broken stone, and by the addition of heavy berms or counterforts of earth, for 700 or 800 feet of its length, to weight the toe.

Similar slips occurred in the Ekruk dam, due to similar causes. These occurrences point to the value of thorough drainage to the outer toe of all earthen dams, and the desirability of the adoption of that form of combination of rock-fill and earth used so successfully in the Pecos dams, wherever rock can be obtained for the outer portion of such embankments.

Vallejo Dam, California.—Wherever earthen dams are constructed partially upon exposed bed-rock foundations, it is essential to provide free drainage to the water which seeks to follow along the bed-rock. An interesting application of this principle was made in the construction of a dam erected a few years since for the water-supply of Vallejo, California. The dam was built for storage purposes and formed a reservoir of 160 acres, 3 miles from the city. The bed-rock was exposed in the channel, and formed a low fall about the center line of the dam. Just above this fall a concrete wall was built upon the bed-rock some 6 feet high, with a drainage-pipe extending out to the lower toe of the embankment. A quantity of broken stone was placed above this wall, which formed a collecting-basin for any seepage that might pass through the embankment or that might creep along bed-rock, and the dam was then built over the wall in the ordinary way. This provision effectually prevents the saturation of the outer slope and keeps the dam well drained. The dam was planned and built by Hubert Vischer, C.E., with Mr. C. E. Grunsky acting as Consulting Engineer.

Earthen dams are usually constructed in one of the following ways:

(1) A homogeneous embankment of earth, in which all of the material is alike throughout;

(2) An embankment in which there is a central core of puddle consisting either of specially selected natural materials found on the site, or of a concrete of clay, sand, and gravel, mixed together in a pug-mill and rammed or rolled into position;

(3) An embankment in which the central core is a wall of masonry or concrete;

(4) An embankment having puddle or selected material placed upon its water-face;

(5) An embankment of earth resting against an embankment of loose rock;

(6) An embankment of earth, sand, and gravel, sluiced into position by flowing water—a form of construction described in the chapter on Hydraulic-fill Dams. Earthen dams have also been built with a facing of plank, made water-tight by preparations of asphaltum or tar. The choice of these various available plans is dependent upon local conditions at the site of the dam to be built, the materials available, and the predilection or education of the engineer planning the structure.

European engineers, judging from their works, lean toward the central puddle-core, and the greater number of the earth dams of the British Empire are constructed on this plan. American engineers appear to prefer the masonry core-wall, or the puddle facing on the inner slope of the embankment to the central puddle-core, as a means of cutting off percolation through the dam and thus securing water-tightness.

The natural slope of dry earth placed in embankment is about $1\frac{1}{2}$ to 1, but in practice it is customary to increase this to 2 to 1 on the exterior, and to 3 to 1 on the interior slopes. The necessary height of the embankment above the high-water mark depends to some extent upon the length and size of the reservoir, and the "reach" of the waves generated by winds, as well as upon the width of the spillway and the height to which water must rise in the reservoir during maximum floods to find full discharge through the spillway. Ample spillway capacity is of primary importance to the security of any earthen dam, unless it be one whose reservoir is filled by a canal or other controllable conduit from an adjacent stream. A lack of sufficient spillway is the cause of the greater number of the failures of earthen dams that have occurred, of which the most memorable case was that of the Johnstown dam, whose rupture caused the loss of two thousand lives and the destruction of many millions of dollars' worth of property. Had the spillway been of ample dimensions, this dam would have resisted any pressure that could have been brought to bear upon it and the disaster would, in all probability, never have occurred.

A common source of failure is in the doubtful practice of building the outlet-pipes through the body of the dam. These should either be laid in a tunnel at one side, or in a deep trench cut into the bed-rock or the solid impervious base of the dam, and the pipes surrounded by concrete, filling the entire trench.

In building earth dams of any type it is essential that the earth should be moist in order to pack solidly, and if not naturally moist it must be sprinkled slightly until it acquires the proper consistency. An excess of moisture is detrimental. It should be placed in thin layers, and thoroughly rolled or tamped, and the surface of each layer should be roughened by harrowing or plowing before the next layer is applied. Droves of cattle, sheep, or goats are often used with success as tamping-machines for earth embankments. They are led or driven across the fresh made ground, and the innumerable blows of their sharp hoofs pack the soil very thoroughly.

