DEPARTMENT OF THE INTERIOR

WATER-SUPPLY

AND

IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 40

THE AUSTIN DAM.—TAYLOR

WASHINGTON
GOVERNMENT PRINTING OFFICE
1900

IRRIGATION REPORTS.

The following list contains titles and brief descriptions of the principal reports relating to water supply and irrigation prepared by the United States Geological Survey since 1890:

1890.

First Annual Report of the United States Irrigation Survey, 1890; octavo, 123 pp.

Printed as Part II, Irrigation, of the Tenth Annual Report of the United States Geological Survey, 1888-89. Contains a statement of the origin of the Irrigation Survey, a preliminary report on the organization and prosecution of the survey of the arid lands for purposes of irrigation, and report of work done during 1890.

1891.

Second Annual Report of the United States Irrigation Survey, 1891; octavo, 395 pp.

Published as Part II, Irrigation, of the Eleventh Annual Report of the United States Geological Survey, 1889-90. Contains a description of the hydrography of the arid region and of the engineering operations carried on by the Irrigation Survey during 1890; also the statement of the Director of the Survey to the House Committee on Irrigation, and other papers, including a bibliography of irrigation literature. Illustrated by 29 plates and 4 figures.

Third Annual Report of the United States Irrigation Survey, 1891; octavo, 576 pp.

Printed as Part II of the Twelfth Annual Report of the United States Geological Survey, 1890-91. Contains "Report upon the location and survey of reservoir sites during the fiscal year ended June 30, 1891," by A. H. Thompson; "Hydrography of the arid regions," by F. H. Newell; "Irrigation in India," by Herbert M. Wilson. Illustrated by 93 plates and 190 figures.

Bulletins of the Eleventh Census of the United States upon irrigation, prepared by F. H. Newell; quarto.

No. 35, Irrigation in Arizona; No. 60, Irrigation in New Mexico; No. 85, Irrigation in Utah; No. 107, Irrigation in Wyoming; No. 153, Irrigation in Montana; No. 157, Irrigation in Idaho; No. 163, Irrigation in Nevada; No. 178, Irrigation in Oregon; No. 193, Artesian wells for irrigation; No. 198, Irrigation in Washington.

1892.

Irrigation of western United States, by F. H. Newell; extra census bulletin No. 23, September 9, 1892; quarto, 22 pp.

Contains tabulations showing the total number, average size, etc., of irrigated holdings, the total area and average size of irrigated farms in the subhumid regions, the percentage of number of farms irrigated, character of crops, value of irrigated lands, the average cost of irrigation, the investment and profits, together with a résumé of the water supply and a description of irrigation by artesian wells. Illustrated by colored maps, showing the location and relative extent of the irrigated areas.

1893.

Thirteenth Annual Report of the United States Geological Survey, 1891-92, Part III, Irrigation, 1893; octavo, 486 pp.

Consists of three papers: "Water supply for irrigation," by F. H. Newell; "American irrigation engineering" and "Engineering results of the Irrigation Survey," by Herbert M. Wilson; "Construction of topographic maps and selection and survey of reservoir sites," by A. H. Thompson. Illustrated by 77 plates and 119 figures.

A geological reconnoissance in central Washington, by Israel Cook Russell, 1893; octavo, 108 pp., 15 plates. Bulletin No. 108 of the United States Geological Survey; price, 15 cents.

Contains a description of the examination of the geologic structure in and adjacent to the drainage basin of Yakima River and the great plains of the Columbia to the east of this area, with special reference to the occurrence of artesian waters.

1894.

Report on agriculture by irrigation in the western part of the United States at the Eleventh Census, 1890, by F. H. Newell, 1894; quarto, 283 pp.

Consists of a general description of the condition of irrigation in the United States, the area irrigated, cost of works, their value and profits; also describes the water supply, the value of water, of artesian wells, reservoirs, and other details; then takes up each State and Territory in order, giving a general description of the condition of agriculture by irrigation, and discusses the physical conditions and local peculiarities in each county.

Fourteenth Annual Report of the United States Geological Survey, 1892-93, in two parts; Part II, Accompanying papers, 1894; octavo, 597 pp.

Contains papers on "Potable waters of the eastern United States," by W J McGee; "Natural mineral waters of the United States," by A. C. Peale; "Results of stream measurements," by F. H. Newell. Illustrated by maps and diagrams.

 (Continued on third page of cover.)

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UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

THE AUSTIN DAM

BY

THOMAS U. TAYLOR

WASHINGTON
GOVERNMENT PRINTING OFFICE
1900

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF HYDROGRAPHY,
Washington, September 20, 1900.

SIR: I have the honor to transmit herewith a manuscript prepared by Prof. Thomas U. Taylor, of the University of Texas, upon the Austin dam, for publication in the series of papers upon water supply and irrigation. This relates to a project which in many ways is of great interest to engineers, investors, and citizens having to do with water-power and irrigation projects. There are many useful lessons to be drawn from the history of such an enterprise, for it often happens that failure is more instructive than success. Throughout the United States many communities are now discussing the utilization of water power for irrigation or other industrial purposes, and they may be saved from mistakes or be led to adopt precautionary measures by a clear understanding of the causes of the disasters which have occurred from the neglect of certain precautions.

In this paper the author describes the preliminary projects, the construction of the dam, the difficulties encountered, the silting up of the storage reservoir, and, finally, the failure of the structure and the probable causes which led to the catastrophe. The attempt is made to present these facts from the engineering standpoint and without unduly reflecting upon the motives or characteristics of the individuals concerned. The object is simply to state the facts as they are understood, so that they may be available to persons who are interested in projects of this character.

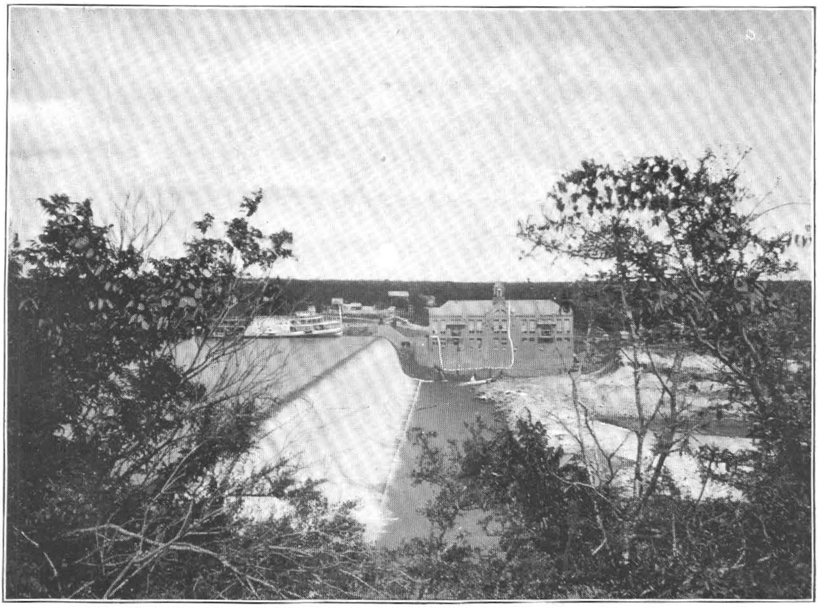
The necessity of water conservation is so great and public appreciation of the matter has reached such a point that the construction of large dams will undoubtedly be entered upon in various parts of the country, notably in the arid region of the West. There are many places where such structures will without doubt be successful, and there are other cases where the situation must be studied with extreme care and where great caution must be exercised in the preparation of plans and in the selection of locations. The attitude most to be feared is that sometimes adopted by a community where, after discussing the benefits of water conservation, the public as a whole becomes convinced of its importance, and in a condition of excitement incurs large debts, usually in the form of bonds, to push forward some project not sufficiently matured. The eagerness to attain results leads the people to disregard or pass lightly over the warnings of the engineers or their requests to be given sufficient time to thoroughly work up all of the preliminary information. The public applauds the sentiment of building the structure first and making the plans afterwards, forgetting that the structure is to last an indefinite time, and that a slight error at the outset, due to lack of knowledge, may subject the community to enormous and useless expenditures of money or result in loss of property and life. This is not an imaginary condition, for at the present time several cities or counties of the West are in the position in which the city of Austin was at the time of the adoption of the water-power project. They are urging immediate construction in order to reap the benefit during this time of drought, and are inclined to treat with disdain any intimation that their knowledge of the water supply, of the amount of silt brought down by the stream, and of the character of the foundation of the dam is too vague to justify the incurrence of an enormous debt.

It is for these reasons that this paper is offered for publication. It will serve to answer many of the inquiries made from various parts of the country and to emphasize the importance and practical application of the work of this division of the United States Geological Survey.

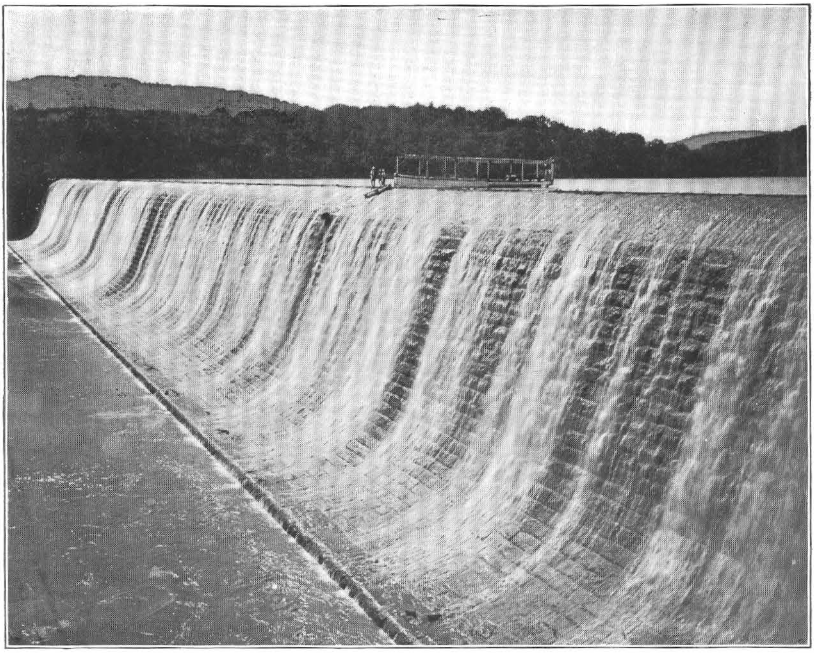
Very respectfully,

F. H. NEWELL,
Hydrographer in Charge.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.



A. VIEW OF DAM LOOKING EAST TOWARD POWER HOUSE.



B. VIEW OF DAM LOOKING WEST FROM POWER HOUSE.

THE AUSTIN DAM.

By Thomas U. Taylor.

INTRODUCTION.

Austin, the capital city of the State of Texas, is situated on Colorado River, about 200 miles from its mouth at the Gulf of Mexico. The drainage area of this river above the city is 37,000 square miles.[1] The position of the city of Austin with relation to the watershed is shown in fig. 1. This watershed extends from relatively humid regions in the vicinity of Austin westerly into the subhumid or semiarid Staked Plains. From 1856 to 1881 and from 1885 to 1899, inclusive, a period of forty-one years, the rainfall at Austin averaged 32.52 inches, as is shown by the table on page 32. The rainfall over the entire watershed may be assumed to be about two-thirds of this, or approximately 20 inches annually.

A water power was created on Colorado River a short distance above the city of Austin, as related in the following pages. After the dam was completed the project was found to be only partially successful, as the amount of water in Colorado River fell far short of the original predictions. There was at the inception a lack of hydrographic knowledge, especially in regard to the minimum flow of the river, and other information, now known to be vital to the proper location of the dam, was not obtained. Finally, during the great flood of April 7, 1900, the dam was destroyed, with great loss of life and property.

