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Report of the Commission

Appointed by

GOVERNOR C. C. YOUNG

to Investigate the

Causes Leading to the Failure of the St. Francis Dam

NEAR SAUGUS, CALIFORNIA

A. J. WILEY, Chairman, Boise, Idaho
Consulting Engineer

GEO. D. LOUDERBACK, Berkeley, California
Professor of Geology, University of California

F. L. RANSOME, Pasadena, California
Professor of Economic Geology, California Institute of Technology

F. E. BONNER, San Francisco, California
District Engineer, U. S. Forest Service
California Representative of Federal Power Commission

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FOREWORD

This report embodies the conclusions of the commission appointed to investigate the causes for the failure of the St. Francis Dam on March 12, 1928.

California deplores the heavy loss of life and property that this disaster entailed. To prevent a recurrence of a like catastrophe, we believe it imperative that whatever lessons the failure of this dam may teach should be made public for the benefit of the people of our state. It was also our thought that the investigation into the causes of the failure of this dam should be made by an agency that was not in any way connected with the preparation of the plans, the construction, or the operation of the dam.

Accordingly a commission of engineers and geologists of expert knowledge and eminent reputation was appointed to make this study. The instructions given its members appear in the body of their report. Despite the arduous service that the investigation required, the members of the commission served without personal compensation to themselves, thus placing their report upon a high plane of unselfish public service. On behalf of the people of California, I extend to them the thanks of the state.

As the future of California depends in a large measure upon the storage of water, and the construction of dams, it is gratifying to note that this report finds that such structures can be built with entire safety when due regard is paid to suitability of foundations and correctness of design.

This is the great lesson of the disaster.

C. C. Young.

Governor of California.

Los Angeles, California,
March 24, 1928.

The Honorable C. C. Young,
Governor of California,
Executive Offices,
Sacramento, California.

SIR: Your commission to investigate the causes leading to the failure of the St. Francis Dam assembled in Los Angeles on the morning of March 19, 1928, and was met at the state offices by Mr. Bert B. Meek, Director of Public Works, and Mr. Edward Hyatt, State Engineer. The initial session of the commission was called to order by Mr. Meek as your personal representative, who delivered your instructions as follows:

> "Not only California, but all the nation, has been appalled by the dreadful calamity which has befallen the beautiful little Santa Clara River Valley in Los Angeles and Ventura counties. This is a matter in which there are obviously three parties at interest—the stricken area of the two counties, the city of Los Angeles, and the public at large. All of these are obviously equally anxious to learn all of the facts connected with this disaster.
>
> "I accordingly feel that it is a duty of the state to assemble a commission of eminent engineers and scientists to investigate the causes leading to the failure of the St. Francis Dam.
>
> "The prosperity of California is largely tied up with the storage of its flood waters. We must have reservoirs in which to store these waters if the state is to grow. We can not have reservoirs without dams. These dams must be made safe for the people living below them. All this is both elemental and fundamental.
>
> "Accordingly our duty is a double one. We must learn, if it is possible, just what caused the failure of the St. Francis Dam; the lesson that it teaches must be incorporated into the construction of future dams. There must be no repetition of this catastrophe if it is humanly possible to prevent it."

Guided by such instructions, the commission has carried out its investigations in field and office. Mr. Meek and Mr. Hyatt have held themselves constantly available for consultation and aid, and it is only through their assistance that the commission has been able to complete its work within such a limited time.

Through the cooperation of Mr. Wm. Mulholland, chief engineer and general manager of the Bureau of Water Works and Supply, city of Los Angeles, your commission has been furnished plans, photographs and other data concerning the design, construction and operation of the St. Francis Dam. These data include the results of certain measurements and surveys made after the disaster.

Independent surveys and measurements were made for the commission by the forces under Mr. C. C. Cortelyou, district engineer of the California Highway Commission. The state highway force also secured all test specimens selected by your commission, and preparation and testing of these specimens were carried out under the direction of Mr. W. A. Perkins, hydraulic engineer of the State Engineer's Office. Mr. Perkins also prepared the table of discharge deduced from the chart made by the water register on top of the dam.

Geological conditions at the dam site have been the subject of careful study by Dr. George D. Louderback, and by Dr. F. L. Ransome, members of the commission.

DESCRIPTION OF ST. FRANCIS DAM

Construction of the dam was begun in April, 1924, and the structure completed May 4, 1926. It was located on San Francisquito Creek in section 1, T. 5 N., R. 16 W., San Bernardino meridian, between San Francisquito Power House No. 1 (upstream) and Power House No. 2 (downstream). The reservoir created by the dam was primarily for terminal storage near the lower end of the Los Angeles Aqueduct which conveys water from the Owens River region. Incidentally it was expected ultimately to catch the run-off from the San Francisquito Creek drainage area above it, of approximately 37 square miles. Legal rights to do this, however, had not been secured, and it is understood that such local waters were passed through the reservoir. The drainage basin of San Francisquito Creek from the dam to its junction with the Santa Clara River, and the course of the Santa Clara River from that point to the ocean, are shown on Plate 1. The drainage area above the dam, and the location of the Los Angeles Aqueduct and power plants with relation to the streams, highways, etc., are shown on the map, Plate 2. A profile of the nearby portion of the aqueduct, including the St. Francis Dam and reservoir, is shown in Plate 3. It will be observed that water which passed to St. Francis reservoir could not be utilized through Power House No. 2.

The dam was of the solid gravity type, curved on a radius of 500 feet to the upstream face at the crest. Its right or westerly end was continued by a wing wall which followed in general the crest of a narrow ridge, finally terminating at a high point about 500 feet from the end of the main dam; a small gap beyond this point was closed by a low concrete wall. The maximum cross-section, and a plan of the dam (including wing walls, etc.) are shown on Plate 4. The stress sheet is presented by Plate 5. Maps and plans furnished by the Bureau of Water Works and Supply show that the crest thickness of the dam was 16 feet, and the maximum section was 205 feet high and 175 feet thick at the base. The batter of the upstream face changed from 1 in 27 to 1 in 10, and finally in the extreme bottom to 3½ in 10. The downstream face was carried up in a series of steps uniformly 5 feet high, and with widths varying from 5.5 feet near the bottom to 1.45 feet near the top. The length of the main dam measured along the center line of the curved crest was 700 feet. The elevations above sea level at various points of the structure were as follows:

Crest of parapet	1,838.06 feet
Crest of spillway lip	1,835.00 feet
1st outlet upstream invert	1,799.00 feet
2d outlet upstream invert	1,763.00 feet
3d outlet upstream invert	1,727.00 feet
4th outlet upstream invert	1,691.00 feet
5th outlet upstream invert	1,658.26 feet
Bottom of maximum section	1,630.00 feet

Both faces of the crest of the dam were vertical for 23 feet. The downstream face of this vertical section was divided into panels 24 feet wide, of which eleven panels in two groups were spillways. Each spillway panel was 20 feet wide by 1.5 feet high clear inside dimensions. The five outlet pipes each 30 inches in diameter, were controlled by sliding gates fastened to the upstream face of the dam.

Storage of water in the reservoir began March 1, 1926, according to Plate 6, which gives a record of the reservoir stages to the date of failure. The approximate maximum storage for 1926 was 13,200 acre-feet at elevation 1779 on June 5. This level was maintained until about August 10, gradually lowered until October 5, and held thereafter at about 1762 until the end of the year. After January 5, 1927, the water was raised at a uniform rate to 1832 on May 10, where it was held until May 27. It was rather rapidly lowered to about 1817 June 20, and then with minor variations brought down to 1813 November 8, after which the level was raised to 1821 by December 31, 1927. From the beginning of 1928, when the water surface was 1821, storage was increased gradually until March 5, when the reservoir was practically filled to capacity of 38,000 acre-feet. The water level was maintained at 1834.75 or 0.25 foot below the spillway crest, until the time of the failure at 11.58 p.m., March 12, 1928.

Photographic evidence and the testimony of witnesses show that little seepage passed through the structure of the main dam. Certain cracks developed in the main structure, which possibly discharged an unimportant amount of water, as is not at all unusual in concrete dams. One or more cracks, with consequent unimportant seepage, also developed in the wing wall extension to the west of the main dam.

Much more important seepage is reported to have taken place through the foundation upon which the dam rested. As the water rose in the reservoir this foundation seepage appears to have increased to a maximum of between one and two second-feet on the afternoon preceding the failure. Rumors of muddy water seeping under or around the dam before its failure are in circulation, but the commission has been unable to verify them.

FAILURE OF THE DAM

It is reported that one of the caretakers was seen on top of the dam at 11 p.m., only an hour before the failure, and apparently up to this time there had been no alarming developments. The caretakers were lost in the flood, and so far as is known there is no living witness of the dam's collapse.

The first indication of failure, given by the automatic water register located on top of the central or standing section of the dam, was a gradually accelerated falling of the water surface, starting about 11.30 p.m. (corrected time) and aggregating about three-tenths of a foot at about 12 p.m., when the failure was indicated on the record by a rapid fall in the water surface.

At 11.58 p.m. there was a break in the Borel transmission line of the Southern California Edison Company which was located in the canyon immediately below the dam. At 12.03 a.m. March 13 the power from the Los Angeles city power plant No. 2 in the canyon about one and one-half miles below the dam went off.

It appears that the failure of the dam took place at, or slightly before, 11.58 p.m., March 12, when the main dam structure, with the exception of a section near its middle, failed completely, leaving the greater part of the left or easterly portion in very large fragments at and just below the dam site and great blocks of concrete up to about 10,000 tons in weight, chiefly from the right or westerly end, distributed for a distance of several thousand feet downstream. See Plate 8.

The magnitude and violence of the wave released on the failure of this dam are hard to visualize even by engineers familiar with floods and flood conditions. The rush of water attained a maximum depth of about 125 feet in the deepest of four sections measured by the commission within three-fourths of a mile below the dam. In the vicinity of San Francisquito Power House No. 2, approximately 1.5 miles along the channel downstream from the dam, an even greater depth was reported. The flood wave completely carried away the heavy concrete power house down to the generator floor, together with the less substantial buildings occupied by the operators and their families. The flood followed down San Francisquito Creek 9 miles from the dam and then down the Santa Clara River 43.5 miles to the ocean. The velocity of the wave and the time required to reach the peak are data of great engineering interest. The following is a summary of these data now available to your commission.

Table of velocities of flood as noted at various locations downstream from the dam. Dam failure assumed at 11.58 p.m.

Location	Time of arrival of flood	Time of travel from preceding location	Distance in miles from preceding location	Velocity in miles per hour from preceding location
Borel Power Line at Dam	11.58 p.m.	----	----	----
City Power Plant No. 2	12.03 a.m.	5 min.	1.5	18.0
So. Cal. Edison Co. Sub-Station near Saugus	12.38 a.m.	35 min.	7.5	12.9
So. Cal. Edison Co. Construction Camp at Kemp	1.20 a.m.	42 min.	7.5	10.7
Fillmore Bridge	2.25 a.m.	65 min.	12.7	11.7
Santa Paula	3.10 a.m.	45 min.	8.5	11.3
Saticoy Bridge	4.15 a.m.	65 min.	6.8	6.3
Montalvo Bridge	5.00 a.m.	45 min.	4.0	5.3

It seems probable that the flood peak immediately below the dam exceeded half a million second-feet and this, together with its occurrence in the darkness, and the suddenness and violence of the wave, was such that very few of the persons in the constricted valley below the dam escaped with their lives, though they were immediately adjacent to the safety of the steep slopes of the bordering hills. Even at a construction camp of the Southern California Edison Company, 16.5 miles below the dam, more than 80 out of about 140 perished.

The damage caused in the path of the waters 52 miles to the sea was very great. The record of known dead at this time is 236 and 200 are still missing. Fortunately no trains happened to be passing over the railroad track inundated, and but few automobiles were on the many miles of highways destroyed. The total property loss of farms, orchards, small towns and public utilities will certainly be many millions of dollars.

METHODS FOLLOWED IN CONSTRUCTING THE DAM

The Los Angeles Bureau of Water Works and Supply placed at the commission's disposal a complete set of construction plans and photographs of the St. Francis Dam. By means of these, and by discussion of construction methods with Mr. Wm. Mulholland and several of his assistants, the essential construction data were ascertained.

The first step was the construction of a concrete wall 8 feet thick (narrowed to 5 feet at the top) and about 80 feet long at the bottom and 155 feet at the top, placed in a trench carried down into tight material under the stream bed to an elevation of approximately 1638. The foundation of the dam was then excavated behind the wall to elevation 1630 across the deepest part of the channel. It will be noted from these elevations that the foundation excavation of the dam was carried 8 feet below the bottom of the wall. The wall was built merely to cut off underflow through the gravel, and small freshets that might come from the San Francisquito drainage during the early construction stages, and convey these waters through a flume past the dam site. Behind this wall the lowest part of the dam foundation was excavated in the dry, and the wall itself finally incorporated into the upstream face of the structure.

The east wing of the dam was notched into the rock of the canyon wall and carried up the natural inclined plane of the rock in the abutment, without steps, and with no cut-off wall. Under portions of the west abutment and about 25 feet from the upstream face, a cut-off trench about 3 feet wide and 3 feet deep, probably with rounding bottom, was excavated longitudinally as deep as it could be carried by use of picks, and finished by prying out rock with gads. The nature of this trench can be observed by inspection of concrete surfaces on one large fragment from the west end of the dam that was carried downstream and now lies upturned showing the original contact with the abutment.

Relief of uplift that might be caused by water pressure underneath the dam was provided for only in the center, or the portion crossing the main channel. On a line about 30 feet in from the face of the dam, 3 holes were bored in line at intervals of 20 feet, while along a second line approximately 15 feet further downstream from the first line there were 7 more holes also at intervals of about 20 feet. The depth of these holes is variously reported to have been from 15 to 30 feet. A small section of pipe with collar was fitted into the top of each hole and cross connections were carried from these pipes to a center outlet pipe which was led out to the lower face near the lowest main outlet pipe. The amount of water draining from this system is understood to have been very small, and was carried down to the caretaker's house, where it was used for domestic supply, lawn watering, etc. Most of this drainage system is included under the portion of the dam which remains standing; this is probably merely a coincidence.

Construction views show that a relatively small cut-off trench was carried along the upper side of the wing wall extending westerly along the ridge from the west abutment of the dam. This trench was largely excavated by a steam shovel.

The concrete aggregate was pit-run sand and gravel taken from the stream bed between one-fourth and one-half mile below the dam, where aggregate used in construction of the aqueduct and the San Francisquito Creek power houses had been secured. The material was neither washed nor graded, but rocks in excess of 6 inches were excluded. It is stated that 1.12 barrels of Portland cement were used per cubic yard of concrete. Specimens deemed typical were taken and tested. These show a satisfactory quality of concrete.

No inspection gallery was carried through the dam, nor was any pressure grouting attempted under any part of the structure. Geological conditions not only at the dam site itself, but for a short distance above and for a considerable distance below, were clearly disclosed by the scouring that took place during the discharge of water from the reservoir.

GEOLOGICAL CONDITIONS AT THE DAM SITE

General Relations.—The geological conditions in the vicinity of the St. Francis Dam are both simple and obvious. San Francisquito Canyon here has a course of south 60 degrees west. The bottom of the canyon and the steep slopes southeast of the stream way are carved from a fairly uniform mica schist. The gentler, less regular slope on the northwest side of the canyon is underlain by a reddish conglomerate, in rather ill-defined beds of great but undetermined total thickness. The contact between the two rocks is a fault which, at the dam site, has a strike that is approximately parallel with the course of the canyon and outcrops a short distance above the stream way, on its northwest side. The dam consequently was placed astride of the fault, the southeast abutment and the foundation of the middle section being schist and the northwest abutment being conglomerate.

The fault is plainly visible in Plates 17, 18 and 22, as a sharp line that separates the lighter colored schist below from the darker conglomerate of the upper slope.

Mica Schist.—The mica schist is an ordinary variety of this fairly common crystalline metamorphic rock. It consists chiefly of quartz, white mica and probably some feldspar. The schistose structure, due to the generally parallel orientation of the constituent minerals, particularly of the mica scales, is very well developed so that the rock has pronounced fissility or cleavage and splits readily into thin plates. As a consequence of this fissility also, the rock weathers and disintegrates into small flakes or scales.

In many places the schist has been strongly sheared, commonly along planes that are roughly parallel with the schistosity or planes of lamination. Along these shear-zones the rock has been changed to an exceedingly fragile flaky material that can be readily excavated with the pick. From a structural point of view such sheared schist is extremely weak material.

The general strike of the schistosity is from north 60 degrees to north 70 degrees east, or about parallel with the course of the canyon at the damsite. The dip is northwesterly. Consequently the lamination of the schist is not far from parallelism with the steep slope of the southeast side of the canyon. This slope, in fact, is conditioned in large part by the laminated structure of the schist. This same structure also is responsible in part for the landslides that have taken place since the dam failed.

The geological age of the schist is not definitely known. The rock, however, is probably at least pre-Cretaceous and may be pre-Cambrian.