The Cuyamaca Dam.—One of the first earthen dams built in California for irrigation storage was the Cuyamaca reservoir-dam, erected in 1886 by the San Diego Flume Company. It is located in a summit valley between two of the Cuyamaca peaks, some 50 miles east of San Diego, at an elevation of 4800 feet. The dam is 635 feet long on top, 41.5 feet high, with inner slope of 2 : 1, and outer slope of 1.5 : 1. The crest of the dam is 6.5 feet above the floor of the spillways, one of which is 90 feet and the other 41 feet in width.

Before work was begun on the dam the site was covered with loose rock, and it was supposed that bed-rock was near the surface. Hence the original plan was to build a masonry dam. Excavations were started for that purpose, and considerable cement was brought to the ground to construct the foundations of masonry. It was soon found, however, that the loose rock was merely a surface layer on top of a bed of clay, and the plan was changed to a dam of earth throughout.

The discharge-sluice of the dam was built through the center of the structure, and consisted of a masonry culvert 3½ feet wide, 4½ feet high, 120 feet long, resting on a bed of concrete 18 inches thick, laid in a trench of that depth cut in the clay. This culvert has a fall of 3½ feet in length. At its upper end is a circular brick tower, 5 feet in diameter inside, with an opening at the bottom 3 feet wide, 4½ feet high, that is closed by a ponderous wooden gate, so large and heavy as to be almost immovable. A second gate, 16 feet higher, of similar size and construction, is provided to close another opening into the tower. These

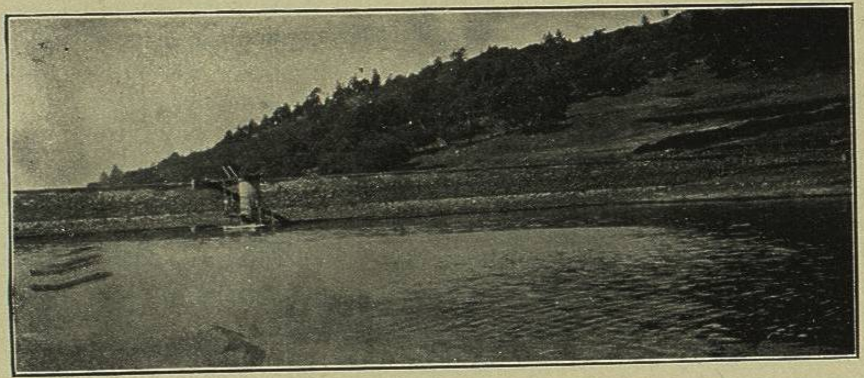

FIG. 285.—VIEW OF CUYAMACA DAM AND OUTLET-TOWER.

gates slide vertically in wooden grooves. An iron gate inside the tower closes the head of the culvert.

The bond between the earthwork and the culvert was imperfect, and considerable leakage ensued after the reservoir first filled, but this was afterwards remedied.

Fig. 285 is a view of the dam from the side of the reservoir, showing the tower.

The dam is reported to have cost $51,000 as originally constructed to the height of 35 feet. In 1894 an addition of 6.5 feet was made to the height of the dam, at a cost of $3400. This addition increased the capacity