From measurements taken in March, 1890, it was concluded that the minimum flow of Colorado River was 1,000 cubic feet per second. Upon this basis, and upon the assumption that this minimum flow would be held back nights and Sundays and utilized only sixty hours a week, it was concluded that the flow over the Austin dam would develop more than 14,000 horsepower. The city's demands were placed at 2,000 horsepower, and it was the intention to sell to manufacturers the surplus of 12,000 horsepower.

On May 28, 1896, when power was being furnished for pumping, for city lighting, and for city motors, the level of Lake McDonald

[1] The Colorado River of Texas should not be confused with the Colorado River of the West, which is formed by the junction of the Grand and Green rivers in eastern Utah, flows southerly through gigantic canyons, and finally empties into the Gulf of California.

sank below the crest of the dam and remained below until July 6, reaching its minimum (5.7 feet below the crest) on July 1. It was also below the crest from August 6 to August 25 and from September 10 to September 22. This condition was sufficient evidence that the minimum flow could not furnish even 900 horsepower, while 5,227 horsepower had been counted upon. It was apparent that much of the inflow was lost by evaporation, the area exposed to evaporation being 3 square miles and the low level occurring during the hottest part of the summer.

Notwithstanding this evidence that the river could not, during certain seasons, furnish power for its existing load of water, lights, and motors, early in 1897 the Rapid Transit Street Railway and the Dam and Suburban Railway were added to the list of power consumers. After that the energy developed by the water power was

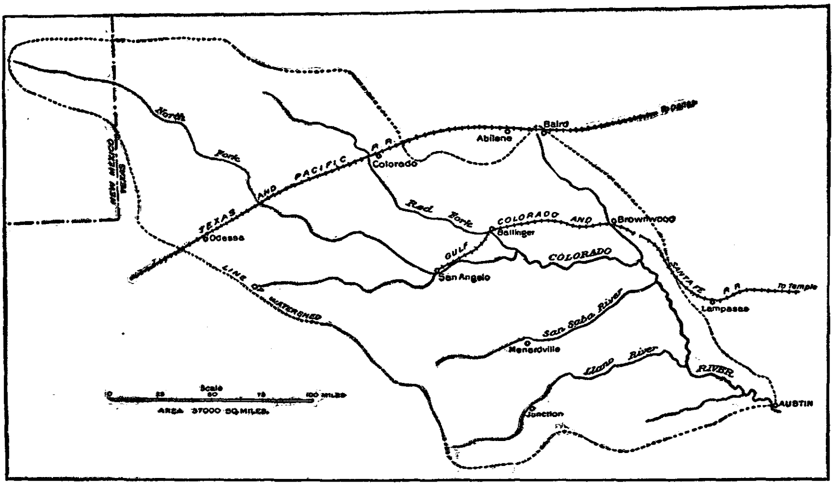


FIG. 1.—Watershed of Colorado River above Austin, Texas.

utilized (1) in pumping water, (2) in furnishing light to city and citizens, (3) in running the Rapid Transit Street Railway, (4) in running the Dam and Suburban Railway, and (5) in running the motors of various users of power in the city—such as for planers, printing presses, etc. To supply all of these demands required a total average of 1,000 horsepower.

On July 4, 1897, the water again dropped below the crest of the dam, but it flowed over again on July 17. It was also below a few days in August, October, and November, and the whole of December. On January 1, 1898, the water was 2.3 feet below the crest, and it did not again flow over until April 13. The lake level was below the crest part of the months of August and September, and it again dropped below on October 10 and continued below until April 20, 1899, reaching a depth of 10.68 feet below crest on March 29. From March 15 to April 17 it was more than 10 feet below the crest. It again dropped below the crest on August 9, and remained below until October 29, reaching a maximum of 10.45 feet below on October 3. Thus during the year 1899 the water was below the crest of the dam one hundred and ninety-one days, during seventy of which the lake level was more than 10 feet below the crest, and during one hundred and sixty-seven it was more than 5 feet below. The evidence was abundant and unmistakable that the flow was not sufficient to carry the city water supply, the street lighting, the street-car systems, and the motors used in the city. Early in 1899 measurements were made at the head of the lake, at Marble Falls, at the forebay, at the tailrace, and at the station below the railroad bridge. These measurements showed conclusively that the minimum flow was less than 200 second-feet. One second-foot, with an assumed effective head of 57.5 feet and a machinery efficiency of 80 per cent, would develop 5.227 horsepower, showing that an average minimum flow of 192 second-feet would be required to produce 1,000 horsepower, not taking into account evaporation and the leaks through the head-gate masonry ("spring"), which would increase the amount. Again, when the lake level fell more water would be required to develop the same power. When the level was 10 feet below the top, 1 second-foot would develop only 4.3 horsepower; and it is highly probable that the efficiency of the machinery was not as high as 80 per cent.

The result was that the enterprise proved disappointing to a large proportion of the citizens. It is true that it had long been before the people, in an indefinite way, but there was not sufficient data at hand to make the results certain. The watershed and rainfall were rather accurately ascertained; but the keystone of the whole project, the biggest and controlling factor, the very life blood of the system, namely, the minimum flow of the river, was overestimated. The feasibility of the enterprise had been demonstrated more than ten years before, and during the interval accurate and reliable data could have been obtained and the minimum flow ascertained with accuracy. Gage heights, rating tables, and flow curves could have been obtained for one-tenth of one per cent of the outlay.

It was found that the minimum flow could be relied upon to furnish water and lights for the citizens and very little more. It was of great value to the city, from a sanitary point of view, that there was during all these years a private water company, whose plant was operated by steam, supplying water and lights to the citizens.

The history of this dam is unique in one respect, and that is in the number of engineers connected with it. Early in 1892 Mr. Joseph P. Frizell resigned, it is asserted, by reason of the fact that he was hampered in his work by the city authorities. Other engineers resigned for similar causes, and at one time a contractor in charge was ordered to follow the instructions of a city official who was not an engineer. This peculiar method of conducting a great public work called forth severe criticisms from engineering journals.

The failure of the dam to meet expectations and its failure structurally were due to—

(1) The lack of hydrographic knowledge, causing (*a*) an overestimate of the minimum flow, and (*b*) an underestimate of the effect of evaporation.

(2) The hampering of the engineers of construction.

(3) The ignoring of geologic formations.

PRELIMINARY PROJECTS.

Texas became an independent Republic in 1836, and a few years later a commission was appointed to consider the question of locating the capital. In their report they referred to the possibility of developing the water power of Colorado River at Austin.

Nothing was done, however, until in 1871, when Mayor Glenn had surveys made by the city engineer. It was the plan at that time to convey the waters of the Colorado, by a canal, from a point near Mount Bonnel to Shoal Creek, for city and manufacturing purposes.

In 1873 a charter was granted to certain parties, some of whom are still living, to erect a dam across the Colorado, but it was allowed to lapse by limitation.

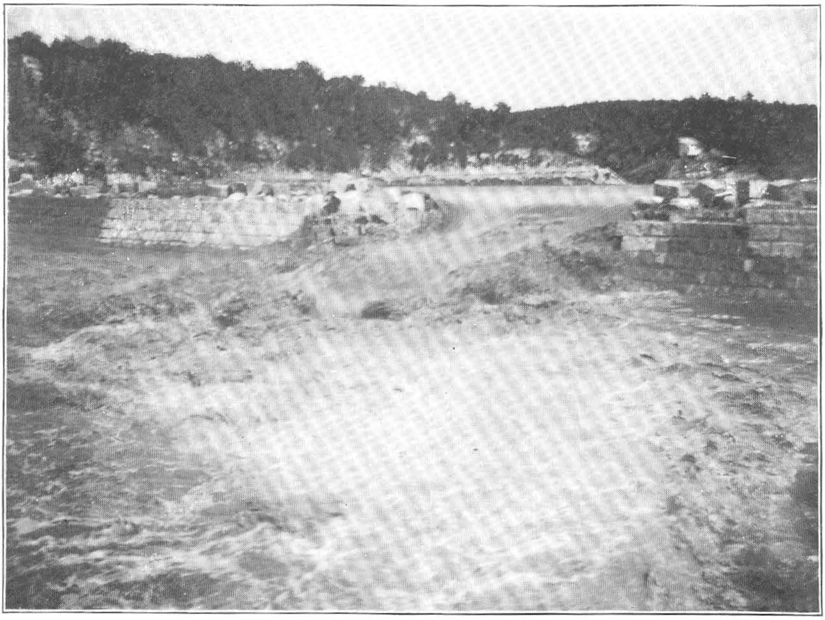
The drought of 1877 called the attention of the public to the possibilities of irrigating the lands on Colorado River below Austin by means of a dam erected near the city.

During Governor Roberts's administration (1879–1883) estimates were made, with a view to lighting the public buildings, of the cost of erecting a dam across Colorado River at Bull Creek.

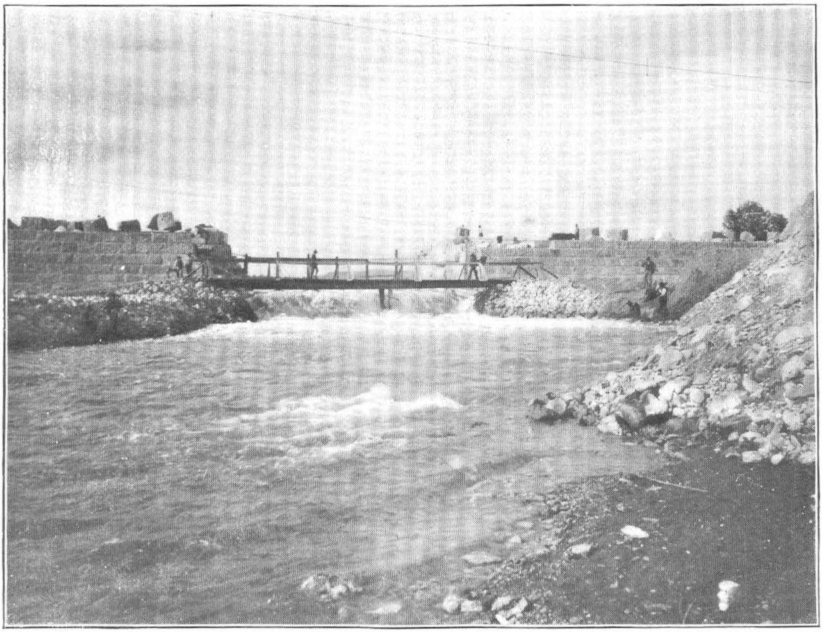
In 1888 the board of trade had surveys made for the purpose of determining the feasibility of damming the river, and during the year 1889 the subject was kept before the people by frequent communications in the newspapers.

In the latter part of 1889, the contest for mayor was largely fought on the issue of building a dam across Colorado River. The result of the election foreshadowed early action in regard to the enterprise. In February, 1890, the city council employed Mr. J. P. Frizell to make a report upon the proposed dam and the necessary adjuncts. The report was submitted on March 26, 1890, and so completely does it discuss the whole problem that the portion which refers to the project in general and the part which deals more particularly with the dam, the water power, and the estimated total cost, are here quoted, as follows:

> The city is, at present, supplied by a water company, upon what is termed the Holly system; that is, without the use of a reservoir, the pressure in the pipes being maintained by the action of the pumps, which are operated by steam, and increased by an automatic device upon the occurrence of fires. The company also furnishes power for the electric-light system of the city. I have not been able to obtain any very complete information in regard to the extent and size of the present system of pipes. From what I can learn I judge that the city is rapidly outgrowing the capacity of the pipes. That by reason of their small size, a great and increasing burden is laid upon the pumps to maintain pressure sufficient for



A. FRESHET FLOWING THROUGH GAP IN PARTIALLY COMPLETED DAM.



B. RIVER FLOWING THROUGH MAIN GAP IN PARTIALLY COMPLETED DAM.

domestic service in remote parts of the system. A large part of the power of the pumps is consumed in the friction of the water in passing through the pipes: and as the city extends and increases, the protection against fire is becoming more and more precarious. There is also a very widespread impression prevailing that the amount paid for water rates, fire service, and electric lighting is sufficient to supply the city on a much more ample and liberal scale, and at the same time secure incidental advantages of great value.

