required if the water has to be supplied by pumping, but preferably a gravity supply of 10 to 30 second-feet, giving greater carrying power and greatly increasing the output of material with the same force of attendants.

(*b*) Shorter top length of dam, permitting the use of steeper gradients in the sluice boxes and delivery-pipes, and consequently giving higher velocities and ability to move rock of considerable size for stability of slopes. In this case much rock was necessarily left in the pit where it was in the way and was a source of diminished efficiency, although greatly needed on the dam, because of lack of transporting power.

(*c*) Delivery from both ends of a dam simultaneously, instead of from one side alone, which would permit of increased gradients and more effective delivery of coarse material throughout the entire length of the slopes.

(*d*) A larger proportion of sand, gravel, or broken stone of less than 10 or 12 inches diameter, rendering the slopes stable without the use of brush, and avoiding the building of dry levees with teams.

Settlement.—The dam was constantly undergoing settlement as the water was being pressed out of it. This was observed by the distortion of the flumes and pipe trestles, and the slope boards on the slopes. The greatest amount of settlement measured on the posts of the last trestle used on the north face was 3.43 feet, or about 9% of the height. The original dam settled 2.5 feet vertically, notwithstanding the fact that it had been exposed to the rains of two previous winters, and was presumably solid.

Comparison of the volume of the dam with that taken from the borrow-pit (covering 7.12 acres, excavated to a mean depth of 21.5 feet) indicated that the former was but 84.6% of the latter, and estimating the silt carried off by the tail-water at 4.4%, the shrinkage of the soil from its natural condition in the bank to its compacted state in the dam was about 11%, a practical illustration of the solidifying action of water in building dams by this process. In fact, from the compact condition of hydraulic-fills generally, it appears certain that it is not possible to secure such density of earth by any other process, even at many times the cost.

Stratification.—The same means were used in this work to prevent or break up stratification across the center as were employed on the Crane Valley dam. The work of thrusting down paddles or planks was continuously kept up, the men working from boats or rafts floating in the pond of mud on top of the dam. Where any tendency was discovered for the formation of local stratification of sand streaks across or near to the center it was corrected by a change in the position of the dump and the grade from the sides toward the center.

Spillway.—The service outlet of the Lake Frances dam is a 30-inch cast-iron pipe, laid through the embankment and surrounded with masonry. Alongside of this pipe a masonry culvert was built for drawing off surplus water at will before the reservoir is filled to the spillway level. The spillway proper is 80 feet long, and is formed by a slab of concrete, 8 inches thick, reinforced with continuous sheets of expanded metal. Owing to the absence of rock this concrete slab, of Ogee form, was laid on the natural earth and discharges into a paved basin, from which a ditch leads to an isolated rock cliff, 500 feet away.

After the completion of the dam, during the winter of 1904–5, the lake was filled to overflowing, with the 5-foot culvert discharging its full capacity, and water ran 22 inches deep over the spillway. Evidently, the original spillway, 40 feet wide without an auxiliary discharge culvert, would have been totally inadequate, so that the first dam was doomed to ultimate destruction even had it not been breached as it was.

Hydraulic-filling of the Milner Dams on Snake River, Idaho.—In the foregoing chapter on rock-fill dams, a description was given of three combination rock-fill dams built on Snake River, Idaho, in 1904–5. The hydraulic filling was of a character quite distinct from that employed in the pure types of hydraulic-fill dams hitherto treated of in this chapter, and is deserving of further notice. The earth available for this work was of one class only, and consisted of fine white or grayish soil which covers the plains of that region to a depth varying from one to twenty feet or more. It is exceedingly fine in texture, an almost impalpable powder, free from grit and wonderfully uniform in quality. A test made by the writer showed that it was like finely-ground cement, as nearly 90% would pass through a sieve of 10,000 meshes per square inch. It is classed as *loess* or wind-borne soil, and is doubtless a fine volcanic ash. It absorbs water slowly in bulk, like flour, but when once wet packs very solidly and becomes as stable, as impervious, and as dense as clay, with this advantage that it does not shrink and crack in drying. Using this material as a backing for the rock-fill, it was very evident that the voids in the rock-fill above the wooden-core wall, described in the previous chapter, could only be filled by sluicing the earth in place with water. It was also considered that desired water-tightness of the mass could best be obtained by a thorough saturation during construction. The earth had to be obtained at a distance of 2000 to 8000 feet from the dam. A portion of it nearest to the dam was scraped into a box at the borrow-pit, by slip and wheel scrapers and dump wagons, and, water being pumped from the river to the box, the earth was thus sluiced through a flume to the point of discharge at the dam. The volume of water discharged by single