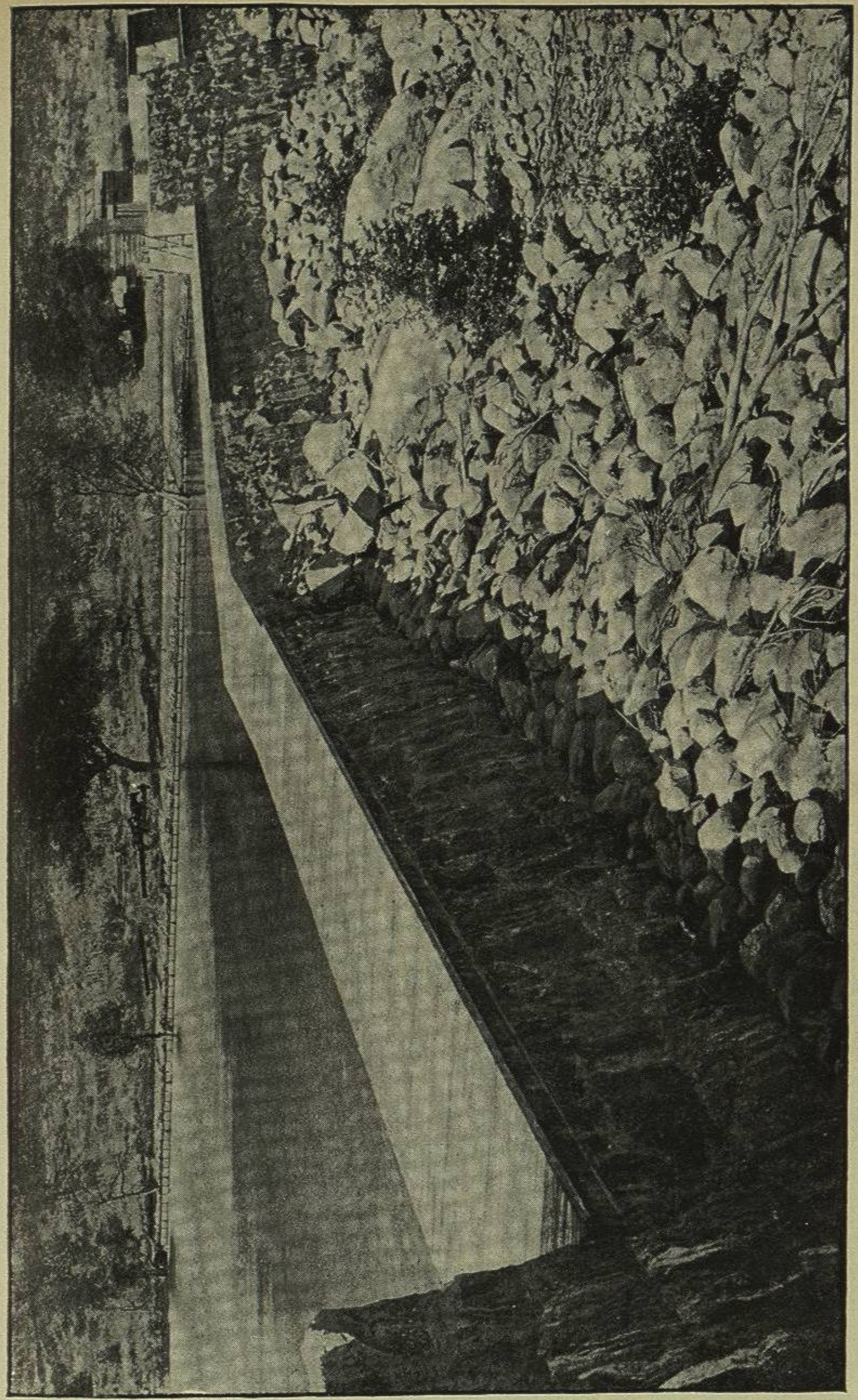

FIG. 286.—MASONRY DIVERTING-DAM OF THE SAN DIEGO FLUME CO., CALIFORNIA.

of the reservoir to 11,410 acre-feet, covering an area of 959 acres to a mean depth of nearly 12 feet. The watershed tributary to the reservoir is about 11 square miles. The following table, prepared by Mr. F. S. Hyde, C.E., from the records of the company in 1896, gives the volume of catchment and use during the first nine years after the completion of the dam:

TABLE OF RAINFALL, RUN-OFF, EVAPORATION AND AVERAGE DRAFT FROM THE CUYAMACA RESERVOIR, SAN DIEGO COUNTY, CALIFORNIA.

Calendar Year.	Rain and Melted Snow. Inches.	Run-off in Acre-feet.	Percentage of Run-off to Precipitation. Per cent.	Run-off per Square Mile. Second-feet.	Evaporation.			Average Draft from Reservoir for Irrigation and City Supply. Acre-feet.
					Total. Ft.	In.	Average per Day. Inches.	
1888	24.05	3,076	21.75	0.385	3	9.50	0.316	
1889	52.83	5,568	17.91	0.697	4	5.00	0.250	2,853
1890	62.91	6,214	16.79	0.768	3	9.25	0.208	2,881
1891	64.96	7,735	20.24	0.969	3	8.75	0.203	3,084
1892	42.56	5,163	20.62	0.647	3	6.75	0.241	4,821
1893	41.51	4,098	16.78	0.512	5	3.25	0.303	5,965
1894	24.90	2,035	13.89	0.255	7	1.00	0.341	2,939
1895	58.52	11,464	33.31	1.436	5	3.75	0.317	6,237
1896	26.44	1,158	7.45	0.145	5	7.50	0.284	5,777
Means ..	44.29	5,397	19.83	0.676	4	8.75	....	4,331

Subsequent years of drouth have resulted in emptying the reservoir entirely. The rainy seasons of 1897–98, 1898–99, and 1899–1900 have furnished practically no water for storage.