The project before the city is:

First. The construction of a massive dam across the Colorado to furnish power for pumping, for electric lighting and propelling street cars.

Second. The construction of a reservoir at a height sufficient to maintain fire pressure in the pipes.

Third. The extension of the distributing system on a scale of magnitude commensurate with the present and prospective wants of the city.

Fourth. As an incident of the project it is expected that there will remain a large surplus of power susceptible of such uses as will greatly promote the future prosperity of the city.

THE DAM.

The Colorado above Austin flows in a deep cut or canyon worn in the limestone rock. It is skirted by limestone bluffs rising often to the height of 150 feet above the bed of the river, broken by the erosion of tributary streams. No extensive meadow or bottom lands exist. This situation permits the construction of a high dam with but little damage to private property. The river, in it normal condition, occupies but a small part of the channel in the rock, the remainder being occupied by alluvial deposits to the depth of average high water. In great floods the river spreads from bluff to bluff.

Several situations have been examined with reference to the construction of the dam. One on Taylor's lime chute, about 3¾ miles from the city limits, appears most favorable to the construction of the dam itself, but one on the Brackenridge property, about three-fourths of a mile nearer town, possesses greater advantages as regards the canal and works appertinent to the water power. This site has been selected for the purpose of the estimate.

The channel in the rock is here about 1,150 feet wide at a height of 60 feet above the summer level of the river. The cross section of the channel is not far from level on the bottom, and is bounded by nearly perpendicular walls of rock rising to the height of a little over 60 feet on the city side of the river and 125 or more on the other side. The river bed proper occupies not more than one-half of this width, the remainder of this being alluvial deposit, rising to the height of 40 or 50 feet above the river bed. The situation here is admirably well situated to the development of water power by a dam about 60 feet in height, the perpendicular face of rock rising to about that height, and thence receding from the river in a gentle slope, forming a bench on which the canal or feeder could be constructed, the alluvial strip of ground between the canal and river furnishing sites for pumping and power stations and any other establishments requiring power. An estimate has accordingly been prepared on the basis of a 60-foot dam.

Its crest will be about 1,150 feet in length [the crest was really 1,091 feet long]. It is contemplated to make it some 16 feet thick at the top, increasing downward and spreading out in a broad toe or apron, to give the water a horizontal direction, making its extreme width at the bottom about 50 feet. The body and upstream face of the dam to be made of limestone rock abounding in the vicinity, the upstream face being of quarry-faced work with close joints. The downstream face and toe are intended to be of granite found in abundance in Burnet County, split to approximately regular shape and laid with but a small amount of tooling. The capping is of granite in as large blocks as can be handled, worked to regular shape. The entire work to be laid in hydraulic cement.

The Colorado at Austin drains some 40,000 square miles, and, of course, carries at times an enormous flow of water. The highest flood within the memory of the people now living was some 45 feet above low water, and from the best data I can obtain the flow of the stream was some 250,000 cubic feet per second. This would imply a depth of 16 feet on the crest of the dam, and the abutments should of course go to that height. At one end of the dam the natural rock goes far above that height. The other end is occupied by an artificial bulkhead, called the gate-house, containing the sluices for drawing off the water. It is expected that the wash of the dam during floods will carry away the alluvial deposit for a considerable distance. The wheels, for this reason, must be some 200 or 300 yards from the dam, and the canal must have that length. As already stated, the formation permits this canal to be excavated in rock. At the entrance to the canal is the gate house alluded to above. Its function is to enable the water to be shut out of the canal in case of repairs and to prevent the canal from being overflowed in time of floods. The water will be drawn from the canal through iron pipes, pass the wheel, fall into the wheel pits and be discharged through underground races into the river.

WATER POWER.

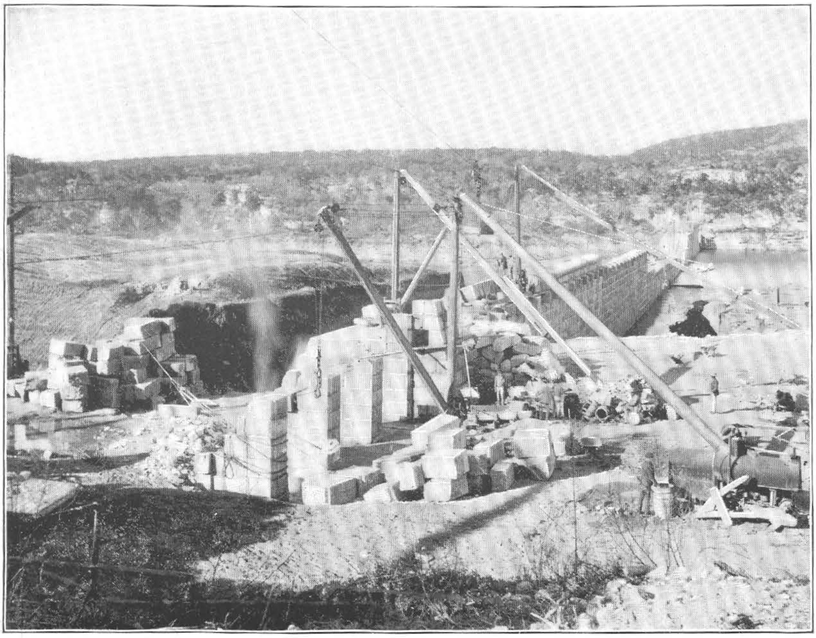
It remains to consider the quantity of water power created by the proposed improvement. This consists of two elements, the fall, and the quantity of water available for power. The former is fixed approximately by the height of the dam. The latter can be inferred with more or less certainty from known facts. It is not the lowest stage that the river is ever known to attain to. It is the flow of water that can be depended on, with reasonable certainty, during ordinary seasons. Stages of the river above this minimum count for nothing unless steam is used to make up deficiencies.

The river is subject to great rises in times of heavy rains. On the cessation of the rains it falls rapidly until it attains a minimum flow, which appears to remain nearly constant. In that condition no water enters the stream from the surface of the ground. Its flow is wholly maintained by springs issuing from cavities in the rock, and is unaffected by current rainfall until the latter becomes sufficient to cause a flow from the ground. This is the present condition, and I conclude we shall not be far wrong in taking the present flow of the stream as the quantity that can be depended upon. This, as I have ascertained by careful measurement, is nearly 1,000 cubic feet per second.

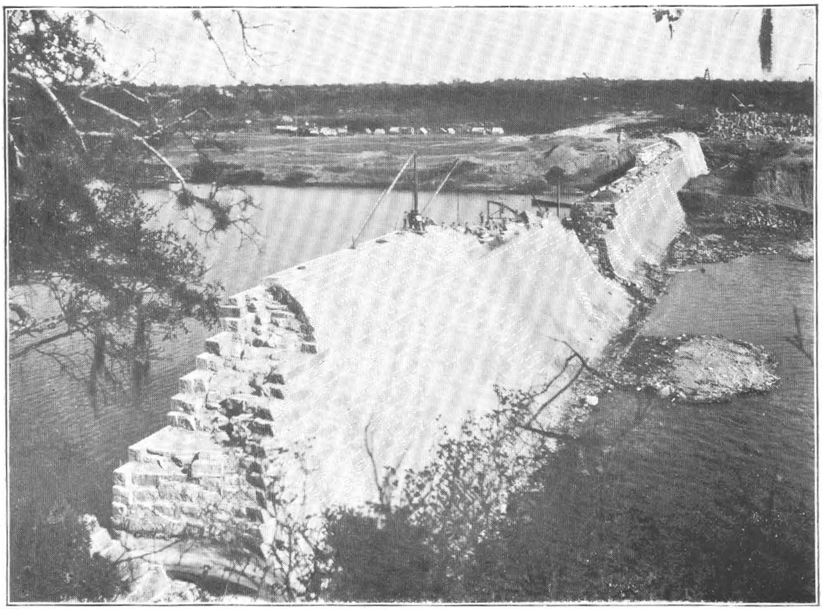
There will, no doubt, be times during the hottest weather when the water will fall below this stage, on account of increased evaporation. I am told, however, that a month very rarely passes without rains in some part of the drainage basin, sufficient to cause a slight rise at Austin. The great extent of the pond will enable a considerable deficiency in the flow of the stream to be made good by storage. From the best information I can obtain, the pond will extend some 30 to 35 miles from the dam, with an average width of one-quarter of a mile, containing a water surface of some 8 square miles, and a total volume of something like 2,800,000,000 cubic feet of water. Should the flow of the stream diminish to one-half the above quantity, a single foot in depth on the pond will make good the deficiency for a period of five days, and 6 feet will make it good for thirty days.

A system of flashboards could readily be applied to hold the water 4 feet above the crest of the dam, and thus hold the surplus of water in store for such deficiencies, without drawing the pond below the crest of the dam. This feature will not become necessary for several years, and need not be considered further at present.

Owing to the imperfection of mechanism we can not hope to utilize, for practical purposes, more than 80 per cent of the absolute power of the water. Moreover, the full head of 60 feet can not be brought to act upon the wheels. Some part of the head will be consumed in the movement of the water through the sluices, canal, penstocks, and races. The head will at times be reduced by high water in the



A. CLOSING GAP IN DAM.



B. DAM NEARING COMPLETION, FEBRUARY, 1893.

river, which rises more below the dam than above. I therefore take 57½ feet as the head acting on the wheels, and assume that we can utilize 80 per cent of the power on that head. This gives, for the total amount of power available for driving machinery, $\frac{57.5\times62.5\times1,000}{550}\times0.80=5,227$ horsepower.

This quantity of power could be furnished constantly, night and day. This, however, would not be suited to the requirements of industry, which ordinarily calls for power only during the working hours of the secular day. It is regarded as a great advantage in water power to be able to hold back the low-water flow of the stream during nights and Sundays and use it during the working hours. This the great extent of our pond readily enables us to do. Concentrating the entire weekly flow of the stream into the working hours assumed at 60 per week, the above amount is increased in the ratio of 60 to 168, giving as the available power 14,636 horsepower.

The total permanent power of the Merrimac River at Lowell, Massachusetts, is not over 11,000 horsepower, on an average during working hours. About the same at Lawrence, Massachusetts, and at Manchester, New Hampshire. This is the power that can be supplied without interruption. At these points the use of water is not confined to the minimum flow of the stream. It is utilized at much higher stages, in connection with steam, the latter being called into use when the flow diminishes. Of course similar methods will prevail here as soon as the demand for power warrants their introduction. This, however, is too remote for present consideration.

It is not easy to state the rental received for water power at the great manufacturing centers in New England, as grants of water are usually covered with grants of land, the water being regarded as an easement of the land. A round sum was paid for the land and a nominal rent for the water, which was intended as the fund for the maintenance of the appliances of the water power. When manufacturers draw in excess of their grant they are charged all the way from $3 to $12 a day for mill power for water terminable at will. My opinion is that $1,200 per annum fairly represents the value of a mill power. These considerations are adverted to as showing the great value of the incidental benefits secured to the city by this improvement. The city's requirements for pumping I put at 600 horsepower twelve hours per day, or 720 horsepower ten hours a day. Reserving an equal quantity for electric lighting, and equally liberal provision for street cars and other purposes, there would remain over 12,000 horsepower, or as much as 180 mill powers, subject to such use as the city might deem conducive to its prosperity.

ESTIMATED COST.