The schist is not a soluble rock, nor is it ordinarily softened by wetting. It is capable of withstanding considerable pressure applied in directions approximately normal to its planes of lamination, but is very weak with respect to stresses applied in directions parallel with or at small angles with those planes. Under such stresses the schist would slip like a pack of cards thrown upon a table.

Conglomerate.—The conglomerate near the dam site strikes north 15 degrees west and dips 46 degrees west. It is composed chiefly of detritus derived from the schist terrane and from granitic masses that are not exposed in the vicinity of the dam. The pebbles, usually rather small and sparsely distributed, are embedded in a relatively large proportion of fine-grained, sandy, micaceous, flaky detritus derived from schist and granite. High above the dam site on the northwest slope of the canyon, can be seen rounded outcrops of the conglomerate that appear to be fairly well cemented and moderately resistant to erosion. At the dam, however, the rock has an entirely different character. As its peculiar properties at this place are at least in part a consequence of the faulting, previously referred to, they will be more fully described in connection with that feature.

The exact age of the conglomerate has not been determined, but it is Tertiary and probably Miocene (Mint Canyon formation) or Oligocene (Sespe formation).

San Francisquito Fault.—The fault which passes beneath the northwestern part of the dam site has long been known and is represented as a "dead" fault on the Fault Map of California compiled under the auspices of the Seismological Society of America. The present investigation shows that there has been no movement on this fault since the dam was built.

At the dam site, the strike of the fault is about north 51 degrees east, or approximately parallel with the course of the canyon. The dip, although variable, is generally between 30 and 45 degrees, to the northwest. At the dam site, a satisfactory exposure of the hanging wall of the slip gave a dip of 40 degrees. The same exposure showed striae that pitch 65 degrees to the northeast, indicative of a slip of which the vertical component, in the plane of the fault, is larger than the horizontal component.

Along the fault, next to the schist footwall, is a well defined, dark, gray, clay gouge, which in places is at least 8 inches wide or thick. This material is chiefly comminuted or triturated schist—ground to clay by movement on the fault. When dry, the gouge is fairly hard, but when wet it is an unctuous, plastic clay, with some enclosed fragments of schist. Under the gouge, in some places for a width of 10 feet, the schist is crushed and sheared. On the upper, or hanging wall side of the main slip-plane, is a reddish gouge, composed of ground-up conglomerate. This gouge is generally thicker than the gray gouge and grades rather indefinitely into disturbed, crushed conglomerate. When dry, this material is firm and coherent, but becomes soft and plastic when wet. In places, this reddish gouge is fully 4 feet thick.

Above the foregoing material, as the slope is ascended, and extending all the way up the northwestern abutment to the top of the dam, the conglomerate is traversed in various directions by intersecting fractures, some of which contain small seams of clay gouge, and others are filled with gypsum. The pebbles in the conglomerate have, in many instances, been fractured, sheared and faulted. Finally, the whole mass of the conglomerate has been so minutely crushed as to have lost most of the strength to be expected in a rock possessing its general appearance. When dry, the rock is moderately hard and fragments of considerable size can be broken out and trimmed down with a hammer to specimen size. When, however, a piece of the rock is placed in water, a startling change takes place. Absorption proceeds rapidly, air bubbles are given off, flakes and particles begin to fall from the sides of the immersed piece, the water becomes turbid with suspended clay and, usually in from fifteen minutes to an hour, a piece the size of an orange has disintegrated into a deposit of loose sand and small fragments, covered by muddy water. Whatever may have been the original cementing material of the conglomerate, its efficiency has been destroyed by crushing, aided possibly by solution, and the rock at present is held together merely by films of clay. It is possible that this part of the conglomerate, as originally deposited, contained considerable clay that never became lithified.

This remarkable characteristic of the conglomerate is probably local and confined to a belt within some undertermined distance from the fault. The rounded outcrops previously referred to as appearing higher up the slope could scarcely exist if the conglomerate at that distance from the fault were equally susceptable to the disintegrating effect of water.

That the same process of disintegration above described was going on rather extensively where the conglomerate was covered by the water of the reservoir, is clearly shown by the character of the residual material left on the conglomerate where the escaping water has not cleaned off all of the surface material.

Clearly, when thoroughly wet, the conglomerate at the northwestern abutment of the dam ceased to have the characteristics commonly denoted by the term rock.

Whether the movement on the fault was normal or reverse is not known. The fact that the conglomerate is obviously younger than the schist suggests a normal fault, although the rather low dip and the condition of the conglomerate in the hanging wall are indicative of overthrust.

Major Earth Movements.—A careful examination of the contact fault in the vicinity of the dam site shows no evidence of recent movement. According to Mr. H. O. Wood in charge of the Seismological Laboratory of the California Institute of Technology, Pasadena, their seismographs recorded no earth tremors of even slight intensity at any time near the time of the dam failure.

There appears to be no reason to believe that faulting or other major earth movement was to any degree responsible for the failure of the dam.

Landslides.—The mica schist which occupies the southeast side of the canyon shows separation planes along the schistosity, and shear surfaces dipping northwesterly at 30 degrees and more. The canyon slopes are steep and approximate the dip of the schistosity and shear surfaces. Landsliding is therefore always imminent and may be produced by any one of several causes.

Above the dam site several marked recent slides have taken place. One, a short distance upstream from the dam, broke the road and carried a large mass of rock and earth down to the floor of the valley. See Plates 29 and 30. A careful examination of the surface of this slide shows no water lines, erosion furrows, or other evidences of the action of the standing or moving water of the reservoir. Evidently the sliding occurred after the withdrawal of the water from the reservoir. The added weight of the infiltrated water while the reservoir was full, and the rapid removal of the water support when the dam failed are sufficient causes for the landslides above the dam.

At the east abutment of the dam and immediately below the dam site much recent sliding has taken place, and during the visits of the commission to the dam site a continuous rain of rock fragments was coming down the slope, accompanied by clouds of dust as shown in Plate 28. This sliding is evidently due to the removal of support as a result of the destruction of the dam and the undercutting of the slope by the waters released by the dam failure.

Smaller landslides and slumps are found along the slopes above the wing wall. These clearly followed the withdrawal of the water from the reservoir and were due to the removal of support from the water-soaked and softened outer portions of the conglomerate.

It is concluded that all of the recent landslides in the vicinity of the dam site took place after and as a result of the failure of the dam and were in no way responsible for such failure.

CONDITIONS AT THE DAM AFTER FAILURE

The wrecked westerly part of the dam from a point 70 feet west of the standing section to the end of the wing wall, as well as the wing wall that still remains, was founded on the conglomerate. Eastward from the base of the conglomerate across the stream bed and up the east side of the canyon the structure rested on schist. The contact between the conglomerate and schist is along a fault plane that shows considerable ancient movement. Water rushing through the westerly break in the dam has scoured both conglomerate and schist to a considerable depth, the principal part of the scouring taking place toward the toe of the dam, probably due both to the character of the material at this particular location and to the fact that a ridge just upstream from and practically parallel to the face of the dam acted as a submerged weir over which the water poured onto the downstream part of the foundation. To the westward of the standing section and against its base a narrow channel was cut through the schist to a depth well below all of the concrete in the structure, with the exception of the concrete cofferdam sections at the upstream face and a thin section carrying the steps on the downstream face. It is therefore possible to observe the character of the material which underlay that part of the dam.

To the eastward of the standing section the water carried away a large amount of the schist not only on the side of the canyon or along the abutment, but in the bottom. Probably due to combined effect of water soaking and undercutting, a very large and conspicuous slide has developed on the hillside on approximately the line of the eastern abutment. Material was still cascading down the face of this slide ten days after the failure, and from observation in the field it is apparent that the slide movement will continue for some time.

The distance to which large masses of concrete from the dam have been transported is probably one of the most impressive phenomena of the disaster. All of the fragments from the westerly side of the dam have been carried some distance down stream. Many of the large fragments from the easterly side have moved only a short distance out of place and now rest against the base of the standing section, but several very large masses of concrete from this side have been carried downstream as far as the large masses from the westerly end, being recognizable from the inclusions of schist upon which they rested. One large mass from the west side is turned bottom up and the foundation material adhering to it shows that it came from the part of the dam directly over the contact between the conglomerate and the schist.

Discharge of water from the foundations and from seeps along construction joints in the concrete of the standing section and in the masses washed downstream was very noticeable immediately after the break, when the site was inspected informally by several members of the commission, but had markedly decreased during the few days that intervened before the commission assembled and during the time that its investigations were under way. The most noticeable discharge was from the seams in the conglomerate about on a line between the standing section of the dam and the broken end of the wing wall, and about two-thirds of the way up the abutment from the bottom. Very noticeable seeps occurred along the top of the gouge between the schist and the conglomerate.

A short length of the two-inch pipe that formed part of the drainage system along the second line of holes drilled under the dam is now protruding from the large slab of concrete that has broken away from the easterly end of the standing section. That is the only part of the drainage system that can now be identified.

The rapid lowering of the water in the reservoir caused several large landslides that are very conspicuous as shown in pictures looking upstream from the dam site. The most important of these is on the easterly side of the reservoir a short distance upstream from the dam, where displacement of a road shows vertical movement of approximately forty or fifty feet along the junction of surface earth and material that is probably very similar to that against which the east abutment of the dam rested.

Seepage from the water soaked slopes of the reservoir basin has contributed a considerable but constantly decreasing stream ever since the break, and four days after the disaster amounted to 15 second-feet.

Triangulation between stations established during construction and the tying in of one fixed point that is available on the top of the standing section, show that the point has moved S. 2° 52′ W. 0.70 feet. The course of the radius at this point was N. 51° 22′ E. It is yet uncertain whether this movement is due to tilting, to horizontal displacement of the whole mass, or to a combination of the two. The surface of the conglomerate on the westerly abutment, shortly after the break, showed marked softening due to water soaking. After a few days drying this material showed clean smooth surface when broken, and some of the hardest specimens rang under the hammer. Many of these, however, go to pieces when immersed in water for a few hours, and samples taken over a considerable area have gone to pieces almost immediately upon immersion. Material from the gouge along the fault between the conglomerate and schist rapidly becomes soft and unctuous when immersed. An attempt was made to prepare two samples of the conglomerate for compression and absorption tests. One broke in preparation, and the other stood only 523 pounds per square inch in compression when dry. See reports from the testing laboratory included as Appendices.

CAUSES OF THE FAILURE

The St. Francis Dam was designed with a gravity section and was arched in plan. Experience has shown that this type of structure is preeminently safe and it is generally accepted by engineers all over the world as a conservative design.

The material in the dam is demonstrated by inspection, by tests, and finally by behavior of enormous blocks remaining from the wreck, to have been of satisfactory quality and adequate strength. Tests of samples cut from typical blocks showed an average crushing strength of about 2400 pounds per square inch, which is much beyond any stresses to which it could have been subjected under normal conditions.

There were no contraction joints built in the dam, which is the case in many existing dams, and, in any event, the failure can not be attributed to their absence.

There can be no question but that such a dam properly built upon a firm and unyielding foundation would be safe and permanent under all conceivable conditions, except perhaps faulting and earthquake shocks of tremendous violence. Indeed such a dam may properly be deemed to be among the most durable of all man-made structures. Unfortunately in this case the foundation under the entire dam left very much to be desired. The material under the central and left, or easterly, end was a mica schist of thin and easily separable laminae. The west end was founded upon a reddish conglomerate which, even when dry, was of decidedly inferior strength and which, when wet became so soft that most of it lost almost all rock characteristics. Numerous samples taken from the present surface which has been eroded to a considerable depth below the original foundation and some samples from underneath the remaining west wing wall, quickly softened and changed into either a mushy or granular mass when immersed in water. Unfortunately this material is of such a nature that when entirely dry it is hard and rock-like in appearance and characteristics, although defective in compressive strength. Of two samples taken from the firmest part of the eroded foundation, one broke in preparation for testing and the other, cut into a 5.77-inch cylinder 7.12 inches long, showed a compressive strength of only 523 pounds per square inch, or between one-fourth and one-fifth that of the concrete in the dam. Greater strength might have been shown had the sample not been moistened by exposure at the time of the dam failure, but on the other hand it would have been much weaker with a larger moisture content.

With such a formation, the ultimate failure of this dam was inevitable, unless water could have been kept from reaching the foundation. Inspection galleries, pressure grouting, drainage wells and deep cut-off walls are commonly used to prevent or remove percolation, but it is improbable that any or all of these devices would have been adequately effective, though they would have ameliorated the conditions and postponed the final failure.

While as yet the manner and chronological order in which the failure of various sections of the structure occurred are not entirely certain, the present locations of the fragments from the west end indicate this as the point of initial failure which was quickly followed by progressive but rapid failure of the east end. Many of the available data indicate that the initial foundation failure occurred near or at the old fault or contact between the conglomerate and schist under the west end, and was due to the percolation of water into and through this section of the foundation, with resulting softening of the conglomerate under the dam. Either a blowout under, or a settling of the concrete at this place, or both, occurred, quickly followed by the collapse of large sections of the dam.

It is probable that the rush of water released by failure of the west end caused a heavy scour against the easterly canyon wall at the toe of the dam. This rapidly cut away the schist including the material under the toe of the east part of the dam and caused the failure of that part of the structure. The escaping water then continued to cut away the schist from the east wall of the canyon until a maximum depth of about 30 feet below the original foundation level was reached. See Plate 8.

A fact which should be very reassuring as to the stability of a gravity dam on reasonably sound bed rock is that although the central section, still standing, must have been exposed to tremendous and sudden stresses amounting to shocks, while still subject to practically full water pressure, it is undisturbed except for an apparent movement at the top of some 5.5 inches downstream and 6 inches toward the easterly abutment.

The record made by the Stevens gage which was located on the standing middle section of the dam is shown in Plate 10. Using this record in connection with the known areas and capacities of the reservoir at varying water elevations, the following table has been made:

Discharge from St. Francis Reservoir, deduced from copy of chart from automatic water-stage register located on top of the portion of the dam that remains in place. The absolute time is obviously in error.

Time interval *From*	*To*	*Drop in water surface, feet*	*Discharge, C.F.S.*
March 12, 1928			
2 p.m.	12 midnight	0.03	22
March 13, 1928			
12 midnight	12–06 a.m.	0.01	740
12–06 a.m.	12–14 "	0.04	2,200
12–14 "	12–20 "	0.05	3,680
12–20 "	12–24 "	0.05	5,520
12–24 "	12–26.7 "	0.05	8,160
12–26.7 "	12–29 "	0.05	9,600
12–29 "	12–30.5 "	0.05	14,700
12–30.5 "	12–31.5 "	0.05	22,000
12–31.5 "	12–32.2 "	0.05	31,500
12–32.2 "	12–33.4 "	0.10	36,700
12–33.4 "	12–34.3 "	0.10	48,900
12–34.3 "	12–34.9 "	0.10	73,300
12–34.9 "	12–35.3 "	0.10	110,000
12–35.3 "	12–35.5 "	0.10	220,000
12–35.5 "	12–35.65 "	0.10	293,000
12–35.65 "	12–35.75 "	0.10	438,300

Too much reliance must not be placed upon this, as the horizontal or time scale of the record is very small and the accuracy of the clock movement is not certain. However, for at least many hours before the record ends there clearly were no water surface fluctuations except a lowering beginning about 2 p.m., which was so slight that it might have been due to upstream wind movement.

This record shows that a water subsidence which could not have been due to upstream winds began about one-half hour before the flow from the reservoir reached enormous proportions, and further, that the curve of emptying is regular up to that point. Such accelerating water lowering, as opposed to an abrupt fall, is apparently contradictory to many data reported as to suddenness of the downstream movement of the flood wave, especially at Power House No. 2, where there appears to have been no such warning as would have been given by a gradually increasing stream flow such as would have resulted from anything like the deduced record given in the table.

In so far, however, as the validity of this record is accepted, the discharge of the impounded waters was something like that given in the table.

CONCLUSIONS

1. The failure of St. Francis Dam was due to defective foundations.

2. There is nothing in the failure of the St. Francis Dam to indicate that the accepted theory of gravity dam design is in error or that there is any question about the safety of concrete dams designed in accordance with that theory when built upon even ordinarily sound bed rock. On the contrary, the action of the middle section which remains standing, even under such adverse conditions, is most convincing evidence of the stability of such structures when built upon firm and durable bed rock.

3. The failure of this dam indicates the desirability of having all such structures erected and maintained under the supervision and control of state authorities. Water storage, with its necessary concomitant dams and embankments, is peculiarly essential to the development of California resources, and in the great majority of cases failures would result in serious loss of life and property. This disaster emphasizes the fact that while the benefits accrue to the builders of such projects, the failures bring disaster to others who have no control over the design, construction and maintenance of the works. The police power of the state certainly ought to be extended to cover all structures impounding any considerable quantities of water.

Respectfully submitted.

A. J. Wiley, Chairman, Boise, Idaho.
Consulting Engineer.

Geo. D. Louderback, Berkeley, California.
Professor of Geology,
University of California.