Referring to the above table of rainfall and run-off, it should be explained that as the rain-gauge on which the precipitation was recorded is located at the dam between two high, wooded peaks, which act as condensers of the moisture-laden clouds, the record shows a greater amount than the average of the watershed, which a few miles east of the dam borders on the desert, where the rainfall is known to be much less. This is borne out by comparing the measured run-off with the "Newell Curve" of run-off, which would indicate that if the recorded precipitation were a mean of the entire area, the yield should be two to three times as great as it actually was. This Cuyamaca rainfall record is misleading as a criterion of mountain precipitation in this region. The water actually flowing in different seasons from a known area, as shown by the table, is more reliable as a guide for estimates of the yield to be expected from adjacent sheds than any single rainfall record, or any possible collection of rainfall statistics without such empirical knowledge of actual yield in stream-flow produced by any given rainfall.

During the period covered by the table the mean annual draft from the

reservoir was 4331 acre-feet, while the mean annual run-off was 5397 acre-feet. The difference between these figures, or 1066 acre-feet, represents the mean annual evaporation, or 19.75 per cent of total catchment.

After flowing down Bowlder Creek and the San Diego River 12½ miles, dropping 4000 feet vertically in that distance, the water released at the dam is picked up and diverted to the flume by means of a masonry weir extending across the San Diego River. This diverting-dam is 340 feet long on top, 35 feet high, 22 feet thick at base, 5 feet at the crest. To cut off leakage under the dam a subwall was built on the up-stream side in the main channel, lapping onto the base of the dam and extending down 15 feet deeper. This wall is 5 feet thick at bottom. The original wall had been founded on disintegrated granite. The subwall was built in a trench that cut deeper into the soft granite, but was not entirely effectual in stopping the leakage. (Figs. 286 and 287.)

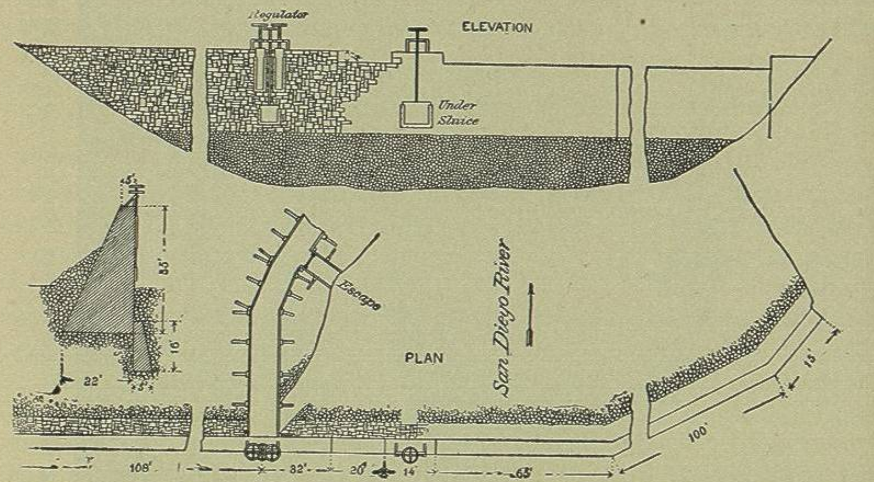

FIG. 287.—PLAN AND ELEVATION OF DIVERTING-DAM OF SAN DIEGO FLUME CO., CALIFORNIA.

The main flume is 34.85 miles in length, 6 feet wide in the clear, with single sideboards 16 inches high, though the frame-posts are 4 feet high and will admit of additional sideboards to give a total depth of 4 feet. If completed as originally designed, the flume would have a capacity of 5000 miner's inches under 4-inch pressure. Its present maximum capacity is not over 900 inches. The flume is supported at places on high trestles, one of which is shown in Fig. 288, and there are a number of long and costly tunnels on the route. The grade of the flume is 4.75 feet per mile. It commands all the irrigable lands of El Cajon Valley, Spring Valley, and the San Diego mesa, and supplies water to about 5700 acres, mostly cultivated in orchards of citrus fruits. The city of San Diego has also received