Dam	$463,325
Gate house	22,950
Canal	49,750
Pump and power house	3,500
Wheel pit	2,123
Culvert	10,210
Wheels and pumps	16,025
Filtering gallery	17,880
Reservoir	104,615
Mains	153,800
Distribution	295,250
Electric light	45,600
Add for contingencies	118,502
Add for engineering and agencies	59,251
Grand total	$1,362,781

On April 3, 1890, the board of public works was created by the city council, to have control of the construction of the dam and of all works connected therewith.

The question of issuing water and light bonds to the amount of $1,400,000 was submitted to the voters of the city of Austin on May 5, 1890, and resulted in 1,354 votes in favor of and 50 votes against the issue. The board of public works met the next day and employed Mr. Frizell as chief engineer and Mr. J. F. Pope as first assistant engineer. In order to guard against possible errors, and to have the advantage of the skill and experience of other experts, Mr. John Bogart, of New York, was employed as consulting engineer, to examine the site and the plans and specifications of Mr. Frizell. After an

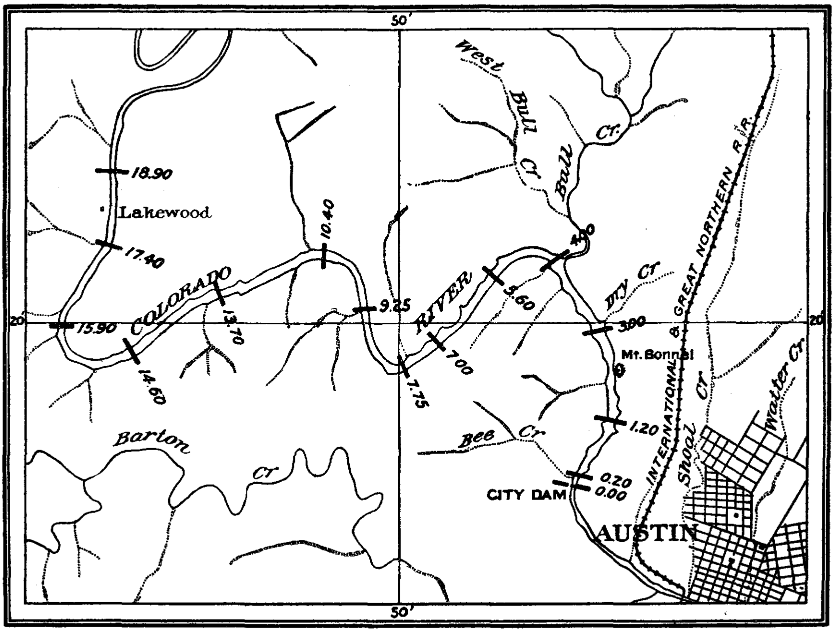
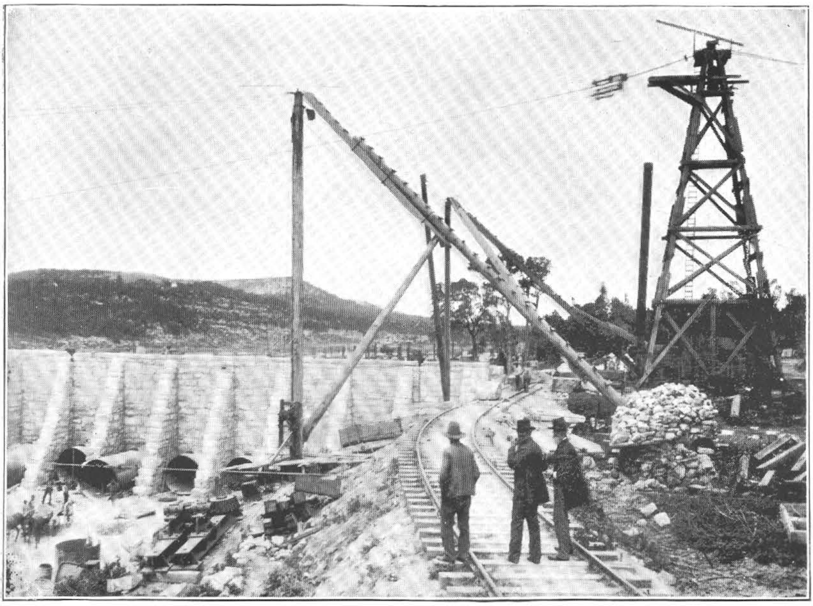


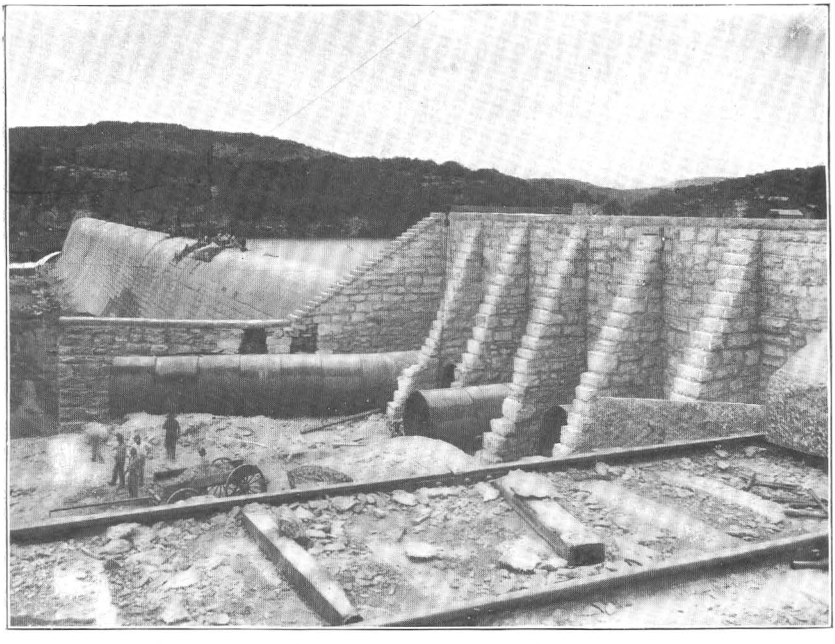
FIG. 2.—Index map of lines of soundings across Lake McDonald, above Austin, Texas. The lake is the broadened portion of Colorado River, extending from sounding 0.00 to sounding 18.90, created by the building of the dam.

extended examination Mr. Bogart made a written report to the board in which he stated that after considerable study he was of the opinion that the site selected by Mr. Frizell was the best place for the location of the dam. In regard to the cross section and shape of the dam Mr. Bogart said:

> Ample precedents exist for the determination of the best lines of profile and methods of construction for such a dam. It will be one of the high dams, but will not be among those very high structures which sometimes excite doubt as to their permanent stability. To provide for the possible height of spring or other floods, the whole crest of the dam will be formed so that the water may flow over it, and the downstream face will be built in such a manner and to such lines and curves as will tend to conduct the overflow to the lower river without damage to the stability of the structure. It is estimated that the highest flood as to which any



A. HEAD-GATE MASONRY AND PENSTOCKS BEFORE MAY, 1893.



B. LAYING THE LAST STONE, MAY 2, 1893.

information can be obtained might give a depth of water of 15 or 16 feet over the crest for a short time. Such a possible flow will be provided for in the construction of the dam. The exact lines of the profile and the detail method of construction are now being determined in consultation with Mr. Frizell.

During the summer of 1890 engineers were put in the field to locate the lake-level contours and to determine the amount of valuable land submerged. These engineers took cross sections of the river at sixteen stations, thus enabling comparisons to be made, which was done by the writer in May, 1897, and in January, 1900. The accuracy of the work under the supervision of Mr. Pope was verified by the fact that at the head of the lake, at the request of a farmer living near, he cut a bench mark, on a big pecan tree, at the crest level. Three years later the water, when it rose to the crest of the dam, reached the notch with exactness. Cross sections of the lake are shown in fig. 6; a general map of the lake is shown in fig. 2.

CONSTRUCTION OF DAM.

On October 15, 1890, the contract for the construction of the dam was awarded to the lowest of seven bidders, Mr. Bernard Corrigan, of Kansas City, Missouri, whose figures were $501,150. The contract was based upon the following specifications:

ROCK EXCAVATION.

12. On the site of the dam all unsound rock and all rock that can be removed without blasting will be taken off. A trench 4 feet wide and as deep as may be directed by the engineer will be excavated along the upstream face of the dam. Trenches, footings, steps, channels, and other excavations will be cut in the bottom and sides of the rock in such forms and to such lines as may be directed by the engineer. In these excavations the kind of explosive used, the amount of the charges, depth and direction of the holes, and the entire process of the work shall be under the immediate personal control of the engineer or his assistant, the object being to do the work in such a manner as to avoid fissures and shakes in the remaining rock. All cracks and fissures that may exist naturally or from any cause shall be thoroughly filled with cement mortar or concrete or pure cement, as may in each case be directed by the engineer.

13. The lines and grades of the canal will be established by the engineer, and no excavation below the grade or bottom or outside the lines will be paid for; but such excavation will be permitted, under the direction of the engineer, for the purpose of obtaining rock for the dam.

14. Any rock obtained from these excavations that the engineer may deem suitable may be used in the rubble masonry of the dam. Rock not suited for this purpose will be disposed of as the engineer may direct—in spoil bank, riprap, filling of cribs, or otherwise—not involving a haul of more than 500 yards. The price of rock excavation will include and cover the cost of all the explosives, tools, derricks, tackle, machinery, teams, vehicles, tramways, stringers, bridges, boats and appliances, materials, and labor used in the excavation of the work. All rock will be measured in excavation.

MASONRY.

15. The upstream face of the dam will be laid of granite.[1] It must be sound,

[1] The original specifications called for fossiliferous limestone for the upstream face, but bids were also received for granite, which material was adopted. The details here given are obviously not proper for granite.

free from seams, cracks, and shakes. The stones will be laid on their quarry beds in regular courses, no course to be less than 12 inches in height. Each course shall be composed of headers and stretchers, and at least one-third of the face length of each course shall be headers. The headers and stretchers shall be regularly distributed in each course, so that the headers shall alternate in position in the adjacent courses and so that each stone shall break bond not less than 12 inches with the stone above and below. A gamut or plan of each course will be prepared and submitted to the engineer before the stones are laid and, if approved by him, will be used for the guidance of workmen in laying the stones. This will be quarry-faced work. Each stone will have a distinct pitch line all around the face. The bed and build joints will be fine pointed to a fair, true surface, out of wind, 9 inches back from the pitch line. The remainder of the bed and build joints to be pointed, so as not to project beyond the plane of the fair, true surface and not to fall away therefrom more than $1\frac{1}{2}$ inches. The width of the stretchers on their beds will not be less than their height. No stretcher will be less than 3 feet in length. The headers will not be less than 30 inches on the face nor less than 4 feet in length. This work will be laid with full mortar joints on the beds. The mortar will be pressed or tamped into the build joints with a proper tool. After the work is laid the mortar will be raked out of all the exposed joints to a depth of $1\frac{1}{4}$ inches, and these joints will be pointed with mortar of neat cement pressed in and rubbed hard.

16. In measuring this work, the headers will be accounted 4 feet long. The width of each stretcher will be considered equal to its height. No stone of less dimension will be laid. If stones are laid exceeding these dimensions the excess will be paid for as rubble filling.

17. The downstream face of the dam is to be laid with granite of good quality, sound and free from imperfections. It will be laid in regular courses; no course to be less than 12 nor over 30 inches high. Each course shall be composed of headers and stretchers, and at least one-third of the face length of each course shall be headers. The headers and stretchers to be regularly distributed in each course, so that the headers shall alternate in position in the adjacent courses, and so that no stone shall break bond less then 12 inches with the stone above and below. The stretchers to be as wide as high, measured on the lower bed. No stretcher to be less than 3 feet; no header to be less than 3 feet on the face and $4\frac{1}{2}$ feet long. On the curved part of the face, except at the toe, the bed joints shall be radial. On the vertical and battered part they will be horizontal. Dowels and clamps of wrought iron will be inserted at the toe as directed by the engineer.

