to 30 inches diameter, and follows the valley for 5 miles, and thence rises to the top of the Chula Vista Mesa 92 feet above sea level. Its entire length is 29,800 feet, and at its terminus the water
is divided into two 24-inch pipes, one running south 1 mile, the other west half a mile, where it is reduced to 18 inches diameter, and is carried northward to and through National City.

At the terminus of the 36-inch main a blow-off gate is located, to be used as a relief to the wasteway of the dam in case of a sudden flood which might exceed the capacity of the wasteway, or to draw off the water from the reservoir if, for any cause, it was desired to do so.

Wrought-iron pipes were used throughout. The total length of mains and laterals that have been laid is 56 miles, with 5½ miles on hand to be laid this season. They are of three classes, viz., straight double riveted pipe, manufactured and laid by the Riordon Iron Works, San Francisco; convergent lock joint, kalameded lap-welded tube, made by the National Tube Works of McKeesport, Pa.; and spiral riveted pipe made by the Abendroth Root Manufacturing Company, New York. About 16 per cent. of the pipe was of the first class, 72 per cent. of the second, and 12 per cent. of the third. The length and diameter of each class furnished was as follows:

**Riordon Iron Works, San Francisco.**

Wrought-iron, straight riveted.......36 inches diameter... 1 594 feet.
30 ".. 28 213 "
24 ".. 2 034 "
18 ".. 16 468 "

**National Tube Works.**

Kalameded tube..................12 inches diameter... 25 903 feet.
8 ".. 7 620 "
6 ".. 132 333 "
4 ".. 50 745 "

**Abendroth, Root & Company.**

Spiral steel and iron..............24 inches diameter... 5 950 feet.
12 ".. 10 029 "
8 ".. 4 039 "
6 ".. 17 870 "

Total............................302 779 "

The introduction of spiral pipe into the system was unfortunate, as it does not stand the test of transportation across the continent, and will
have to be taken up and specially treated to make it water tight. It will answer very well for sub-irrigation, if it could be properly controlled, but as it is laid in streets and avenues that system is not desirable or conducive to comfort in traveling.

The total cost of the pipe lines was as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe</td>
<td>$301,928.80</td>
</tr>
<tr>
<td>Freight</td>
<td>39,188.63</td>
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<tr>
<td>Distribution</td>
<td>6,271.06</td>
</tr>
<tr>
<td>Gates</td>
<td>1,849.62</td>
</tr>
<tr>
<td>Materials, tools, etc.</td>
<td>5,992.57</td>
</tr>
<tr>
<td>Right of way and miscellaneous expenses</td>
<td>2,968.00</td>
</tr>
<tr>
<td>Pipe laying</td>
<td>144,630.78</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$502,763.86</strong></td>
</tr>
</tbody>
</table>

_Probable Duty of the Works._—One of the most interesting questions to the Stockholders of the Company is the result that may be reasonably expected in the way of irrigation from such a reservoir. The assumption is made that in average years, say three out of five, the watershed will yield a sufficient supply to fill the reservoir, besides maintaining the consumption through the rainy season, thus starting on the irrigation season about May 1st with a full reservoir. From May 1st to October 1st is the average season of irrigation—about one hundred and fifty days. Where pipe distribution is in use, a fair average allowance in Southern California is a duty of ten acres per miner's inch (five hundred acres per cubic foot per second). There are instances of a much higher duty having been attained—a duty of even forty acres per miners' inch having been accomplished in one place. Alloting 700,000,000 gallons for the annual consumption of National City, and for loss by evaporation during the summer months, the remainder would yield a flow of 2,000 miners' inches per day for two hundred days; with a duty of ten acres per inch, this amount would irrigate 20,000 acres. In the course of time it is expected that a duty as high as twenty acres per inch will be reached, in which event, a reservoir full may be extended over two years' time, and still irrigate 20,000 acres, and afford a domestic supply to the town of National City.

Water rights, giving to the purchaser simply the privilege of becoming a customer for water have been sold on the San Diego Flume Company flume at the rate of $2,000 per miners' inch. At this rate the value
of the irrigation supply of the reservoir is $4,000,000. The construction of the works has already added a value of $1,500,000 to the principal tract of five thousand acres which has been supplied with a complete system of water pipes, and another million to the value of town property in National City, and lands in its immediate vicinity.
The Plates accompanying this paper are:

Plate XXIII. Front View of Sweetwater Dam; Mount San Miguel in the distance.

" XXIV. Rear View of the Dam.

" XXV. View from lower end of Wasteway looking Northeast.

" XXVI. The Waste Weir.

" XXVII. The Tower; showing one of the Inlets with Basket Screen in position.

" XXVIII. Plan of Sweetwater Dam.

" XXIX. Elevation of Dam with details of Waste Weir.

" XXX. Section of Dam and Tower, with Outlet Conduit.

" XXXI. Map of San Diego Bay Region, showing location of the Sweetwater Dam and Reservoir and the District commanded by Pipe Lines from it.

" XXXII. View of Bear Valley Dam.

" XXXIII. Profile of Bear Valley Dam.
DISCUSSION ON HIGH DAMS.

DISCUSSION.

JAMES B. FRANCIS, Past President Am. Soc. C. E.—I do not think I understand enough about this particular design to criticize it much. One thing strikes me as dangerous, and that is the wasteway being stopped up by planks or flash-boards and the relying on any one's opening it on proper occasion. Floods come very suddenly sometimes here, and I presume they do in that region. There would be great risk in this method.

H. W. BRINCKERHOFF, M. Am. Soc. C. E.—What is the surface area of the reservoir when full?

The Secretary.—721.86 acres.

Mr. Francis.—What is the area of the water-shed?

The Secretary.—The water-shed, tributary to the dam, 186 square miles, of which one-third is above an elevation of 3,000 feet.

Mr. Francis.—The area of the reservoir is then the one hundred and sixty-fifth part of the area of the water-shed, and a depth of 1 inch flowing off of the water-shed, corresponds to a depth on the reservoir of 165 inches. I take it, in that region, a rain-fall of 6 inches in twenty-four hours, or even more, should be provided for, which would require a very large spill-way.

The Secretary.—The paper refers to occasional rainfalls of great severity.

Mr. Francis.—It seems that extraordinary provisions should be made for the overflow.

JAMES D. SCHUYLER, M. Am. Soc. C. E.—The dimensions of the wasteway were proportioned to carry a volume equal to or greater than the maximum flood discharge of the stream, as it was indicated by high water marks left by the freshet of 1884, the highest in the recollection of the oldest residents. With a blow-off gate equal to twenty per cent. of the capacity of the wasteway, which may be opened on the approach of a flood wave in advance of the rise of the water to the floor of the wasteway, the gate-keeper has full control of the floods. Moreover, before the parapet wall could be surmounted, the capacity of the wasteway would be doubled the flood discharge of the freshet of 1884, or about 3,000 cubic feet per second.

The flash-boards are not intended to be used until the end of the rainy season, to accumulate the later flow of the stream before it dwindles to its summer stage.

EGYPTIAN, JR., M. Am. Soc. C. E.—In discussing the excellent paper which has just been read, the first point to which I wish to call attention, is that in this dam, as in all similar structures built recently in California, the plan of the wall is curved, being convex up-stream. While all engineers will readily admit that the curving of the plan adds
additional strength to a dam which has been built across a narrow valley, considerable difference of opinion exists as regards the advisability of adopting this plan of construction in the case of a wide valley. The pressures in the masonry resulting from a curved dam, acting as a horizontal arch, depend upon the radius of curvature and upon the thickness of the dam.

In considering the strains in the masonry, which may result from a dam acting as a horizontal arch, three cases may occur:

First.—The dam may act perfectly as an arch.
Second.—It may act imperfectly as an arch.
Third.—It may not act as an arch at all.

In the first case, the pressures in the masonry are to be calculated by the usual formulas.

In the second case, in which the amount of pressure transmitted by the dam to the lateral sides of the valley is supposed to be uncertain, we ought, in order to insure safety, to take an extreme assumption, namely, that the whole thrust of the water might have to be borne by the dam acting as an arch, which would make this case the same as the first.

Finally, the dam may not act as an arch at all, in which case the curving of the plan by adding to the length of the wall, would involve a waste of masonry.

That the stability of a dam may depend upon its acting as a horizontal arch, is proved by the Zola Dam in France, in which the line of pressure, reservoir full, falls considerably outside of the base of the wall. But in this case, the valley is narrow and the radius of curvature small, so that the maxima pressures arising from the arch action in the dam are within the limits of safety. Should we have, however, to deal with a wide valley, requiring a radius of about 1,000 feet for curving the plan of the dam, the pressures resulting from the arch action, as calculated by the usual formulas, would be found to be excessive. In all probability no part of the water-pressure is transmitted by a dam to the sides of a wide valley, as, owing to the length of the masonry, a considerable compression would have to occur before even a moderate amount of pressure could be transmitted.

Just where the distinction between a wide and a narrow valley should be made, must remain, in our present state of knowledge, a matter of judgment. A good rule to follow is, not to curve the plan of a dam, when the pressures arising in its masonry from its acting as a perfect arch are in excess of what is considered safe.

W. BARCLAY PARSONS, M. Am. Soc. C. E.—What does Mr. Wegmann consider the limit of radius?

Mr. WEGMANN.—I cannot give the exact radius, but a pressure of 14 tons per square foot should not be exceeded.

Mr. Parsons.—Acting as an arch?
Mr. Wegmann.—Yes, sir; taking into consideration the dam acting as an arch.

Mr. Parsons.—What radius is that?

Mr. Wegmann.—I should think that it may be five or six hundred feet. The Zola Dam depends entirely upon its arched form for stability; it would be overturned were it not for its curved plan. This is the only case of this kind I recollect, unless the Bear Valley Dam, built in California recently, is another example. In this dam I think the line of pressure is very near the toe. The Bear Valley is narrow, and I think in that case there is no doubt but that the dam should be arched.

J. J. R. Crosse, M. Am. Soc. C. E.—The pressure in pounds per unit of surface depends on the thickness of the dam at the elevation under consideration. The total arch pressure exerted at any point is equal to $P \times R$; that is, the pressure per square foot on the face multiplied by the radius; this represents the total horizontal thrust on a voussoir joint, and this must be divided by the thickness of the dam in feet, to give the arch pressure per square foot of the joint.

Mr. Schultze.—The Bear Valley Dam in San Bernardino County, Cal., cited by Mr. Wegmann, has no parallel among masonry dams in the civilized world. Its dimensions are so bold, it is so wide a departure from all previous theory and practice, and it has so long stood against the pressure of a full reservoir, that its profile is worthy of reproduction. See Plates XXXII and XXXIII.

At base it has a thickness of 22 feet, and it was carried up to the height of 16 feet the first year, and left in that condition during the winter. In the spring following, finding the cost of the original plan was to be greater than its projectors could afford, the structure was narrowed to a thickness of 8.5 feet, and carried to a height of 46 feet further, or 62 feet in all. At the top its thickness is but 2.5 feet.

These dimensions are more slender than have been heretofore reported, but I have taken pains to verify their correctness.

Considering the upper 46 feet of the dam independently, the resultant of gravity and water pressure (reservoir full) falls fully 15 feet outside the toe, or nearly twice the thickness of the masonry. Its radius is something over 250 feet, and the arch thrust on voussoirs is over 40 tons per square foot. The material is granite, laid in cut blocks, with Portland cement. The stability of the structure is, of course, entirely dependent on its arched form. The whole of the upper 46 feet acts as an arch, and withstands strains far beyond the theoretical limit. That it has stood for so long has been a matter of surprise to engineers who have known of its extraordinary frailness, but the fact that it has stood, with a full reservoir behind it (an enormous reservoir, too, covering some 2,000 acres, and impounding 10,000 million gallons), for at least three
years, should convey some useful suggestions on arch action in masonry
dams worthy of careful study and investigation by the profession. It
would seem to be a standing menace to the thousands of acres of vine-
yard and orange groves that lie in the valley below, and yet it remains
a standing marvel, as curious as it is instructive. The company owning
the dam are proposing to strengthen and increase the height of the struc-
ture.

Mr. Weisman.—Professor Rankine states that all calculations treat-
ing a dam as a horizontal arch are so indeterminate that they are of no
value. He recommends, therefore, that a dam should be made suffi-
ciently strong to resist by gravity alone, and that the plan be curved as
an additional safeguard whenever the local conditions make this ad-
vizable. Of course, that leaves still a wide field for judgment. I should
limit the curved plan to valleys of about 800 feet or less.

Mr. Chosa.—There are cases, where, in a valley of over 500 or 800
feet in width, a straight line would not be the most economical.

Mr. Weisman.—That would depend upon local conditions. The
question of architectural effect may also deserve consideration; a curved
dam may give a finer effect. The curved plan can do no harm under
any circumstances, because when the valley is very wide the dam will
simply not act as an arch; the only damage being a waste of masonry.

L. L. Buck, M. Am. Soc. C. E.—Some curiosity is expressed to know
why, if it was necessary to curve this dam at all, two different radii were
adopted. The pressure against all points of the dam at equal depths
below the surface of the water is equal, and hence it should ordinarily
have a uniform curvature, if any, for the reason that, by compounding
the curve, the flat portions will tend to thrust the sharp portions up-
stream. I do not intend by my question to criticize the strength of the
dam, but to ascertain the motives for compounding the curve.

Mr. Schuyler.—An examination of the plan will reveal the fact
that on the up-stream face the curve is carried around with but one
radius. It is only on the lower face next the waste-way that the com-
 pound curve was introduced to increase the thickness of the wall and
relieve any possible shock that might be sustained by an extraordinary
flow of water over the waste-way, as well as facilitate an increase of width
of the latter. The compounding of the curve for a short distance simply
adds a little thickness at one end of the dam in a curved wedge form, and
does not affect the structure in any way except to increase its stability.

Mr. Buck.—It may not be out of place here to say a few words
regarding the subject of straight versus curved dams.