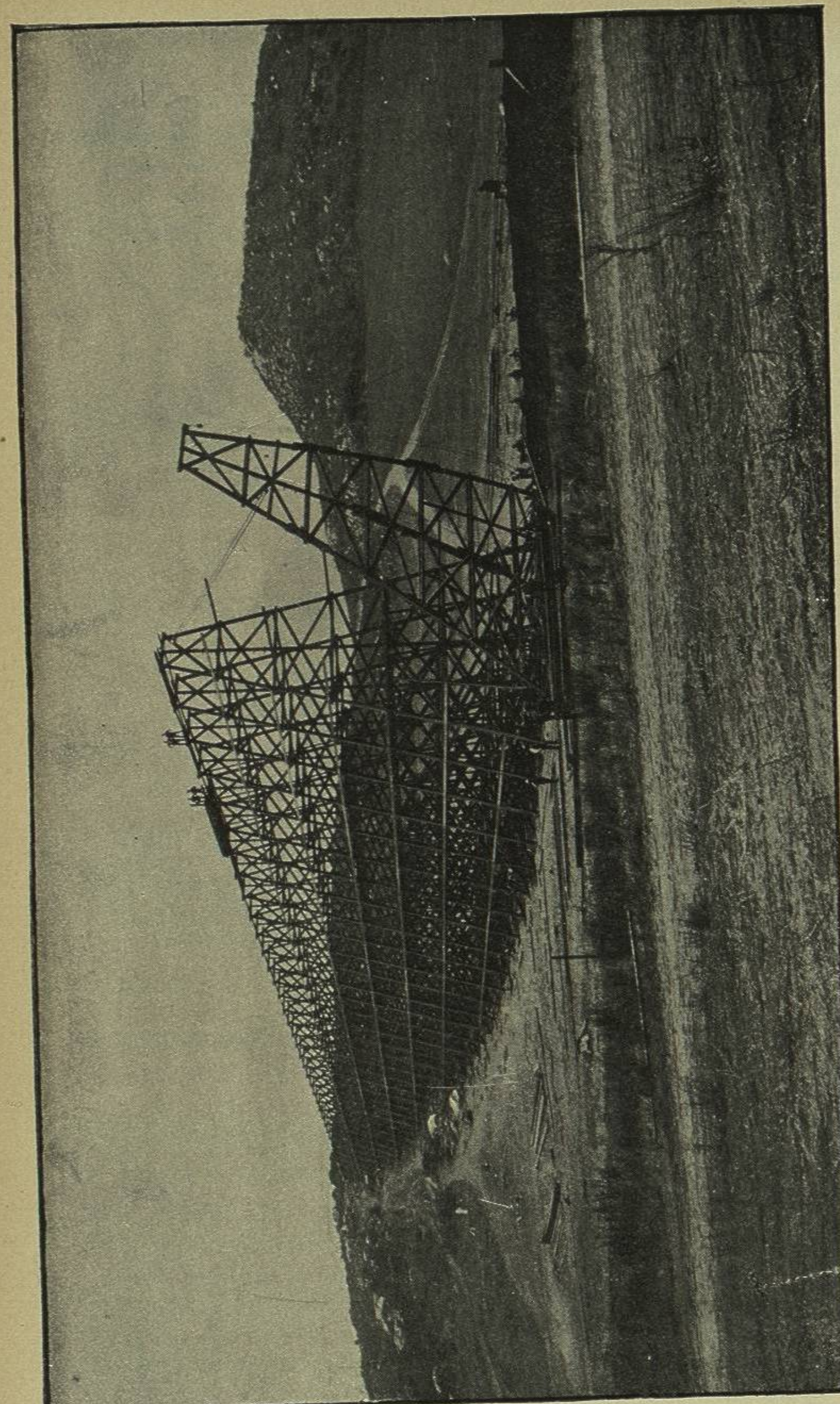

Fig. 288.—Sample of High-trestle Construction on San Diego Flume, California.

its domestic supply from this source during the greater portion of the time since its completion, through a 15-inch steel-pipe line laid over the mesa, from the end of the flume to the city, about 10 miles.

In the summer of 1897–98 the reservoir was quickly exhausted, and it became necessary to install an independent system of supply for the orchards and the city of San Diego. For the orchard supply this was accomplished by sinking a series of bored wells in the gravel bed of the San Diego River, above El Cajon Valley, where the flume leaves the immediate valley of the river. Pumping-stations were erected, and the wells, which were placed at intervals of 50 feet along a horizontal suction-pipe 1000 to 1300 feet in length, were drawn upon in series simultaneously, the water being forced up to the flume with a lift of 300 feet. About 3 second-feet (150 inches) were thus obtained, and though the supply was meager it was sufficient to maintain the life of the trees and keep them in bearing with good cultivation. The city was supplied in a similar manner by wells sunk in the river-bed in Mission Valley, from 2 to 4 miles above the main pumping-plant. The water was lifted to the surface at several points and conveyed to the pump-station by small flumes. Over 3,000,000 gallons daily were thus obtained. These plants have had to be maintained and increased in capacity. The inhabitants of southern California have reason to congratulate themselves that Nature has provided underground storage-reservoirs capable of being drawn upon so liberally that they are able to endure such an unprecedented period of drouth as they are now experiencing. To obtain the supply, however, by wells and pumps is generally far more costly than water stored in surface reservoirs.