18. The exposed faces of all these stones are to have distinct pitch lines all around. The face not to project or recede more than $1\frac{1}{2}$ inches from that line. The beds and builds to be pointed off to lay a three-fourth inch joint for 12-inch back from the pitched line.

19.[1] If this work is laid with fossiliferous marble, the specifications will be the same in every respect as for granite, except that the beds and builds will be dressed to a $\frac{3}{8}$-inch joint instead of a $\frac{3}{4}$-inch joint. Bids will be received for either kind of stone. A gamut or plan of each course will be prepared as specified for the upstream face.

20. In measuring this work the headers will be taken as $4\frac{1}{2}$ feet long, the stretchers as wide as high, measured on the lower bed. No dimensions less than these will be accepted. If stones of greater dimension are laid, the excess will be paid for as rubble filling. All of this work is to be laid in cement mortar.

RUBBLE MASONRY.

21. Rubble masonry will be laid in the body of the dam. This will be composed of any firm, strong, and sufficiently heavy stone. It must not weigh less than 150

[1] This paragraph is eliminated from specifications.

pounds per cubic foot. At least two-thirds of it must consist of blocks having a bed of not less than 4 square feet. Smaller stones may be used to fill up the spaces between blocks. All stones must be bedded in mortar and all interstices filled with mortar. Such practices as laying down stone and pouring grout into the cavities will not be allowed, and the inspector will require such work to be torn up and relaid whenever discovered. The rubble work will be well bonded with masonry on the up and down-stream faces. The trench along the upstream face of the dam will be filled with fragments of granite ["or fossiliferous marble," erased in specifications], of any form and size, carefully laid in cement mortar. Should distinct veins or streams of water enter this trench, the water will be allowed to rise through earthenware drain-pipes set in the masonry, or through openings left in the masonry, and discharged above the dam.

22. The capstones will be of granite of the best and soundest quality, free from all imperfections. They will be 3 feet in depth, not less than 3 feet wide, measured lengthwise of the dam, and each cap will consist of not more than three stones. The stones of the adjacent caps will break beyond 24 inches. A distinct pitched line will be cut around the weather face, following the outline of the stone, as shown on the plan. The weather face will not be more than 1 inch out as regards this line. The beds and builds will be cut to a half-inch joint, 12 inches back from this line. The stones will be bedded in mortar; the build joints will be filled with melted sulphur, of quality approved by the engineer. Dowels of wrought iron will be inserted as indicated on the plan, and also bedded in sulphur; the stones will be fastened together on the top with wrought-iron clamps and dowels, as directed by the engineer.

23. The price of masonry will include furnishing the stone, cement, and sulphur and all materials and labor required for the excavation of the work as herein provided.

24. Before commencing the laying of any masonry the rock on which it is to rest must be swept and washed clean with brooms, and the same must be done when new masonry is joined on to old. All stones must be washed before being laid in the work. A tank and other appliances satisfactory to the engineer must be provided for this purpose.

CEMENT.

25. The cement furnished for this work must be from manufacturers of established reputation, and such as has satisfactorily stood the test of time and experience. It will be subjected to such tests as the engineer may require from time to time, and such as is rejected must be immediately removed from the work. Quick-setting cement will not be used. Cement showing on chemical analysis magnesia or lime in proportions sufficient to injure the work will be rejected. American natural cement will, in general, be expected to exhibit a tensile strength of 50 pounds per square inch at the end of thirty days, when mixed with twice its bulk of sand. Portland cement will be expected to show a strength of 150 pounds per square inch at the end of thirty days when mixed with three times its volume of sand. Cement shall be stored in sheds sufficiently water-tight to exclude rain, with floors raised at least 12 inches above the ground, and permitting a free circulation of air. To give opportunity for tests the contractor shall have no less than sixty days' supply of cement on hand at all times. [Only Portland cement was used.]

MORTAR.

26. The mortar is to be prepared from cement of the quality above described and clean, sharp sand, free from loam or other impurities, in the proportion of 1 part cement to 2 of sand, by measure. If made by hand it is to be mixed dry, and

a sufficient quantity of water afterwards added to produce a paste of proper consistency, and thoroughly worked with hoes or other suitable tools. If required, the contractor shall provide a mortar mill of such form as the engineer may prescribe, to be worked by steam or horsepower. The mixing of the mortar will be under the constant supervision of an inspector. Sand offered for the work shall be washed and screened, if the engineer shall so direct, in such manner as he shall prescribe.

40. And the said contractor hereby agrees to receive the following prices as full compensation for furnishing all materials and for labor in executing all work contemplated in this contract, and for all risks of loss incident to the nature of the work, to floods and freshets on the river, or to other action of the elements, to strikes and combinations of workmen, to changes in market values during the progress of the work, and to all other causes:

(*a*) For bailing and draining, including the construction and maintenance of all necessary cofferdams, the furnishing, setting, and operating of steam engines, boilers, and pumps, and all labor and materials required for the removal and exclusion of water from the work during its entire progress, as specified, the sum of $8,000.

(*b*) For all earthwork excavation above the low-water level of the river, including the disposal of the same in spoil banks or in cofferdams, and all clearing and grubbing, the sum of 14 cents per cubic yard.

(*c*) For all earth excavation below the low-water level of the river, including the disposal of the same, the sum of 50 cents per cubic yard.

(*d*) For rock excavation on the site of the dam, including the disposal of the rock in spoil banks, riprap, or otherwise, as may be required, the sum of $1.60 per cubic yard.

(*e*) For rock excavation from the canal and site of gate house, including the disposal of the rock, the sum of 80 cents per cubic yard.

(*f*) For the masonry of the upstream face of the dam, of granite, cut and laid as specified, the sum of $11 per cubic yard.

(*g*) For the masonry of the downstream face of the dam, of granite, the sum of $11.25 per cubic yard.

(*h*) For rubble masonry laid with stone paid for as excavation, $2.50 per cubic yard.

(*i*) For rubble masonry laid with stone not paid for as excavation, the sum of $3.50 per cubic yard.

(*j*) For rubble masonry laid with granite in trenches, the sum of $6 per cubic yard.

(*k*) For the granite capstones dressed and laid as per specifications, the sum of $15 per cubic yard.

(*l*) For drilling bolt holes for wrought-iron clamps and dowels, the sum of 24 cents per linear foot of hole drilled.

(*m*) For furnishing and inserting wrought-iron clamps and dowels as required by the specifications, the sum of 10 cents per pound.

(*n*) For laying masonry of any kind in Portland cement mortar in excess of the price received for the same work laid in mortar of American natural cement, the sum of 50 cents per cubic yard. [There were more than 90,000 yards excess.]

41. And it is further agreed that the engineer shall make approximate monthly estimates of the work done, and the materials delivered, and the payments shall be made of 85 per cent only of the amount of such monthly estimates.

42. And said contractor hereby further agrees that the said board be, and is hereby, authorized to deduct and retain out of any money due the contractor the sum of $500 per day as liquidation damages for each and every day the aforesaid

work shall remain uncompleted beyond the time herein stipulated for its completion; provided, however, that the board shall have the right to extend the said time, should it decide to do so.

43. And it is further agreed that of the sum agreed on as compensation for bailing and draining, three-fourths shall be considered as earned when the entire masonry is raised to a height of 3 feet above the low-water level of the river, and the remainder when the dam is fully completed according to the terms of this contract, and that these sums shall be subject to the above-mentioned deduction of 15 per cent.

43a. The power of the board of public works and the engineer acting under them as now constituted only extends to executing the contract as it is made by the city; and all changes of the contract and final approval of work done shall be by the city council upon the recommendation of the board of public works, or by the proper city authorities that may be provided by law from time to time as the work progresses.

43*b*. This contract is conditioned upon a railroad being constructed by the city or some persons other than the contractor from the depots in the city of Austin to the site of the proposed dam, and the said city guarantees to the said contractor the use of the said railroad track free of charge for hauling all material for the construction of the dam. It is understood that all time which may be lost by the contractor by reason of the noncompletion of said railroad shall be credited by said contractor on the time stipulated for the completion of the dam.

The cross section originally adopted is shown in fig. 3, left half. The contractor commenced the work of excavating the alluvial soil on the east bank on November 5, 1890, and the first stone was laid in the foundation of the dam May 5, 1891, exactly one year after the election authorizing the issue of the bonds. The east half of the dam was built to a safe height above ordinary freshets, and then the work was pushed from the west end. The foundation work at the east end was protected by a natural dirt cofferdam and at the west end by a wing wall of broken limestone for body and hay and dirt as fillers. This deflected the water toward the west end of the eastern portion, and the western section of the dam was thus built out to within a short distance of the eastern portion. The gap was closed by first constructing a small dam in front of it, thus forcing the water through a gap in the eastern portion only a few feet higher than the foundation courses. In this way the water was played from one gap to the other at the pleasure of the contractor. The gaps left in the dam while the work of construction was proceeding are shown in Pls. II and III. When the courses reached a sufficient height, a framework dam was made to check the flow through the gaps. In September, 1892, three sluice pipes, each 3 feet in diameter, were built into the dam at a level $43\frac{1}{2}$ feet below its crest, so that there could be no basis for complaint of stopping the flow of the river, and, incidentally, to assist the contractor in controlling the water. At a later stage of the construction one of these pipes, half open and under a head of 36.5 feet, passed the whole flow of the river.

The dam cost over $110,000 more than Mr. Corrigan's original bid. The causes of this increase were—

1. Increased excavation at east end of dam	$8,914.60
2. Extra masonry	56,793.32
3. Extra limestone masonry	21,839.80
4. Extra allowance for Portland cement	44,180.25
5. Change in shape of crest	2,337.45
6. Allowance for pumping, excavating without explosives, and cement	3,385.49
Total	137,450.91
Overestimate	27,255.62
Total extra cost	110,195.29
Original bid	501,150.00
Total cost of dam	611,345.29

The plans recommended by Mr. Frizell contemplated a canal several hundred feet long and a power house south of the site subsequently selected, located upon the alluvial soil below the dam. In January, 1892, it became manifest that some members of the board of public works did not approve the plans submitted by Mr. Frizell in so far as they related to the canal. They advocated the abolition of the canal, and suggested that the water be taken directly from the lake by the penstocks, and that the power house be located near the east end of the dam. At this juncture the board requested Mr. E. C. Geyelin, of Philadelphia, to visit Austin and report upon the questions at issue. In his report, dated February 17, 1892, Mr. Geyelin recommended, among other things, that the power house be located upon a rock foundation at least 100 feet from the dam, and that the water be conveyed from the lake by a series of large pipes. (The power house was afterwards located at an average distance of 130 feet from the dam.) Mr. Frizell took issue with these recommendations, and the board then decided to ask the advice of Mr. J. T. Fanning, of Minneapolis. After spending several weeks in Austin investigating the problems, Mr. Fanning, on June 24, 1892, submitted his report to the board, and among other things said:

This dam is being constructed of solid masonry and is faced on each side with large blocks of excellent granite. Not for its length alone or its great area of flowage is the dam remarkable, for in France we observe three longer masonry dams—at Bouzey, Chazilla, and Gros Bois, 1,545, 1,759, and 1,805 feet long, respectively—and in Wales the Vyrnwy dam, 1,350 feet long, the latter being for the storage reservoir of the Liverpool water supply.

Not in the height alone, for in France there are 3 dams, in Spain 2, in Belgium 1, and in the State of California 1 masonry dam exceeding 150 feet in height. There are 14 other notable masonry dams having heights exceeding 100 feet.