The dam is a retaining wall designed to hold the water of a river or
other stream, to resist the pressure of this water and transmit such
Profile of Bear Valley Dam.—Plate XXXIII.
pressure to such immovable, natural foundation as the site selected will afford. It should be the aim of the engineer to effect this result with the least expenditure of capital that will render the structure perfectly safe. The nature of its service is such that it must retain its integrity of form, connection of parts to each other, and to the bottom and sides of the ravine or valley in which it is located.

Of the forms of masonry dams, there are two which have received the most attention in the discussions upon dams, viz:

First.—A straight dam, with sufficient thickness to enable it, by its weight and strength, to safely resist the pressure brought against it by transmitting such pressure directly down to the natural rock on which the dam is built. In such a dam, the masonry on the down-stream side is compressed in excess of what pressure its own weight produces, while that produced on the up-stream side, caused by its own weight, is reduced by the pressure of the water. The effect of this action is to depress the lower side and elevate the upper. Consequently, the dam must lean down-stream to a greater or less extent, dependent upon the ratio of its height to its thickness. If the dam is properly designed and constructed, the amount of such leaning will be very slight. This is the most simple form of masonry dam.

Second.—This form of dam is curved in plan so as to present its convex side up-stream. The intention of this curved form is to cause the structure to act as an arch and transmit the pressure of the water to the sides of the valley or ravine. As the materials of which this arch is composed are shortened by such pressure, which means the shortening of the arc of the dam, while the ends must not approach each other, the curve will be flattened. Consequently this dam will also lean down-stream. The amount of such leaning will increase in some ratio with the length and height of the dam, and the decrease of its curvature and thickness. It must have thickness enough to do its duty as an arch, to prevent the water finding its way through or underneath, and as the bottom must not move, it must be thick enough and heavy enough to prevent any part sliding on that below; or the whole sliding on the foundation. But if the thickness is too great, it may not allow the dam to lean enough to get the benefit of the arch form without cracking the masonry on the side exposed to the water. In this form of dam there can be no arch action at the bottom, nor, practically, for a considerable distance above, while its maximum is at the top. Hence it is practically a combination of the two systems and subject to the complicated stresses always attending such compound structures. As it must not have too flat a curvature, and as the chord of its arc must be somewhat less than twice its radius, it could, at best, be adapted only to situations where the valley is narrow in proportion to the height of the dam. In fact, its application should be limited to cases where the site is a very narrow, deep rock cañon or fissure, in which the distance from the middle of the
The idea of combining the two forms of dam, considered above, has gained some adherents among engineers. As I understand it, the plan proposed by its advocates consists of a curved dam. It is proposed, at the same time, to make it in every respect strong enough to be perfectly secure, had it not have been curved, but it is curved as a means of additional precaution. Here then we have a structure primarily built upon a system in which the pressure is transmitted to the solid rock on which it rests, possessing abundant stability, having a form of cross-section which cannot, and is not expected to, change (excepting to an almost inappreciable degree), and yet which it is proposed to render additionally secure by giving it a plan that could only accomplish its object by transmitting the pressure to very much more distant points, and could only do this after the first system had failed. No claim is made that the rock at the bottom does not afford every bit as reliable a foundation as that at the sides, or that it is not in a perfectly legitimate direction to transmit the pressure. And yet the advocates of this plan propose to increase the cost of the structure, by ten or fifteen per cent., by introducing such a complication as this. They find no fault with the simple and thoroughly scientific system of the gravity dam, in which the strains all lie in parallel direction, and end in the best possible foundation. Will some of them explain why, if additional security is required, it would not be best to seek it by simply extending the system on which the structure is designed?

Mr. Wiesmann.—The profile of the Sweetwater Dam has evidently been designed on scientific principles, and differs probably but slightly from a theoretical type having the minimum area. Among the many masonry dams which have been built within recent years in strict conformity to the requirements of theory, only one—the Habra Dam—has failed, and that was on account of bad workmanship and poor materials. The maxima pressures in the masonry, which in the first scientific profiles was limited to 4 to 6 tons per square foot, reached in recent structures 8 tons per square foot. In these dams the extreme positions of the lines of pressure, reservoir full or empty, are generally made to lie within the center third of the profile. I presume that this condition has been observed in the Sweetwater Dam.
The Chair.—I think Mr. Schuyler said they were inside the middle-third.

Mr. Weismann.—It would be interesting to ascertain that fact.

The Secretary (read from paper).—"In designing the plan of the higher structure," etc. (See page 206.)

Mr. Weismann.—The design seems to be bolder than I thought. As the line of pressure, reservoir full, falls considerably outside of the center-third of the profile, I think it would be hazardous to trust to the dam's strength to resist overturning merely by its weight. As the valley is narrow, however, at the site of the dam, the curved plan adds undoubtedly to the strength of the structure.

The weight of the masonry is given as 164 pounds per cubic foot. I know of only one dam in which the masonry was equally heavy, viz., Vyrwy Dam near Liverpool. The stones of which the Sweetwater Dam was built must have had a very high specific gravity.

The Secretary.—The weight is given as 175 to 200 pounds per cubic foot.

Mr. Weismann.—That accounts for the great weight of the masonry.

The Secretary.—The stones placed in the wall are also said to have been large.

A. Fryer, M. Am. Soc. C. E.—In connection with the question of weight of masonry, I will refer to two experiments made in 1885, to ascertain the probable weight of rubble stone masonry, such as might be used for the proposed construction of Quaker Bridge Dam.

Two blocks, about 1 cubic yard in volume, were built on a platform of rough stones, ranging in size from a common spall to about 3 cubic feet. The mortar used was made of Portland cement, mixed in the proportion of one of cement to two of sand. The stones used appeared to be gneiss.

After several months, the two blocks were measured and weighed with care, and found to have an almost identical weight of 156 pounds per cubic foot. The computations subsequently made to determine the profile of the dam, were based on the weight thus ascertained.

Mr. Chese.—Would it be advisable to assume that a large mass of masonry would have the same specific gravity as small samples prepared in the manner indicated?

Mr. Fryer.—The two samples just mentioned were taken from two different quarries in the vicinity of the proposed structure. The experimental blocks were built in the same manner as the mass of the dam should be built, and although it cannot be stated that the whole structure would be the same throughout, it seems fair (especially when it is admitted that the stones used in the final structure will be generally of a large bulk) to state that it is safe to use in the computations the weight determined experimentally.
Mr. Francis.—One point occurs to me in connection with a curved dam. Suppose one to be built depending entirely on the curved form or arch; when the pressure of the water comes against it there would be a compression of the material and the arch would be flattened, which would cause it either to crack or slide on the bottom. I am taking an extreme case, that of a dam depending entirely on the arch form.

Mr. Plyley.—Mr. Rankine, when speaking of the advisability of adopting a curved form for the plan of a masonry dam, says that “in the present state of science, the calculations of stability, treating the dam as a horizontal arch, are so uncertain as to be of doubtful utility.” If, in connection with the above we consider a very long dam, the length of which is several times greater than the longest known arch, and built of rough stones without any attempt at any radial disposition of the joints, the superiority of the arch form does not appear a matter of certainty.

In such a case it is much more reasonable to suppose that whatever be the plan of the dam; straight, curved up-stream or down-stream, or with any irregular shape that may be determined by the topography of the ground, a failure would occur as it would in a retaining wall of indefinite length, between two weak points.

The uncertainty of relying upon a long curved dam as an arch, is so well recognized by those who advocate the curved form, that they recommend at the same time, as the most essential part of the design, a gravity section with a large margin of safety. Moreover, they admit that, in a curved dam of large span the structure will not act as an arch except after the force of gravity has been overcome. In such a contingency the condition of the structure designed to resist by its own gravity (say) twice the greatest expected strain, may well be imagined, and its chances to be then held by arch action would appear decidedly uncertain to those living below.

If the arch form, or any other form, is more economical than the straight line, it would be well to consider it favorably; if not, it is not advisable. Should it be advocated on account of architectural beauty, it remains with those in charge to determine whether the additional expenditure would be justified by the superior appearance of the structure.

C. B. Comstock, M. Am. Soc. C. E.—Of course the strata at the bottom of the dam would be carried by the rock on which the dam rests, and as the lower course of the dam cannot move on this rock the arch effect there could not come into play at all; the arch effect only comes into play when there is some arch compression. When you strike the center of a vertical arch the crown sinks, the arch changing form. That cannot take place at the base of the dam. But at the top of the dam, although the water pressure is less than at the base, this pressure
acting as on the top of a vertical beam fixed at its base, bends the top of the dam down-stream. This bending compresses the horizontal arch formed by the top of the dam, and transmitted to the abutment, increases in some degree the power of the dam to resist overturn, considered only with a gravity section. You get some additional strength by giving it the curved form.

A gentleman suggests that there would be cracks in the dam. Of course, if the strains on the dam were nearly enough to break it by overturning there would be cracks on the upper face. I am supposing a dam so strong that those cracks would not take place, the bending of the dam not being sufficient to produce them. Then the arch resistance would increase the strength of the dam and reduce the factor of safety needed for a gravity section.

Mr. Croes. — Some experiments have recently been made by a board appointed by the Government, on the strength of brick arches, and the conclusion reached by the board was that these brick arches did not act as arches but as beams; that the masonry was monolithic, and that the strains were not arch strains at all, but were simply beam strains.

Mr. H. W. Brinckerhoff said that these experiments were referred to in the Engineering and Building Record of October 18th, 1888, and mention was there made of experiments noted in Vol. VIII., Van Nostrand’s Engineering Magazine, October, 1879, as to the action as beams, of arches of brick.

Theodore Cooper, M. Am. Soc. C. E.—I do not agree with the idea advanced that a masonry dam of large radius can exert much resistance as an arch. To do so it would be necessary for the arch to slide upon the foundations or at some intermediate point—an idea which no one would consider as possible or desirable. For a curved dam to act in any manner as an arch it must move from its original position. The bottom being fixed, motion can only take place by the bending of the cross-section down-stream, which means that the greatest arch action will be at the top and nothing at the bottom. This bending down-stream of each cross-section induces also crushing strains at the toe.

So that we must have, with our arch action, a resistance from the cross-section acting similarly to a pure gravity form. What is the relative value of the two actions? Arch action is dependent upon the amount of the deflection of the top of the dam down-stream. The crushing effect of the toe is measured by the same deflection. By assuming or calculating this deflection for a dam having a cross-section like the one before us, I am confident that the amount of arch action which could be found for a safe toe pressure, would be relatively very small, especially for large radii. The calculation is not a difficult one, and the least known
nest of the pure arch type of dam, there is a point where the arch is not called into action, and resistance to pressure comes solely from the gravity of the structure. As the water rises the gravity point is passed, and then the excess of strain beyond the amount which the gravity of the mass is capable of resisting, is transmitted to the abutments. I do not think it can be maintained that when arch action begins, all the strays produced by water-pressure are necessarily borne by the arch, or any part of them, except those which the gravity of the dam cannot withstand. The dam must resist strain by its gravity to the extent of its weight, be that more or less, and from that point on it calls in the arch to its aid, and the two act together. You cannot get rid of the gravity of the mass in an arched dam. It is always there and always acting against an overturning force to the extent of its ability. I cannot conceive by what reasoning it should occur to any one that in order to permit a dam to act as an arch it should be necessary to increase the profile. If the profile is designed of such dimensions that it will resist by gravity the quiet pressure of water, the arch is not called into action until the pressure is increased by some extraordinary event, such as wave action, ice-threat or earthquakes. This is the basis of reasoning upon which the profile of the Sweetwater Dam was designed. It was not designed to rely wholly upon the arch for its stability. If it had been, the experience of the Lolo and Bear Valley dams would perhaps have justified a more slender profile. Nor was it intended to rely solely upon gravity for its factor of safety. It is stable under quiet pressure, and its arched form is believed to protect it from extraordinary shocks. The effect it was to produce upon the public mind in the inspiration of confidence was not disregarded, and in this respect its arched form adds such an appearance of solidity that it has been a marked success. It has been visited by thousands from all parts of the world, and no doubts are ever expressed of its thorough stability. It inspires the admiration, respect and confidence which every dam should inspire.

Mr. Cooper.—It has struck me, that the point which the author did not explain, is the building of three dams, one on top of the other; I do not think the author has anywhere given a description of the manner in which he put those three structures together.

Mr. Cooper.—I think there is a deficiency in the paper in that respect. There was a large dam built before this was begun, and no description is given of the manner in which the masonry of the old dam is joined to the new one. If they were built in the same way, and care was taken, to make the joints between the old and the new work good, and the new work had time to set thoroughly before pressure was put upon it, I don’t suppose it would make much difference.

Mr. Wegmann.—The dam was remarkably water-tight; is not that a proof that the joining must have been made thoroughly?
Discussion on High Dams.

The point where the arch is not called into action, and resistance to pressure comes solely from the gravity of the structure. As the water rises the gravity point is passed, and then the excess of strain beyond the amount which the gravity of the mass is capable of resisting, is transmitted to the abutments. I do not think it can be maintained that when arch action begins, all the strains produced by water-pressure are necessarily borne by the arch, or any part of them, except those which the gravity of the dam cannot withstand. The dam must resist strain by its gravity to the extent of its weight, be that more or less, and from that point on it calls in the arch to its aid, and the two act together. You cannot get rid of the gravity of the mass, in an arch dam. It is always there and always acting against an overturning force to the extent of its ability. I cannot conceive by what reasoning it should occur to any one that in order to permit a dam to act as an arch it should be necessary to increase the profile. If the profile is designed of such dimensions that it will resist by gravity the quiet pressure of water, the arch is not called into action until the pressure is increased by some extraordinary event, such as wave action, ice-thrust or earthquakes. This is the basis of reasoning upon which the profile of the Sweetwater Dam was designed. It was not designed to rely wholly upon the arch for its stability. If it had been, the experience of the Lolo and Bear Valley dams would perhaps have justified a more slender profile. Nor was it intended to rely solely upon gravity for its factor of safety. It is stable under quiet pressure, and its arched form is believed to protect it from extraordinary shocks. The effect it was to produce upon the public mind in the inspiration of confidence was not disregarded, and in this respect its arched form adds such an appearance of solidity that it has been a marked success. It has been visited by thousands from all parts of the world, and no doubts are ever expressed of its thorough stability. It inspires the admiration, respect and confidence which every dam should inspire.