4-inch centrifugal pumps was about 1.5 second-feet. The flumes were about 12 inches square, open at top. No determinations were made of the percentage of solids carried in this way, but the water seemed to be well loaded at all times, and flowed freely on grades of 2% to 5%.

In building the two dams in the high-water channels there was no difficulty in maintaining a levee of dry earth at the outer toe of the slope with teams, the earth being hauled in by wagons and scrapers. All of the earth for the south dam and a large part of that for the middle dam, except for the base, was hauled by cars and electric locomotives from borrow-pits a mile or more away, on the south side of the river. It was loaded into the cars either by teams through traps, or by an electric shovel, and dumped at the nearest end of the dam at such an elevation that the water would carry it on a grade to the further end. The grade naturally assumed by the earth thus sluiced was from 2% to 4%. The liquid mud freely entered the voids of the rock-fill, and filled them solidly as far as the center core-wall of wood. As it rose in height some slight leakage would show below for a time, but the joints in the wood quickly swelled and filled with mud and became entirely tight. The earth was always twenty feet or more below the top of the rock-fill, and the work progressed at such a moderate rate that the embankments had ample time to settle and solidify. The earth packed so readily that in four days' time after sluicing was suspended a team could be driven over the embankment without sinking in, although while sluicing was in progress a pole could be pushed down into the mud to a depth of 10 feet or more, particularly at the extreme end where the water stood longest in the pool.

Very little surface drainage was required to get rid of the surplus water. It seemed to be absorbed and disappear, without showing up either above or below the dam. The earth came to the dam in a pulverized, dusty condition, and the water was sprayed upon it and at once saturated it to the softest of mud. About 80% of the earth in the south and middle dams was sluiced in place, and 20% put in by teams at the outer slope. This dry portion constantly absorbed moisture from the adjacent mass of mud, and thus became equally hard and solid.

The hydraulic-filling of the north or channel dam was principally delivered from the north side of the river through a flume into the upper end of which a receiving-box was placed, into which the earth was dumped from wagons through a trap where the pumped water sluiced it down to the dam.

The earth was loaded into the wagon by means of a travelling excavator with belt conveyors that delivered a continuous stream of earth to the wagons travelling by its side until each received its load.

In this case the water used was about 1 second-foot and the lower end of the flume discharged along the upper side of the wooden core-wall, on top of the rock-fill, first filling the voids in the rock and then extending up-stream into deep water 20 to 30 feet in depth. On reaching the water it assumed a very flat slope under the water-line of 6 or 7 to 1. When the fill had reached the top of the water by this process the slopes were drawn in to the regular 4 on 1 slope.

The contract prices for this work were as follows:

Dry earth embankment—..........	27.5 cents per cu. yd.
Earth embankment placed by sluicing	37.5 " " "

These prices were necessarily high on account of the remoteness of the locality, the high cost of fuel, labor, supplies, and materials.