But none of these dams are upon great rivers, and very few of them have any water pass over their crest. On the other hand, the Austin dam is in the channel of the Colorado River, where it has 40,000 square miles of watershed, and will have floods of 200,000 to 250,000 cubic feet of water per second to pass from its crest to its toe. Your citizens will appreciate your responsibility when they learn that no dam in existence has to pass a volume of water, in flood, even approximating this, through so great a height. Limestone and sandstone yield rapidly to the eroding force of falling waters. The evidences of this are abundant in the canyon of the Niagara River below Niagara Falls, in the canyon of the Genesee River below the Genesee Falls, the Mississippi River below St. Anthony Falls, and here of the Colorado River across Travis County, as well as in the channels of numerous streams that flow down each of the Rocky Mountain slopes. Such evidences admonish us that this great flood must not be permitted to have a sheer fall through so great a height and act with a destructive force such as has heretofore created canyons, but it must be made to glide down the slope of the dam and not be permitted to exert the force due to its velocity except at such distance below the dam that the foundations will not be endangered.

The profile [fig. 3, left half] as shown to me seems not to fulfill the required conditions for passing the floods, because of the slightly rounded or nearly angular form at the front of its crest. Another diagram [fig. 3, right half] presented shows an advised modification of the profile of the upper part of the dam, which is better adapted to pass the flood in a gliding sheet down the face of the dam and to deliver it to the lower level without a direct blow, and so that its velocity will

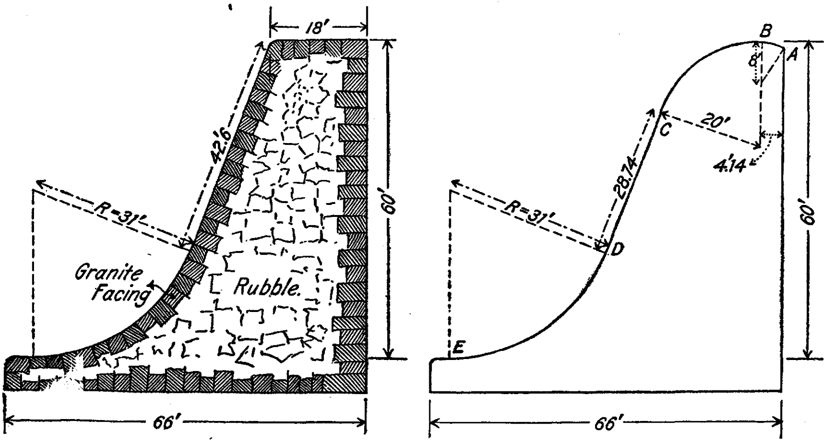


FIG. 3.—Cross sections of dam: Left side as proposed by Frizell; right side as constructed by Fanning.

be expended chiefly in a horizontal direction in the backwater below the dam and in eddies at a safer distance below the toe of the dam. The lower part of the downstream face of the dam has a curve of 31 feet radius to which low-water surface is tangent. The central part of this face has a batter of 4½ inches to the foot.

The new profile at the top part, as suggested, completes the downstream face and crest of the dam with a curve of 20 feet radius, to which both the front batter and the surface of the pond at a level of the crest are both tangent, this curve ending on the crest at 5 feet from the upper angle of the crest. The upper angle of the crest is then rounded off with a smaller curve, and the entire front of the dam becomes a reverse curve of ogee form, the form of dam best of all adapted to pass a large volume of water through so great a height. The top curve conforms nearly to the theoretical form of a medium flood stream. At higher flood stages there will be tendency to vacuum under the curve stream immediately after it has passed the crest, which, together with the pressure of the atmosphere upon the top of the stream, will keep the full flood stream in full contact with the curved face of the dam, and cause even the highest flood to glide down the fall without shock upon the face of the dam or the soft rock foundation.

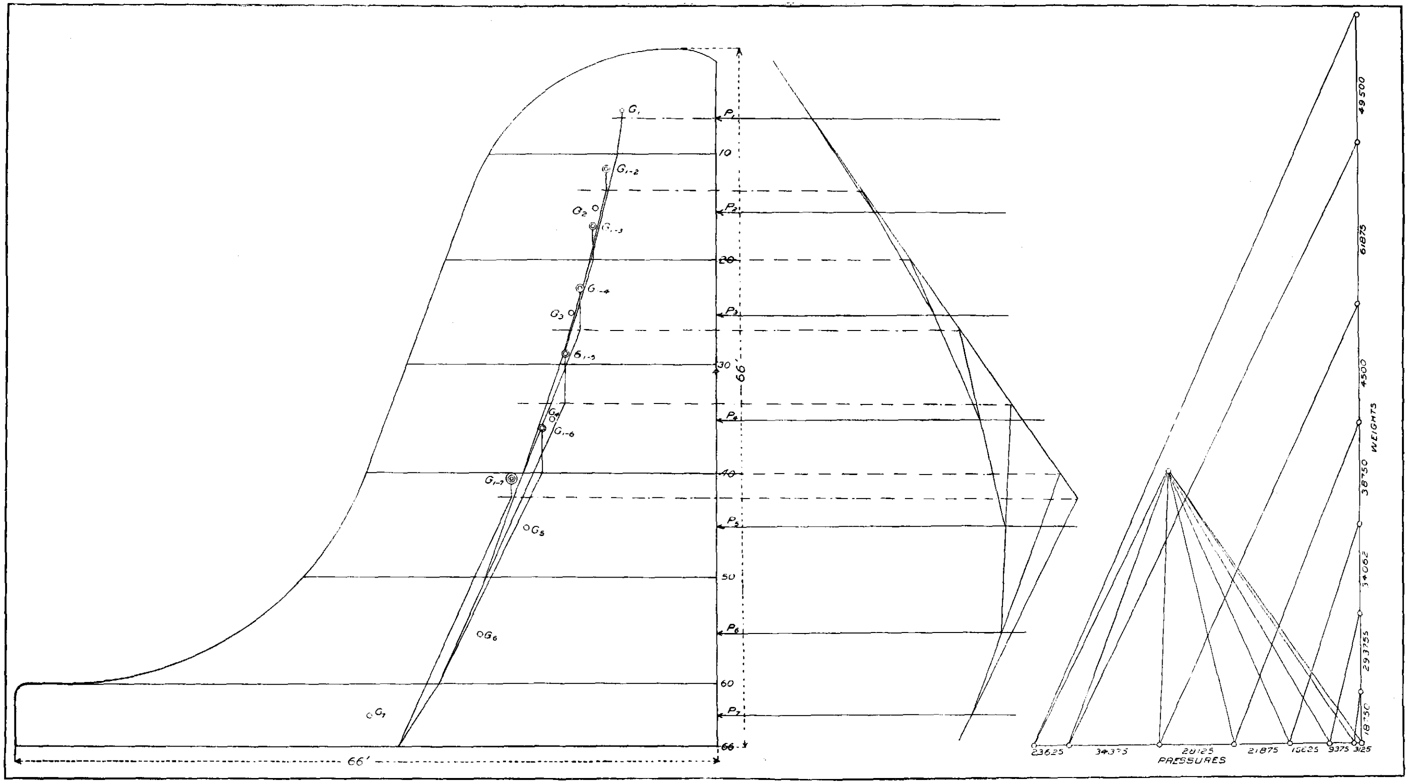
In addition to this, Mr. Fanning recommended that the power house be located in the position shown in fig. 5, and that the river side of the power house rest on a granite revetment wall 250 feet in length, to protect it from the force of the water.

The board of public works finally determined to change the cross section of the dam to that shown in fig. 3, right half, to locate the power house near the east end of the dam, and to take the water from the lake through 9-foot penstocks. The head-gate masonry before May, 1893, is shown in Pl. IV, *A*, which also illustrates the positions of the wrought-iron penstocks.

Pl. V shows the "line of resistance" of the dam, on the assumption that the masonry averages 125 pounds per cubic foot. This line of resistance falls within the middle third, and shows that the cross section was well designed to resist the pressure of the water.

To find the line of resistance of the dam, the height was divided into six equal sections of 10 feet depth, leaving the bottom or seventh section 6 feet deep. The areas of these sections were found to be 150, 235, 271, 310, 360, 495, and 396 square feet, respectively. Their centers of gravity were found and marked G_1, G_2, G_3, etc. For 1 foot in length of the dam the above areas became the volumes of the sections, in cubic feet. The weight of each section was found by multiplying the volume by 125, which was assumed to be the weight, in pounds, of a cubic foot of masonry. While the granite face of the area would have weighed more than this, the limestone cement core would have weighed less. The weights of the sections were 18,750, 29,375, 34,062, 38,750, 45,000, 61,875, and 49,500 pounds, respectively, and they will be referred to in this description as W_1, W_2, W_3, etc.

The horizontal water pressures were found to be 3,125, 9,375, 15,625, 21,875, 28,125, 34,375, and 23,625 pounds, respectively, and they will be referred to as P_1, P_2, P_3, etc. The forces acting upon the first section were the horizontal water pressure of 3,125 pounds (represented by P_1 in Pl. V) and its weight of 18,750 pounds, acting through G_1. By producing the force P_1 and W_1 to intersect, finding their resultant, and producing this resultant to cut the bed joint, we find the first point in the line of resistance. The forces acting on the first two sections were the two water pressures P_1 and P_2 (3,125 and 9,375 pounds, respectively), amounting to 12,500 pounds, and acting as represented by the dot-dash horizontal line between P_1 and P_2; and the sum of the weights (W_1 and W_2) of the first two sections, amounting to 48,125 pounds, acting through their common center of gravity G_{1-2}. By producing these two forces to intersect, and finding where their resultant cuts the second bed joint, we determine a second point in the line of resistance. Similarly, the intersection of the resultant acting on that part of the dam above any bed joint with said bed joint can be found. By joining the consecutive points where the resultants cut their corresponding bed joint the line of resistance is determined.



RESISTANCE LINE OF DAM.

In the case of the Austin dam the line of resistance fell within the middle third of the bed joints, and there was therefore no tension on any bed joint.

By using the force polygon shown on the right-hand side of Pl. V, the work of constructing the line of resistance can be greatly facilitated. Lay off consecutively, in a vertical line, W_1 (the weight of the first section), W_2 (the weight of the second section), W_3 (the weight of the third section), etc., and in a horizontal line lay off P_1 (the first water pressure), P_2, P_3, etc. It is clear that the lines in this diagram joining the ends of W_1 and P_1, W_2 and P_2, W_3 and P_3, etc., are parallel and equal in magnitude to the resultants acting on the first-second, the first-second-third, etc. All that is necessary to find the line of resistance is to produce P_1 to intersect a vertical through G_1, and through the point of intersection draw a line parallel to the first diagonal in the force diagram, to cut the first bed joint, thus determining the first point in the line of resistance. Again, produce the line of horizontal pressure represented by the dot-dash line between P_1 and P_2 to cut a vertical through $G_{1\text{-}2}$, and through the point of intersection draw a line parallel to the second diagonal in the force diagram, to cut the second bed joint, thus determining the second point in the line of resistance. In this way all of the points in the line of resistance can be found.

If it is desired to use graphical methods to find the position of the resultants of the pressures, select any convenient point as a pole and join it to the ends of P_1, P_2, P_3, etc., as shown in the smaller diagram on the right-hand side of Pl. V; then construct the equilibrium polygon, as shown in the diagram to the right of the section of the dam, as follows: First draw a line parallel to the line connecting the pole with the right-hand end of P_1; this line will cut P_1 at any assumed point; then draw a line parallel to the second diagonal from the pole, and passing through the point of intersection of our first diagonal of the equilibrium polygon and P_1; this line will cut P_2; and through this point of intersection a third line of the equilibrium polygon is drawn parallel to the third diagonal from the pole; this diagonal will cut P_3. In this way the complete equilibrium polygon is constructed. The position of the resultants of P_1 and P_2 can be found by producing the third diagonal of the equilibrium polygon until it meets the first diagonal; that of P_1, P_2, and P_3 can be found by producing the fourth diagonal until it meets the first diagonal in the equilibrium polygon; and so on. By drawing lines through these points of intersection parallel to the resultant pressures on the respective sections, we have the positions of the resultant pressures, as shown in the diagram (Pl. V) by the dot-dash horizontal lines. The first pressure in the case before us was not absolutely horizontal, on account of the rounded edge at the top on the upstream face, but it was so nearly horizontal that it will not materially modify the final analysis.