The Merced Reservoir Dam, California.—The highest and longest earthen dam closing a reservoir chiefly devoted to irrigation in California is that which forms the so-called "Yosemite Reservoir," 6 miles north-east of the town of Merced. This dam was constructed in 1883–84 by the Crocker-Hoffman Land Company as a part of its general system of irrigation, by which some 150,000 acres are commanded for irrigation. It has a maximum height of 50 feet, and is built entirely of earth composed of a sandy clay with inner slopes of 3 : 1 and outer slopes of 2 : 1. From the top down for 15 feet the interior is paved with loose rock, 12 inches thick, for wave-protection. The entire length of the dam is 2200 feet, of which 1400 feet is less than 10 feet high. It was built up as a homogeneous bank of earth, without a puddle-wall, or without adding to the natural moisture of the soil. The earth was simply put in place with scraper-teams, the material being deposited with care in thin layers. The top width is 20 feet, base 290 feet. The dam rests on a very firm foundation of cemented gravel, into which a wide, deep puddle-trench was cut and carefully re-

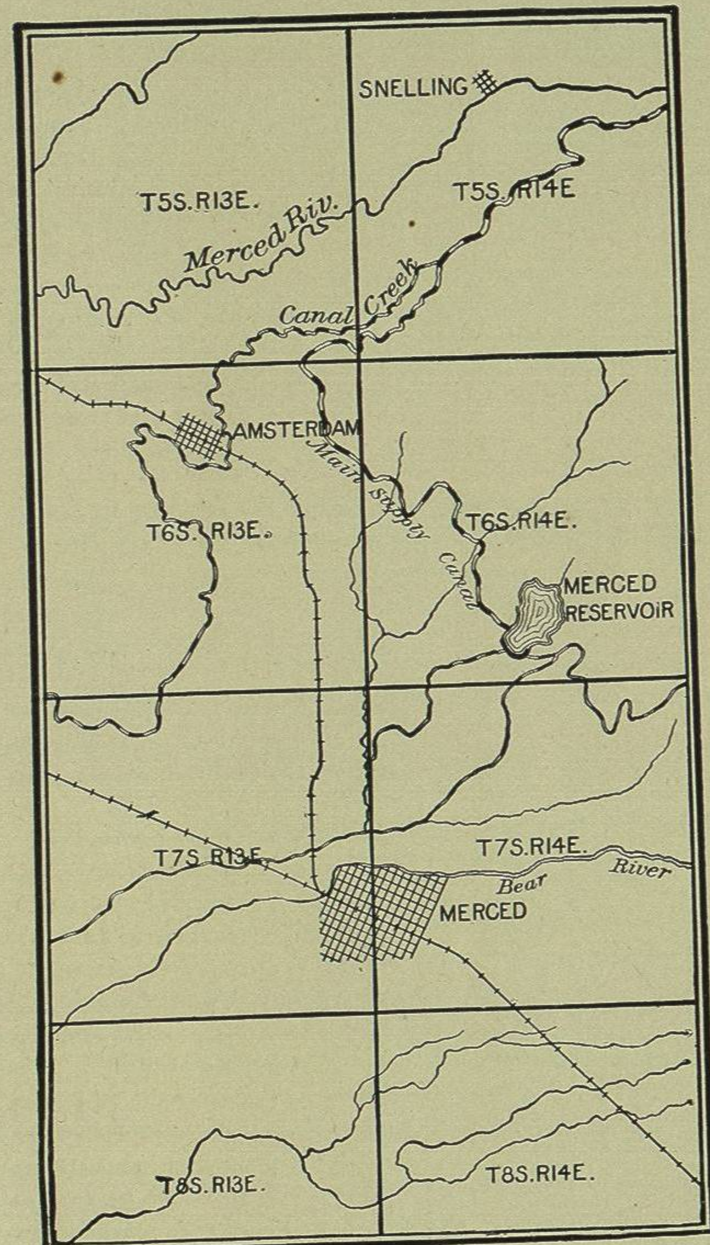

Fig. 289.—Map showing Location of Merced Reservoir, California.