Waialua Dam, Hawaii.—Beginning about the year 1889, extensive development in the growth of sugar-cane was made upon the island of Oahu by means of irrigation with water from artesian wells located near the seashore, the water being forced by powerful pumps to varying levels up to 650 feet above the sea-level. Costly pumping stations were installed and provision made for the delivery of very large volumes of water. The fertility of the soil is such that an expenditure of $50 to $75 per acre per annum for pumping water was amply justified by the yield of cane to be secured by that means. One of the latest and largest of the pumping systems installed on the island is on the Waialua Sugar Plantation, 22 miles from Honolulu, stretching for several miles along the north shore, and extending back to an elevation of 700 to 800 feet. The aggregate capacity of the pumps in the four great pumping-stations on this plantation is 72,000,000 gallons per 24 hours, their average lift being from 231 to 540 feet, with an extreme lift of 650 feet. The cost of pumping runs into high figures. The fuel bill for irrigation pumping alone in 1902, before the introduction of California oil, was over $180,000, and the average cost of water was $63.36 per acre for that year. To reduce this cost of lifting water to the higher levels, as well as to increase the water-supply and extend the irrigable area, the plantation manager decided in 1903 to undertake the storage of flood water by the building of a dam on an intermittent stream, called the Kaukonahua Gulch, which flows through the property, and in May of that year the author was engaged to report on the construction of the dam, which had been projected by the Wahiawa Water Co. This company had been organized by Mr. L. G. Kellogg some years before to supply water to the Wahiawa Colony lands, located on a high plateau between the two forks of the Kaukonahua Gulch, where a colony of Americans were engaged in growing pineapples. The company built a ditch to the Colony, and subsequently surveyed the reservoir-site and contracted with the Waialua

Sugar Plantation to take stock in the Water Company to supply funds for building the dam, and purchase the reservoir water at an agreed rate.

The Kaukonahua heads in the Koolau Mountains at an elevation of 2360 feet, where the annual rainfall is about 180 inches, well distributed through the year. The watershed is of limited area, but the run-off is at times very great, fluctuating spasmodically between wide extremes, so that storage is needed to utilize the stream to any advantage. From the limited data available it was estimated that the total annual run-off was about 50,000 acre-feet, so distributed through the year that the reservoir, which has a capacity of but 7800 acre-feet (2,500,000,000 gallons) could be filled and emptied several times each year, and therefore be as serviceable as a much larger reservoir filled less frequently, inasmuch as the irrigation season is practically continuous. The reservoir occupies two forks of the stream which join immediately above the dam, water backing up in each from 4 to 6 miles. They are generally parallel, and are practically two miniature canyons cut down through a sloping plain to a depth of 150 to 200 feet. The formation thus exposed in section is all of volcanic origin and consists of decomposed lava, in alternating layers and of all shades of color from red to reddish brown and purple to bright yellow. This formation is generally quite free from any tendency to slide, and will often stand vertically in trenches or tunnels without timbering for an indefinite time. It is so free from grit that it resists the erosive action of water in a remarkable manner. It was apparently not sufficiently stable to afford a reliable foundation for the masonry dam that had been originally considered, and after examining the site the author recommended the adoption of a combination rock-fill and hydraulic-fill, with a wooden diaphragm in the rock-filled portion, to be imbedded at the bottom in a concrete wall, the latter to be carried down in a trench far enough to intercept various strata of porous, cinder-like material encountered in the test-pits; the earth-fill to be sluiced into place against the rock-fill and the diaphragm and to have an up-stream slope of 4 on 1. Mr. H. Clay Kellogg, C.E., of Santa Ana, California, who had made the original surveys and test pits of the dam and reservoir-site, was employed to build the dam, and carried out the work in a very efficient manner, substantially on the plans described. The dam has the following dimensions:

Maximum height above stream-bed	98	feet
" " above base of core-wall	136	"
Length on crest	460	"
Width on crest	25	"
Total width of base, up- and down-stream	580	"

The rock-fill portion has a base width of 80 feet, crest width 11.5 feet, down-stream batter 0.75 : 1, up-stream face vertical; volume 26,000 cubic yards. The wood diaphragm is located two feet below the up-stream face of the rock-fill, which is chiefly composed of a hand-laid dry wall. The diaphragm consists of double 2-inch redwood plank, laid horizontally and spiked to 3 by 6 inch posts, placed two feet apart, center to center, with a double layer of burlap dipped in hot asphaltum between the two layers of plank. This latter precaution secured absolute water-tightness to the diaphragm during construction, preventing any leakage of liquid earth through the rock-fill.