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Mr. Wagman.—The dam was remarkably water-tight; is not that a proof that the joining must have been made thoroughly?
DISCUSSION ON HIGH DAM.

Mr. Coose.—The writer states that the dam is perfectly water-tight, but judging from some of the photographs of the dam here there is very evidently water coming through the dam at the point at which that joining was made.

The Secretary.—It is suggested that that may be water or it may be mortar.

Mr. Coose.—The mortar would not run out in that way unless there was water to bring it out.

A Member.—The author did not say that the dam did not leak; the conduit did not leak.

Mr. Coose.—A few months ago I visited the Boyd's Corners Dam in Putnam County, N. Y., which is 20 feet high and was built about eighteen years ago, and there were in places streams of water running down the face of it. Immediately after this dam was built an earth embankment was built against the up-stream or water face. The joints in the masonry on this face of the dam were never thoroughly pointed before the earthen embankment was put against it. About 30 feet below the flow line there are places where the water is running down the face of the dam between the stones and the joints appear to be full of mortar, except at these few places. The face of this dam is of stones, from 2½ to 5 feet deep (bed), and from 18 to 20 inches rise, and the heart is of concrete, yet the water gets through it.

There was a small dam built of rubble masonry at New Rochelle, N. Y., about two years ago, which leaked very badly when the reservoir was first filled, the water passing through the masonry and spouting out with considerable force from some of the joints on the lower face. The proprietors had not considered it necessary to have the work inspected by an engineer during its construction, but called on one to remedy the defects which appeared on its completion. Mr. C. W. Hunt, M. Am. Soc. C. E., had charge of the repairs.

Charles W. Hunt, M. Am. Soc. C. E.—On examining the water-face it was found that there were a good many joints not properly filled with mortar. The water was then drawn down gradually, and masons working from a raft raked out the joints in the face and filled them up with cement mortar, well rammed in. Holes were found in which a stick could be pushed in three or four feet without meeting with any obstacle. In some holes as much as eight or ten pailsful of mortar were rammed in. The whole water face was pointed up in this way with well compacted mortar, and the dam does not leak at all now.

Mr. Schuyler.—The original structure of the Sweetwater Dam was eneased by the secondary dam on both sides, as shown by the cross-section. It was narrow, and low, irregular in form and surface, with
numerous re-entering angles; and the union of the new masonry with the old was perfectly formed, with a grout of richer mortar than was commonly used. The bond was similarly formed between the secondary dam and its extension. The steps on the lower face of the former gave seat for the new work, and the omission of pointing mortar, as well as the irregularity of the face stones made the bond a good one. The work was allowed to set several months before it was subjected to much pressure.

As stated in the paper, the leakage through and under the secondary dam was entirely cut off by the new toe, but when the gates were closed and the reservoir allowed to fill, sweating took place through the masonry, principally above the level of the top of the secondary dam, and along the sides, through the minute seams of the bed-rock, carrying with it an efflorescence, forming an incrustation on the face which appears in the photographs. This sweating has dried up to a large extent. The total leakage through and under the wall at its maximum measured about 60,000 gallons daily. It is now reduced to about one-fifth that quantity, the greater portion of which is in minute trickling streams through crevices under the dam. All the leakage comes through without pressure, and can be stopped on the lower side, by pricking cotton or any fibrous substances into the tiny pinholes in the mortar through which it oozes. There is nothing like a jet or spurt of water anywhere apparent.
Concrete Arch Dams
Jan A. Veltrop

The following is an excerpt of this document.
Section 3

CONCRETE ARCH DAMS

by Jan A. Veltrop
EVOLUTION OF ARCH DAM SHAPE, HEIGHT AND THICKNESS

Pre - 1900's

BEAR VALLEY 1864
SWEETWATER 1885
LA GRANGE 1894
UPPER OTAY 1901

Beginning 1900's

LAKE CHEESMAN 1906
PATHFINDER 1909
BUFFALO BILL 1910
THEODORE ROOSEVELT 1911

The Constant Angle Concept
(1910's - 1920's)

SALMON CREEK 1914
LAKE SPAULDING 1919
STEVENS CREEK 1920
PACOIMA 1929

The Trial Load Method
(1930's)

GIBSON 1929
OWYHEE 1932
HOOVER 1935
PARKER 1938
The Medium Thick Arch Dams
(1940's - 1960's)

- Ross 1949
- Hungry Horse 1953
- Glen Canyon 1964

Double Curvature Dams
(1960's)

- Boundary 1967
- New Bullards Bar 1968
- Morrow Point 1968
- Mossyrock 1969

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(1970 - Present)

- Nambe Falls 1970
- Crystal 1977
- Strontia Springs 1982
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AN HISTORICAL PERSPECTIVE OF ARCH DAM DEVELOPMENT

Long before the advent of modern technology provided durable structures for water storage, man, through his creative imagination, had satisfied his need for ensured water supply and control of river flows through the invention of an arched structure. Much later, through sophisticated methods of structural analysis, improvements in concrete technology and progress in construction techniques, engineers developed such arches into technically sound, safe and economical structures.

Although American engineers have contributed significantly to the development of the arch dam concept, many of the early structures were developed in the Middle East and Europe. The principle of arch design has been used since antiquity in the design of small dams for impounding water and later, especially during the Roman Empire, for the construction of arched bridges and aqueducts. Chryseis of Alexandria, builder of one of the earliest flood control and water supply structures on the Turkish-Syrian border (around 550 A.D.), noted that the dam was constructed “in the form of a crescent, in order that its arch, which was turned against the stream of the water, might be better able to resist its violence.”

The principle of an arch dam so conceived is an excellent example of Bronowski’s view of the historical development of the physical and life sciences. Throughout the highly acclaimed television series based on his book The Ascent of Man, Jacob Bronowski traced the development of science as an expression of the special gifts that characterize man and make him preeminent among animals. It is man’s imagination which results in progress through the continuing interplay between needs and inventions. Throughout this chapter this interplay will be seen as a strong motivator. Then too, man’s imagination was caught by the inherent beauty of the arch dam and its natural blending with the environment.

The development of arch dam design and construction is the result of an interplay between need and demand on the one hand, and the opportunity to apply progress in science and engineering on the other. For some time during the later decades of the 19th century there had been a demand in the Western United States for lower cost dams for the development of irrigation, flood control, water supply, and later also for power. Streams in southern California were often torrential in winter and carried large volumes of water, but in summer and fall, when most needed for irrigation, were almost dry. Water therefore had to be captured in the mountains, where fortunately nature had provided numerous favorable sites for dam construction. Many failures of earth dams had taken place due to overtopping as a result of underestimating the size of floods, and the corresponding underdesign of spillway capacities. Masonry dams were being developed using less material than the “gravity” dams, which, while stable, relied solely on the weight of the material used. The dams which were introduced at that time commenced the practice of carrying at least part of the water load in arch action, relying on the strength of the materials used.

An arch dam is a structure curved in plan, which transmits water load primarily by means of thrust to the abutments, thereby utilizing the compressive strength of its material. As will be seen, such transmission of water load turns out to be much more complicated when attempts are made to calculate the magnitude of the stresses set up in the dam. Deriving their structural behavior from masonry strength rather than the sheer weight of the dam, arch dams were recognized for their structural competence (against overtopping) and economical construction, and were increasingly adopted in remote locations where thin arch dams became popular.

The October 25, 1900 issue of Engineering News contained a letter to the editor (page 281) dated September 29, 1900, from Luther Wagoner, an early pioneer of arch dam design, in which he expressed the advantage of arched masonry dams over straight dams as follows:

Sir: In reading the account of the failure of the Austin dam, and also the Minneapolis dam, I cannot help thinking that both structures might still be intact if they had been arched. The masonry appears to have been of excellent quality, and the experience gained in the Bear Valley dam in California shows the enormous increase in strength gained by curving a dam [Fig. 3–1]. The calculations made by Mr. Vischer and myself [see paper ‘On the Strains in Curved Masonry Dams,’ Proceedings of the Technical Society of the Pacific Coast, for December, 1889] show the enormous resistance gained by curvature. This dam is
improvements of concrete and other construction materials, and (4) construction methods and utilization of equipment in building arch dams expeditiously and economically. These factors account largely for the gradual change from the early arch dams with their circular, horizontal, constant thickness arches and vertical upstream faces to the sophisticated thin double curvature arch dams with variable radii, variable thicknesses and pronounced overhangs. The history of significant progress in arch dam development is part of the 20th century.

There is no single type of arch dam which can be readily adapted to every site. Therefore, a number of types have naturally been developed and applied to satisfy the different demands as these have presented themselves. In the words of the late Dr. Manual Rocha: "there are no standard shapes and a trend is even observed towards diversification due to the permanent wish to obtain more economic solutions and the increasing progress in the body of knowledge and in the analytical and experimental means available to predict the structural behavior which makes possible an ever improved adequacy of the structure to local conditions."

Engineers have always realized that the design of an arch dam is not finished with the determination of the most efficient and economical proportions, but must include considerations of the most suitable appurtenant structures for release of impounded water through power generation, outlet release, and spillway discharges. It is the most economical project overall which deserves and requires the attention of the designer. Engineers in the United States have contributed to these developments in many ways. Based on intuition, experience, and analysis, they have enhanced the development of arch dams through innovative and, at times, daring steps. These contributions are recorded in this chapter.

The author also has attempted to bring out the continuing controversies, debates and discussions among prominent engineers of the time as to the trust one could place in arch dams. While it was
generally accepted that a curved gravity dam could be reduced somewhat in cross section because of arch action (especially in narrow valleys), many had difficulty placing confidence in arch dams when distribution of load between arch and cantilever actions could not be calculated and stresses in the body of the dam could not be estimated. This was considered a major impediment to applications of arch dams in wide valleys. The inability of engineers to calculate stresses in arch dams limited the early application of the arch principle to relatively low dams. Prior to 1912, any engineer proposing an arch dam over 300 feet high would have been considered a dreamer and unreliable, even if he designed it for cylinder stresses of only 200 psi. Nothing but a full-sized gravity dam was then considered proper. It is no wonder that many of the earlier cross sections closely approached those of gravity dams with a curvature in plan provided mainly for additional safety against whatever unexpected or unpredictable extreme loading (flood, earthquake and uplift) might be imposed upon the dam. Progress was forced when arch dams of greater height were considered, because of the economy they promised in volume of material used.

Many eminent engineers, including Professor Rankine, thought there were so many uncertainties involved with the assumptions made in the analysis of arch action that a masonry dam should always be designed so as to be able to resist the pressure of water by its weight alone, and that, in the case of a narrow valley, the plan of the dam should be curved as an additional safeguard to utilize the benefits of arch action. In fact, many of the oldest arch dams were not as bold and daring as the thin structures at Bear Valley and Upper Otay. Others agreed that the first duty of the engineer in making designs was to demonstrate beyond all question that the proposed structure would be safe under all internal and external forces to which it could be subjected. But they held with equal fervor that all parts of the proposed structures should be so proportioned that no unnecessary expense would be incurred by the construction of portions which would not add to its stability. Some, like John S. Eastwood, asked why is it that engineers who design bridges and buildings with wide ranges of variable live loads are free from the interference of the sentimental notions of people without technical training or expertise, while in the design of dams people say there are too many risks to human life to take chances on any shape but that of one that meets the lay idea of strength and safety, namely, a huge mass of poorly disposed materials. Eastwood looked forward to the day when dams would be designed as were other structures, on rational and definite principles regardless of the fear or favor of the lay ideas of strength; that is, not as mere masses of obstruction, but as well designed structures.

In 1917, in his book Engineering for Masonry Dams, W. P. Creager recommended that the influence of beam action be neglected and that the thickness of the dam be determined by the cylinder formula. The effect of temperature changes in combination with other influence, he wrote, is indeterminate, and therefore, must be compensated for by the factor of safety in the unit stresses. He observed that arch stresses are much lower for higher dams, probably because of the adoption of a larger margin of safety. Because of the uncertainty as to the actual stresses in arch dams, he continued, the design should be carefully compared with similar existing structures, and due allowance made for any variation in shape and local conditions that make for increased stresses. He went on to say that even though arch dams had proved their reliability, because of the great number in successful use without a single failure, such structures could hardly be expected to be received with equanimity upstream of communities of large size, on account of their apparent stability being so much less than that of the well-known gravity types, but succeeding years would probably bring increased confidence in this perfectly safe and most economical type of masonry dams.

In 1920, Jørgensen noted: 
"To make fairly complete calculations of an arch dam is always difficult, but to make correct assumptions is still more difficult. It is not much use to complicate calculations and expect more accurate results when the assumptions are not correct in the first place." To which Smith answered: "If complete account is taken of all the actual conditions, a mathematical solution of an engineering problem is impossible."

In his discussion of Cain’s paper in 1922, Noetzli also questioned the usefulness of applying equations of great accuracy for water load, because of the fact that there were so many other factors influencing stresses and deflections, which were not taken into consideration, such as modulus of elasticity, range of temperature, degree of shrinkage of concrete, fixity of arches at abutments, swelling of concrete, lateral expansion (Poisson’s ratio effect), secondary arch action, and "wedge" action.

B. F. Jakobson defined the main aim of engineers to be to bring down the cost of engineering structures. With the increased cost of labor and materials, engineers, he said, must use more skill and forethought in designing structures leading to better utilization of materials and the use of a lower
coefficient of safety. If the design engineer can be sure of a uniformly high grade of concrete, the cost of many important structures can be cut very materially, because it is almost as expensive to make poor concrete as it is to make good concrete.

The same writer wrote in 1924 that “there has come into existence during the last 25 years or so, a belief that it is always beneficial to curve a gravity dam. This belief amounts to almost an article of faith with some engineers, and they must find it extremely convenient when they become suddenly charged with the design of a great dam and realize their lack of ability to investigate the stress distribution in such a complicated structure. This simple and very plausible doctrine does away with all necessity to investigate stresses and reduces the design of a dam to the very simple proposition of making the base about two-thirds of the height and curving the dam in plan. It is decidedly true that the stress determination is only one of the details necessary to a successful design, but it is a very important detail if an economical structure is to result.”