F. L. Ransome, Pasadena, California.
Professor of Economic Geology,
California Institute of Technology.

F. E. Bonner, San Francisco, California.
District Engineer, U. S. Forest Service
and California Representative of Federal
Power Commission.

H. T. Cory, Los Angeles, California.
Consulting Engineer.

F. H. Fowler, San Francisco, California.
Consulting Engineer.

STATE OF CALIFORNIA
GOVERNOR'S OFFICE
Sacramento

C. C. YOUNG
GOVERNOR

April 20, 1928.

MR. A. J. WILEY, *Chairman,*
And Associate Members of
St. Francis Dam Commission.

GENTLEMEN: Your report of the causes leading to the failure of the St. Francis Dam is herewith placed in the hands of the public, with the highest appreciation of the ability and painstaking care with which you performed the arduous task which was submitted to you.

While fully cognizant of the appalling loss of life and great destruction of property caused by this frightful disaster, it is at the same time self-evident that the full development of this great commonwealth requires that her water resources be fully conserved. This can be done only by continuing the construction of great dams, such as those which are now doing their work without sign of weakness. I am pleased to note that you have called attention in your report to the fact that such structures can be built with entire safety when constructed on proper foundations and correctly designed.

On behalf of the people of California I wish to thank you for this valuable and eminently fair report, prepared by you as a public service, and without personal compensation.

Yours very sincerely,

C. C. Young.

Governor of California.

To: A. J. Wiley, Chairman, Consulting Engineer, Boise, Idaho.
Geo. D. Louderback, Professor of Geology, University of California, Berkeley, California.
F. L. Ransome, Professor of Economic Geology, California Institute of Technology, Pasadena, California.
F. E. Bonner, District Engineer, U. S. Forest Service, and California Representative Federal Power Commission, San Francisco, California.
H. T. Cory, Consulting Engineer, Los Angeles, California.
F. H. Fowler, Consulting Engineer, San Francisco, California.

REPORT OF COMPRESSION TEST OF ROCK

Testing of Materials

General
Physical and Chemical
Tests
Cement-Steel-Oil-Asphalt
Shipments Gauged

Representing
Hildreth & Company
New York
Inspection Engineers

Eastern Steel-Mill and Shop
Rails-Cars-Machinery

RAYMOND G. OSBORNE

BUREAU OF TESTS
AND
INSPECTION

Office and Laboratories
Rives-Strong Building

Phones Tucker 5222
Tucker 1931

Representing
Falkenburg & Co. Seattle
Chemical Engineers

Inspection of Creosoted
Materials
Paving Blocks-Creosoted
Timber

LOS ANGELES

March 23, 1928

REPORT OF COMPRESSION TEST OF ROCK

Test made for: Commission appointed by Governor Young to investigate failure of St. Francis Dam.

Description of specimen: Cylindrical core, 5.77 inches diameter, 7.12 inches high, cut from sample selected by the Commission at the dam site. Core was cut by L. A. County Road Department in presence of Mr. Perkins and a representative of the laboratory. No water used in coring this specimen.

LABORATORY DATA

Test number, 17857.
Specimen mark, R.B.
Weight, total lbs., 15.21.
Weight per cu. ft., lbs., 150.60.
Specific gravity, 2.414.
Average diameter, in., 5.77.
Average height, in., 7.12.
Area, sq. in., 26.14.
Compressive strength—
  Total lbs., 14,570.
  Lbs. per sq. in., 557.
Corrected to standard specimen—
  Lbs. per sq. in., 523.

REMARKS—Height divided by diameter is 1.23, correction made by multiplying crushing strength by 0.94 (according to American Society for Testing Materials) Standard method for securing specimens of hardened concrete from the structure, Serial Designation C42-27; character of fracture—conical.

After coring, specimen was given three coats of shellac to prevent absorption of water during test for specific gravity. The smaller specimen of stone submitted, fractured during the coring process. A test for rate of absorption was made on a portion of this specimen and the following results were obtained:

Total time elapsed	*Per cent absorption by weight*
10 minutes	0.59%
20 minutes	.67%
30 minutes	.69%
40 minutes	.71%
50 minutes	.73%
1 hour	.73%
1 hour 10 minutes	.75%
1 hour 20 minutes	.75%
1 hour 30 minutes	.77%
1 hour 40 minutes	.77%
1 hour 50 minutes	.79%
2 hours	.79%
2 hours 30 minutes	.79%
Total porosity	2.25%

In making the above test, the rock was broken up into pieces passing a 1½-inch ring, and placed in a bottle of water; each piece was carefully brushed to remove loose particles; the total sample weighed 503.6 grams dry. At the end of 20 minutes the samples had disintegrated in a very marked way, and a layer of sand about three-eighths of an inch deep was formed on the bottom of the bottle.

The absorption was measured by adding small amounts of water to keep the total volume constant, and the total porosity was obtained by evacuating the sample in the bottle.

Respectfully submitted.

RAYMOND G. OSBORNE LABORATORIES.
By S. S. Stahl.

REPORT OF COMPRESSION TESTS OF CONCRETE

Testing of Materials

General
Physical and Chemical
Tests
Cement-Steel-Oil-Asphalt
Shipments Gauged

Representing
Hildreth & Company
New York
Inspection Engineers

Eastern Steel-Mill and Shop
Rails-Cars-Machinery

RAYMOND G. OSBORNE

BUREAU OF TESTS
AND
INSPECTION

Office and Laboratories
Rives-Strong Building

Phones Tucker 5222
Tucker 1931

Representing
Falkenburg & Co. Seattle
Chemical Engineers

Inspection of Creosoted
Materials
Paving Blocks-Creosoted
Timber

LOS ANGELES

March 23, 1928

REPORT OF COMPRESSION TESTS OF CONCRETE

Tests made for: Commission appointed by Governor Young to investigate failure of St. Francis Dam.

Description of specimens: Cylindrical cores approximately six inches diam. cut from blocks of concrete selected by Commission at dam site. Cores were cut by L. A. County Road Department, in presence of Mr. Perkins, and a representative of the laboratory.

LABORATORY DATA

Test number	17854	17855	17856
Specimen mark	1	3	4
Age ......About	2 years	2 years	2 years
Weight, total lbs.	23.23	27.58	25.45
Weight, per cu. ft., lbs.	137.4	142.8	141.7
Specific gravity	2.202	2.289	2.271
Average diameter, in.	5.89	5.85	5.85
Average height, in.	11.50	12.50	11.75
Area, sq. in.	27.25	26.88	26.88
Compressive strength—			
Total lbs.	69,810	53,940	73,020
Lbs. per sq. in.	2,562	2,007	2,717

CHARACTER OF FRACTURES—

Specimens 1 and 3 failed in planes nearly parallel to the axis of the specimen; No. 4 showed a partly conical fracture; Specimen No. 3 contained a spherical piece of soft conglomerate (?) about 2½ inches in diameter and one large piece of laminated stone probably mica schist. Specimen No. 2 broke while the ends were being prepared for capping; a section broke off which revealed a large laminated stone, which rendered the core unfit for testing. The specific gravity of this stone was 2.705.

REMARKS:

To expedite completion of tests, specimens were all tested as received, that is, air dry except for some water absorbed during the coring process.

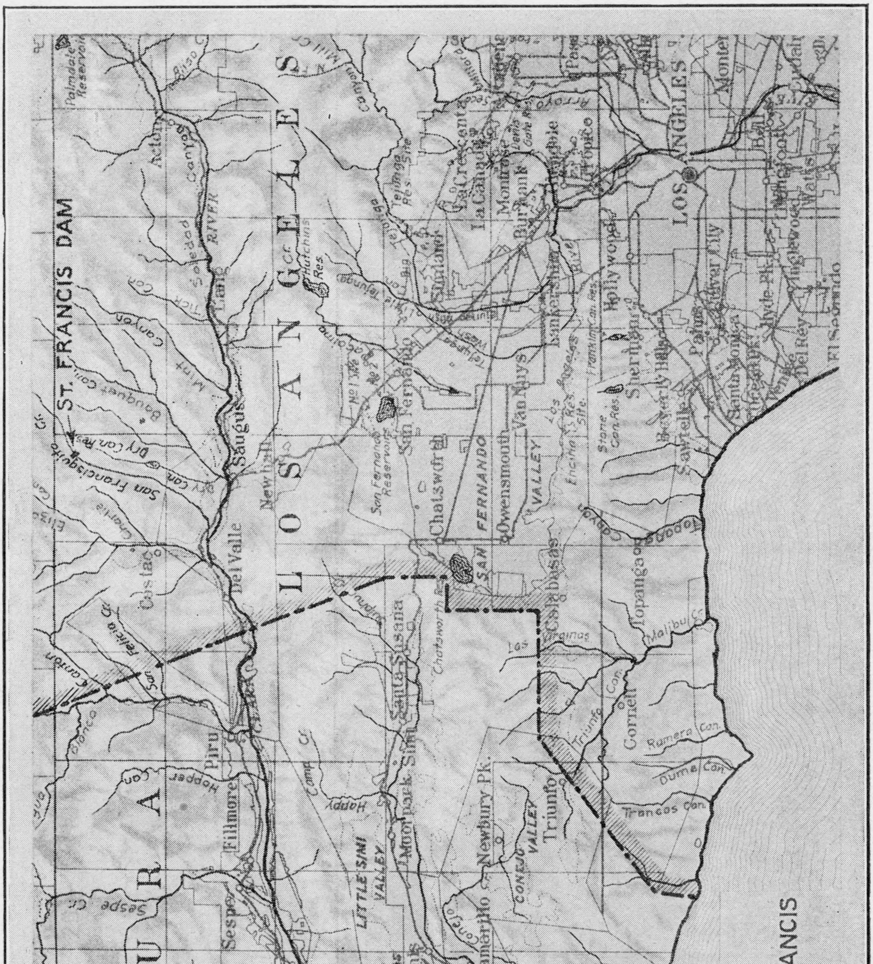
Tested in Olsen Universal Testing machine; speed of moving head—.05 inches per minute.

Tests witnessed by Messrs. Wiley, Bonner, Hyatt, and Perkins.

Respectfully submitted.

RAYMOND G. OSBORNE LABORATORIES.
By S. S. Stahl.

PLATE 1



GENERAL MAP
OF
LOCALITY BETWEEN ST. FRANCIS
DAM AND THE OCEAN

PLATE 2

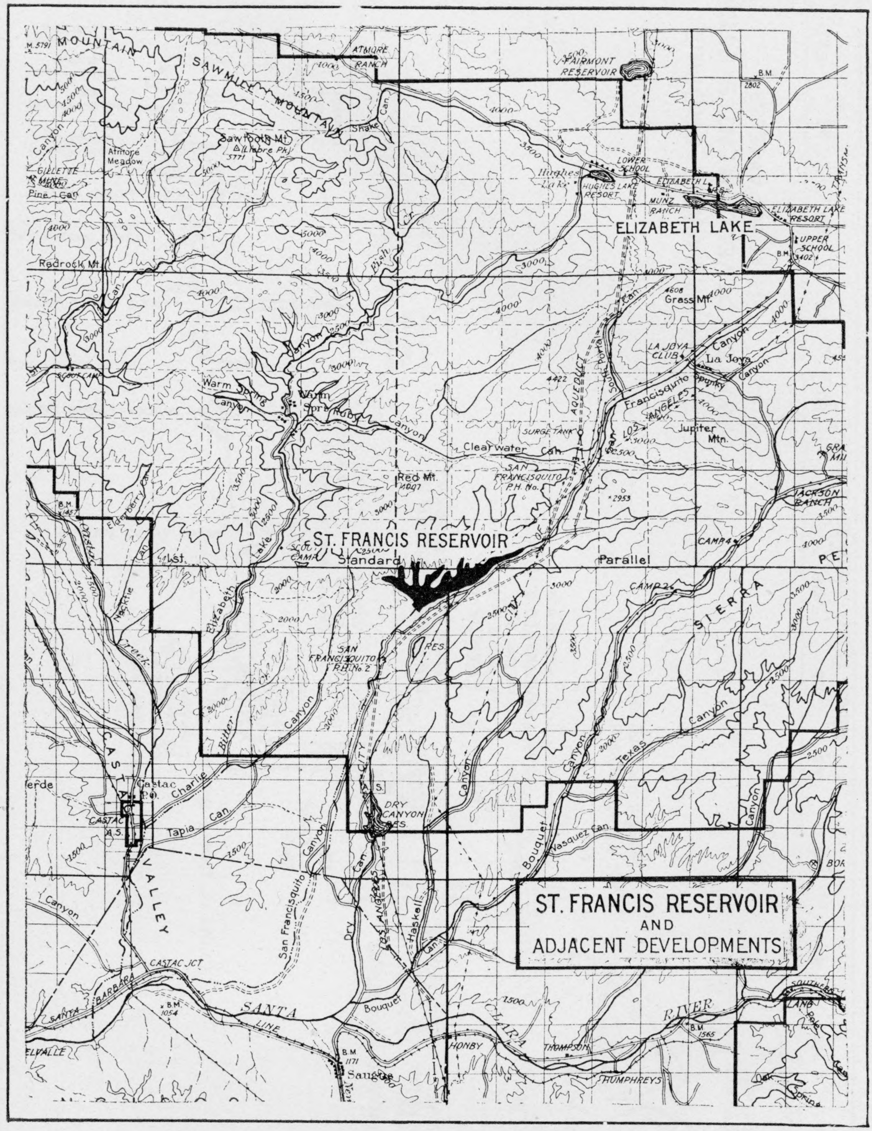

ST. FRANCIS RESERVOIR
AND
ADJACENT DEVELOPMENTS
ST. FRANCIS RESERVOIR
ELIZABETH LAKE
SAWMILL MOUNTAIN
Sawtooth Mt.
Redrock Mt.
Warm Spring Canyon
Red Mt.
Clearwater Can.
SAN FRANCISQUITO P.H. No. 1
SAN FRANCISQUITO P.H. No. 2
Grass Mt.
La Joya
LA JOYA CLUB
Jupiter Mtn.
JACKSON RANCH
SIERRA
DRY CANYON RES.
CASTAIC VALLEY
Castac P.O.
CASTAC JCT.
SANTA CLARA RIVER
Saugus
Bouquet
Vasquez Can.
Texas Canyon
Elizabeth Lake Canyon
San Francisquito Canyon
Dry Can.
Haskell Can.
Tapia Can.
Charlie
Standard
Parallel
AQUEDUCT
HONBY
THOMPSON
HUMPHREYS
HUGHES LAKE RESORT
FAIRMONT RESERVOIR
ELIZABETH LAKE RESORT
MUNZ RANCH
UPPER SCHOOL
LOWER SCHOOL
CAMP 2
CAMP 4
ATMORE RANCH
Atmore Meadow
SURGE TANK