The rock was brought to the site by a train of cars and locomotive from a distance of one to six miles, and consisted of basaltic boulders

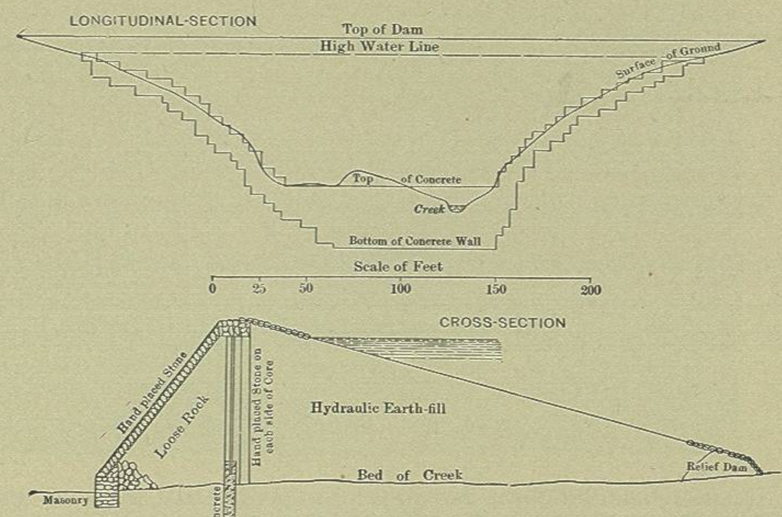

Fig. 93.—Waialua Dam Sections.

found in the dry-stream channels of the Waianae Mountains, many of which required blasting for convenience of loading by hand.

They were dumped from the top of a trestle built at the outset to the full height of the dam (see Fig. 95), and the larger stones selected from the dump for laying up the faces of the wall. The height from which the rocks were dropped consolidated the embankment quite effectively, so that little or no settlement has been noticeable since the completion of the dam, although shortly before completion the outer facing wall, some 2 feet thick, bulged out about a foot beyond the slope line over a limited area, indicating that some settlement had occurred. This was corrected by relaying the bulged portion to the true line, after which no further movement was observed.

The concrete core-wall, as shown by the longitudinal section (Fig 93) extends to a depth of 38 feet entirely across the bottom of the valley. and into the hillsides laterally from 10 to 20 feet.