Much was written in the early history of design and construction of arch dams about methods of design, difficulties encountered during construction, and solutions to these problems. In places the author has summarized his impressions, in other instances he felt that only a complete quotation would do justice to the thinking, the reasoning and the many considerations given by the designers of those days. Of course, those comments and quotations have to be read in the context of the time.

There is hardly a subject to be found in engineering where two factions of engineers have been opposed to one another so definitely as that of gravity action versus arch action in curved concrete dams. They stress practical experience and the need for testing to demonstrate the safety of arch dams and their application to sites above heavily populated areas. Engineers have always recognized that safe and economical design of great concrete dams is of the utmost importance to the public.

This section traces the continuing evolution in analysis, design, materials, and construction techniques over a period of about 100 years. It presents the thinking of leading engineers up to the present covering their ideas concerning improvements in methods of analysis, as well as criticism thereof and their doubts about assumptions made. It shows, paradoxically perhaps, a return to the thin arch dams of yesteryear, but this time of much larger dimensions.

Because the subject of this commemorative book is the history of dam design and construction in the United States, this section does not include

<table>
<thead>
<tr>
<th>NAME OF DAM</th>
<th>YEAR OF COMPLETION</th>
<th>CRITERIA FOR SELECTION</th>
</tr>
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<tbody>
<tr>
<td>Bear Valley</td>
<td>1864</td>
<td>First, boldest and most slender arch dam in the USA.</td>
</tr>
<tr>
<td>Sweetwater</td>
<td>1888</td>
<td>Highest at time of completion. Unusual history of raising and overtopping.</td>
</tr>
<tr>
<td>LaGrange</td>
<td>1893</td>
<td>Designed for overflow.</td>
</tr>
<tr>
<td>Upper Otay</td>
<td>1901</td>
<td>Slenderest arch dam to be built after Bear Valley and the first to be built of concrete and recertified for safety.</td>
</tr>
<tr>
<td>Lake Cheesman</td>
<td>1905</td>
<td>Largest arch dam at time of completion. First one to be analyzed by a crown cantilever type of analysis.</td>
</tr>
<tr>
<td>Pathfinder</td>
<td>1909</td>
<td>Unprecedented height at time of construction. First dam to be analyzed by arch and crown cantilever method and reanalyzed in 1941 by the trial load method with radial adjustments and shear deformation, including temperature changes.</td>
</tr>
<tr>
<td>Buffalo Bill</td>
<td>1910</td>
<td>First multipurpose project, first dam to be built of mass concrete with a large percentage of plum rock, and the highest at time of completion.</td>
</tr>
<tr>
<td>Theodore Roosevelt</td>
<td>1911</td>
<td>Remains the highest rock masonry dam in the world.</td>
</tr>
<tr>
<td>Salmon Creek</td>
<td>1914</td>
<td>First constant-angle dam. First use of vertical contraction joints. First measurements of deflections due to temperature change.</td>
</tr>
<tr>
<td>Lake Spaulding</td>
<td>1919</td>
<td>One of the highest and largest cyclopean masonry dams with record placement rates. Raised in three stages. Keys used in grouted contraction joints.</td>
</tr>
<tr>
<td>Stevenson Creek</td>
<td>1928</td>
<td>Thin, constant radius arch dam, built for experimental purposes solely to test methods of design.</td>
</tr>
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<td>NAME OF DAM</td>
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<tr>
<td>Pacolma</td>
<td>1929</td>
<td>Highest concrete arch dam at time of completion. Survived the 1971 Sylmar earthquake.</td>
</tr>
<tr>
<td>Gibson</td>
<td>1929</td>
<td>First arch dam to be designed by the trial-load method. First dam with instruments to measure structural behavior. Overtopped in 1964.</td>
</tr>
<tr>
<td>Owyhee</td>
<td>1932</td>
<td>Model for Hoover Dam specifications. First arch dam with artificial cooling and concrete temperature control. Foundation cutoff constructed by mining methods.</td>
</tr>
<tr>
<td>Hoover</td>
<td>1935</td>
<td>Nearly twice as high as any existing dam at the time. First complete application of trial load method. Used new construction techniques with pipe cooling and staggered contraction joints. Used advanced concrete technology, first use of low-heat cement.</td>
</tr>
<tr>
<td>Parker</td>
<td>1938</td>
<td>World's &quot;deepest&quot; arch dam. Severe alkali-aggregate reaction. Largely surficial effects. Dam structurally safe.</td>
</tr>
<tr>
<td>Ross</td>
<td>1949</td>
<td>Designed with provisions for successive raising.</td>
</tr>
<tr>
<td>Hungry Horse</td>
<td>1953</td>
<td>First USBR dam to use air-entrained concrete and fly ash pozzolan.</td>
</tr>
<tr>
<td>Glen Canyon</td>
<td>1964</td>
<td>First use of 7.5-ft lifts. First use of water-reducing admixture.</td>
</tr>
<tr>
<td>Boundary</td>
<td>1967</td>
<td>Slender arch with seven large low-level spillway sluice openings through dam.</td>
</tr>
<tr>
<td>New Bullards Bar</td>
<td>1968</td>
<td>Highest arch dam owned and operated by an irrigation district.</td>
</tr>
<tr>
<td>Morrow Point</td>
<td>1968</td>
<td>First USBR thin double curvature arch dam with first free fall spillway. First underground powerhouse for USBR. Concrete placed on horizontal construction joints without a cement slurry.</td>
</tr>
<tr>
<td>Nambe Falls</td>
<td>1976</td>
<td>First concrete double curvature thin arch dam to be prestressed with mechanical jacks. Massive thrust block and earth embankment.</td>
</tr>
<tr>
<td>Crystal</td>
<td>1977</td>
<td>Thinnest arch dam with width to height ratio of 0.0906. Used lift heights of 10 feet with carefully scheduled sequences. No shear keys, 90-ft wide blocks. Environmental protection measures included limiting haul and access roads to left abutment, forbidding use of cableway. Design of overflow spillway avoided major cut in abutment.</td>
</tr>
<tr>
<td>Strontia Springs</td>
<td>1982</td>
<td>Two-stage spillway; first free fall, and second fuse plug. Special containment treatment for shear zone in right abutment. Lift height of 10 feet with no shear keys in contraction joints. Dynamic earthquake analysis using finite element method for dam and intake towers. Combined use of water conductor for low level outlet works and 1.1 MW power plant.</td>
</tr>
<tr>
<td>Swan Lake</td>
<td>1984</td>
<td>First double curvature thin arch dam to use elliptically shaped arches. The dam has a circular shape at the vertical reference plane. Central ungated, 100-ft wide, free overflow spillway with十八届 and excavated plunge pool.</td>
</tr>
</tbody>
</table>
the many and important contributions made by designers in European and other countries. It is recognized, of course, that progress in the design of arch dams depends to a considerable extent on the exchange of ideas and experiences among engineers from many countries. Therefore, this section is necessarily somewhat regional and cannot be a complete history of arch dam development with respect to design, analyses, materials, foundation behavior, construction equipment and techniques, instrumentation, and monitoring, without seeming to neglect the contributions of engineers from other countries. Neglect is not intended, but necessarily only contributions of United States engineers are highlighted and illustrated. The dams shown in Table 3-1 have been considered to be landmarks in the development of arch dams in the United States. Major dimensions of these dams are shown in Table 3-2.

### Table 3-2 LANDMARK ARCH DAMS: CONCRETE VOLUMES, MAJOR DIMENSIONS AND RATIOS

<table>
<thead>
<tr>
<th>NAME</th>
<th>VOLUME (cu)</th>
<th>LENGTH (ft)</th>
<th>HEIGHT (ft)</th>
<th>BASE THICKNESS (ft)</th>
<th>TOP THICKNESS (ft)</th>
<th>l/h</th>
<th>b/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Bear Valley&quot;</td>
<td>3,000</td>
<td>450</td>
<td>64</td>
<td>22</td>
<td>3</td>
<td>7.0</td>
<td>0.34</td>
</tr>
<tr>
<td>Sweetwater (original)</td>
<td>19,750</td>
<td>360</td>
<td>98</td>
<td>46</td>
<td>12</td>
<td>3.7</td>
<td>0.47</td>
</tr>
<tr>
<td>Sweetwater (raised)</td>
<td>53,773</td>
<td>700</td>
<td>127</td>
<td>73</td>
<td>15</td>
<td>5.51</td>
<td>0.57</td>
</tr>
<tr>
<td>LaGrange</td>
<td>38,500</td>
<td>336</td>
<td>131</td>
<td>79.5</td>
<td>24</td>
<td>2.6</td>
<td>0.61</td>
</tr>
<tr>
<td>Upper Otay</td>
<td>3,770</td>
<td>350</td>
<td>89</td>
<td>14</td>
<td>4</td>
<td>3.9</td>
<td>0.16</td>
</tr>
<tr>
<td>Lake Cheesman</td>
<td>103,000</td>
<td>670</td>
<td>227</td>
<td>176</td>
<td>18</td>
<td>3.1</td>
<td>0.78</td>
</tr>
<tr>
<td>Pathfinder</td>
<td>65,700</td>
<td>432</td>
<td>214</td>
<td>97</td>
<td>10.9</td>
<td>2.0</td>
<td>0.45</td>
</tr>
<tr>
<td>Buffalo Bill</td>
<td>82,500</td>
<td>200</td>
<td>325</td>
<td>106</td>
<td>10</td>
<td>6.2</td>
<td>0.33</td>
</tr>
<tr>
<td>Theodore Roosevelt</td>
<td>355,800</td>
<td>723</td>
<td>280</td>
<td>184</td>
<td>16</td>
<td>2.6</td>
<td>0.66</td>
</tr>
<tr>
<td>Salmon Creek</td>
<td>54,000</td>
<td>648</td>
<td>170</td>
<td>47.5</td>
<td>6</td>
<td>3.8</td>
<td>0.28</td>
</tr>
<tr>
<td>Lake Spaulding</td>
<td>189,900</td>
<td>800</td>
<td>276</td>
<td>94</td>
<td>11</td>
<td>2.9</td>
<td>0.34</td>
</tr>
<tr>
<td>*Stevenson Creek</td>
<td>370</td>
<td>140</td>
<td>60</td>
<td>7.5</td>
<td>2</td>
<td>2.3</td>
<td>0.12</td>
</tr>
<tr>
<td>Pacoima</td>
<td>226,140</td>
<td>640</td>
<td>372</td>
<td>100</td>
<td>10.4</td>
<td>1.7</td>
<td>0.20</td>
</tr>
<tr>
<td>Gibson</td>
<td>167,500</td>
<td>950</td>
<td>199</td>
<td>117</td>
<td>15</td>
<td>4.8</td>
<td>0.59</td>
</tr>
<tr>
<td>Owyhee</td>
<td>537,500</td>
<td>833</td>
<td>417</td>
<td>265</td>
<td>30</td>
<td>2.0</td>
<td>0.64</td>
</tr>
<tr>
<td>Hoover</td>
<td>4,400,000</td>
<td>1,244</td>
<td>726</td>
<td>660</td>
<td>45</td>
<td>1.7</td>
<td>0.91</td>
</tr>
<tr>
<td>Parker</td>
<td>380,000</td>
<td>856</td>
<td>320</td>
<td>100</td>
<td>39</td>
<td>2.7</td>
<td>0.31</td>
</tr>
<tr>
<td>Ross</td>
<td>908,200</td>
<td>1,300</td>
<td>540</td>
<td>208</td>
<td>33</td>
<td>2.4</td>
<td>0.39</td>
</tr>
<tr>
<td>Hungry Horse</td>
<td>3,086,200</td>
<td>2,115</td>
<td>564</td>
<td>330</td>
<td>39</td>
<td>3.75</td>
<td>0.59</td>
</tr>
<tr>
<td>Glen Canyon</td>
<td>4,901,000</td>
<td>1,580</td>
<td>710</td>
<td>300</td>
<td>25</td>
<td>2.2</td>
<td>0.42</td>
</tr>
<tr>
<td>Boundary</td>
<td>120,000</td>
<td>740</td>
<td>340</td>
<td>32</td>
<td>8</td>
<td>2.2</td>
<td>0.09</td>
</tr>
<tr>
<td>New Bullards Bar</td>
<td>2,697,537</td>
<td>2,200</td>
<td>635</td>
<td>195</td>
<td>25</td>
<td>3.5</td>
<td>0.31</td>
</tr>
<tr>
<td>Morrow Point</td>
<td>365,180</td>
<td>724</td>
<td>488</td>
<td>52</td>
<td>12</td>
<td>1.5</td>
<td>0.13</td>
</tr>
<tr>
<td>Mossyrock</td>
<td>1,270,000</td>
<td>1,250</td>
<td>606</td>
<td>125</td>
<td>27</td>
<td>2.1</td>
<td>0.21</td>
</tr>
<tr>
<td>Nambe Falls</td>
<td>32,000</td>
<td>334.5</td>
<td>150</td>
<td>15</td>
<td>5</td>
<td>2.2</td>
<td>0.10</td>
</tr>
<tr>
<td>Crystal</td>
<td>154,400</td>
<td>620</td>
<td>323</td>
<td>29</td>
<td>10</td>
<td>1.9</td>
<td>0.09</td>
</tr>
<tr>
<td>Stromlofa Springs</td>
<td>93,000</td>
<td>650</td>
<td>292</td>
<td>30</td>
<td>10</td>
<td>2.2</td>
<td>0.10</td>
</tr>
<tr>
<td>Swan Lake</td>
<td>26,000</td>
<td>480</td>
<td>174</td>
<td>17</td>
<td>5</td>
<td>2.8</td>
<td>0.098</td>
</tr>
</tbody>
</table>

*Not a Landmark Dam, added for comparison only.
1 Rubble masonry (mortal).
2 Concrete.
3 Cyclopean masonry (concrete).
4 Rubble masonry in plug, concrete in dam.
5 Cyclopean concrete (large spalls of rock in concrete).
6 Mortar for bedding, concrete for filling vertical joints.
Even though the use of early arch dams had originated in Europe and the Middle East, their use gradually faded in those areas. In the late 19th century, arch dams began to prosper in North America and later in Australia. By 1922, over 80 single-arch dams and 22 multiple-arch dams had been constructed in California, mainly for irrigation districts, and to a lesser extent for hydroelectric projects. Cost savings and safety against overturning were prime reasons for this popularity. American pioneers, according to Andre Coyne, had the courage of constructing arches, lots of arches. The most daring of these are, curiously enough the oldest: Bear Valley and Upper Otay.10

The histories of these early dams have much of value to offer for today's engineers as they confronted their builders with a broad variety of very similar problems and issues. Many of these historic experiences were recorded in the literature of the time, either as books or as commentary in engineering journals. The engineers responsible for these designs, realizing the short comings and inaccuracies of the cylinder formula, limited compressive stresses to about 300 psi according to G. E. Goodall in his discussion of Coyne's paper.10 Only a few of these records are referred to here, selected mostly because they are striking yet typical. Subjects included are considerations and criteria for the design and construction of the Bear Valley arch dam. Also discussed is the interesting and informative case of the tenfold increase in spillway capacity for the Sweetwater arch dam project, incorporated during several raisings in the early years.