The best modern appliances were used in the construction of th dam. The granite material for the facing was obtained from Granit Mountain, near Marble Falls, being hauled from the quarry to tl dam over the Austin and Northwestern Railway, a distance of ' miles, and delivered at the east end of the dam, as shown in Pl. IV. The granite blocks were of average dimensions and weighed 4 tons each. The four classes of material used—i. e., the limestone rubble, the cement, the sand, and the granite—were transported from the end of the dam to place by a cable $2\frac{1}{2}$ inches in diameter, stretched between two towers—one on the east and the other on the west bluff—1,350

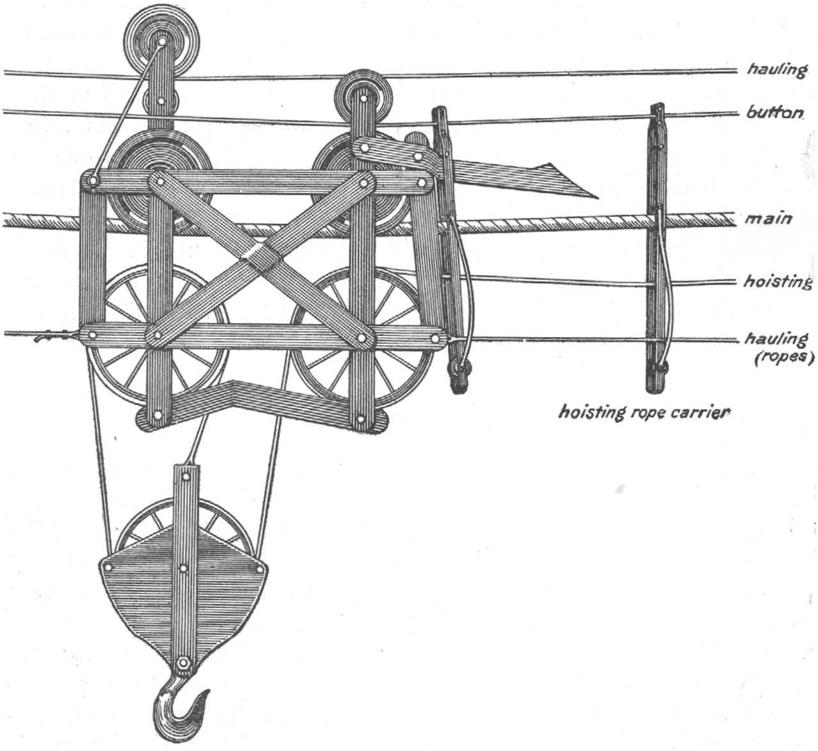
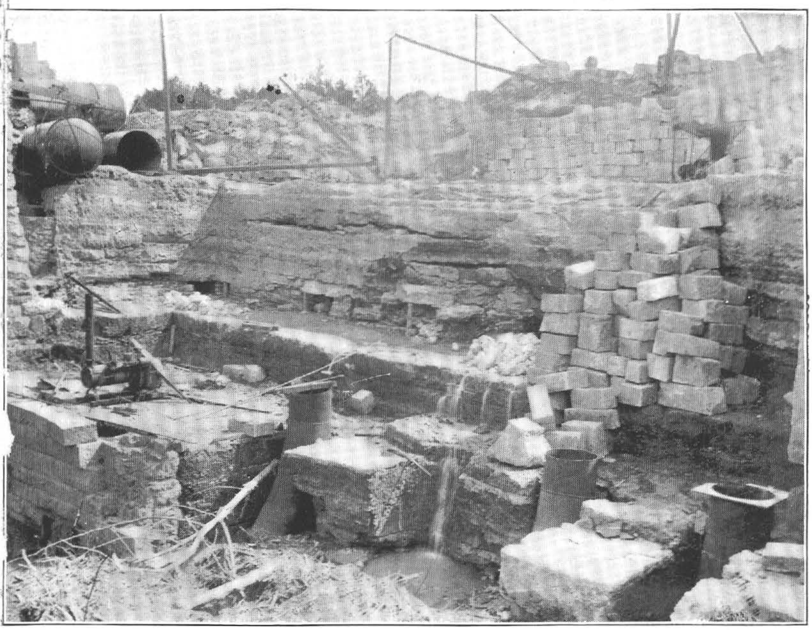


FIG. 4.—Saddle used on cable conveyer.

feet apart. The cable was anchored to "dead men" at the ends, weighted down by stone. The saddle shown in fig. 4 was specially designed for this work, and ran on the main cable. The wire ropes were known as the "hauling rope," the "hoisting rope," and the "button rope." The hauling rope was attached to the lower part of the frame work of the saddle, passed over pulleys at both towers, and wound around a drum under the east tower. The endless hauling rope was operated by an engine to which its drum was attached. It was completely under the control of the operator, and could be stopped in any position along its course. After being checked in the



A. POWER-HOUSE FOUNDATIONS AND OUTLET PIPES FROM TURBINES A FEW DAYS BEFORE FAILURE OF DAM.

B. LIMESTONE STRATA AT HEAD GATE.

position desired, the drum operating the hoisting rope was brought into motion and the load was lowered to the dam.

The granite blocks and the larger limestone rubble stones were handled by immense tong-like grips. The cement and sand were loaded into cages, transported to the place of construction, and there dumped on the dam. The cement mortar was made at the place where it was to be used, and the blocks of masonry were placed where needed by crane derricks shown in Pl. IV, *B*.

A wire rope one-half inch in diameter was used in connection with the cable and saddle to prevent excessive vibration of the operating ropes. On this rope there were buttons which increased in size from the tower to the west. The hoisting rope was supported at different points by carriers which rested, when the saddle was stationary, on the main cable. This carrier consisted essentially of two parallel bars, between which and near the lower end a small pulley was supported to carry the hoisting rope. A series of slots were arranged in the upper part of the carriers through which some of the buttons could pass. When near the east tower the saddle supported all of the carriers on a horn. In moving from the tower to the west, the smaller button passed through all of the carriers except the last, which it took off the horn; the second button passed through all of the remaining slots except that in the second carrier, which it pulled off the horn; etc. The carriers were thus stripped off the horn by the buttons and rested on the main cable, affording a groove or support for the hoisting rope and reducing its vibration.

LEAK UNDER HEAD GATE.

On May 30, 1893, the water from the lake cut under the east bulkhead and undermined the proposed foundation of the power house. It entered a seam in the limestone slightly above the point indicated at B in fig. 5, about 90 feet from the dam. From this point the course of the water was at an angle of about 30 degrees to the axis of the river to the left, and it also took a downward course and passed about 25 feet under the foundation of the head-gate masonry. A view of the power-house foundation a few days before the break is given in Pl. VI, *A*. The water issued from the west wall of the proposed power-house foundation and soon wrecked it. The general course of the water was from a point near the east end of the head-gate masonry diagonally across the foundation to the point of exit.

A cofferdam about 125 feet long was constructed of framework, with dirt and hay as fillers, from a point on the shore above the entrance to the crevice to a point near the end of the dam. This effectually cut off the water from the proposed forebay, and the work of repair commenced. As originally designed, the head-gate masonry contemplated 9 large pipes, but only 7 were put in.

The head-gate masonry cracked about 40 feet from the end of the dam, along the line HM in fig. 5, and settled. The earth east of the east end of the head gate settled for a distance of 25 feet. Plans were immediately adopted for raising and strengthening the cofferdam so as to provide against floods, for rebuilding the head gate, and for the construction of a power-house foundation. The broken part of the head-gate masonry was removed (leaving only that over penstocks 1

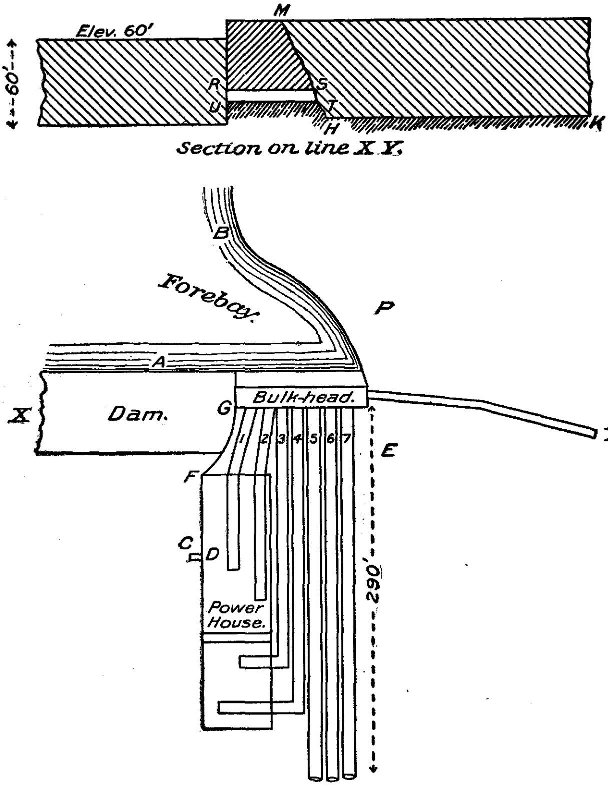
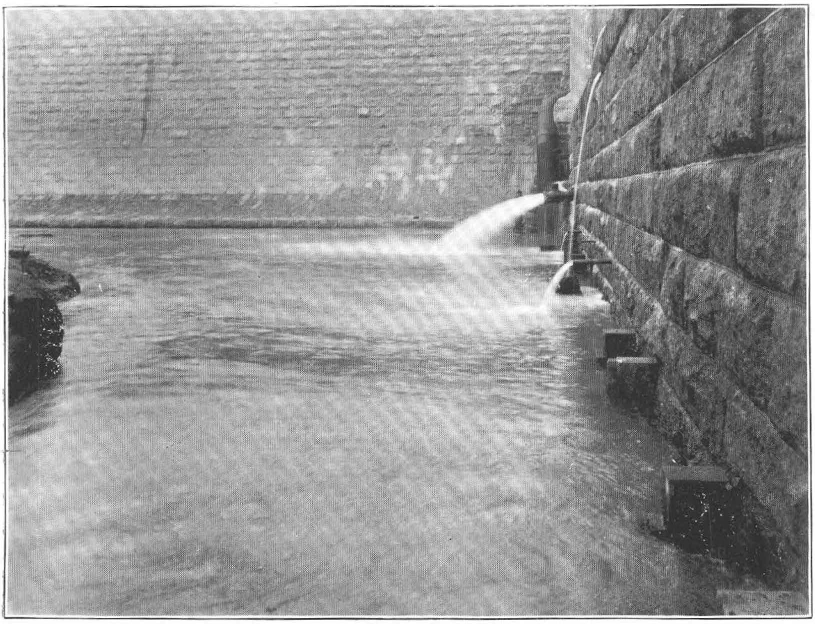
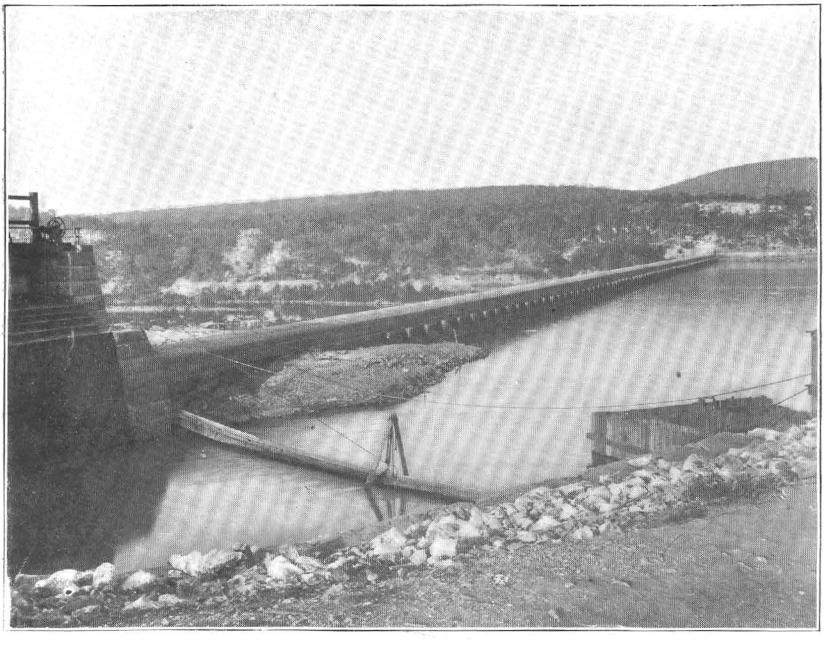