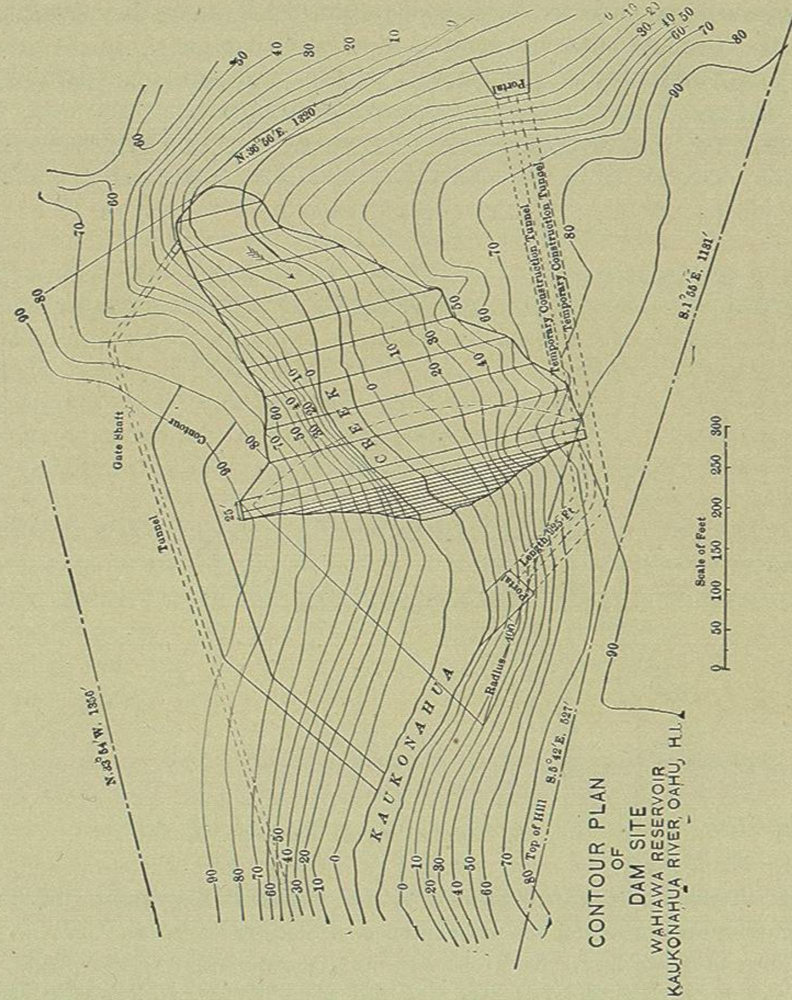

FIG. 94.—CONTOUR PLAN OF WAIALUA DAM.

The trench was cut about 5 feet wide and entirely filled with concrete. The wall extends 2 to 4 feet above the surface, stepped down the sides of the canyon in horizontal and vertical steps as indicated. During construction the flood-waters were handled by a large flume, supplemented by three capacious tunnels, one of which was subsequently

utilized for the permanent outlet of the reservoir by a 48-inch pipe laid through it.

Water for hydraulic sluicing was delivered by a pipe laid from the lower end of the Colony ditch to a point about 50 feet higher than the top of the dam and 2000 feet distant from it. Between this point of delivery and the dam was a body of earth, consisting of the decomposed lava described, which was considered suitable for the embankment. The method employed for moving the earth was that known in placer mining parlance as "ground sluicing." As the head available was in-

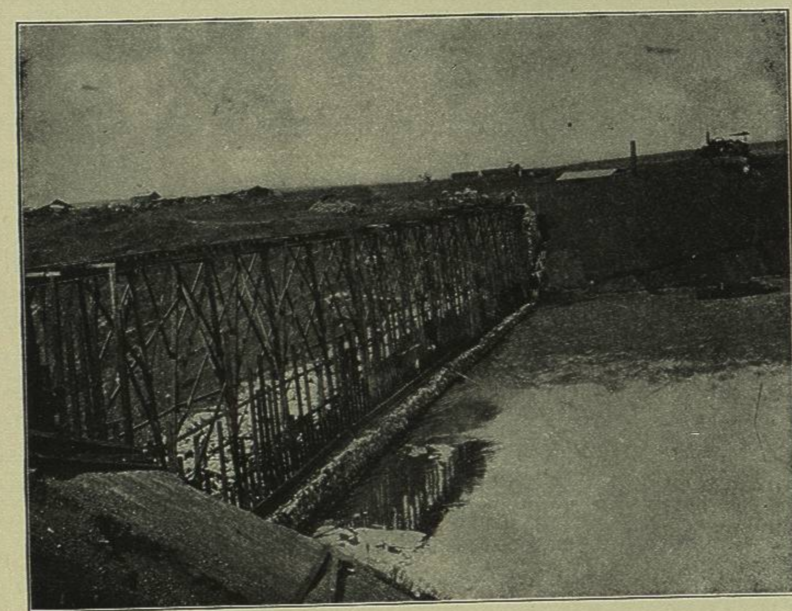

FIG. 95.—WAIALUA DAM, SHOWING HYDRAULIC-FILL BEING SLUICED IN AGAINST THE ROCK-FILL.

sufficient to do effective work in cutting and loosening the earth by the hydraulic jet usually employed, and as the material was peculiarly resistent to erosion, it became necessary not only to plow the ground, but to devise means for placing the loosened material into the flowing stream of the ditch in order to accomplish its delivery to the dam. Ordinary soils can be washed very readily by flowing water over the surface, even without plowing. In this case, however, the peculiar cohesiveness and unctuous character of the soil made it exceedingly difficult to sluice, and the method finally adopted was to dig a ditch about 4 feet deep at the upper end, and 12 to 16 feet deep at the lower end next to the dam, having a bottom gradient of about 4%, through which the water was turned to the amount of 8 cubic feet per second.