Leading engineers of the time were personally and directly involved with the design and often were present during the construction of arch dams. Time and again one reads in these historic documents: "at the direction of the engineer," "contracting grouting under the direction of the engineer," and "must first be approved by the engineer," that is, the design engineer who was present in the field. Such a reading makes one want to compare today's responsibilities and liabilities of engineers with those of bygone years, but such an effort seems almost impossible to carry out and would be beyond the scope of this book. And, as we shall see, in those early days the courts were involved too when the public interest was affected.

**Bear Valley Dam (1884)**

As previously noted, one of the earliest arch dams, Bear Valley was the boldest on record [Fig. 3-3]. To the engineering fraternity it was the "eighth wonder of the world."11 It was completed in 1884 at over 6,800 feet above sea level in the San Bernardino mountains, some 80 miles east of Los Angeles. The owner was the Bear Valley Mutual Water Company of Redlands, California. The necessity to transport all construction materials over 100 miles of rugged terrain led the young engineer and land developer, Frank E. Brown (1856–1914), to build the dam as thin as possible. With a height of 64 feet, the bottom thickness was only 22 to 24 feet and the top thickness was 3 feet, with a crest length of 450 feet. It spans an arc of only 42.5 degrees and has a radius of 337 feet. Reservoir capacity was 1,482 million cubic feet. The dam performed quite satisfactorily, but was replaced in 1911 by a more conservatively designed multiple-arch dam. The maximum compressive stress, as computed years later, reached a value of 620 psi, very much higher than the figure of 200 psi maximum used for arch and gravity dams as referred to also by Schuyler in his book on Reservoirs11 (page 119). Perhaps, the designer was more daring than the contemporary state of knowledge really warranted.12

Four years after its construction, knowledge of the existence of this daring early structure was lacking, even among engineers and engineering publications, as is illustrated by an excerpt from a letter by Schuyler, another early pioneer of arch dam design, to the editor of Engineering News, published in its April 7, 1888 issue.13 He writes as follows:

> Here is a dam that is without a parallel in the civilized world, so far as I have been able to learn—the most ultra radical of the pure arch type—and yet it has stood with reservoir brimming full every year back of it, for nearly five years, and still awaits the earthquake that is to effect its ruin. For the lessons which this daring experiment may teach I think it is worthy of more attention than it has received at the hands of the profession. Its remoteness and difficulty of access
accounts for the meagre information obtainable regarding it.

Soon thereafter, Brown described his project in a letter to the editor of *Engineering News*, published in its June 23, 1888\(^{14}\) issue:

I send you herewith some photographs [Figs. 3–4a and 3–4b], maps, etc. which will give you some idea of the Bear Valley dam, which I have been intending to send for some time, but have been unable to do so.

At the time a friend [Hon. H. M. BARTON] and myself discovered the natural fitness of Bear Valley for a reservoir, in May 1883, there were comparatively few people in this section. The problem was to build a dam that would stay, and retain the water, with the amount of money at our disposal. Everything excepting the rock had to be hauled 100 miles by teams, over two mountain passes and across a desert. I saw that the only way we could accomplish our desire, was by building an arched dam of the fine granite blocks at hand. About 2½ miles up the valley we built a low
earth dam (6 ft. high) the same summer (1883). Above this dam we caught and retained all water in the stream, causing it to overflow about 450 acres. Then began work in earnest in July, 1884.

From July till December I remained in Bear Valley working about 100 men. After cleaning off the bedrock, ... we built the dam, by placing derricks on rafts of big logs, and floated these up gradually by drawing water from the Lake above, as needed. As you see by the contour map and table sent you, the stored water enabled us to build the dam up to quite a height, working nearly on a level. We opened our quarry on the edge of the water about 500 to 600 ft. away from dam, and supplied the derricks with rock, by means of big scows working like ferry boats. As the water raised we moved our quarry back higher, etc.

The dam cost $75,000. The taming bill was very large, as it took each team from 10 to 12 days to make the round trip. We had all the teams in the country from the big desert freight teams of 16 or 18 mules to the little 2 horse teams. I kept my force of men of such a number as to just keep up with our supply. I rarely had more than 1 or 2 days supply of cement on hand, yet never ran out, though one noon, when the men went to dinner, there was just one hour's supply on hand. Fortunately some arrived while the men were eating. It was my aim to get the dam high enough before the floods of winter came, to let the surplus water out of the waste weir, as I did not wish to have it pour over the top of the new dam. But I let the water follow the dam up rapidly as we built it in order to bring the pressure to bear upon the arch before the cement was set very hard, and thus to let the whole arch take its bearings, and transmit the pressure to the mountains at the ends.

Of course there was some seepage through the dam, but this is gradually decreasing. There were also some fissures in the hard, solid rock at south end, through which some water works out.

Proposed Raising—Bear Valley arch dam stood successfully for a period of 26 years from 1885 until 1911, having frequently been subjected to full pressure. The pressing need for additional water prompted the construction of a new dam. It was found desirable to build an 80-ft high dam in order to increase the storage capacity of the reservoir about three times, and to provide new, larger and controlled outlet works. Plans were also considered to make the new dam 120 feet high, increasing its capacity fivefold over the 80-ft dam and nearly fourteenfold over the existing dam. The basin would then be completely occupied so that no spilling would be needed at the dam; instead the spillway would be at the upper end of the lake, over the divide into another watershed.

The New Bear Valley Dam was designed to be safe under all normal conditions, and was to be built as a curved gravity structure to provide additional security against an earthquake. The design engineer, James S. Black, recognized the relationship between rainfall, snow melt, reservoir volume, and discharge capacity of outlet works and spillways. His discussion also illustrates the infancy of the science of hydrology at the time, and the important interplay between spillway capacity and arch dam design.

The specification to govern the construction of this new dam was included in detail in the Engineering News article of November 30, 1889. It covered foundation cleanup and treatment, masonry, cement and concrete work. Emphasis was placed on the high class of workmanship required for all work, and on the role and responsibilities of the engineer.

The proposed raising of the Bear Valley arch dam was not executed, because of concern about the development of bond between the long vertical face of the old dam and the new work and therefore, that the resulting seam would become filled with water under hydrostatic pressure. Of equal importance was the difficulty of constructing an inside gate well to enable repairs on gates and pipes without drawing down the reservoir. These considerations alone were deemed sufficient to justify selecting a location just downstream of the existing dam. Perhaps the controversy raging over its safety also played a role. The well-known engineer E. Wegmann, in his book entitled The Design and Construction of Dams, said "the irrigation company which built the dam decided to replace this rather dangerous structure by a more substantial dam to be built about 200 feet further downstream." On the other hand, the adequacy of the Bear Valley arch dam was never doubted by Consulting Engineer John S. Eastwood when he wrote in the Engineering News-Record of 1913:

Mr. Brown's development consisted in the erection of the famous example of single-arch dam, noted as the lightest section masonry single-arch dam in the world. This old dam has been described many times and many a critic of note has visited it. It has been condemned by many as absolutely unsafe and the adverse criticism was so profuse and from those considered in such high authority that the reservoir was not allowed until the last few years to fill up to its complete capacity, but the winters of 1909-10 and
9. In recent years several dams have been analyzed with the finite element method, both for static and dynamic loading. In the latter case the most modern state-of-the-art determinations for maximum credible earthquakes have been used. Arch structures have been found adequate and safe for these loads, mainly for two reasons: (1) the excellent quality of construction, and (2) the very large factors of safety used in the original dimensioning.

This evidence underlines the inherent safety of arch dams when constructed on solid, massive hard rock foundations. Many of these dams, which set slenderness records were analyzed by the cylinder formula applied to independent arches such as Sweetwater Dam and Upper Otay Dam southeast of San Diego. The latter furthers the use of concrete, while the former, the highest arch dam at the time of its completion, has a history of overtopping with removal of significant quantities of rock downstream (10,000 cubic yards). Other dams, discussed below and built between 1887 and 1895, are Hemet and LaGrange.

Sweetwater Dam (1888)

Twice overtopped, each time with an unprecedented flood flow, and three times enlarged to provide either larger storage or larger spillway capacity, the Sweetwater Dam, near San Diego, California, is a notable example of the revision of an engineering structure to meet new conditions not considered when it was built (Fig. 3-5). First constructed between 1886 and 1888, its purpose was to provide storage of water for the irrigation of large tracts of land and the supply for National City. The builders were the San Diego Land and Town Co., which already owned a large body of fertile land that was unsalable owing to the lack of water. After 100 years, the dam is still serving its original purpose of storing flood water for irrigation. The project presents an example of the problems which engineers have faced throughout 100 years of dam building history and shows how they have coped with these challenges.

The original arch gravity dam had a height of 98 feet, was 46 feet thick at the bottom, and 12 feet at the top, had a crest length of 360 feet, and was curved on a radius of 213 feet. It was designed as a gravity dam with trimmed down profile because the weight of the stone was 190 lbs per cubic foot. The dam was curved to increase its stability. The masonry was a rough rubble laid in a mortar of Portland cement and sand in the proportions of 1 to 3. The construction of the dam was started in November 1886 and after only 2 months of work and the expenditure of $35,000 the design was modified. By June 1, 1887 the dam was 60 feet high, contained 7,500 cubic yards of masonry and had cost about $100,000. Meanwhile surveys had shown that a 90-ft high dam would impound 5,882 million gallons, or nearly five times as much as the 60-ft dam. The increased storage would considerably increase the commercial value of the improvement in times of drought, which consideration led to adoption of the higher structure. Construction was completed in 1888.

The dam was overtopped 58 inches in 1895 over the entire 396 foot length of its crest for a period of 40 hours. The waste weir was designed for a flood of 1,500 cfs, but the actual flood reached a maximum flow of 18,150 cfs. The dam withstood the shock without the slightest damage. The waterfall formed a basin in the refuse rock at the base of the dam, which acted as a cushion. The masonry at the toe of the dam was not exposed to the erosion of overflow.

Plans for reconstruction included increasing the waste-weir capacity from seven to eleven bays and to twice the original height. Four outlet works were added, with 30- and 36-in diameter gated pipes. A timber crib in the form of a grillage was built across the canyon 50 feet below the toe of the dam. A concrete apron was added from the waste-weir to the bottom of the canyon.

The cost of these repair works was about $30,000. Masons were paid $4 to $5 per day, common labor $2 to $2.50, foremen $4 to $6, carpenters $3.50 to $4, blacksmiths $4, teams including driver $5, machinists $0.80 to $1.00 per hour. The work was done in the midst of the “boom” in southern California when labor of all kinds was difficult to obtain, independent and restless on account of the general feverish excitement, and inclined to pick up at any moment and move in search of better pay.

Some years later Sweetwater Dam was raised 20 ft as reported by Consulting Hydraulic Engineer, Schuyler, in the March 30, 1911 issue of Engineering News under the title “The Extension of the Sweetwater Dam.” He reported that the dam would be raised 20 feet in order to double its reservoir capacity. After the January 1895 flood a period of ten years of drought followed. Subsequent flows had been superabundant and much valuable water had been wasted from lack of reservoir capacity. The spillway capacity was increased from 1,500 to 5,500 cfs. Subsequent to a major flood in 1916, which reached a peak of 45,500 cfs, the spillway capacity
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The dam was overtopped 58 inches in 1895 over the entire 396 foot length of its crest for a period of 40 hours. The waste weir was designed for a flood of 1,500 cfs, but the actual flood reached a maximum flow of 18,150 cfs. The dam withstood the shock without the slightest damage. The waterfall formed a basin in the refuse rock at the base of the dam, which acted as a cushion. The masonry at the toe of the dam was not exposed to the erosion of overflow.

Plans for reconstruction included increasing the waste-weir capacity from seven to eleven bays and to twice the original height. Four outlet works were added, with 30- and 36-in diameter gated pipes. A timber crib in the form of a grillage was built across the canyon 50 feet below the toe of the dam. A concrete apron was added from the waste-weir to the bottom of the canyon.

The cost of these repair works was about $30,000. Masons were paid $4 to $5 per day, common labor $2 to $2.50, foremen $4 to $6, carpenters $3.50 to $4, blacksmiths $4, teams including driver $5, machinists $0.80 to $1.00 per hour. The work was done in the midst of the “boom” in southern California when labor of all kinds was difficult to obtain, independent and restless on account of the general feverish excitement, and inclined to pick up at any moment and move in search of better pay.

Some years later Sweetwater Dam was raised another 20 feet as reported by Consulting Hydraulic Engineer, Schuyler, in the March 30, 1911 issue of Engineering News under the title “The Extension of the Sweetwater Dam.” He reported that the dam would be raised 20 feet in order to double its reservoir capacity. After the January 1895 flood a period of ten years of drought followed. Subsequent flows had been superabundant and much valuable water had been wasted from lack of reservoir capacity. The spillway capacity was increased from 1,500 to 5,500 cfs. Subsequent to a major flood in 1916, which reached a peak of 45,500 cfs, the spillway capacity
was increased to 50,000 cfs in 1918. Currently, the capacity is 71,624 cfs for the estimated probable maximum flood peak inflow of 82,224 cfs.