PLATE 3

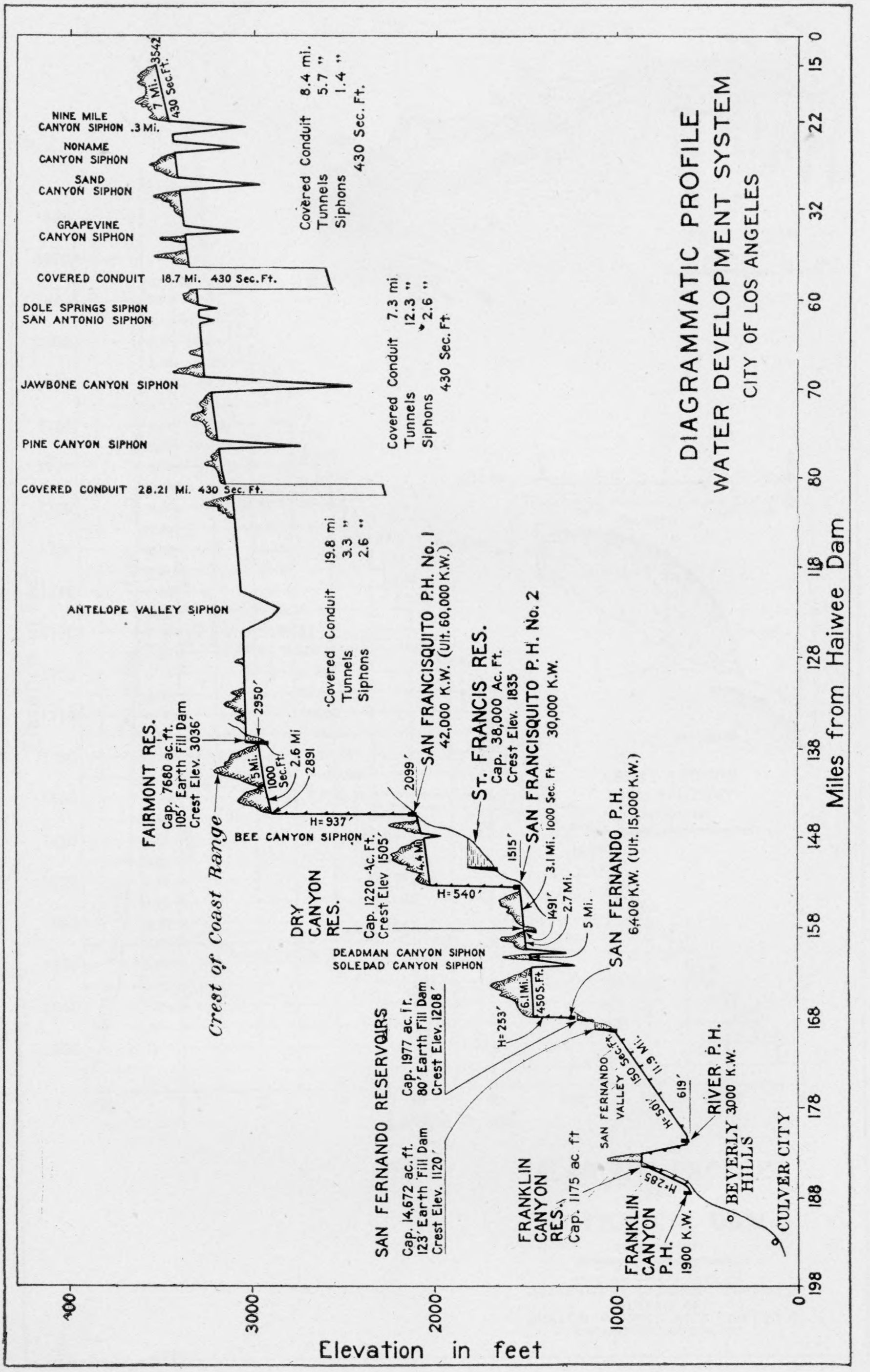
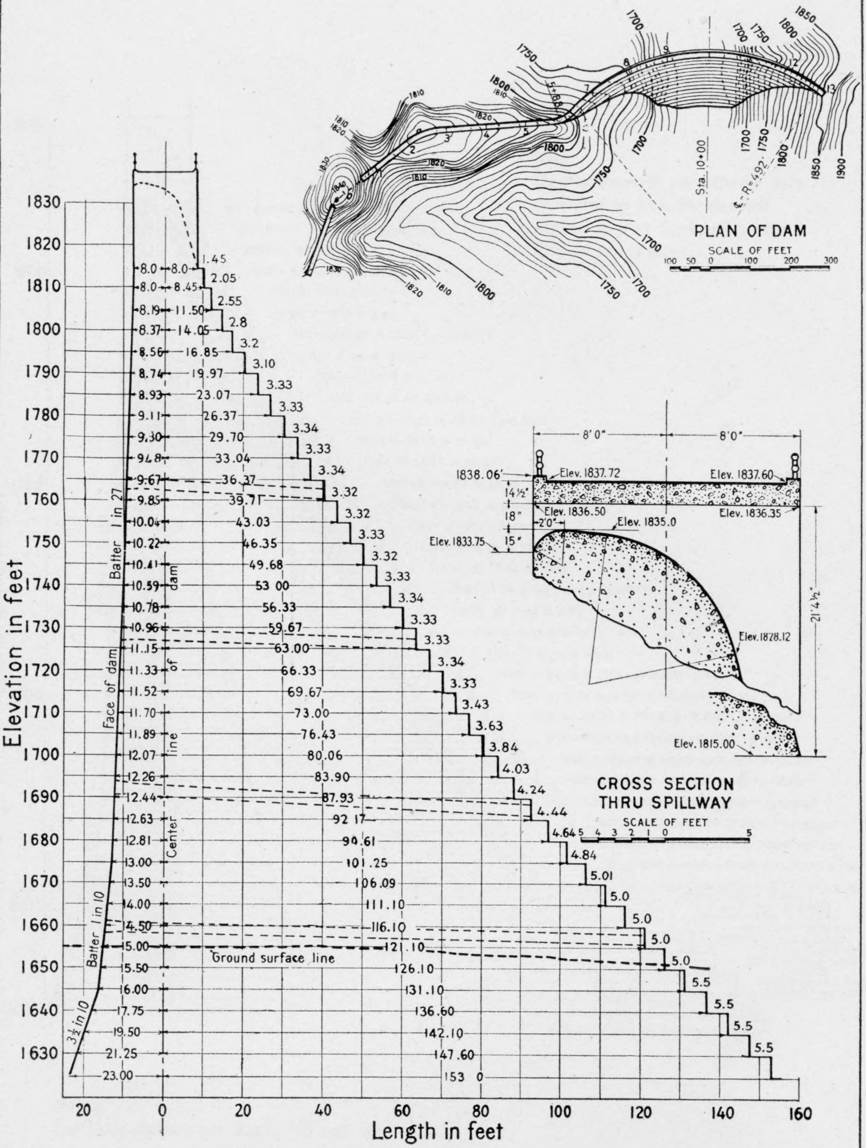

DIAGRAMMATIC PROFILE
WATER DEVELOPMENT SYSTEM
CITY OF LOS ANGELES
Miles from Haiwee Dam
Elevation in feet
NINE MILE CANYON SIPHON .3 Mi.
7 Mi. 430 Sec. Ft.
3542
NONAME CANYON SIPHON
SAND CANYON SIPHON
GRAPEVINE CANYON SIPHON
Covered Conduit 8.4 mi.
Tunnels 5.7 "
Siphons 1.4 "
430 Sec. Ft.
COVERED CONDUIT 18.7 Mi. 430 Sec. Ft.
DOLE SPRINGS SIPHON
SAN ANTONIO SIPHON
JAWBONE CANYON SIPHON
PINE CANYON SIPHON
Covered Conduit 7.3 mi.
Tunnels 12.3 "
Siphons 2.6 "
430 Sec. Ft.
COVERED CONDUIT 28.21 Mi. 430 Sec. Ft.
ANTELOPE VALLEY SIPHON
Covered Conduit 19.8 mi
Tunnels 3.3 "
Siphons 2.6 "
FAIRMONT RES.
Cap. 7680 ac. ft.
105' Earth Fill Dam
Crest Elev. 3036'
2950'
5 Mi.
1000 Sec. Ft.
2.6 Mi
2891
Crest of Coast Range
H = 937'
BEE CANYON SIPHON
2099'
SAN FRANCISQUITO P.H. No. 1
42,000 K.W. (Ult. 60,000 K.W.)
ST. FRANCIS RES.
Cap. 38,000 Ac. Ft.
Crest Elev. 1835
SAN FRANCISQUITO P.H. No. 2
30,000 K.W.
DRY CANYON RES.
Cap. 1220 Ac. Ft.
Crest Elev 1505'
4.4 Mi.
H = 540'
1515'
3.1 Mi. 1000 Sec. Ft
1491'
2.7 Mi.
5 Mi.
DEADMAN CANYON SIPHON
SOLEDAD CANYON SIPHON
6.1 Mi.
450 Sec. Ft.
H = 253'
SAN FERNANDO P.H.
6,400 K.W. (Ult. 15,000 K.W.)
SAN FERNANDO RESERVOIRS
Cap. 14,672 ac. ft.
123' Earth Fill Dam
Crest Elev. 1120'
Cap. 1977 ac. ft.
80' Earth Fill Dam
Crest Elev. 1208'
SAN FERNANDO VALLEY
150 Sec. Ft.
11.9 Mi.
H = 501'
619'
RIVER P.H.
3000 K.W.
FRANKLIN CANYON RES.
Cap. 1175 ac. ft
H = 285'
FRANKLIN CANYON P.H.
1900 K.W.
BEVERLY HILLS
CULVER CITY

PLATE 4

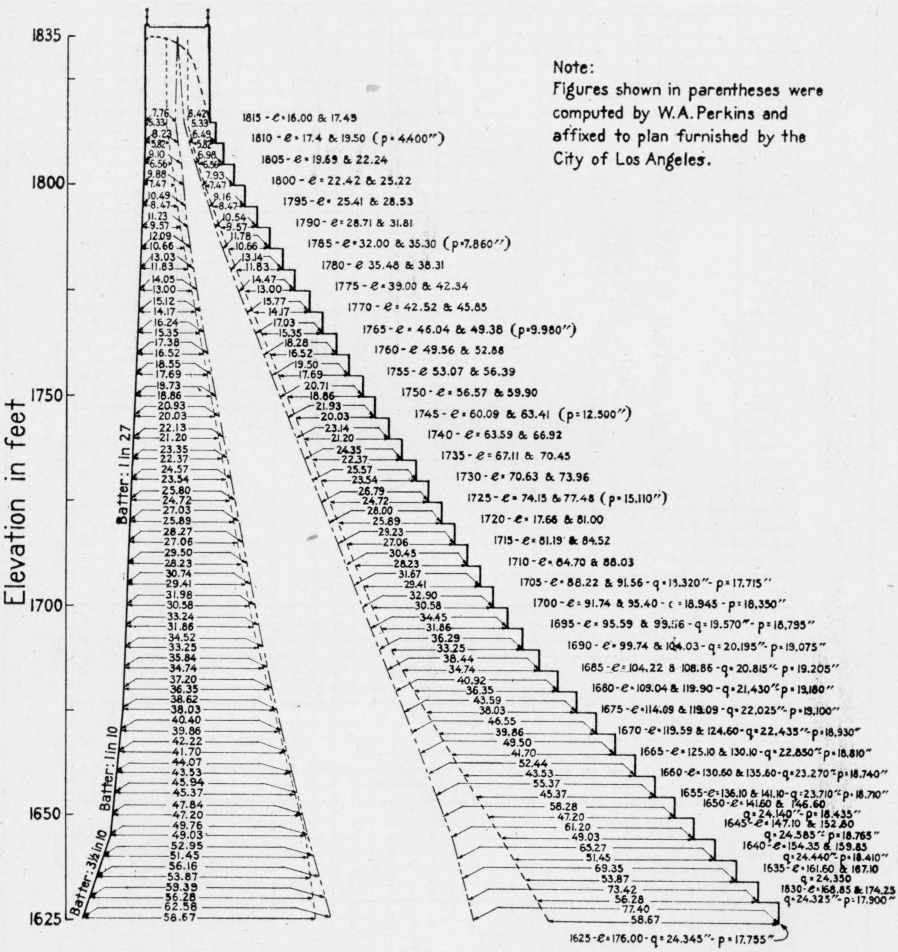


PLAN AND PROFILE
OF
ST. FRANCIS DAM

SCALE OF FEET
5 0 5 10 15 25 35

CITY OF LOS ANGELES
DEPARTMENT OF PUBLIC SERVICE
BUREAU OF
WATER WORKS AND SUPPLY
ENGINEERING DEPARTMENT

PLATE 5



Notes

For computations see Books 119 and 120

Formulae used are given in "Masonry Dam Design" by Morrison and Brodie, second edition. Overturning moment due to horizontal water pressure only was considered.
No allowance made for freeboard.
Pressure on toe of dam, or downstream face, "p" limited to 20,000# per sq. ft.
Pressure on heel of dam, or upstream face, "q" limited to 24,000# per sq. ft
Unit weight of concrete = 140# per cubic foot.
Unit weight of water = 62.5# per cubic foot.
Dam designed as gravity section without considering any arch action.

PROFILE
OF
ST. FRANCIS DAM

CITY OF LOS ANGELES
DEPARTMENT OF PUBLIC SERVICE
BUREAU OF
WATER WORKS AND SUPPLY
ENGINEERING DEPARTMENT

PLATE 6

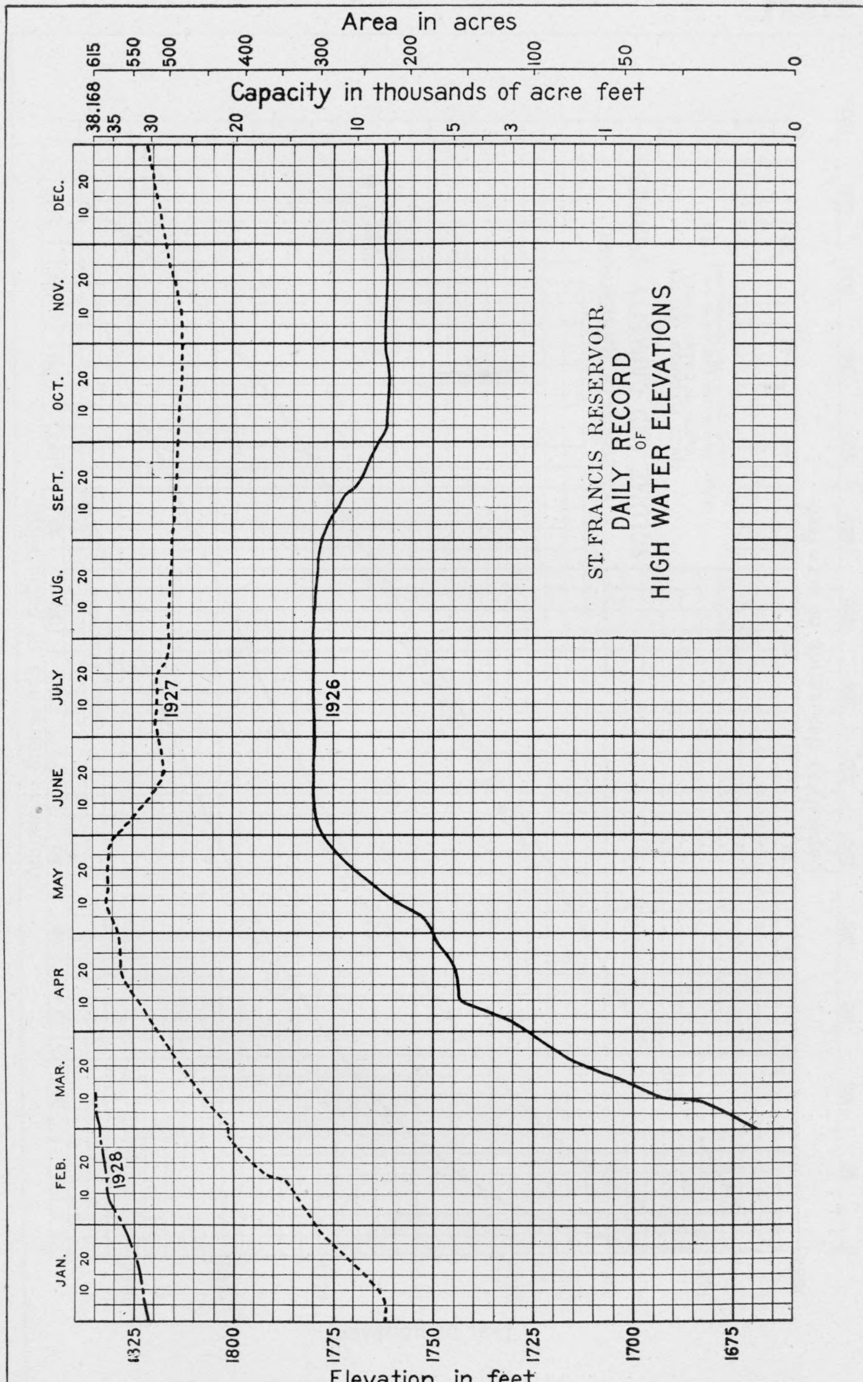

Area in acres
Capacity in thousands of acre feet
Elevation in feet
ST. FRANCIS RESERVOIR
DAILY RECORD
OF
HIGH WATER ELEVATIONS
1926
1927
1928
JAN.
FEB.
MAR.
APR
MAY
JUNE
JULY
AUG.
SEPT.
OCT.
NOV.
DEC.