This ditch was 1300 feet long. The soil was then plowed to a width of 12 feet on either side by means of plows drawn by cables from portable winding engines stationed at each end—the ordinary English steam plow. After plowing the ground, the traction-engines of the plow were used to drag a V-shaped scraper or "Crowder," as it was called, along the plowed surface, thus crowding the loosened earth into the running water of the ditch alongside. Receiving its load of earth in this way, the velocity of the water was sufficient to carry the material to the dam, although when merely turned over the surface of the plowed ground the water ran over it clear without picking it up and washing it away, for lack of the gritty, cutting-tools of erosion, such as sand or gravel. This process of alternately plowing and crowding was continued until the ditch grade was reached, when a new strip was plowed, and the ditch shifted over to the bluff bank on either side of its original position. This work of loosening and delivering the soil to the ditch was done by Japanese under contract for eight cents per cubic yard. The cost of distributing it on the dam averaged 3 cents per cubic yard, a total of 11 cents per cubic yard. The total volume of the earth-fill was 141,000 cubic yards, of which 100,000 cubic yards were put in by the aid of the four steam-plows borrowed from the plantation. The remaining 41,000 cubic yards were put in by hand labor, blasting, picking, and shovelling into the ditches. An area of eleven acres was stripped to an average depth of 8 feet to secure the material for the dam. The total cost of the dam was $281,000, including a diverting or relief dam, 29 feet high, built at the up-stream toe of the main dam, with sheet-piling core, and also including four long tunnels around the dam, the regulating-gate tower, 48-inch outlet-pipe and gate, and the spillway, which is 135 feet in width, 6 feet deep, lined with concrete, stone rip-rap on the upper face, 18 inches thick, etc.

The material composing the hydraulic-fill had the remarkable quality of settling so rapidly that the water flowing off at the further side of the dam was clear enough to drink, while the fill immediately became hard enough to walk upon, and within a few days the outer surface became so firm that stakes could be driven into it with difficulty. There appears to have been no settlement of the embankment whatever after completion of the dam, and when examined by the author in May, 1907, a year after it had been filled and in service, the water-line along the slope was an absolutely straight line, without deviation or distortion whatever.

During the first year of service a stream of clear water measuring about 0.4 second-foot issued from the lower toe of the dam, apparently coming from the sides, and probably around the dam. Since that time, this leakage is reported to have materially diminished and practically

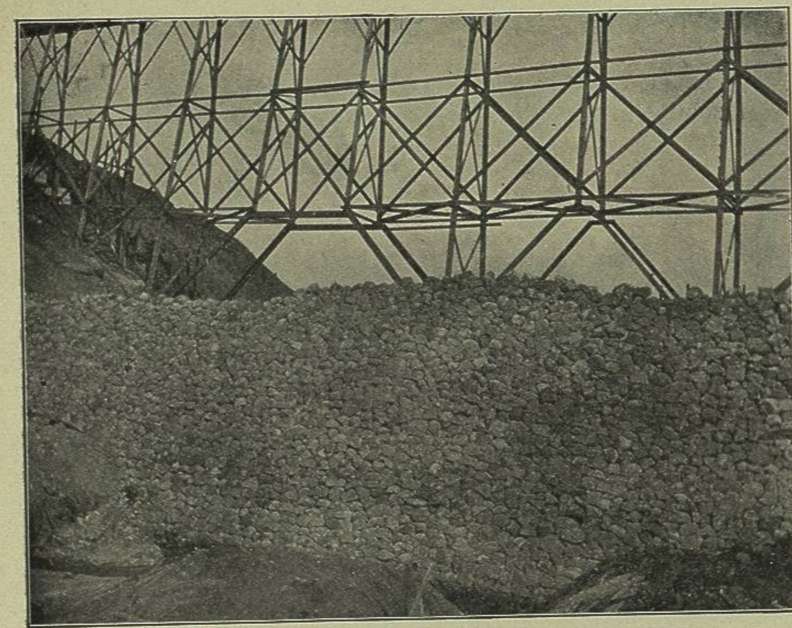

Fig. 96.—Rock-fill on Down-stream Side of Waiaula Dam.