Repair works to the face of the dam, foundation improvements, pressure cells for monitoring foundation pressures, earthquake analyses and new flood studies have all been carried out in the intervening years and are described in Description No. 3-1 under the heading "History of Sweetwater Dam."

Owners were subjected to lawsuits even in those days, as illustrated in the following quote from the January 6, 1917 issue of Engineering News:

Holding that the Sweetwater Water Company's dam near San Diego, Cal., was constructed by competent engineers, and that the flood of last January which carried away a dike that formed a part of the reservoir was an act of God, a decision recently rendered in a San Diego court exonerates the company for damages to property below the dam. The suit was for $13,000. Similar suits have been filed against the company for amounts of aggregating $200,000 and also against the city of San Diego for damages caused by the washing out of the city's Lower Otay dam. In this trial evidence was introduced that the rainfall of Jan. 27 was three times greater than ever before recorded for one day in San Diego.

The Consulting Engineer, H. N. Savage, and the owner were well aware of the public’s concern about the safety of the redesigned structure and decided on a policy of "open house," as described in the May 3, 1917 issue of Engineering News:

The enlarging of the spillway capacity at the Sweetwater dam, near San Diego, Calif., which has included the construction of a siphon-type spillway, has involved work of a character and magnitude that would naturally attract the interest of layman as well as engineer, particularly in the case of residents of the vicinity. H. N. Savage, consulting engineer in charge, adopted a policy of welcoming all visitors and allowing them the freedom of the work.

Signs were posted on all roads leading to the dam, giving direction and distance and bidding visitors welcome. The customary "Positively No Admittance" signs were all removed, and instead at the entrance gates there was posted a "Visitors Welcome" placard accompanied by directions.

As a result of this policy during the construction period a great number of visitors inspected the work nearly every day and went away with a definite idea of what was being done and how it was accomplished. In consequence, there is now a general impression that the work is adequate and of a substantial nature particularly among residents of the valley below the dam.
No accidents have been suffered by visitors, nor has any delay or inconvenience to workmen resulted from their presence on the work. Not infrequently visitors have expressed surprise at a policy so radically different from that usually in effect, and with the surprise has been a feeling that the company had nothing to conceal and was proud of the character of work being done.

LaGrange Dam (1893)

This large curved masonry dam, also called Turlock Dam, arched on a 300-ft radius is distinguished by its height of 127 feet. The dam was designed by Luther Wagoner as an overflow dam. Located across the Tuolumne River, two miles above the old mining town of LaGrange, California, it was constructed in the period from the fall of 1891 to early 1894. Its function was to divert water from the river into two canals, which begin at the dam, one on each side of the valley. A distinguishing feature of the dam was that free overflow was avoided, thereby reducing chances of erosion of rock immediately downstream of the dam. The downstream face of the dam was curved so that water up to 4 or 5 feet deep would flow down the face of the dam rather than falling against the toe. During a flood 46,000 cubic feet of water, corresponding to a depth of 12 feet on the crest, has passed over the dam. As no storage was contemplated, the dam was not provided with outlet pipes. The canyon back of the dam was allowed to fill with flood debris. The project is illustrated further in Description No. 3–2.

Lake Hemet Dam (1896)

Lake Hemet Dam is a rubble masonry arch-gravity dam located on the South Fork of the San Jacinto River approximately 20 miles east of San Jacinto and about 100 miles from San Diego, California (Fig. 3–6). The project is owned and operated by the Lake Hemet Municipal Water District. It was constructed between 1891 and 1895 to form a reservoir for irrigation purposes, but is now also used for recreation.

When the dam was originally discussed in Engineering News, the idea was to make it of the ultra-curved type with the shortest possible radius and a thickness of only 4 feet from top to bottom. But the original irrigation company did not approve so radical a design and after reorganization the company utilized what water it could without storage works. A fill dam was discussed and the idea abandoned. The present structure was designed by J. D. Schuyler, who also supervised construction. The dam has a maximum structure height of 135.0 feet, a crest length of 324 feet and varies in thickness from 6.75 feet at the crest to approximately 100 feet at the base [Fig. 3–7]. The upstream face has a batter of 1H to 10V, and the downstream face 1H on 2V. A thin arch-shaped concrete wall constructed at the top of the dam in 1923 has a height of 12.5 feet and a base width of 8 feet [Fig. 3–8].

The dam has a center overflow section which acts as a secondary spillway. The length of the overflow section is approximately 243 feet. The main spillway is located about a third of a mile south of the dam and consists of an arch-shaped concrete overflow section which discharges into a spillway chute. There are three separate operable outlets through the dam consisting of two 22-in diameter outlet pipes and one 34-in diameter outlet pipe. The outlets serve to regulate releases for irrigation and fish.

The drainage area of Lake Hemet Reservoir is 57 square miles, ranging from El. 4,350 to a maximum El. 8,800. In February 1927, a severe storm caused the dam to be overtopped by approximately 7 feet. The maximum runoff into the lake was computed to be 25,000 cfs. The Probable Maximum Flood would have a volume of 60,861 ac-ft over a 72-hour period with a peak inflow of 48,743 cfs, which would overtop the dam to a maximum depth of 8.4 feet for about 50 hours.

The dam rests on quartz diorite, a granitic rock composed chiefly of acid plagioclase, quartz, hornblende and biotite. The foundation rock is generally only slightly to moderately weathered, very strong and closely to moderately jointed. Foundation treatment consisted of stripping with the aid of a cable way for conveying and dumping the waste below the
dominated by the San Andreas Fault and a system of subparallel, but smaller faults lying to the west. A magnitude $M=7.5$ was estimated for the Maximum Credible Earthquake on the San Jacinto Fault for seismic evaluation of the dam. The peak ground acceleration at the damsite, with an epicenter distance of 4 km is estimated to be 0.62g.

Three-dimensional Finite Element Method (FEM) stress analyses, conducted in 1983–1984 as part of the assessment of the stability of the dam, indicated that the dam would be stable under extreme loading conditions. The stresses in the dam were obtained for two loading conditions: reservoir water level with PMF stage, and normal maximum reservoir with seismic loading (MCE). Both considered uplift pressures and silt loadings. The values of sustained modulus of elasticity of the rubble masonry and concrete of the dam used in the analyses were 2,500,000 psi and 3,000,000 psi, respectively. The maximum allowable tensile stress in the rubble masonry and concrete materials for the extreme loadings were 400 psi and 500 psi, respectively.

Results of the FEM analysis indicated that the allowable stresses in the masonry of the dam will be exceeded in a very localized area near the top of the dam during MCE. However, because of the relatively small area of overstress and because the number of such stress exceedances during the earthquake is low, it is considered that the dam would not be seriously affected during a major earthquake.

The total content of the structure is 32,320 cubic yards with about 20,000 bbls of cement, which had to be hauled 23 miles over steep grades. The teams hauled wood and timber on the return trips. All stone was quarried within 400 feet of the dam, on both sides of the canyon, above and below. The material was taken to the dam by two cableways,
each about 800 feet long and of 1.5-in wire cables. Derrick's were used on the dam for swinging stone into place, being operated with power from a 3-ft Pelton wheel. The concrete used for embedding the blocks was of 1 part cement, 3 of sand, and 6 of stone, the latter crushed to pass through a 2.5-in ring. All mortar and concrete were mixed by machinery. Sand was accumulated in a temporary log dam reservoir as it was brought down by the flowing stream and conveyed to the mixing platform by a wire-rope carrier with triangular buckets placed at intervals of 20 feet.

The stones were placed 6 inches apart at the nearest, and the spaces between were filled with concrete and smaller stone all well rammed into place with iron tampers. This use of concrete enabled unskilled laborers to do much of the work, and stone masons were employed only in the facings, which were laid in mortar mixed richer than the concrete. The mixing of both mortar and concrete was done in iron boxes revolved by water power. In his report to the owner, Schuyler noted that the class of masonry of which the dam was built "certainly was the finest I ever saw, and I doubt if it has any superior in America in work of this kind. When completed it will unquestionably not only the highest, but the finest dam on the continent."

In May 1980, following damage caused by a heavy storm runoff, work was begun on construction of a concrete-lined spillway chute and training walls. This work was completed in March 1981. Other repair work included installation of rock bolt tie backs and shotcrete in the right down-stream groin of the dam/abutment interface to stabilize blocks of rock that might become dislodged during overtopping flood flows.

**Upper Otay Dam (1901)**

The Upper Otay Dam is located on the north branch of the Otay River, contiguous to the Lower Otay Reservoir, at an elevation of 550 feet above sea level, and about 20 miles from the city of San Diego. The dam, built of concrete, has a storage capacity of nearly 2,000 ac-ft and cost $80,000.

Considering its 89-ft height with base thickness of 14 feet and top thickness of 4 feet, combined with a crest length of 350 feet and the very large upstream radius of 359 feet, the dam probably outranks in minimum section and minimum cost any structure of the kind built up to 1900 except Bear Valley. The use of concrete for other arch dams was furthered by experience on Upper Otay. Schuyler, in his *Reservoirs for Irrigation* referred to the Upper Otay Dam as, with the exception of the famous Bear Valley Dam, "the slenderest dam in California or any other part of the globe," and "the dam must be regarded as one of the most interesting of modern structures in that line, whose ultimate fate will always be looked upon with curiosity by the profession."

The dam was subjected to a severe test in 1916 by a flood that destroyed the Lower Otay rockfill dam. In 1985 a dam modification project was completed at a cost of $121,545. The project is briefly described in Description No. 3-3.

**BEGINNING 1900S—BIRTH OF ANALYSIS**

Improved methods of analysis developed gradually during the early decades of the 20th century, incorporating increasing sophistication to account for the actual behavior of the arch dam, and taking into consideration many other loading and stress-causing effects. Much effort was dedicated to two major aspects of the calculation of stresses in an arch dam. The first was the analysis of a single arch including rib shortening and abutment fixity, the second to line up horizontal deflections of these arches with the crown cantilever.

Variable thickness was soon introduced to reduce bending stresses as compared with an arch of constant thickness. Tables and graphs were developed by a number of authors to facilitate application of the rather complicated formulas and calculations that were often rather lengthy. Bending stresses caused by abutment resistance, elastic shortening, temperature changes and other factors were accounted for. In the early days of the California State Supervision of Dams (created in 1929), maximum arch stresses computed by the Cain formula were limited to 600 psi in compression, and tensile stresses, even when occurring at contraction joints, were limited to a maximum of 100 psi.

Several authors questioned the need for such sophistication when the actual behavior of an arch dam was so obviously different from single, independent, horizontal arches. This led to the second major advance. New methods of analysis were used...
### Table 3-4 LANDMARK CONCRETE ARCH DAMS

<table>
<thead>
<tr>
<th>DESCRIPTION NO.</th>
<th>NAME OF DAM</th>
<th>LOCATION</th>
<th>YEAR OF COMPLETION</th>
<th>HEIGHT (FT)</th>
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<tr>
<td>3-1</td>
<td>SWEETWATER</td>
<td>CA</td>
<td>1888</td>
<td>127</td>
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<td>3-2</td>
<td>LAGRANGE</td>
<td>CA</td>
<td>1893</td>
<td>131</td>
</tr>
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<td>3-3</td>
<td>UPPER OTAY</td>
<td>CA</td>
<td>1901</td>
<td>89</td>
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<tr>
<td>3-4</td>
<td>LAKE CHEESMAN</td>
<td>CO</td>
<td>1905</td>
<td>227</td>
</tr>
<tr>
<td>3-5</td>
<td>PATHFINDER</td>
<td>WY</td>
<td>1909</td>
<td>214</td>
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<tr>
<td>3-6</td>
<td>BUFFALO BILL</td>
<td>WY</td>
<td>1910</td>
<td>325</td>
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<td>3-7</td>
<td>THEODORE ROOSEVELT</td>
<td>AZ</td>
<td>1911</td>
<td>230</td>
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<td>3-8</td>
<td>SALMON CREEK</td>
<td>AK</td>
<td>1914</td>
<td>170</td>
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<tr>
<td>3-9</td>
<td>LAKE SPAULDING</td>
<td>CA</td>
<td>1919</td>
<td>276</td>
</tr>
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<td>3-10</td>
<td>PACOIMA</td>
<td>CA</td>
<td>1929</td>
<td>372</td>
</tr>
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<td>3-11</td>
<td>GIBSON</td>
<td>MT</td>
<td>1929</td>
<td>199</td>
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<td>3-12</td>
<td>OYWHEE</td>
<td>OR</td>
<td>1932</td>
<td>417</td>
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<td>3-13</td>
<td>HOOVER</td>
<td>AZ</td>
<td>1935</td>
<td>726</td>
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<td>3-14</td>
<td>PARKER</td>
<td>AZ</td>
<td>1938</td>
<td>320</td>
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<td>3-15</td>
<td>ROSS</td>
<td>WA</td>
<td>1949</td>
<td>540</td>
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<td>3-16</td>
<td>HUNGRY HORSE</td>
<td>MT</td>
<td>1953</td>
<td>564</td>
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<td>3-17</td>
<td>GLEN CANYON</td>
<td>AZ</td>
<td>1964</td>
<td>710</td>
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<td>BOUNDARY</td>
<td>WA</td>
<td>1967</td>
<td>340</td>
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<td>3-19</td>
<td>NEW BULLARDS BAR</td>
<td>CA</td>
<td>1969</td>
<td>635</td>
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<td>3-20</td>
<td>MORROW POINT</td>
<td>CO</td>
<td>1968</td>
<td>468</td>
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<td>MOSSYROCK</td>
<td>WA</td>
<td>1968</td>
<td>606</td>
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<td>3-22</td>
<td>NAMBE FALLS</td>
<td>NM</td>
<td>1976</td>
<td>150</td>
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<td>3-23</td>
<td>CRYSTAL</td>
<td>CO</td>
<td>1977</td>
<td>323</td>
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<td>3-24</td>
<td>STRONTIJA SPRINGS</td>
<td>CO</td>
<td>1982</td>
<td>292</td>
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<td>3-25</td>
<td>SWAN LAKE</td>
<td>AK</td>
<td>1984</td>
<td>174</td>
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</tbody>
</table>
No. 3-1
SWEETWATER DAM
OWNER: SOUTH BAY IRRIGATION DISTRICT
TECHNICAL DATA

GENERAL

Purpose
Water storage for irrigation and municipal supply
Location—State/Nearest City
California/San Diego
River
Sweetwater
Drainage Basin Area
182 mi² (471 km²)
Date of Completion
1898/first stage, 1911/second stage, 1915/final stage

DAM

Type
Arch-gravity; composite rubble-masonry and concrete
Height above Foundation
127 ft (38.7 m)
Thickness at Top/Base
15 ft (4.6 m)/73 ft (22.3 m)
Length of Crest
700 ft (213.4 m)
Volume of Dam
1,992 cu (1,523 m³)

SPILLWAYS

Max. Discharge Capacity
71,624 cfs (2,027 m³/s)
Side Channel Spillway
Left abutment with flashlight slots
Siphon Type
Six-barrel siphon spillway
Overflow Length
36 ft (11 m)
Ogee Overflow Type
Concrete ogee overflow
Overflow Length
345 ft (105 m)

RIVER OUTLETS

Location No. 1
At center of main dam
Intake Type
53-in (1.4-m) inside diameter intake tower in reservoir, 9 openings
Length of Conduits
555 and 160 ft (169 and 49 m)
Location No. 2
Left abutment diversion tunnel
Number/Diameter of Conduits
Two 35-in (0.9-m) diameter and two 30-in (0.8-m) diameter
Length of Conduits
138 ft (42 m)

POWER FACILITIES
None
GENERAL PLAN OF SWEETWATER DAM

ELEVATION OF SWEETWATER DAM LOOKING UPSTREAM
SECTION OF SWEETWATER DAM AND OUTLETS
Location—Sweetwater Main Dam was first constructed between 1886 and 1888 by the San Diego Land and Town Company of Boston, Massachusetts, and is located about 6 miles northeast of Chula Vista, and 10 miles southeast of San Diego, California.