PLATE 7

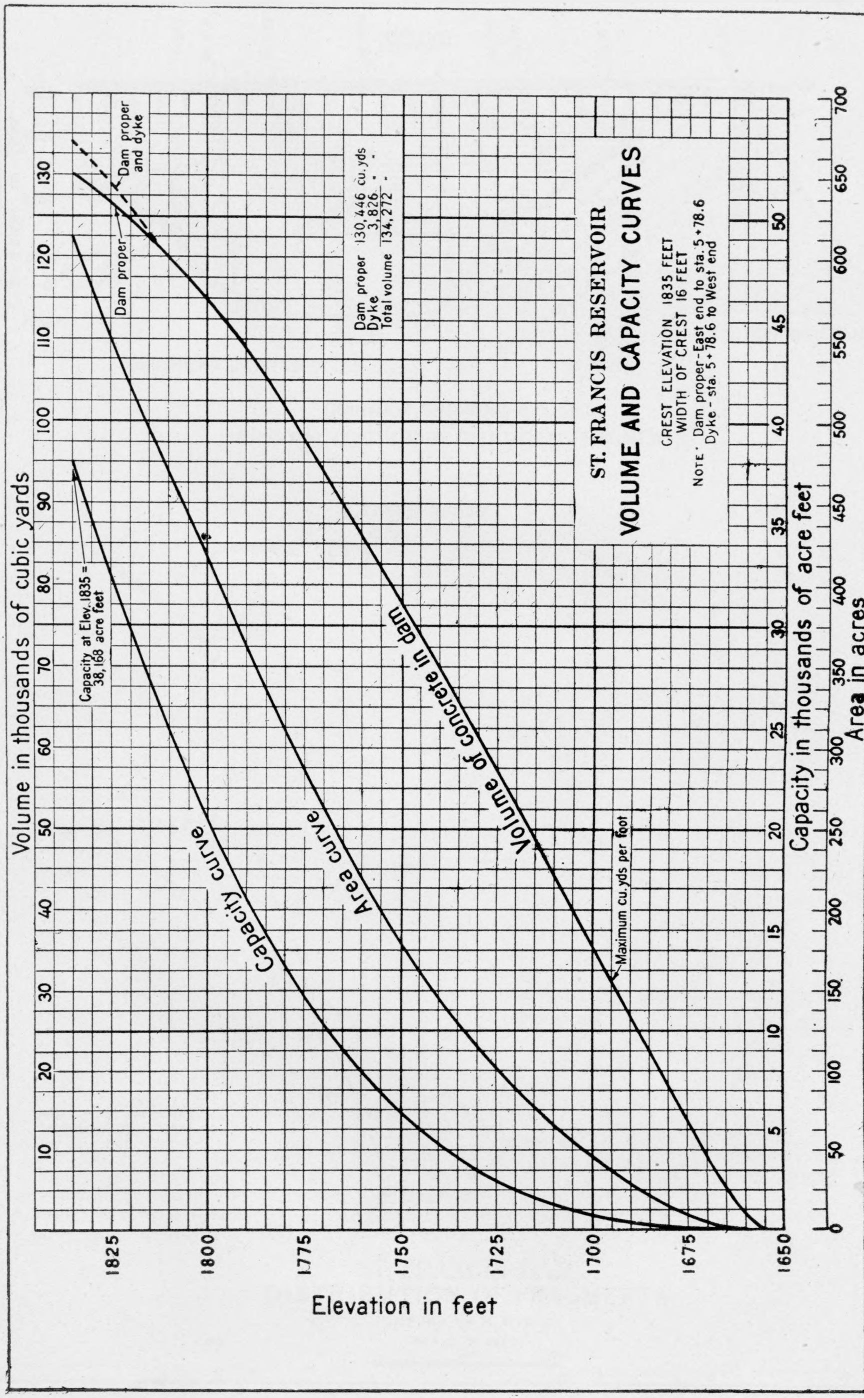

ST. FRANCIS RESERVOIR
VOLUME AND CAPACITY CURVES
CREST ELEVATION 1835 FEET
WIDTH OF CREST 16 FEET
NOTE: Dam proper - East end to sta. 5+78.6
Dyke - sta. 5+78.6 to West end
Dam proper 130,446 cu. yds
Dyke 3,826 " "
Total volume 134,272 " "
Dam proper
Dam proper and dyke
Capacity at Elev. 1835 = 38,168 acre feet
Capacity curve
Area curve
Volume of concrete in dam
Maximum cu. yds per foot
Volume in thousands of cubic yards
10
20
30
40
50
60
70
80
90
100
110
120
130
Elevation in feet
1825
1800
1775
1750
1725
1700
1675
1650
Capacity in thousands of acre feet
5
10
15
20
25
30
35
40
45
50
Area in acres
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700

PLATE 8

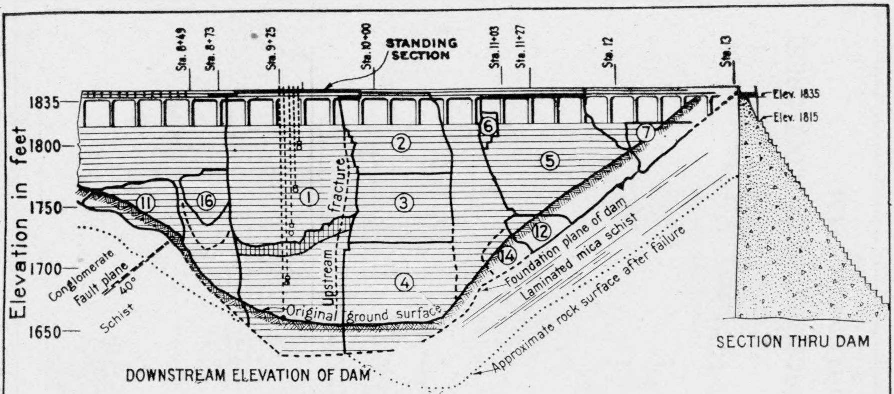
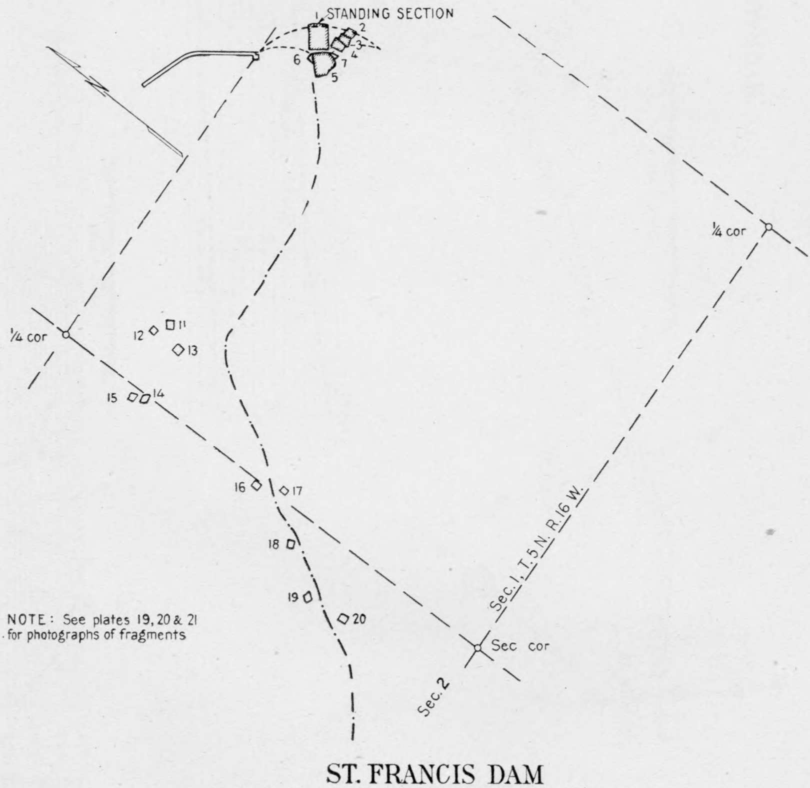


DIAGRAM SHOWING EROSION AND ORIGINAL POSITION OF IDENTIFIED FRAGMENTS



ST. FRANCIS DAM
DISTRIBUTION OF FRAGMENTS
Survey by H. Wildy
SCALE OF FEET
0 500 1000

PLATE 9

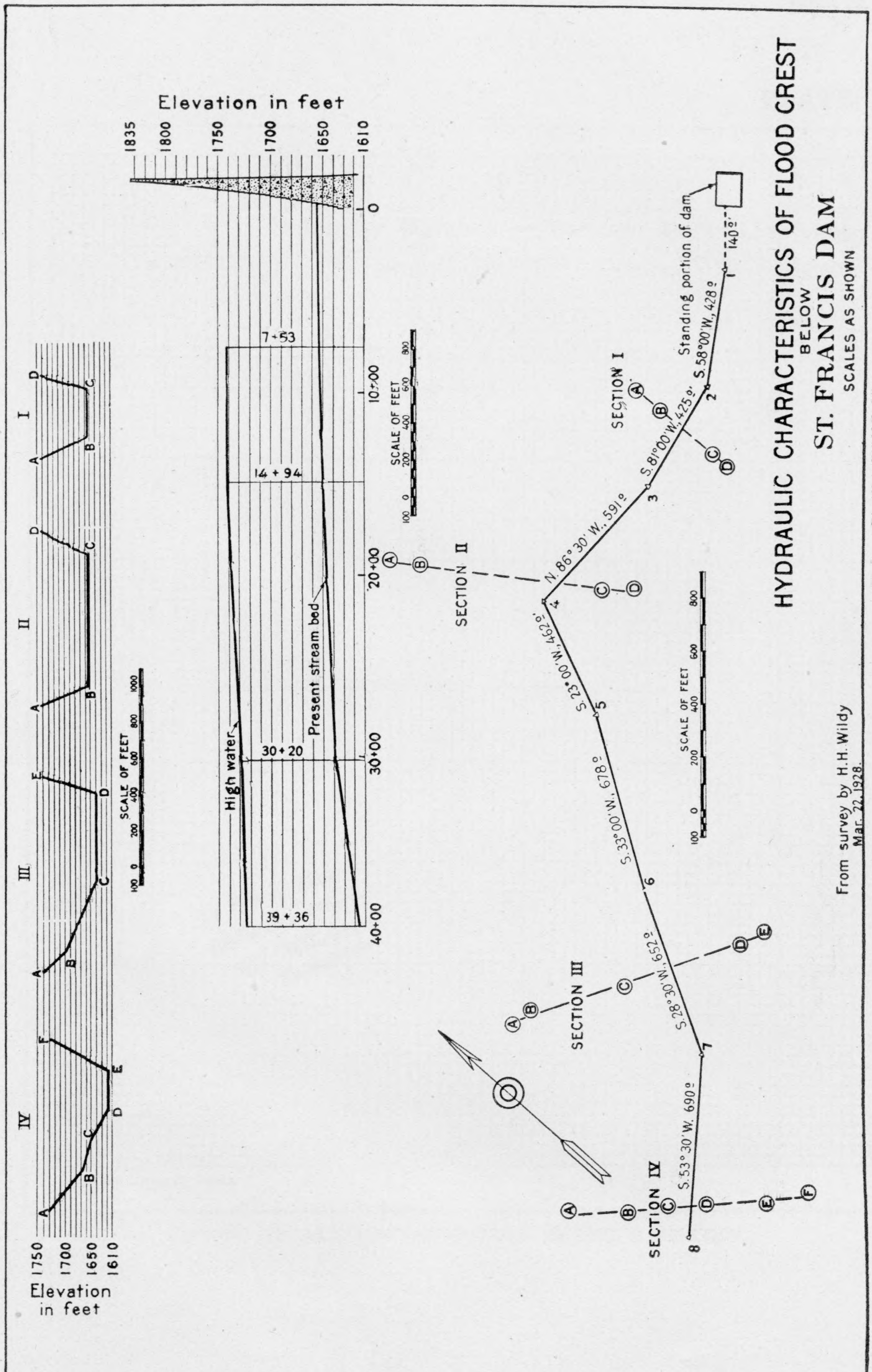

HYDRAULIC CHARACTERISTICS OF FLOOD CREST
BELOW
ST. FRANCIS DAM
SCALES AS SHOWN
From survey by H.H. Wildy
Mar. 22, 1928.
Elevation in feet
High water
Present stream bed
SCALE OF FEET
Standing portion of dam
SECTION I
SECTION II
SECTION III
SECTION IV
S.58°00'W., 428°
S.81°00'W., 425°
N.86°30'W., 591°
S.23°00'W., 462°
S.33°00'W., 678°
S.28°30'W., 652°
S.53°30'W. 690°
7+53
14+94
30+20
39+36

PLATE 10

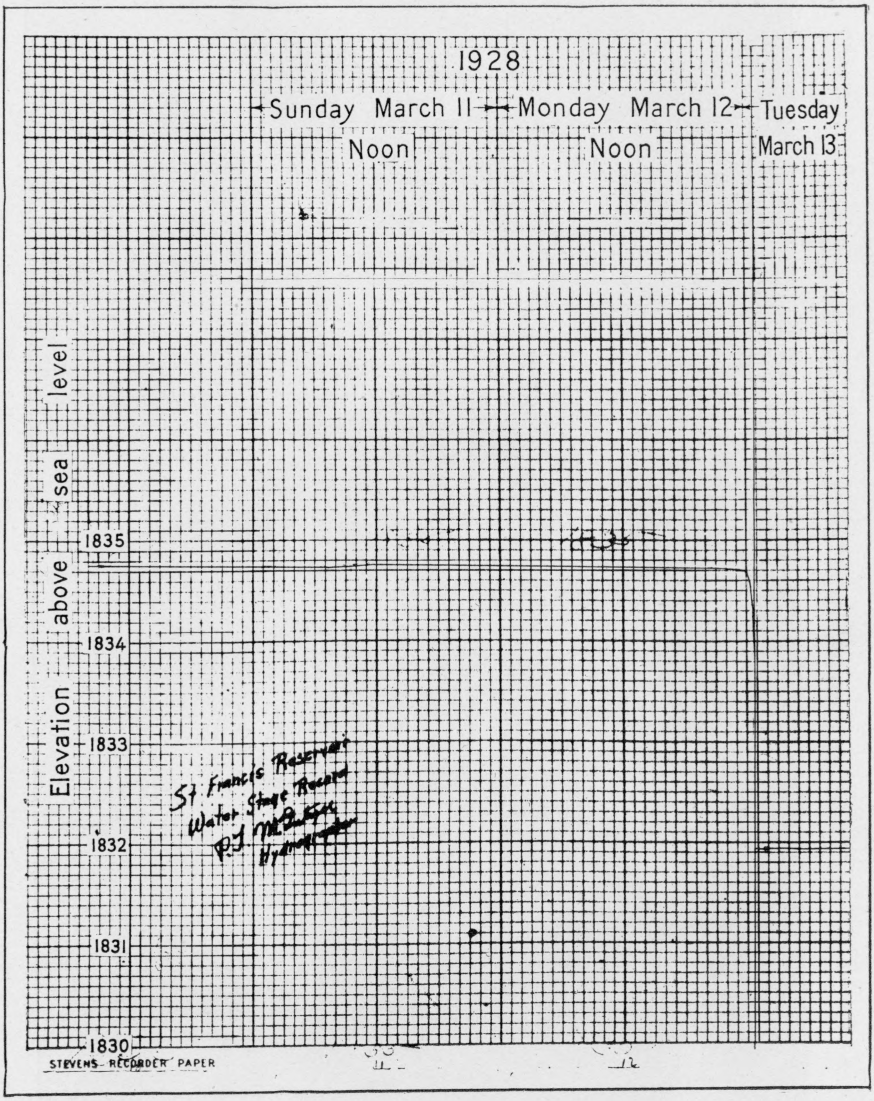
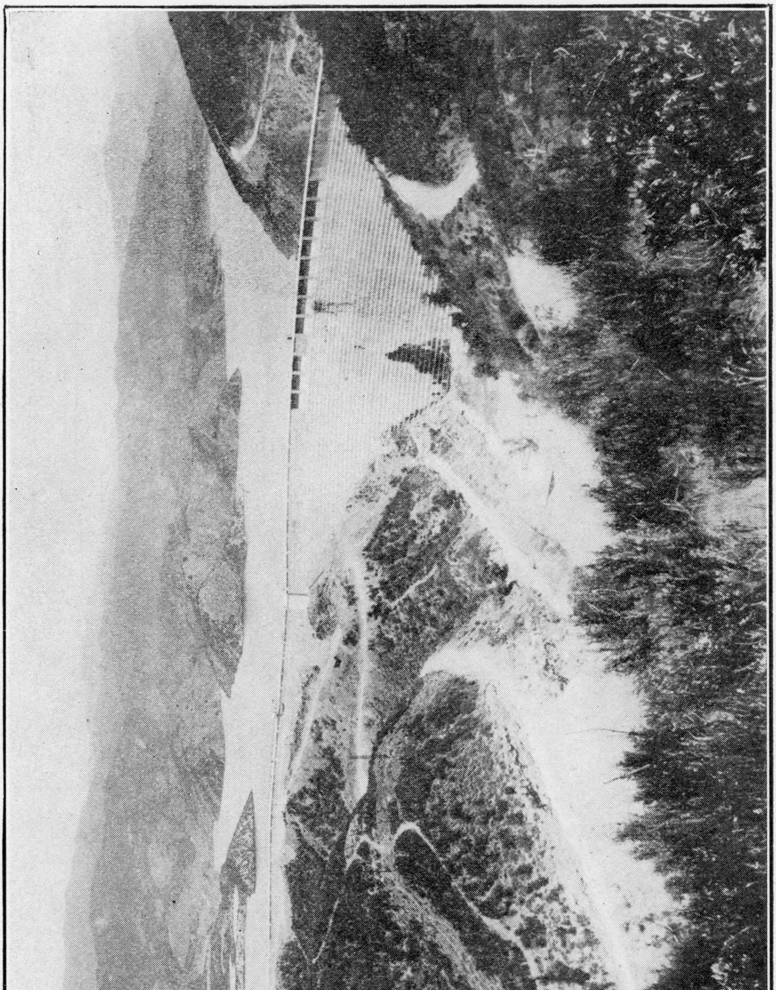