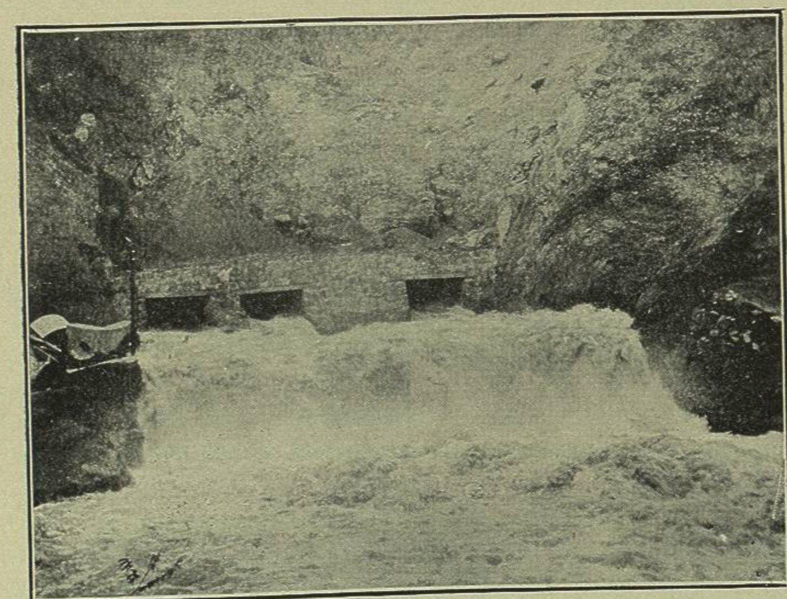

Fig. 97.—Waialua Dam, Hawaii, Showing Flood Discharge through Outlet Tunnels during Construction, under Head of 8 Feet at Upper End of Tunnels.

ceased. The elevation of the spillway of the dam is 844 feet above sea-level, and the ditch taken from the outlet commands all lands on the plantation below the 700-foot level.

After the completion of the dam in 1905, it was decided to widen the spillway from 50 feet to 125 feet and the material excavated was sluiced to the lower toe of the dam against the rock-fill, where it assumed a natural slope of about 5 on 1, reaching to a height of 25 to 30 feet upon the down-stream face of the dam. This addition was considered of doubtful value because it was not previously underdrained, and tended to cut off the drainage afforded by the rock-fill although increasing the stability of the steep rock-slope. Inasmuch as seepage has steadily decreased, however, since this work was done, it must be admitted that the toe embankment is unobjectionable. During the freshets in the summer of 1907 the reservoir was filled to overflowing, and water poured through the enlarged spillway to a depth of 2 feet for a considerable time.

The ditch from the reservoir was built a distance of eleven miles, with a capacity, of 96 sec. ft. It involved the excavation of twenty-one tunnels, $6' \times 6'$, aggregating 20,780 feet, the longest being 1700 feet. They were excavated by contract at a cost of 40 cents per linear foot in earth, 60 cents to $1.00 per foot in soft rock, and $4.00 per linear foot in solid rock. Open ditch excavation cost 16.5 cents per cubic yard. It also required the building of three notable inverted siphons of riveted steel pipes of following dimensions:

Pohamoho Gulch,	54 inches diameter,	1320 feet long,	400 feet max. head.
Halemano	" 54 " "		300 " " "
Opaeula	" 48 " "	900 " "	200 " " "

All work was done by Japanese laborers and artisans, including the placing and field riveting of the pipes.

At one point a ravine was crossed with a temporary flume, 50 feet high, which was subsequently substituted by an earth dam sluiced in place by the water from the ditch and forming a convenient service reservoir for night-water storage. This work was planned and executed by Mr. W. W. Goodale, manager of the Waialua Plantation, the entire dam being finished in about three weeks to a height of 50 feet. It has slopes of about 2 on 1 on each side. It is composed entirely of the red volcanic soil of the country.