General Description—Following initial completion in 1888, Sweetwater Main Dam received nine major modifications, including the addition of the south dike. The Sweetwater Main Dam now is a 127-ft-high composite rubble-masonry and concrete gravity-arch dam. The south dike is a 30-ft-high rolled earth dam with concrete facing.

In 1902 the dam was acquired by the Sweetwater Water Company, which became the Sweetwater Water Corporation in 1928. The latter became the California Water and Telephone Company in 1935 and was in turn succeeded in 1966 by the California American Water Company. In August 1977 the Sweetwater facilities were acquired by the South Bay Irrigation District and simultaneously leased to the Sweetwater Authority for operation and maintenance.
Purpose—The purpose of the project is to collect and store runoff water for irrigation and for use by the adjacent Sweetwater Treatment Plant and also to store and divert water released from Lake Loveland upstream, for the same purpose.

The supply of water for irrigation and domestic use for National City and Chula Vista in San Diego County necessarily involved the construction of storage reservoirs. The streams of the county are of intermittent character with torrential flow in winter carrying large volumes of water, but in summer and fall when water is most needed for irrigation, the streams are almost dry.

SITE CONDITIONS

Geology—The dam is at the westerly edge of the tilted mountain block which forms the Peninsular Ranges Geomorphic Province. The province is bounded on the east by the Colorado Desert and on the north by the Transverse Ranges. The northwest trending San Jacinto and Elsinore Faults divide the province parallel to its long axis, and the Santa Monica and Sierra Madre systems form the northern boundary.

Individual mountains that form the ranges have plutonic cores and are known collectively as the Southern California Batholith. The composition of the batholith ranges from gabbro to granite, but the bulk of the rock is tonalite and granodiorite. Metamorphic rock is found as roof pendants and locally isolated bodies along the border of the mountain ranges. Cretaceous sediments and Tertiary volcanic and sedimentary rock lie along the western flank of the batholith. Quaternary sediments fill inland valleys and coastal estuaries and cover portions of the coastal margins.

The foundation of the main dam is the Jurassic Santiago Peak Formation. The south dike and most of the reservoir is underlain by the Pliocene San Diego Formation. The San Diego Formation overlies the Santiago Peak Formation unconformably, and where present in this area has a maximum thickness of about 150 feet. The Santiago Peak Formation consists of a metamorphosed dacite with either aphanitic or porphyritic texture. It is hard and sound with only a few feet of surface deterioration. Slight differential weathering at the dam can be attributed to variations in joint and fracture patterns and spacing. The San Diego Formation is generally composed of fine to medium grained, poorly indurated [frangible] sandstone. It also contains beds of cobble conglomerate, bentonite, marl, and mudstone. The topography of this formation consists of gently rounded hills.

Foundation rock in the area of the main dam is metavolcanic. Photographs indicate a generally wide joint spacing, estimated to be 3 to 6 feet or more. Photos showing erosion of the rock resulting from spillway overflow, and photos of foundation scaling indicate that a closer spaced micro-fracture system may also exist. Core drilling and seismic profiling indicate that the foundation is generally sound and intact in place.

Water pressure testing indicates low to medium permeability in the rock with lowest permeability under the 1910 extension. Although the contact of the dam and bedrock is not described on the drill logs, water pressure tests in the exploratory hole indicate that the bond is probably generally good.

Seismicity—Sweetwater Main Dam is located within Zone 4 [Great Seismic Probability] on the Seismic Zone Map [California, Nevada, and Arizona] extracted from the U.S. Army Corps of Engineers' Recommended Guidelines. Table 3–1.1 shows estimated earthquake characteristics for faults most likely to cause severe shaking at the dam.

<table>
<thead>
<tr>
<th>FAULT</th>
<th>LA NACION</th>
<th>ROSE CANYON</th>
<th>AGUA BLANCA</th>
<th>SAN MIGUEL</th>
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</thead>
<tbody>
<tr>
<td>Maximum Credible Magnitude</td>
<td>6.3</td>
<td>6.3</td>
<td>7.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Distance from dam (mi)</td>
<td>2.5</td>
<td>8</td>
<td>21*</td>
<td>27</td>
</tr>
<tr>
<td>Peak Base Acceleration, Bedrock (g)</td>
<td>0.6</td>
<td>0.4</td>
<td>0.25</td>
<td>0.2</td>
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<tr>
<td>Duration of Bracketed Strong Motion greater than 0.05 g (sec)</td>
<td>17</td>
<td>23</td>
<td>27</td>
<td>25</td>
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<tr>
<td>Predominant Period (sec)</td>
<td>0.28</td>
<td>0.31</td>
<td>0.37</td>
<td>0.35</td>
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<td>Principal Historic Events</td>
<td>None known</td>
<td>1964, M 3.7</td>
<td>1954, M 6.3</td>
<td>1958, M 6.8</td>
</tr>
<tr>
<td></td>
<td>1800, Est. M 6.5</td>
<td>1892 Est. M 6.9</td>
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<td></td>
</tr>
</tbody>
</table>

*The neareast fault trace is offshore; the location is somewhat uncertain.
Hydrology—The drainage basin is 182 square miles and consists of gentle to steep foothills, ranging from El. 240 to El. 6,515, with low to moderate density brush growth prevailing over about half of the basin. About half of the basin is within the Cleveland National Forest. The precipitation over the basin is quite variable, with the average annual precipitation being about 20 inches. The 25,000 ac-ft capacity, Lake Loveland Dam is located about 19.1 miles upstream from the Sweetwater Dam.

The Division of Safety of Dams independently estimates flood inflows for all dams where the state of California exercises supervision for safety. The Clark Unit Hydrograph technique is utilized. Precipitation data for the Probable Maximum Flood (PMF) was developed using the U.S. Weather Bureau Hydrometeorological Report No. 36 (for the General Type Storm) and Hydrometeorological Report No. 49 (for the Local Storm).

In routing the PMF, tributary runoff was routed through Lake Loveland, and allowing a travel time of 1.65 hours, was combined with runoff from the remaining 84 square miles; and then the combined runoff was routed through Sweetwater Reservoir. It was assumed that both Lake Loveland and Sweetwater Reservoir were filled to the level of their lowest spillway at the onset of the PMF and that the outlets remain closed during the PMF. The inflow hydrographs and the routed overflow for both studies were developed using the U.S. Army Corps of Engineers computer program “Flood Hydrograph Package” HEC-1.

The General Type (Hydrometeorological Report No. 36) PMF Storm was the most critical, it yielded a maximum routed outflow of 71,624 cfs which would overtop the lower parapet wall (El. 248) at Sweetwater Dam by 0.6 feet. The routed outflow for 80 percent of the General PMP Storm would be 54,433 cfs and would result in 1.6 feet of freeboard to the lower parapet wall (El. 248). The south dike was constructed to a crest elevation of 250 feet.

DESCRIPTION OF MAIN FEATURES

Spillways—The main dam is equipped with a 6-barrel siphon spillway on its right abutment, an ungated central overflow spillway, and an ungated side channel spillway adjacent to its left abutment. Downstream cushion and stilling pool dams provide pool for energy dissipation during spillway flows. The routed outflow of 71,624 cfs from the General Type PMP Storm would overtop the lower parapet wall (El. 248) for about 2 hours by as much as 0.6 feet. Such short term overtopping in itself, would not threaten the safety of the Sweetwater Dam.

Outlet Works—The main dam has a central intake tower that feeds two parallel blowoff conduits and a larger parallel 36-in diameter water supply conduit that supplies the adjacent Sweetwater Water Treatment Plant. It has a left abutment tunnel that feeds four blowoff outlet conduits. All conduits are equipped with manually operated gate valves. There is no rating curve for the various outlet conduits. Correspondence from the previous owner stated that the combined capacity of the four left abutment drain pipes in the left tunnel and the centrally located 18-in blowoff pipe at full reservoir head is 420 cfs. It was also reported that the full reservoir [27,500 ac-ft] could be drained within 35 days, using these drainage facilities.

HISTORY OF MODIFICATIONS OF SWEETWATER DAM

The dam has been subject to many modifications which are chronologically described in the following, based on the information prepared by Consulting Engineer N. H. Savage.

1886—The lower portion of what was to be a 50-ft high thin arch concrete masonry dam was constructed by F. E. Brown.

1887—Prior to completion of the thin arch, James Schuyler revised the original design and supervised construction of an uncoursed rubble masonry gravity-arch dam built over the lower portion of the previous arch to a height of 60 feet. A 50-ft wide, 20-ft thick clay blanket placed in layers and well rammed was extended upstream from the arch to reduce seepage through the bedrock seams. During construction, the stream was carried in a 30-in square conduit extending through the masonry near the bottom of the original creek bed. This conduit was reported to be subsequently filled (solid) with masonry.

1888—Under the supervision of Mr. Schuyler and using the same materials and construction procedures, the dam was raised to 90 feet, reaching the crest elevation of 215 feet—Sweetwater Datum (SWD), and a parapet wall elevation of 218 feet. The
dam was equipped with a free standing masonry inlet tower provided with seven inlet elbows at different levels, each provided with a saucer valve and basket screen. The outlet tower was equipped with three outlet pipes (18-in and 14-in concrete-encased cast iron blowoff pipes and the water supply conduit) which extend through the dam and were provided with downstream manually operated gate valves. The main water supply pipe extends from the base of the inlet tower to the center of the dam as a mortar-lined 40-in circular masonry conduit, where it joins a 36-in diameter, 0.5-in thick iron outlet pipe.

1889—By court order, an 8-ft by 12-ft tunnel was drilled through the hill on the south side of the main dam to ensure that certain upstream lands would not be flooded.

1893—The spillway capacity was increased from 1,800 to 5,500 cfs.

1895—Floodwaters overtopped the main dam for 40 hours by as much as 22 inches and severely damaged the spillway, the left abutment tunnel outlet, the north end of the dam, and washed out the downstream pipeline. Subsequently, the discharge capacity of the left abutment spillway was increased by adding four bays to the original seven and by doubling the effective depth of the bays. The eroded bedrock spillway discharge-way was filled with rock and covered with a thick reinforced-concrete apron. The face of the rock slopes below the spillway were protected with a grillage of iron embedded in concrete and the small downstream stilling basin dam was constructed. Minor alterations and additions were made to the upstream parapet to provide an emergency spillway equipped with flashboards over the central 200 feet of the arch and to increase the storage capacity.

The reservoir dewatering tunnel under the left abutment was modified and put under control to discharge through four concrete-encased blowoff pipes, two 36 inches and two 30 inches in diameter. The downstream tunnel was reinforced with crown beams and the top of the gate shaft was reinforced. Each pipe was fitted with tandem closure valves. Each pipe inlet was provided with a saucer valve and basket screen, operable by hoists located at the top of the left abutment gate shaft. Each pipe has an in-line downstream manually operated gate valve located in the tunnel.

1909—In March 1909, the dam was again overtopped.

1910 and 1911—[1] The parapet was raised 20 feet and extended to the ends of the 1888 dam. An earthfill and concrete core wall extended from the end of the 1888 dam into the abutments. [2] A mass cyclopean concrete gravity section was constructed against the downstream face of the 1895 structure. [3] The left abutment spillway was modified to include a 200-ft-long side channel spillway. [4] A 650-ft long, 23-ft-high compacted embankment dike was constructed in a saddle about 1 mile south of the main dam. [5] The height of the inlet tower was increased.

1916—In January 1916, the Sweetwater Reservoir rose to El. 243.5, overtopping the main dam by 3.5 feet. The earthfill and extension core walls and part of both abutments of the main dam were washed away, leaving a channel 90 feet wide and extending 45 feet below the parapet at the north abutment and a 20-ft wide by 40-ft deep gap at the south abutment. This performance demonstrated that the dam with the hollow modular parapet was statically stable to resist failure without arch support in the upper regions. There was no reported damage done to the composite masonry section of the dam. However, there is no record of a detailed inspection of the upstream face for cracking. The 1919 south dike was also destroyed during this flood.

The repairs were initiated the same year under the direction of Hiram N. Savage. The overflow spillway at the south end of the dam was rebuilt and made larger. A siphon spillway consisting of six barrels, each measuring 6 feet by 12 feet at the throat, was constructed at the right abutment. The siphon spillway structure is ballasted with a loosely placed rockfill cap.