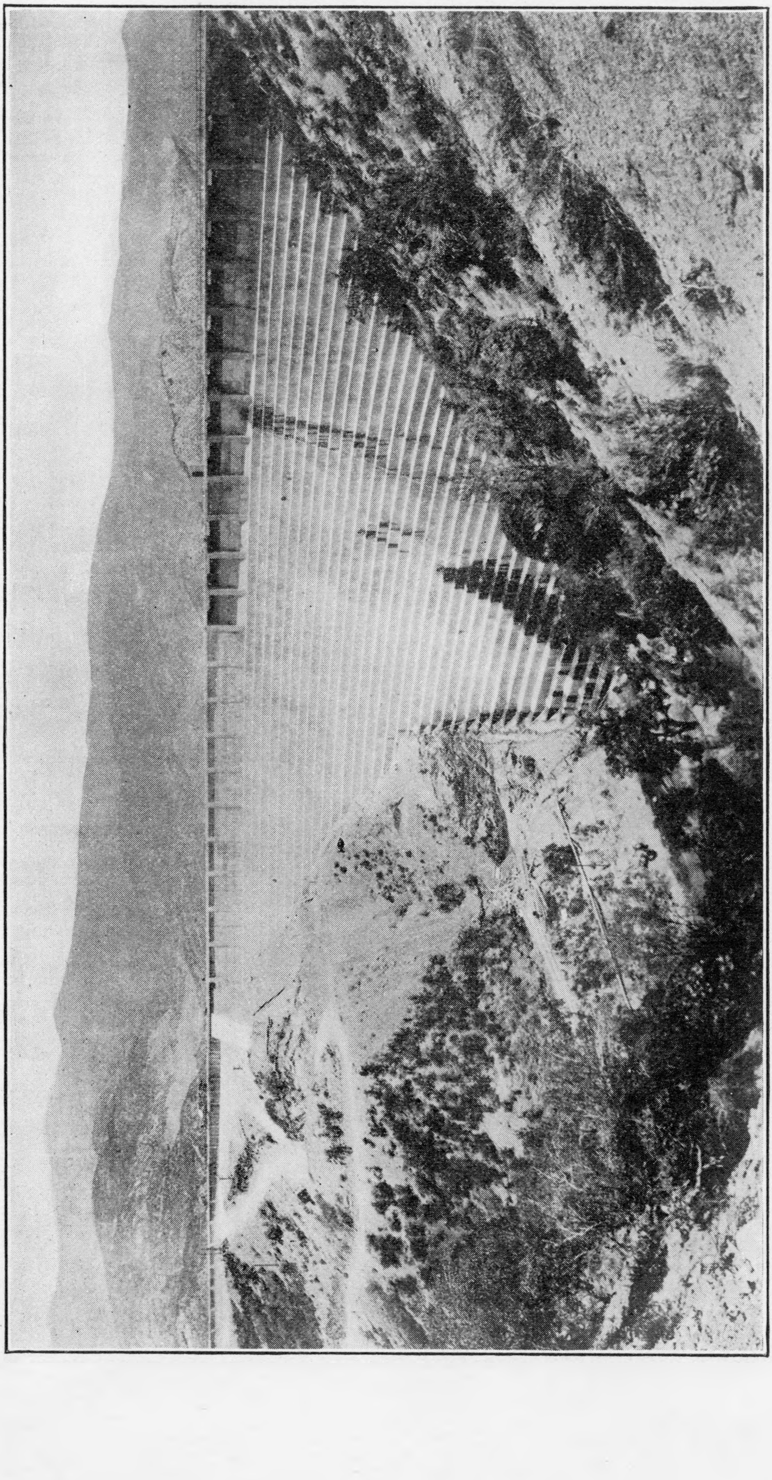
CHART OF AUTOMATIC WATER STAGE REGISTER.

PLATE 11



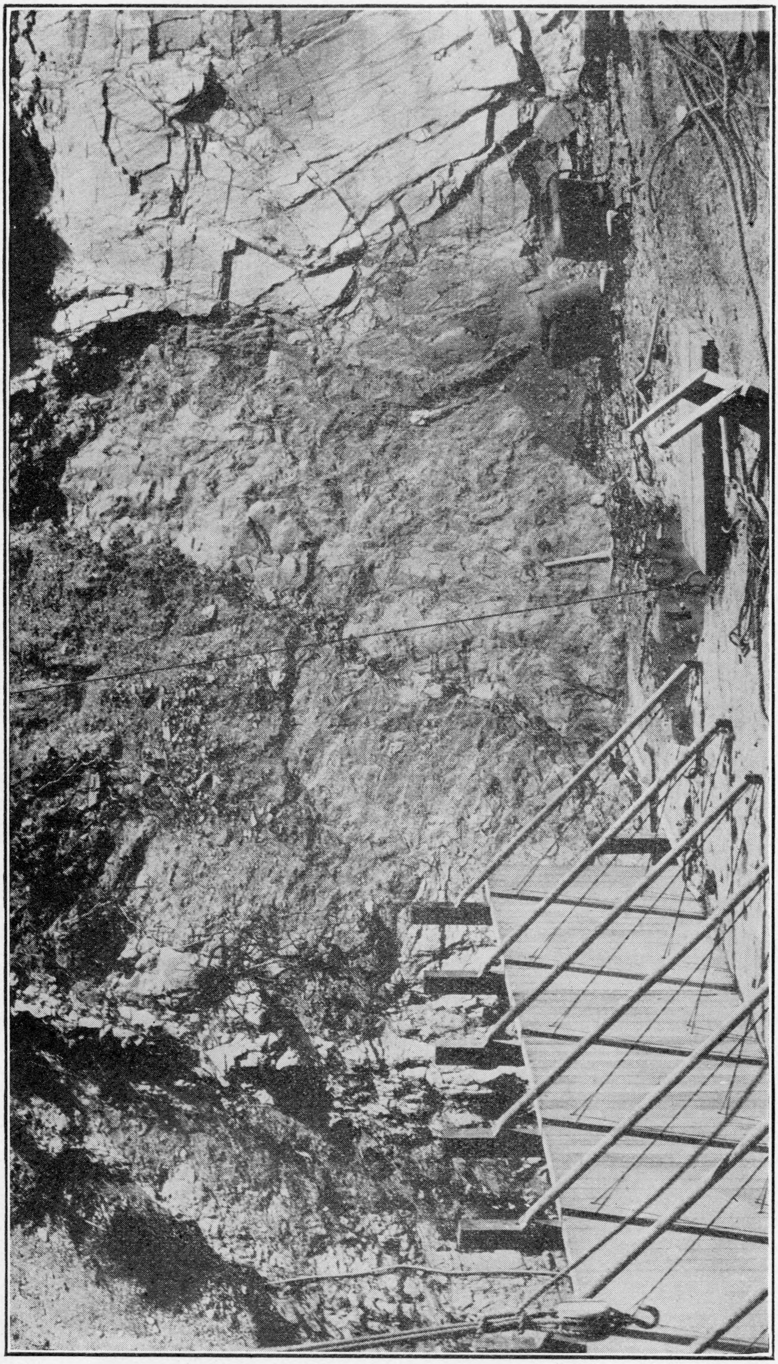
GENERAL VIEW OF COMPLETED ST. FRANCIS DAM AND RESERVOIR.

PLATE 12



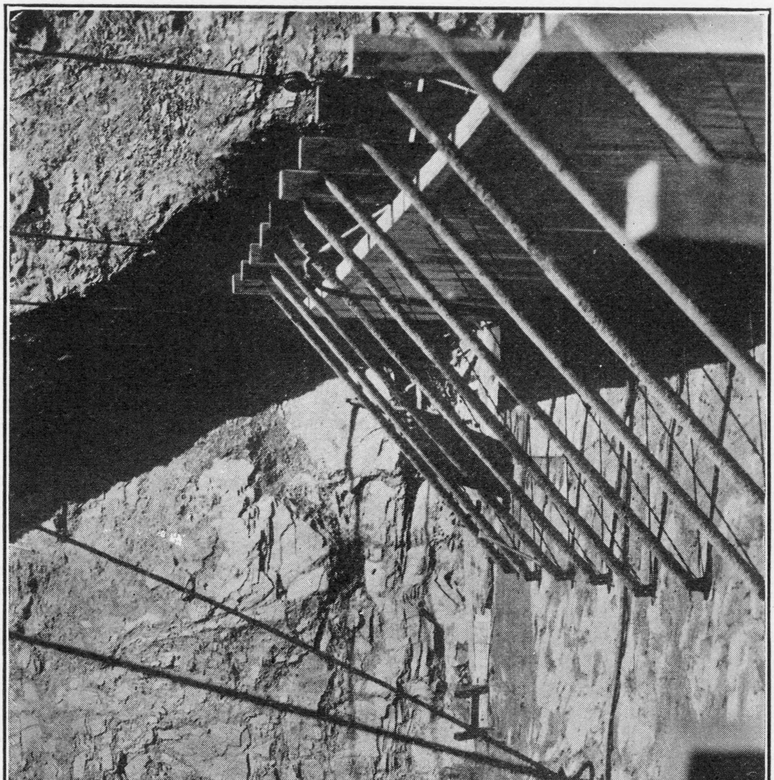
DOWNSTREAM FACE, ST. FRANCIS DAM FROM SOUTH.

PLATE 13



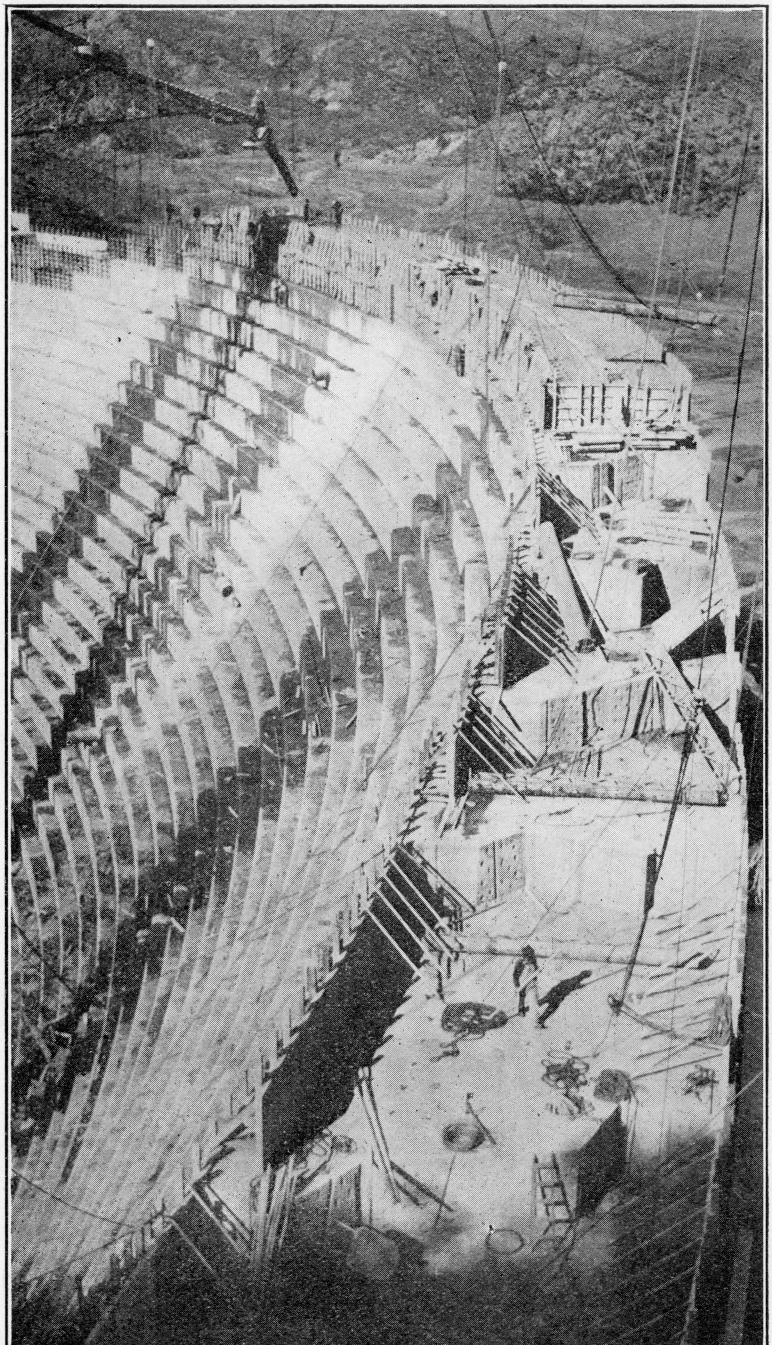
CONSTRUCTION VIEW SHOWING SHAPING OF EAST ABUTMENT AT UPSTREAM WALL.

PLATE 14



PLACING CONCRETE AGAINST EAST ABUTMENT.

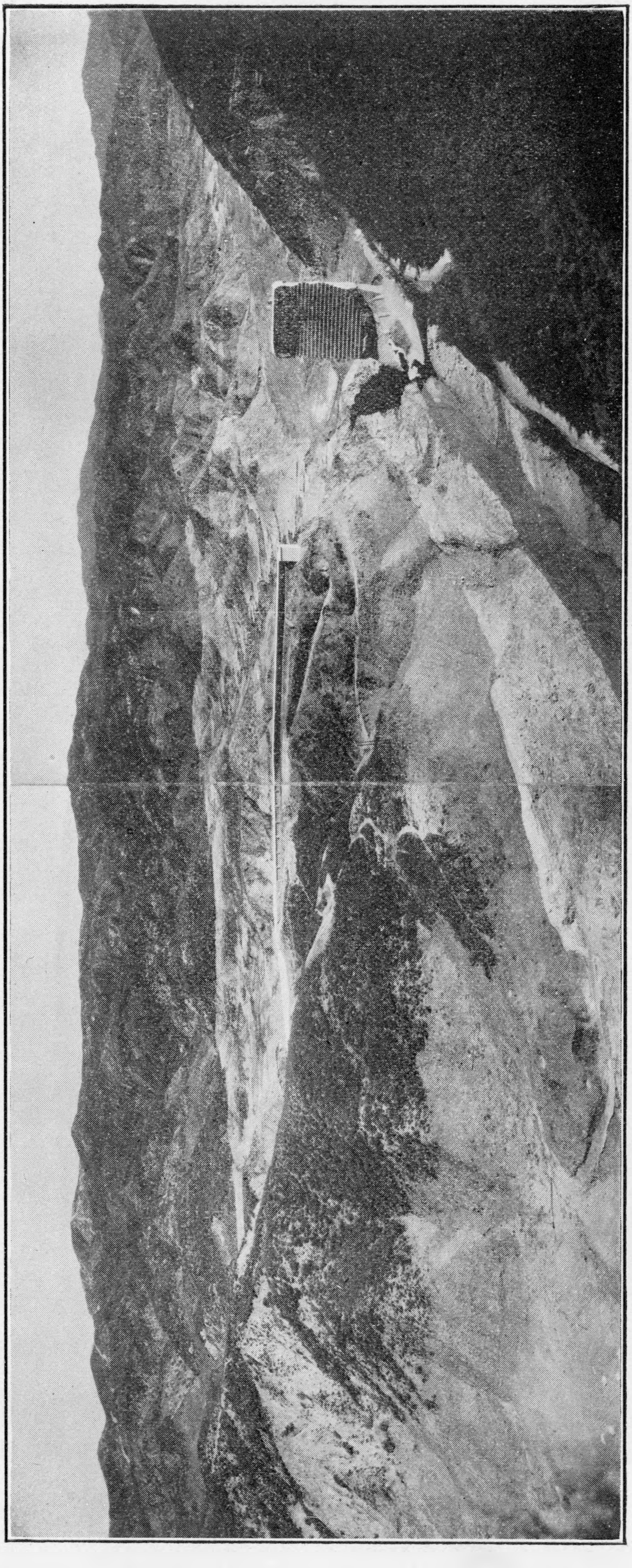
PLATE 15



CONSTRUCTION VIEW SHOWING DAM NEARING COMPLETION

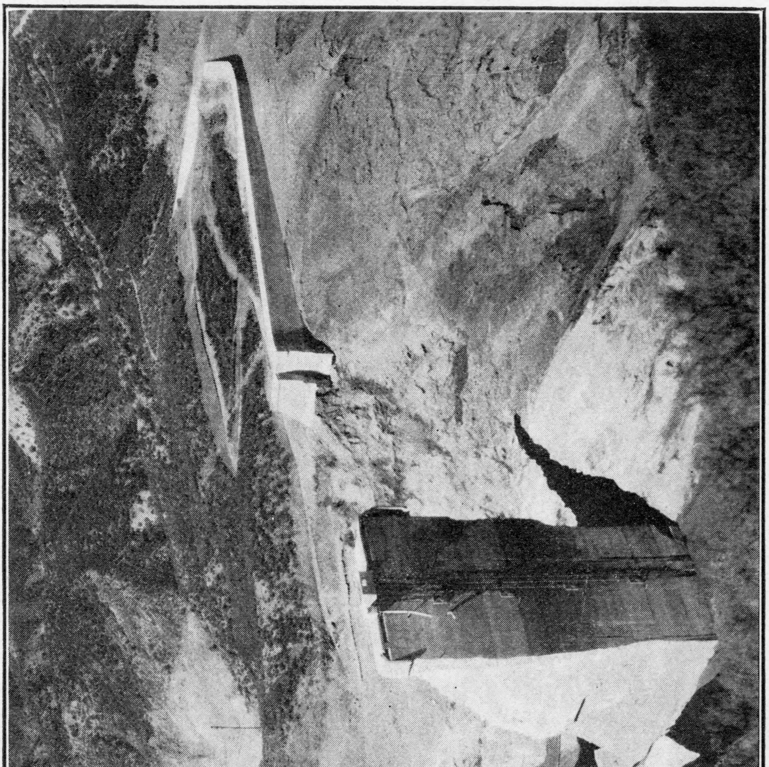
PLATE 16

EXCAVATION FOR WING WALL SECTION.