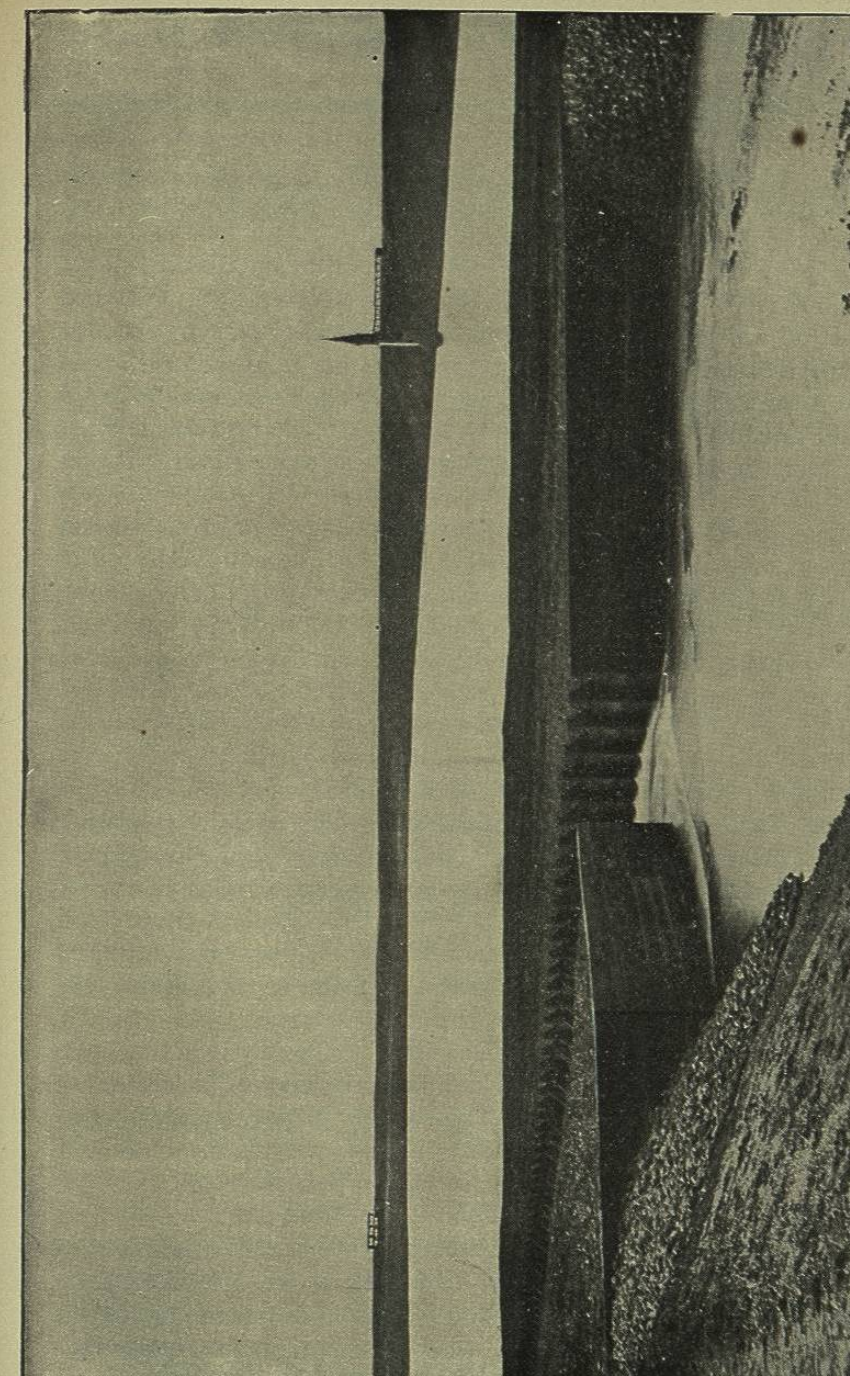

Fig. 290.—View of Yosemite Reservoir, Merced, Cal., showing Feeder-canal and Outlet-tower.

filled. Much of the material used in the dam had to be loosened by blasting.

The reservoir-outlet consists of a masonry conduit, made of brick laid in cement mortar, placed in a trench cut in the cemented gravel. This conduit carries the main, cast-iron, delivery-pipe, 24 inches in diameter, and a blow-off sluice-pipe. The conduit is 4 feet in diameter in the clear, the brickwork being 12 inches in thickness.