The parapet design was modified to create a solid concrete structure rather than the hollow modular type built in 1910. Also, the ends of the parapets were raised to El. 253 (13 feet higher than the normal crest) "to ensure that the dam would not be blanked by any passing flood." A large void between the siphon spillway and the main dam (on the downstream side) was filled with a rockfill ballast and the general area was protected with reinforced-concrete protection.

In 1916, a new 1,260-ft long, 37-ft high south dike compacted embankment was constructed somewhat within the reservoir area from its predecessor. It has reinforced concrete facing of the water side and a crest elevation of 250 feet (SWD). The modifications were made to ensure safe passage of a 50,000-cfs flood. [Maximum inflow in 1916 was estimated at 45,000 cfs.]

A stilling pool reinforced-concrete slab and but-
tress dam [arch in plan] was constructed about 275 feet below the toe of the main dam to dissipate the energy involved in the increased spillway capacity and reduce erosion at the toe of the dam.

1927—The siphon spillways operated intermittently, with considerable vibration reported during spillway operation.

1934–1936—Between December 1934 and December 1936, the entire upstream face of main Sweetwater Dam between El. 184 and El. 225 was waterproofed with a coating of asphalt fibers and asphalt emulsion to reduce seepage on the downstream face. There was some reduction in seepage.

1937—Maximum spillway flow was 2,100 cfs. The siphon spillways operated intermittently and “fitfully.” Installed water level recorder on stilling pool dam to measure total spillway flow.

1938—Maximum spillway flow was 3,400 cfs with 2.8 feet of flow over the downstream stilling pool dam. Intermittent operation of the siphon spillways was reported to cause considerable vibration at the dam.

1939–1940—The upstream parapet crest wall along the center 345-ft section of the arch was removed and replaced with a rounded spillway shape, thus reducing the central crest elevation by 3 feet to El. 237 (SWD) and increasing the spillway outlet capacity. At the same time, the bridge to the inlet tower was lowered.

1946—Grouted under the side channel spillway to reduce leakage through horizontal drain pipes on the left wall of the spillway during high reservoir levels. Grouted downstream tunnel walls to reduce seepage. Installed rock and gunite wave protection on reservoir side of side channel spillway.

1961—A 36-in waterline for the adjacent Sweetwater Treatment Plant was extended through the right abutment parapet wall. The DSOD issued the current Certificate of Approval authorizing storage to El. 235.0 (SWD).

1969—Consultants for the owner made exploratory borings through the dam and its foundations. Field and laboratory tests of some of the extracted samples were made. They concluded that the physical condition of the dam and its component material was more than adequate. Subsequently, nine of the exploration borings were equipped with pressure cells to measure foundation uplift pressures.

1973—In view of the magnitude of the uplift pressure measurements over the previous 4-year period, DSOD requested that the owner make an analysis of the Sweetwater main gravity-arch dam for stability against uplift.

1975—Consultants completed a stability analysis of the Sweetwater main dam for the California-American Water Company in response to DSOD’s request. Their report concluded that for static conditions, the dam may be safely operated continuously at reservoir levels below El. 215 (SWD) and based on its previous performance it should be safe to allow it to be overtopped during brief periods to a depth of about 6.5 feet over its present height.

This report also included a preliminary estimate of the dam’s seismic stability during earthquakes. However, this estimate only covered pseudo-static loading in the downstream direction and did not evaluate the two appurtenant spillway structures. As to such seismic stability, the report states that when viewed as a whole, the Sweetwater Dam is a relatively low, thick arch and will consequently be understressed under most conditions. It was also concluded that since the likelihood of very intense shaking at this dam is small, it would probably be an acceptable risk to operate the dam at some reduced pool level, even during seismic shaking of moderate intensity. It was recommended that a more complete engineering evaluation of the risk associated with different earthquake probabilities is needed to define such an operating level.

1976—Consultants completed their probability study for flood and earthquake. Their report gives a probability of occurrence of 0.000072 for the maximum credible earthquake when the reservoir is above El. 215 (SWD). This was predicted on the assumption that any time the reservoir is above El. 215, water would be released from the reservoir at 300 cfs or more and that the maximum normal operating level for the lake is El. 200.

1977—Ownership of Sweetwater Dam[s] acquired [under eminent domain procedures started about 1969] by South Bay Irrigation District and leased to Sweetwater Authority for operation and maintenance.

The DSOD advised the Sweetwater Authority that the analytical results of the report were accepted as satisfactory. In consonance with the report, the owner was requested to consider future improvements to facilitate a reduction of hydrostatic pressures in the dam and its foundation [i.e., constructing an impervious membrane on the upstream
face and providing drainage for the structure and foundation and to perform necessary modifications and testing of outlet pipes to assure that a significant portion of the reservoir storage capacity at the existing 36-in [main outlet pipe], the 18-in and 14-in outlets with free discharge immediately downstream from the dam or its equivalent was to be provided.

1978—The owner reported that the 18-in outlet was successfully tested and discharged about 180 cfs.

1979—The owner reported that the two left abutment 30-in blowoff lines were successfully operated.

1980—On February 21, 1980, the owner reported a spillway flow of 6,900 cfs. All six spillway siphons were reported to have operated smoothly and for 4 or 5 days.

1981—In May 1981, the operation of three of the left abutment gate valves and blowoff lines was witnessed by the DSOD’s Field Engineer. Only the lower right 36-in blowoff valve was inoperable.

CONSTRUCTION

Foundation Preparation—There was no information available as to foundation preparation for the initial work in 1886 by F. E. Brown. However, in view of the longevity and performance of Brown’s very similar ultra-thin Bear Valley Masonry Dam constructed under his supervision in 1884, the foundation and abutment preparation here was probably similar and is at least adequate.

Bedrock was apparently very sound on the surface in the channel area and at depths up to 25 feet on the abutments. Even so, seams were treated by deeper excavation until they pinched out, followed by slush grouting over the seams [applied with brooms], before starting the masonry. Foundation and abutment preparation of the 1887-1888 work, by Schuyler, consisted of removing loose and seamy rock, thoroughly cleaning all crevices, generally hand scrubbing foundation bedrock and filling all crevices with cement grout.

The specifications, by Schuyler, for the 1910-1911 widening of the dam base called for the same detail in foundation preparation as was required in the 1887-1888 work. The specified intent for the foundation treatment of the 1910 extension was to remove “all surface soil, loose, unsound, or seamy rock.” Core drilling and water pressure testing indicate that the foundation excavation for the 1910 extension was probably deeper than for the original 1886 dam. Photos made in 1911 indicate excellent foundation preparation and removal of rock to a greater depth than in the adjacent older work. The results of the 1969 exploration program found that the degree of competence, rigidity and imperviousness was generally better under the 1911 construction work.

The foundation for the left and right abutment spillway additions in 1916 were well prepared down to bedrock by the 1916 flood that washed out and scoured both abutments. The foundation of the south spillway was grouted in 1945. Grout take under the spillway in the deeper holes which penetrated bedrock averaged 17 sacks per foot of hole. This probably did not all go into bedrock fractures, however. The state inspector stated that fill material in the upper end of the spillway foundation took large quantities of grout, and some surface leakage did occur in nearby bedrock. Some of the grout may have dissipated between the bedrock and the spillway structure.

Flows over the spillways and the dam have caused erosion of the foundation in the past. Steps have been taken to minimize any such damage due to flood flows in the future. Foundation conditions and treatment for the south dike are unknown. The dike has apparently performed well.

In view of the above and after reviewing the 1969 drill logs, it is concluded that the foundation under the entire existing main dam and its intersecting spillway segments were adequately cleaned down to bedrock prior to construction and generally are in intimate contact with the base of the dam. There is no impervious cutoff wall below this dam.

Materials and Methods—Schuyler, in his article “Reservoirs for Irrigation” (p. 674), describes the care taken during the original construction of the dam. The original construction of the dam was of the best class of uncoursed, rough rubble masonry, laid in rich mortar of Portland cement and sand, and founded on bedrock of porphyry, which was stripped and cleaned with the utmost care, while every stone that went into the work was thoroughly washed and scrubbed with hand brushes.

The original 1886-1888 masonry arch structure was fitted together by stone masons using metavolcanic rocks ranging up to more than 6,000 lbs. in maximum size. Voids were filled with mortar consisting of one part cement to three parts clean sand, except within 4 feet of the upstream face where one part cement to two parts clean sand was used.
The rock came from a quarry 800 feet below the face, had no well-defined cleavage, but usually had one or more tolerably good faces and it had a specific gravity of from 175 to 200 pcf. The average weight taken in calculation was 164 pcf of masonry. Portland cement of the best quality was used in the proportion of 1 cement to 3 of sharp clean river sand, and for the 4 feet next to the water a richer mixture of 1 to 2 was employed. A tramway ran along the face of the dam at the 60-ft level, supported on brackets suspended from bolts, and was used to the end of the work in the delivery of materials, with great economy over previous methods of delivery by hod-carriers.

The stone was hauled on wagons and on stoneboats made of 3-in planks with boiler iron bottoms [cost $30 each], and placed on these from simple shear-leg derricks. All the hoisting was done by horsepower, as fuel was scarce and costly, and earlier experience had proven that horsepower was the most economical and convenient. The work was finished April 7, 1888, having occupied 16 months in construction, including 2 months of delay on account of shortage of cement. There was no loss of human life and no serious accidents during the work.

PERFORMANCE

Incidents and Repairs—The painstaking care taken during construction resulted in a structure that has successfully withstood a test on the 17th and 18th of January 1895 far more severe than is usually imposed on reservoir walls of such comparatively slender dimensions and beyond any previous calculations or expectations. The storm produced, within 1 week, a runoff three times the capacity of the reservoir. At the same time, it demonstrated the ability of the dam to cope with such an emergency and not a stone of the masonry was disturbed or moved from place. Overtopping of the dam resulted in loosening some 10,000 cubic yards of solid rock. In addition, all the debris from earlier construction up to 20 feet in depth was removed by the sheer of water falling some 90 feet. Energy was first expended in excavating a deep hole in the loose debris and then making a water cushion so that excavation never reached the solid bedrock of the foundation.

The repair work in 1895 was carried out with concrete because of the greater ease with which all the materials could be handled and the work performed by unskilled labor. The concrete was mixed by machinery, and one engine performed all the work of crushing the stone, revolving the mixer, and hoisting the concrete to the top of the dam where it was distributed by wheelbarrows. Iron, in the form of old rails and scrap bars of all sizes, was embedded in the concrete wherever it would add to the strength.

In view of the relative ease with which the flood of 1895 had stripped off the abutment rock “leaf after leaf,” the designer [Mr. Schuyler] for this addition shifted to a gravity structure with the arch action considered to be an extra safety factor. Sheets of corrugated steel and a 2-in layer of sand were placed between the old downstream masonry dam face and the new concrete to prevent bonding, “so as to avoid the development of internal stresses which would arise during the settlement of the new work from adhesion of the two walls together.” To avoid pressure buildup between two walls, seepage that flowed through the old masonry face and down the corrugated sheets was collected by drain pipes that lead from the upstream face of the sheets to the drainage gallery or to the downstream face of the dam. The mass concrete addition was heavily reinforced with steel rails primarily in the central section of the upstream face with corresponding stirrup reinforcement (to simulate a large beam fixed at its base). A heavy mat of inclined and horizontal steel was placed on the base of the central section of the mass concrete addition to better distribute the pressures. The new parapet was built primarily on the old masonry arch dam. The parapet was a modular reinforced concrete type structure and was connected to the old masonry by a set of two 1¼-in twisted steel bars that act in conjunction with up to four parallel rails tied into the new downstream concrete gravity section.

The 1910–1911 concrete mixture used in the cyclopean gravity section and in other work in 1911 was 1 part cement, 3 parts sand, and 5 parts aggregate by volume. Five to ten percent by weight of the cement was replaced with pure hydrated lime. Water was added, as necessary, to make the mixture “semifluid” to flow into the forms without tamping. The aggregate used in the concrete consisted of crushed metavolcanic rock up to 2.5 inches in maximum size. Specifications called for immersing the larger rocks in the concrete, however, photos taken at the time show chuting concrete onto in-place rock. [This could explain some of the porous concrete areas in 1969 exploration holes.] The larger rock in this gravity section comprises about 22 percent of its volume. The exterior faces of all the 1911 concrete work was coated with at least two coats of mortar.
Inspections—A detailed report on the condition of the Sweetwater Dam was prepared based on a detailed visual inspection of the main gravity-arch and South Dike dams, a review of the DSOD files for Sweetwater main dam and additional items. The Railroad Commission exercised jurisdiction over safety of Sweetwater Dams starting in 1916 and until 1929. After 1929, the supervision of the safety of Sweetwater Dams came under jurisdiction of the State Division of Water Resources [now Department of Water Resources].

Operating Procedures—The normal operating procedure is to store winter runoff and releases from Lake Loveland for subsequent release as necessary to keep the Sweetwater Water Treatment Plant supplied. There are no specific provisions for flood control operation of the dam.

The previous owner reported that it would require about 35 days to evacuate the full reservoir (27,500 ac-ft) utilizing the four left abutment blow-off pipes and the center 18-in diameter blowoff pipe.

The current DSOD Certificate of Approval authorized the impoundment of water to EL 235.0 (SWD).

Hazard Potential—The Sweetwater main gravity-arch dam is located in a canyon on Sweetwater River less than 2 miles upstream from the residential communities of Sunnyside and Bonita and less than 6 miles from the heavily developed city of Chula Vista. The estimated evacuation in case of threatened failure greatly exceeds 1,000 and the potential economic loss due to its failure would greatly exceed $15 million. The hazard potential is high.

Emergency Procedures—There is no downstream automatic warning device. Inundation maps are on file with the State and County Offices of Emergency Services. The operating agency [Sweetwater Authority] has a set of detailed emergency procedures to be implemented jointly with the San Diego County Office of Emergency Services covering the notification and evacuation of persons downstream in the event of a threatened failure of Lake Loveland and/or Sweetwater Dam.

ACKNOWLEDGEMENTS

The project is owned and operated by the South Bay Irrigation District.

This summary description was prepared by J. A. Veltrop of Harza Engineering Company, based on materials supplied by the owner and the references listed below.

BIBLIOGRAPHY