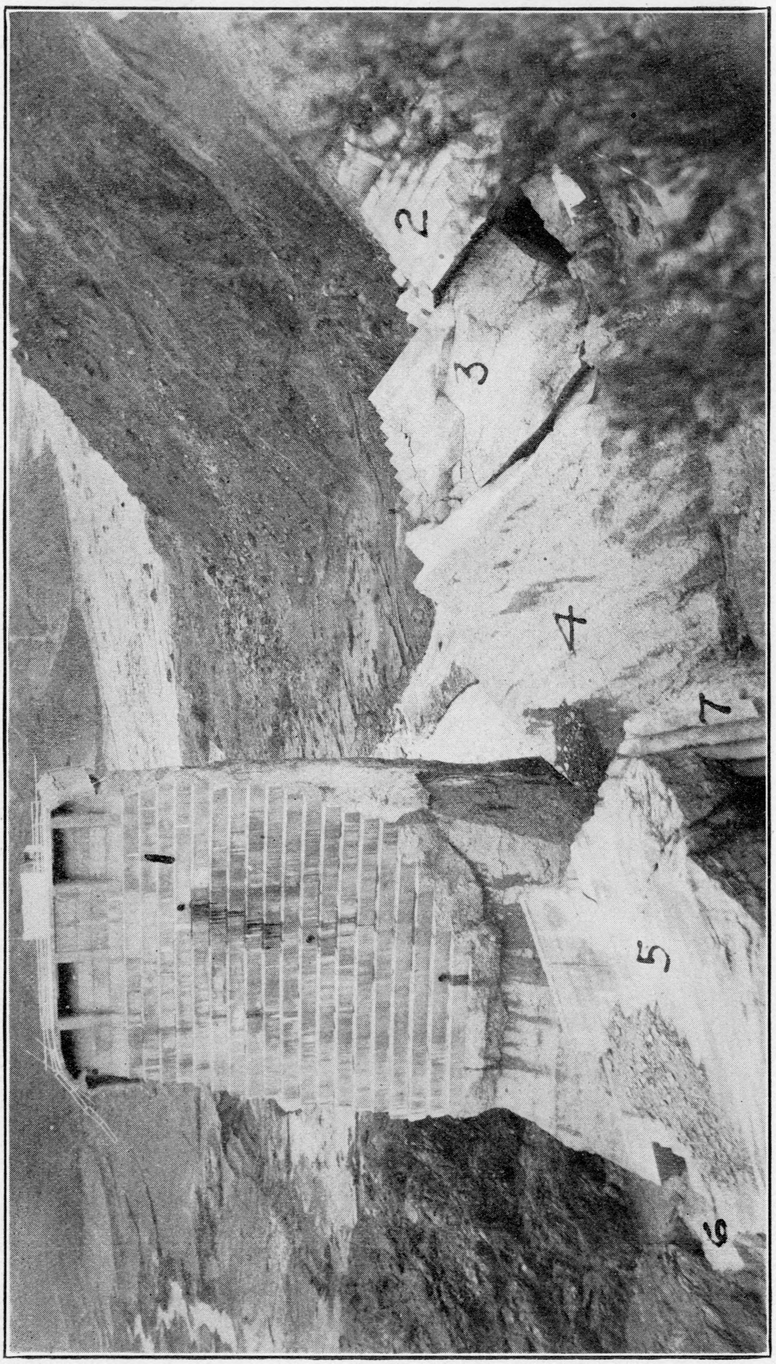
PANORAMA UPSTREAM SHOWING RUINS OF DAM AND LOWER PART OF RESERVOIR SITE.

PLATE 18



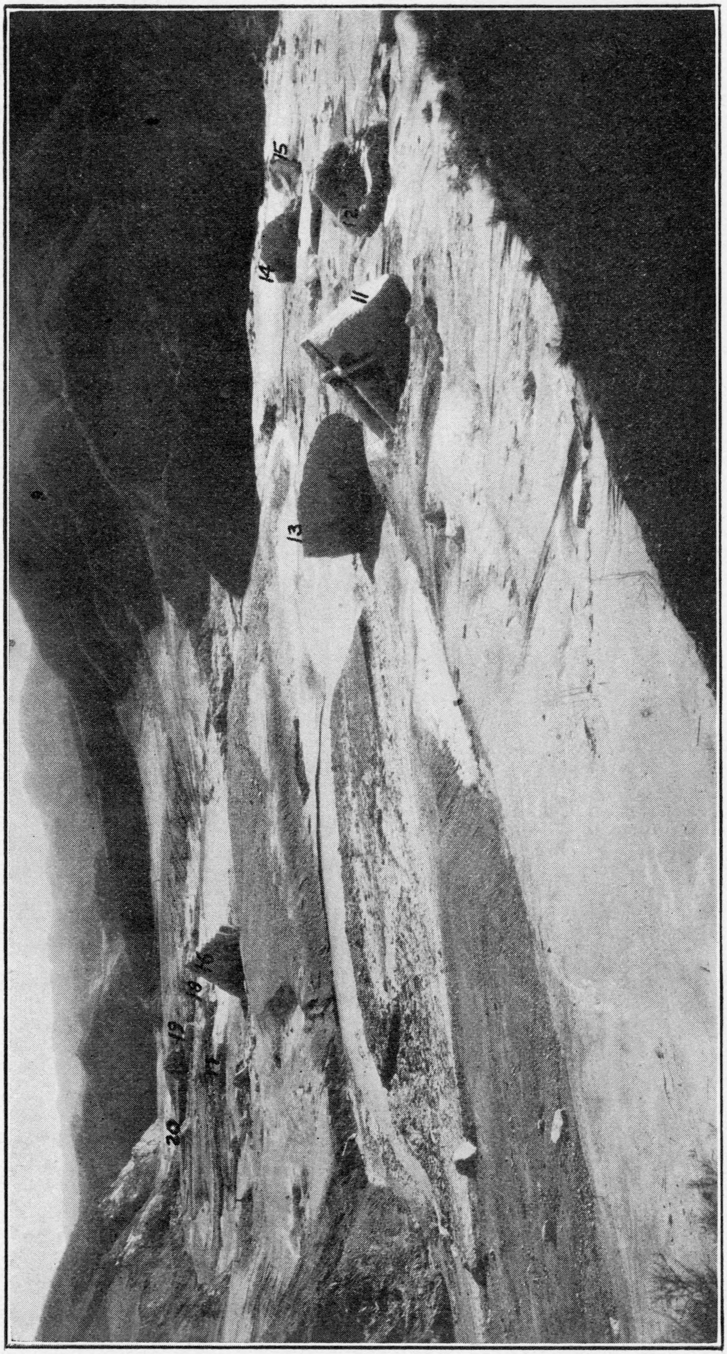
GENERAL VIEW DOWNSTREAM FROM EASTERLY BANK SHOWING DAM AND WRECKAGE.

PLATE 19



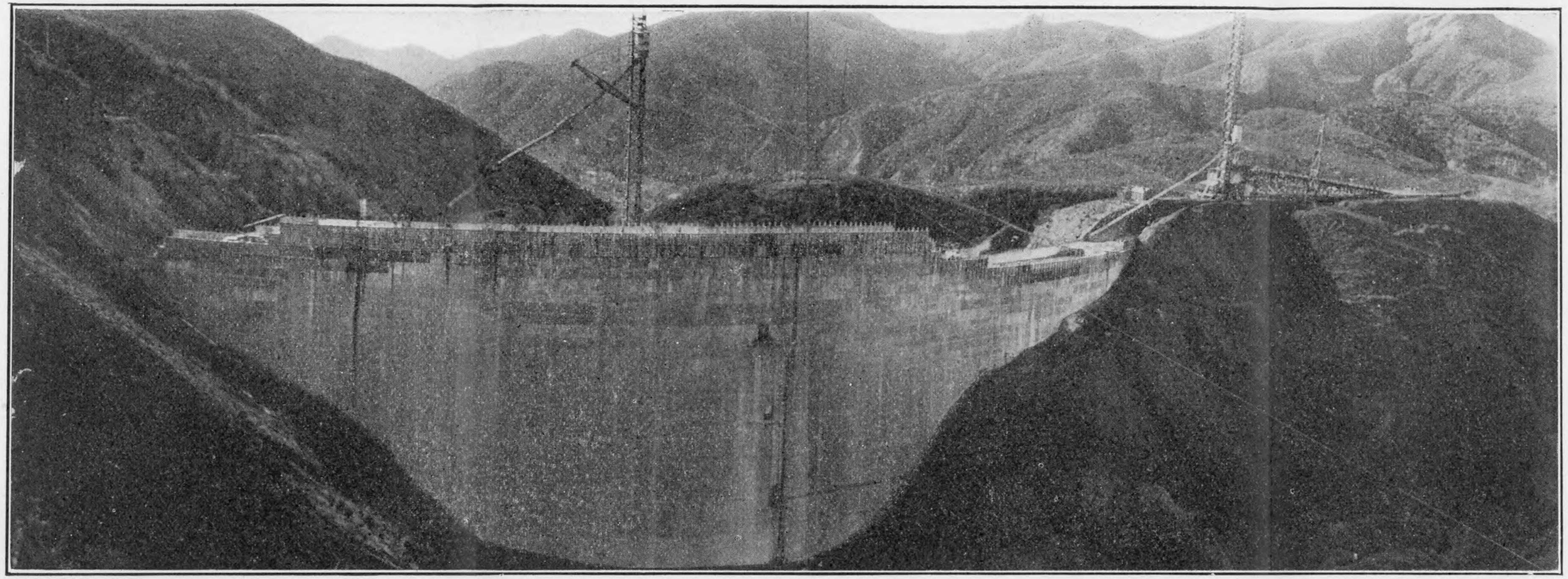
VIEW UPSTREAM SHOWING WRECKAGE OF EAST ABUTMENT SECTION.

PLATE 20



CONCRETE FRAGMENTS OF DAM DEPOSITED DOWNSTREAM BY FLOOD WAVE.

PLATE 15-A

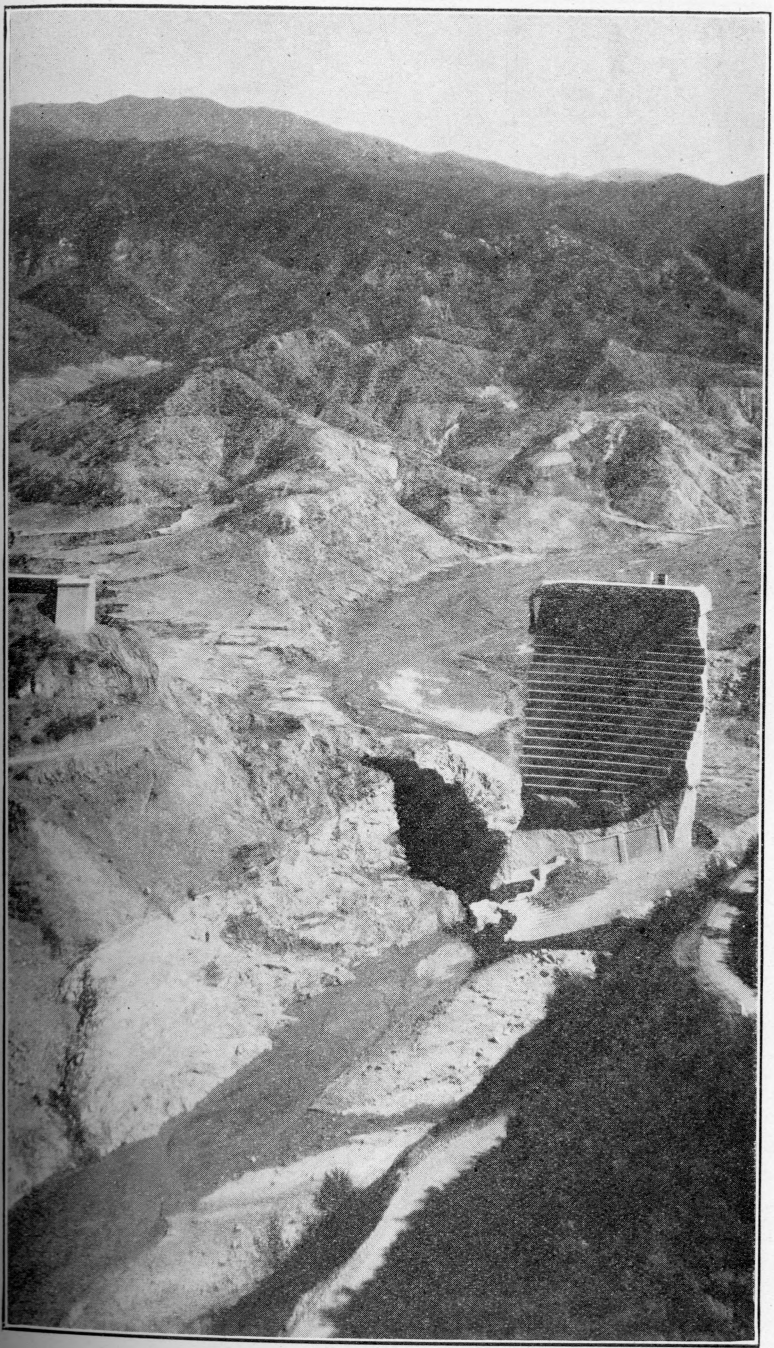


VIEW OF UPSTREAM FACE OF DAM NEARING COMPLETION.

PLATE 21

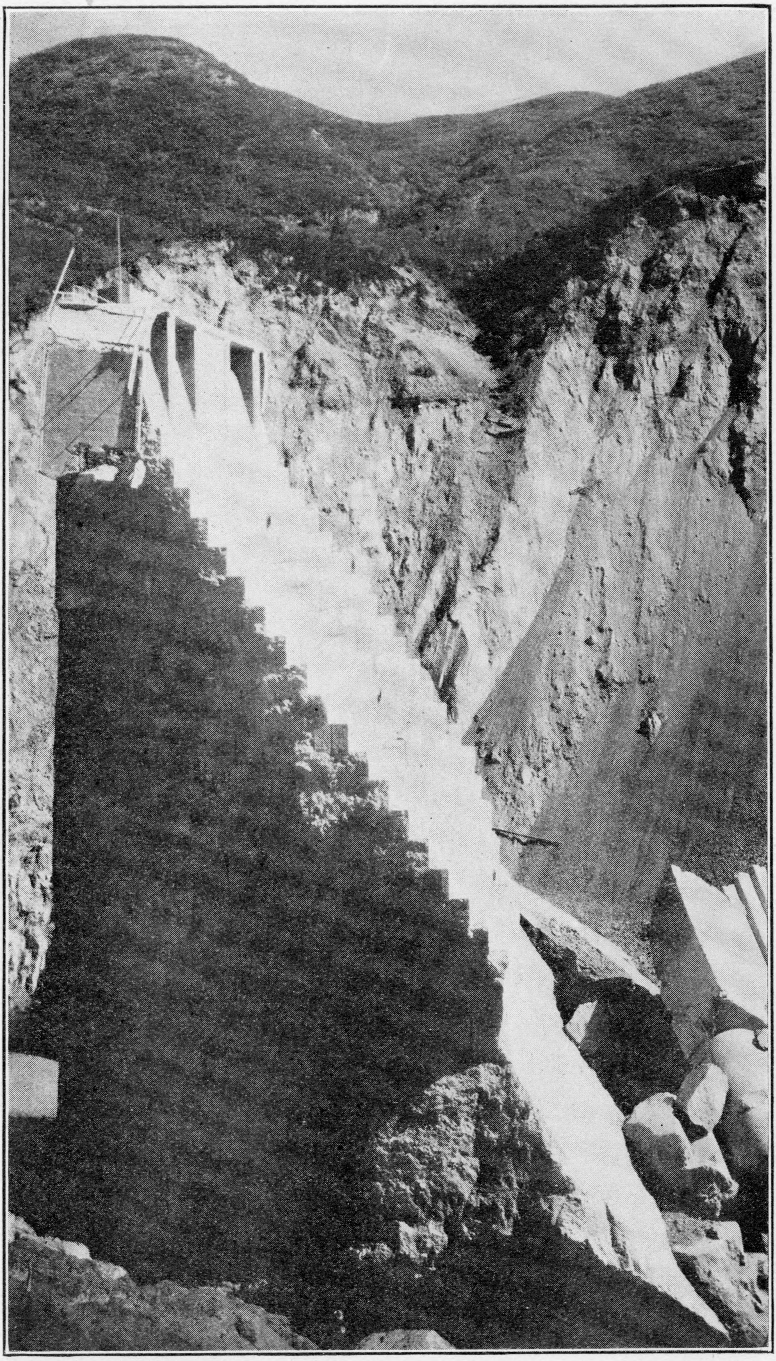
PANORAMA SHOWING FRAGMENTS DEPOSITED DOWNSTREAM.