The description of the work has been given somewhat *in extenso* because it is unique in many respects, and is a successful example of the marked advantages of the hydraulic-sluicing system in overcoming natural difficulties that were generally regarded as insurmountable. With the experience derived from the behavior of the soil under hydraulic sluicing, it is apparent that there would have been no risk in building

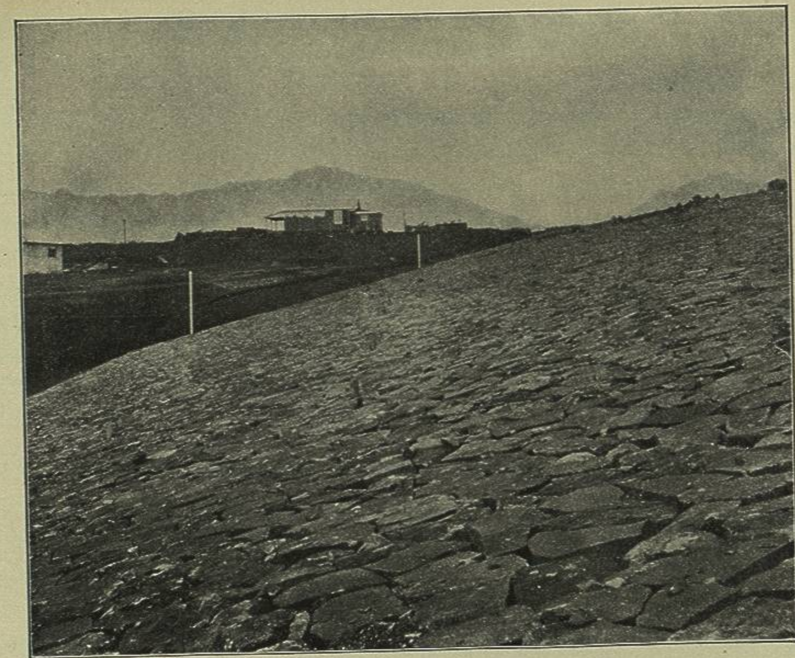

Fig. 98.—Rip-rap on Face of Hydraulic-fill, Waialua Dam.

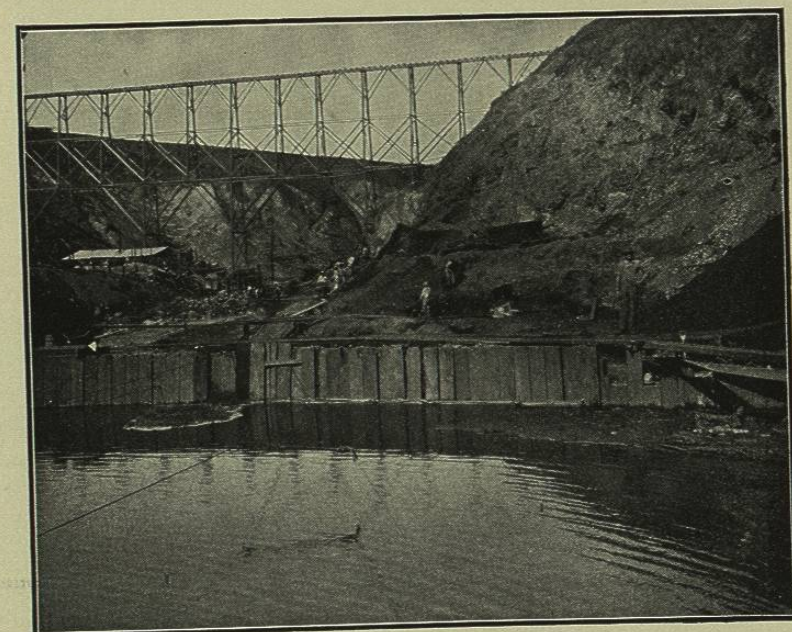

Fig. 99.—Waialua Dam, Hawaii. Looking Down-stream through Dam-site, Showing Diverting Dam at Upper Toe, and Trestle for making the Rock-fill.