The reservoir, dam, and outlet-tower are shown in Fig. 290.

The reservoir covers 600 acres and has a capacity when full of 15,000 acre-feet, of which about 20% is annually lost by evaporation. It is fed by a canal 27 miles in length, leading from a diversion-weir placed in the Merced River a short distance above the town of Snelling. For the first 8 miles the canal has a maximum capacity of 1500 second-feet, which is the largest canal in California. The total cost of the canal system, with its laterals, and the reservoir was about $1,500,000.

The watershed area of the Merced River above the head of the canal is 1076 square miles, in which is included the famous Yosemite Valley. The mean annual flow of this stream as determined by the California State Engineering Department for the six years from 1878 to 1884 was about 1600 second-feet, the maximum being 6510 second-feet in the month of June, and the minimum 65 second-feet in the months of November and December. During the three months of May, June, and July, when the greatest amount of irrigation is required, the mean discharge of the river in the period named was about 4000 second-feet.

Buena Vista Lake Reservoir, California.—The large storage-tank formed of Buena Vista Lake, in the southern end of the San Joaquin Valley, is the largest irrigation-reservoir in the State, covering an area of 25,000 acres to a mean depth of nearly 7 feet. The volume of water which it is capable of impounding above the level of the outlet-canal is 170,000 acre-feet, and in its general characteristics it more nearly resembles the great tanks of India than any reservoir in this country.

The reservoir is formed by a straight dike, or dam, 5.5 miles in length, following a township line from the foot-hills at the base of the mountains, due north. The maximum height of the dam is 15 feet, tapering out to nothing at either end. Its top width is 12 feet, and the slopes are 4 : 1 inside, 3 : 1 outside, the crest being 4 feet higher than the high-water level of the reservoir when full. The erosion of this bank due to wave-action rendered it necessary to riprap the face with stone over a long section from the south end northward, where there were no tules growing to serve as a breakwater to lessen the effect of wave-action, as was the case at the north end. To procure the material for this riprap a narrow-gauge railroad was built for some ten miles from a quarry at the base of the mountains. The cost of this work was more expensive than the construction of the embankment and brought the entire cost of the dam and outlets up to about $150,000. The dam divides the reservoir from what was formerly known as Kern Lake, before its bed was drained and cultivated.

The reservoir now receives all the surplus water of Kern River and the waste at the tail end of all of the Kern Island canals below Bakersfield. The water thus stored is only available for use on a belt of arable land that was formerly a swamp, extending from Buena Vista Lake to Tulare Lake. This land before reclamation was periodically overflowed when the water of the river was not so extensively absorbed in irrigation in the delta and upon the adjacent plains as it has been in recent years. Since its reclamation it requires to be irrigated, and the reservoired water is devoted to that purpose.

The reservoir was first filled in 1890, and has been in service ever since. Its creation was the result of the compromise of the most extensive and costly litigation over water-rights that has ever arisen in California. The title of the action was that of Lux *vs.* Haggin. It will go down in history as the case in which the Supreme Court of California, by a majority of one, first established the English common-law doctrine of riparian rights as applicable to the streams of the State. It is believed that this doctrine, though greatly modified by subsequent decisions, has been a serious draw-back to irrigation development in California.

The surface of the reservoir is so large as compared with the volume stored that the annual loss by evaporation is estimated at 120,000 acre-feet, or 70% of the total capacity. This is an enormous waste of water, which might be saved to a considerable extent by the construction of storage-reservoirs in the mountains, where the ratio between surface area and volume would be very much less, and the rate of evaporation smaller. The reservoir is generally filled from about May 1st to July 20th, during the melting of the snows, after which time to September 1st the inflow is about sufficient, ordinarily, to offset evaporation. Thus during the five hottest months, when nearly 70% of the total evaporation of the year takes place, the loss is supplied by the river, and by the return waters of irrigation. Therefore, in those seasons when the run-off is sufficient to supply the demand of the canals and yield a surplus great enough to fill the reservoir by September 1st, in addition to evaporation, the net amount available for use from the reservoir would approximate 125,000 to 135,000 acre-feet. Measurements of the river taken daily from 1879 to 1884, and from 1894 to 1897,—ten years in all,—show a minimum yearly discharge of 364,000 acre-feet, a maximum of 1,760,000 acre-feet, and a mean of 789,000 acre-feet of water discharging into the valley at the mouth of the canyon.

The Pilarcitos and San Andrés Dams, California.—The water-supply of San Francisco is largely derived from the storage of storm-waters on