PLATE 22



GENERAL VIEW OF DAM SITE FROM DOWNSTREAM.

PLATE 23

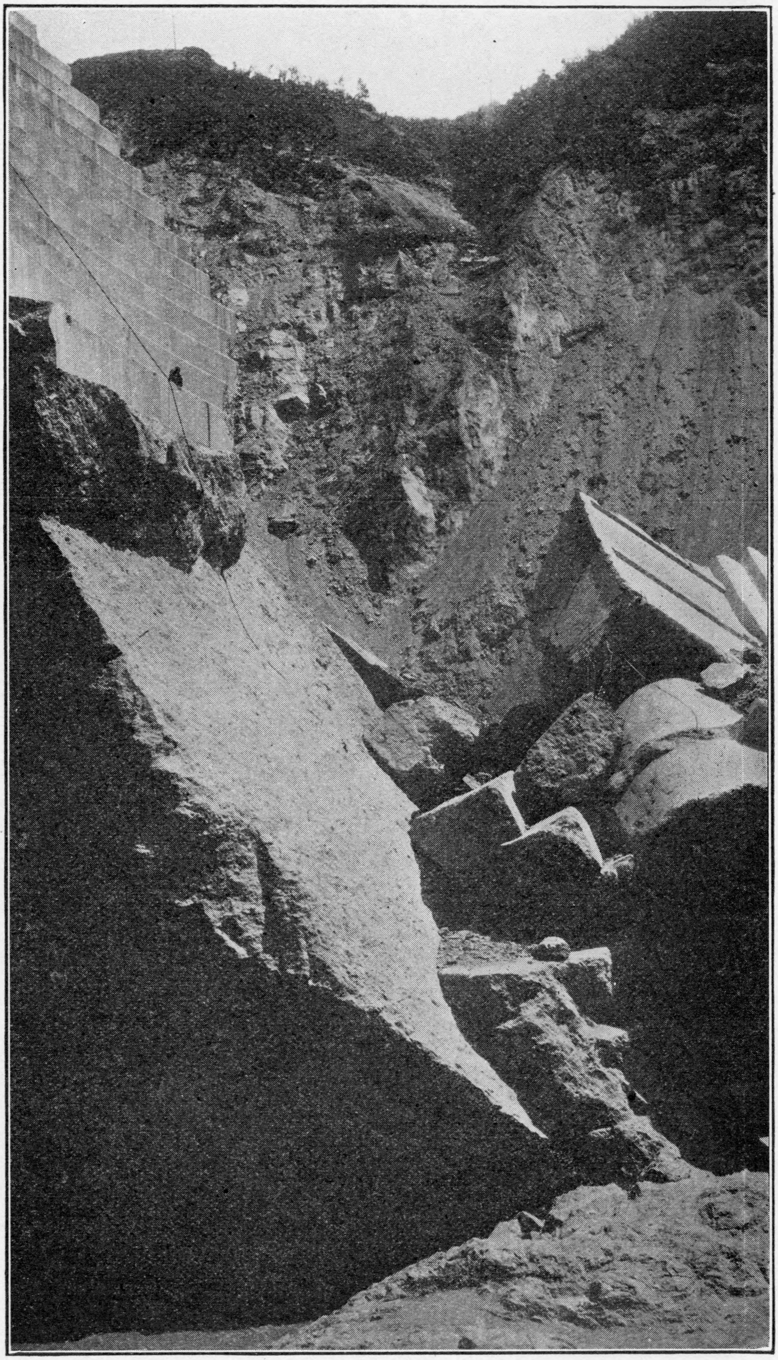


PROFILE OF STANDING SECTION AND VIEW OF EAST ABUTMENT.

PLATE 24

WEST FACE OF STANDING SECTION SHOWING CONTACT PLANE WITH FOUNDATION.

PLATE 25

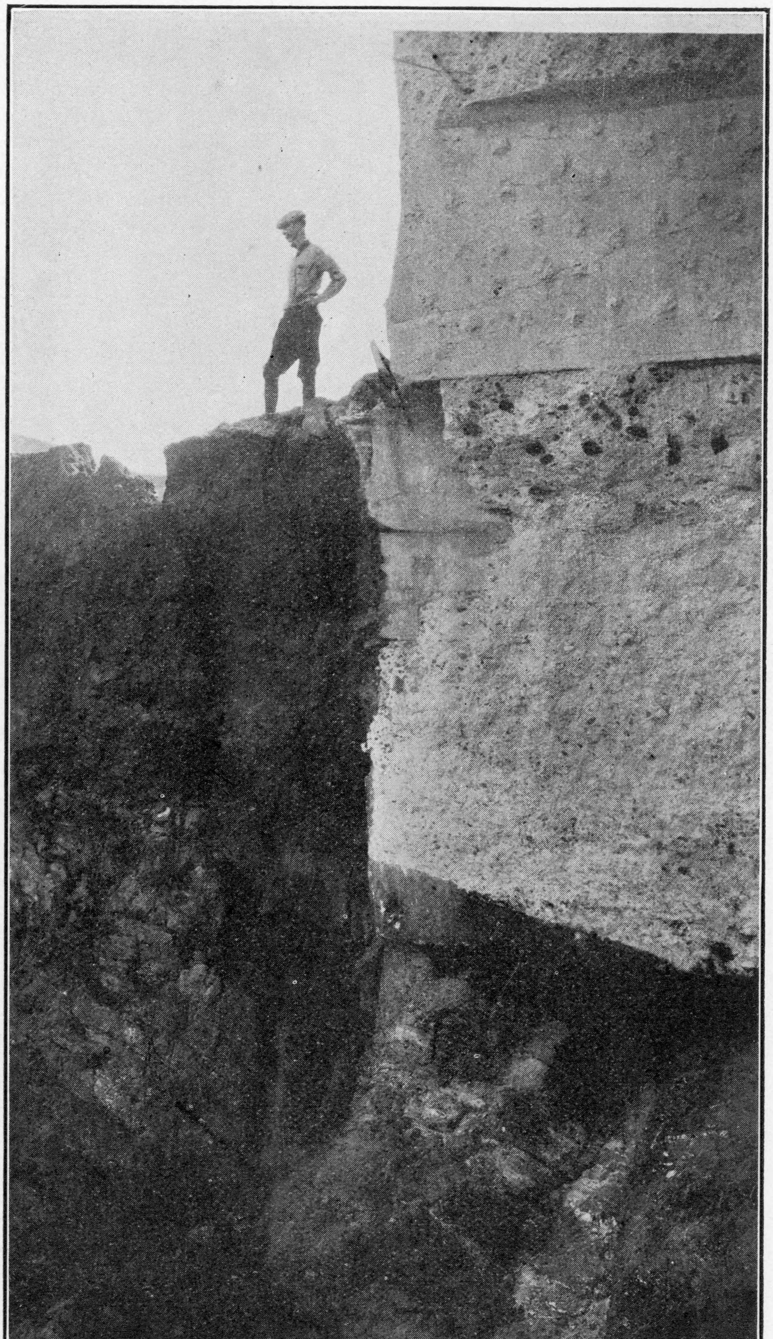


CONTACT PLANE BETWEEN CONCRETE AND FOUNDATION NEAR DOWNSTREAM TOE OF STANDING SECTION.

PLATE 26

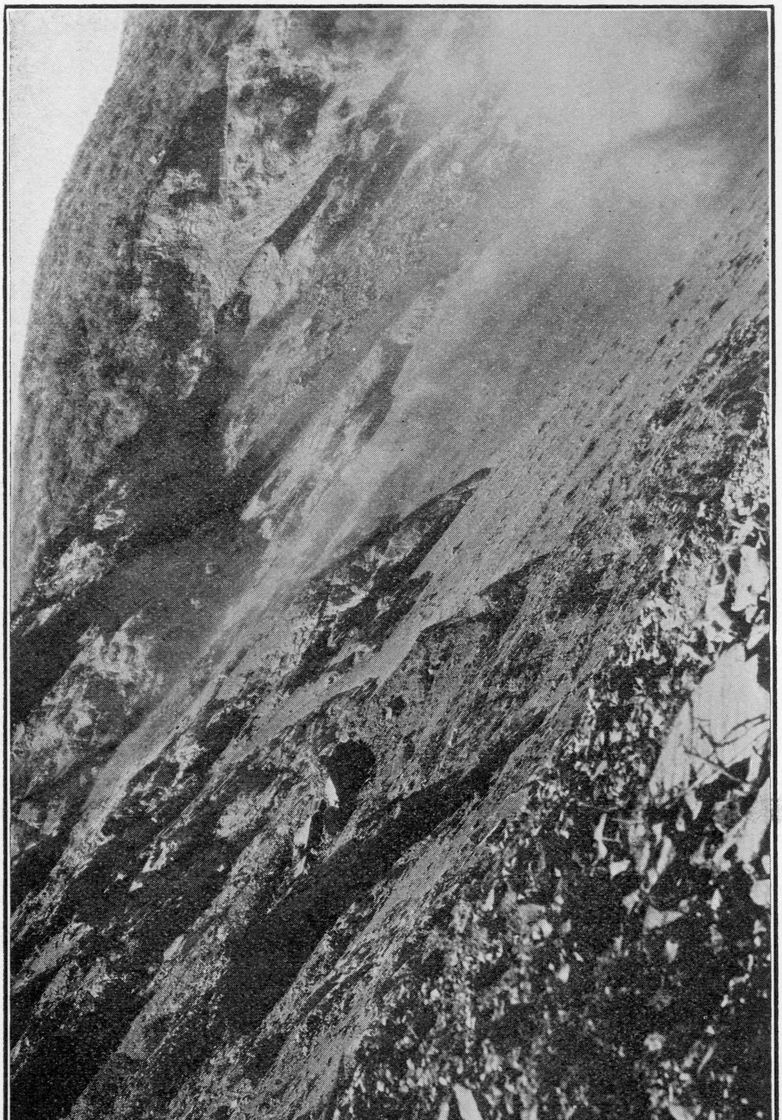
DOWNSTREAM PROFILE OF STANDING SECTION SHOWING SHEER PLANE.

PLATE 27



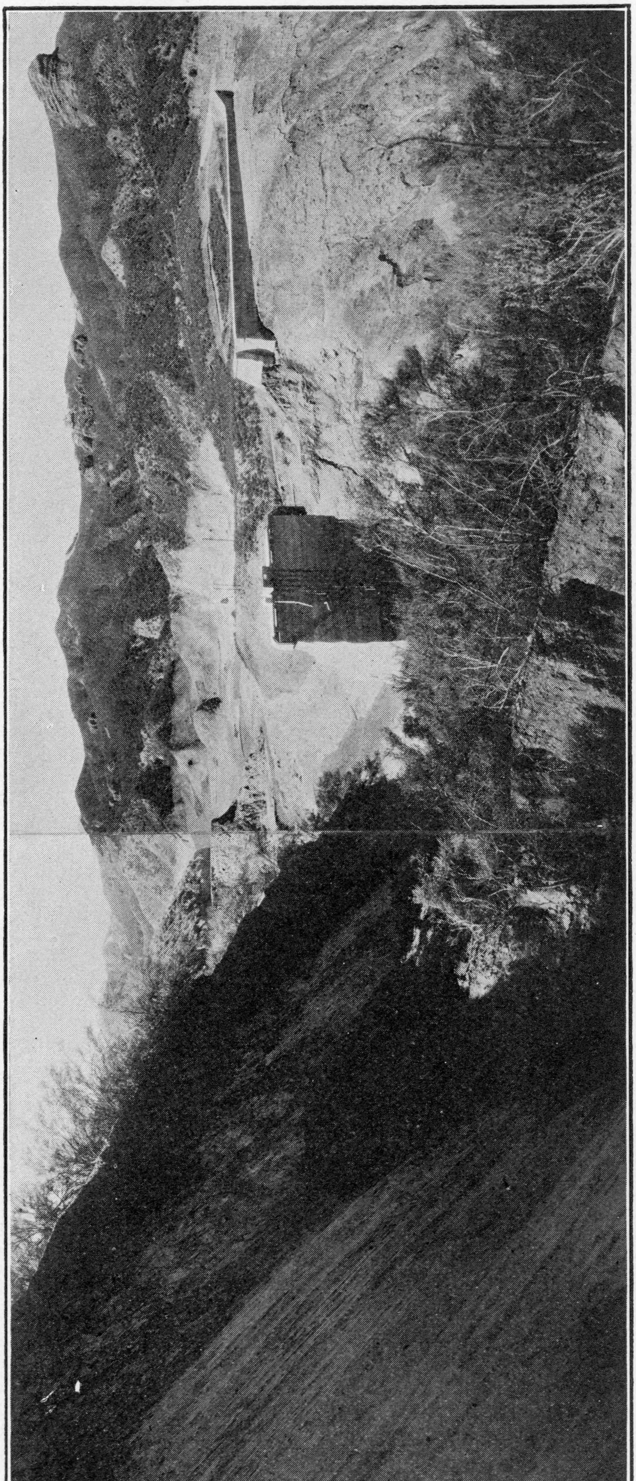
FACE OF BUTTRESS AT WEST END OF MAIN DAM.

PLATE 28



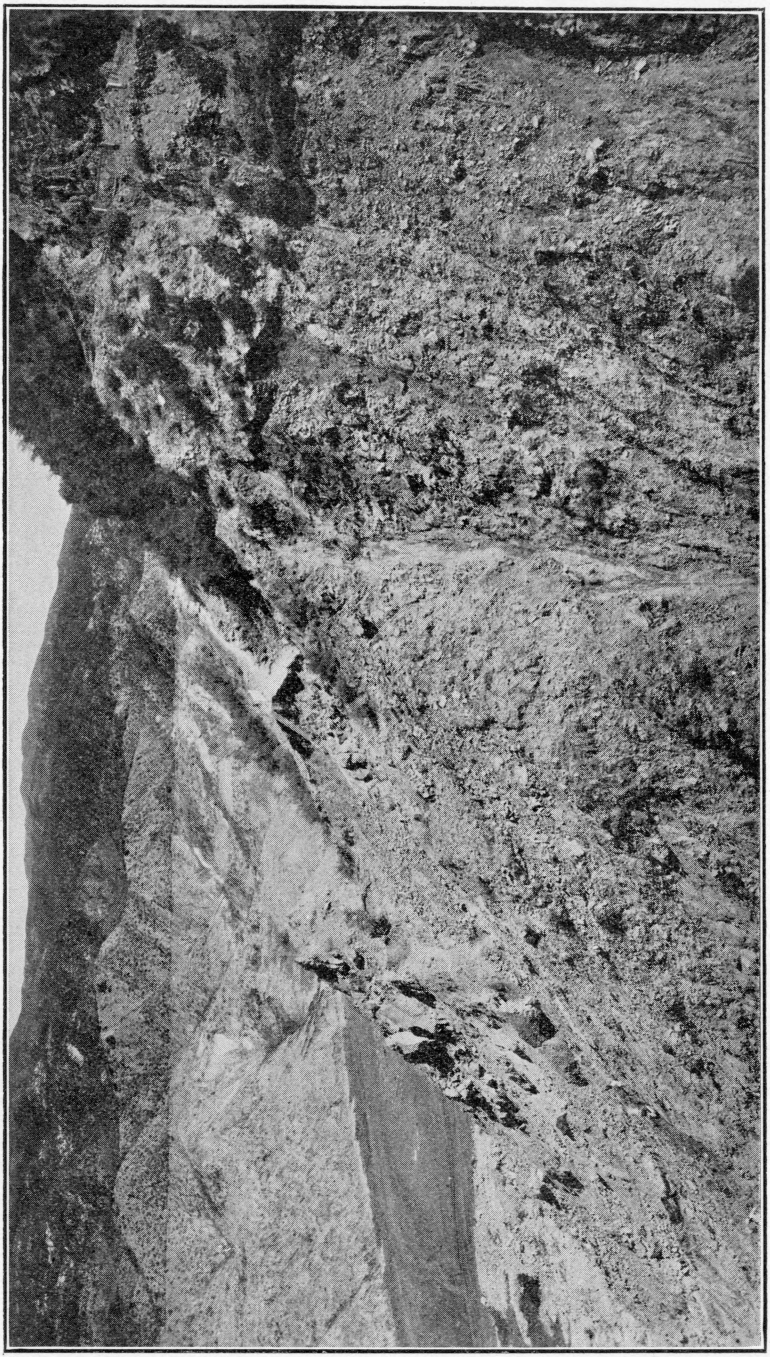
EAST ABUTMENT SHOWING ACTIVE SLIDING.

PLATE 29



GENERAL VIEW OF DAM SITE FROM HEAD OF LANDSLIDE UPSTREAM FROM DAM.

PLATE 30



VIEW OF LANDSLIDE EASTERLY BANK UPSTREAM FROM DAM.

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