FIG. 5.—Section and sketch plan of bulkhead, showing location of power house and penstocks. HK is bottom layer of concrete filling resting on hard limestone strata; HM is line of crack; RS is the original level of bulkhead masonry; RSTU is tunnel (6 feet by 6 feet by 60 feet long) filled with concrete; A is point where drift indicated leak in the spring of 1899; B is location of leak discovered in the fall of 1899; P is point from which view shown in Pl. VII, *B*, was taken; FG is wing wall; C is 10-inch horizontal pipe projecting from wall of power house, known as "the spring;" D is cement chamber for controlling water and directing it through C; 1 to 7 are penstocks; E is the point at which the leak in penstock was found in February, 1900.

and 2), and an excavation nearly 200 feet long and 70 feet deep, with an average width of 7 feet, was made. This trench reached to a level of 57 feet below the crest of the dam, or within 3 feet of the level of the toe. The head-gate masonry was rebuilt, provision being made for only seven 9-foot penstocks, the rest of the excavation being filled by a concrete wall 112 feet long, which was 8 feet thick for the 90



A. DISCHARGE OF LAKE THROUGH DAM, OR THE SO-CALLED "SPRING."



B. VIEW SHOWING TWO METHODS EMPLOYED TO STOP LEAK THROUGH DAM.

feet next to the head gate and only 5 feet thick for the rest of the distance. In excavating for this extension wall, alternate layers of hard and soft limestone were encountered, as shown in Pl. VI, *B*. The bottom layer of the concrete filling (HK, fig. 5) was laid on one of these hard strata, but it was fully demonstrated that a current of water was running underneath. Several holes were drilled, through which the water welled up in jets several inches high. However, it was thought safe to plug these holes and to ignore the stream below. The bulkhead masonry originally extended to the level RS, fig. 5, 36 feet below the top of the dam; but as an extra precaution a tunnel (RSTU) 6 feet by 6 feet square and 60 feet long was cut under the bulkhead masonry back to the end of the dam proper, and the space was filled with concrete. The space below the 42-foot level under the tunnel was not disturbed.

The foundation for the power house was then excavated to a depth of more than 80 feet below the crest of the dam. The original contractors, after a dispute in regard to the excess of water flooding their work, surrendered their contract. The new contractors succeeded in controlling this water by the use of a cement chamber at D, fig. 5, and a 10-inch horizontal pipe, which projects from the wall of the power house at the point C, about 54 feet below the crest of the dam. This is often referred to as "the spring." A view of it is shown in Pl. VII, *A*, where it is being discharged through a 10-inch pipe in the third course of granite above the toe of the dam. Measurements taken in October, 1895, showed a range, on the horizontal surface of water in the tailrace, of 5.1 feet and a fall of 5.8 feet, giving a discharge of 4.6 feet per second. A 3,000,000-gallon pump entirely exhausted this "spring." In May, 1897, the flow from the so-called "spring" suddenly increased. An average of several measurements gave a range of 11 feet and a fall of 5.8 feet, and therefore a discharge of about 10 second-feet. Measurements recently taken give a range of 8.8 feet and a fall of 5.8 feet, and therefore a discharge of 8 second-feet.

In the spring of 1899 it was discovered, from the behavior of drift, that water was disappearing from the lake at point A, fig. 5. This source of leakage was stopped by filling the lake at that point with clay, loose and in bags. While the filling in was going on the discharge of water from the 10-inch pipe almost ceased for a few hours, but soon reached its normal amount. The filling kept the water discolored and muddy.

In the fall of 1899 it was noticed that water was disappearing at point B, fig. 5, only a few feet from the shore. A cofferdam of sheet piling was constructed around this point and it was filled with hay and earth. A view, taken from point P, fig. 5, of the two leaks and of the method of filling by clay and sheet piling is shown in Pl. VII, *B*. The clay filling is the pile of dirt adjoining the upstream face of the dam.

In the latter part of December, 1899, the earth in front of and between the power house and bulkhead, and at point E, fig. 5, began to sink and continued to sink until it was determined to remove the earth covering the 9-foot penstocks under the sunken areas, in order to discover the cause. The removal of the earth showed that penstock No. 3 (fig. 5) was buckled, and that at one place it had sunk about 20 inches. A bold stream of water—at least 2 second-feet in amount and 16 feet below the top of the dam—was found when the earth was taken out between the power house and penstock No. 3, and between penstocks Nos. 3 and 4. The stream of water was partly deflected around the north end of the power house and under penstocks Nos. 1 and 2. The water did not rise in the excavation, and it was discharged through some 2-inch pipes at F, fig. 5, 14 feet below the crest of the dam, through two or three other small pipes, and by absorption through the wing wall FC and through the east wall of the power house. Penstock No. 5 was also found buckled at a joint about 35 feet from the bulkhead. The water which caused the settling came from a broken 2-inch pipe tapped into the bottom of penstock No. 5. The break was at an elbow just below the penstock, at a point about 16 feet below the crest of the dam and 40 feet from the south side of the bulkhead masonry.

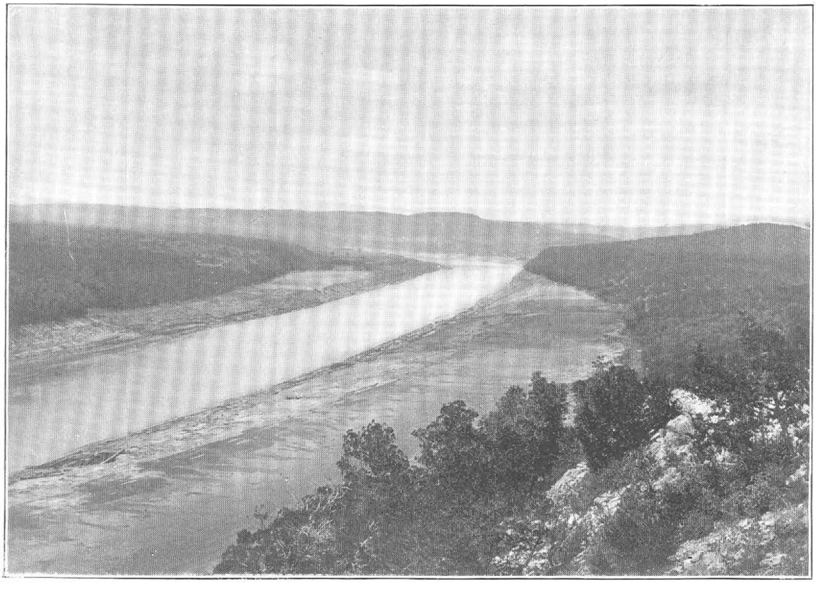
FLOW OF COLORADO RIVER.

The minimum flow of Colorado River was estimated in 1890 to be 1,000 cubic feet per second; and it was upon this estimate that the engineers based their calculations of the power that would become available by the erection of a dam 60 feet high above low water. With an effective head of 57.5 feet and a machinery efficiency of 80 per cent of the theoretic, for this flow there would be available continuously 5,227 horsepower, and if held back nights and Sundays and used only 60 hours a week, 14,600 horsepower.

After February 10, 1897, the city's plant furnished power for its own water and light system, for the Dam and Suburban Railway, for the Rapid Transit Street Railway, and for various motors in the city. This required, in the opinion of the superintendent of water and lights, an average of about 1,000 horsepower; that is, with a machinery efficiency of 75 per cent, about 200 cubic feet of water per second. During 1897 the lake level was below the crest of the dam eighty-nine days, showing that the supply of water at the forebay was not sufficient to carry the load upon it. In 1898 the water was below the crest one hundred and eighty-six days, and in 1899 it was below two hundred and four days, making a total of four hundred and seventy-seven days during the last three years, or 43 per cent of the time from January 1, 1897, to January 1, 1900.

The maximum flood height occurred on June 7, 1899, when the water level of the lake was 9.8 feet above the crest of the dam, giving

A. MARBLE FALLS, ABOVE LAKE McDONALD.



B. VIEW UP RIVER FROM MOUNT BONNEL, AFTER DESTRUCTION OF DAM.

a flood discharge of 101,000 cubic feet per second, or enough water passing each second to run the plant eleven days.

From March 15 to April 17, 1899, the lake level was more than 10 feet below the crest of the dam; and again, from September 16 to October 23, it averaged about 10¼ feet below the crest. In all, it was more than 10 feet below the crest of the dam during seventy-two days in 1899, or about one-fifth of the year. During these periods of low lake level the following measurements of the flow were taken:

Discharge measurements of Colorado River during low lake level.

Date.	Locality.	Gage height.	Discharge.
1899.		*Feet.*	*Second-feet.*
January 31	Head of lake	—7.60	210
March 13	Marble Falls	—9.85	197
March 15	Forebay at dam	—10.00	206
Do	Tailrace at dam	—10.00	233
Do	Forebay at dam	—10.05	186
March 17	Tailrace at dam	—10.05	203
Do	Between bridges	—10.05	267
October 3	Head of lake	—10.45	134
October 4	do	—10.35	134
October 6	Marble Falls	—10.25	105
October 4	Head of lake	—10.35	136

In explanation of these measurements it is necessary to say that the low level of the lake compelled the authorities of the city to cut off the power from the Rapid Transit and the Dam and Suburban railways on March 20 and September 9, and from the tower lights on January 22 and September 6. The flow (206 and 186 second-feet) into the penstocks was then being utilized for pumping water, for operating the street-car systems, and for running a few motors in the city. The effective head on the turbines was about 50 feet, giving a theoretic horsepower of 850. The actual horsepower was about the same. The flow below the dam, at the tailrace, was in excess of the inflow by 27 and 16 second-feet, respectively. The flow through "the spring" pipe was 10 second-feet, and the rest can be accounted for by the momentary fluctuations in the supply to the turbines that ran the street-car systems. This fluctuation was caused and controlled by the demand made by the motors and the cars for power. The inflow was controlled by automatic gates that responded to these demands.

The difference between the inflow and the flow at the station between the bridges was 81 second-feet. Barton Springs supplied 20 second-feet of this, the power-house "spring" 10 second-feet, and other small springs along the river between the dam and the railroad bridges supplied a large part of the remainder.

While the city plant was furnishing power for all of the purposes mentioned, the average flow at the tailrace was about 300 second-feet, which should have developed 1,500 horsepower. During the day the flow was less than during the active hours of the night, but measurements taken on the tailrace gave a flow of 295 second-feet, with the turbines which ran the city's pumps, the street-car systems, and the city motors in full operation.

All measurements at the station between the railway and the highway bridges were so completely controlled by the flow through the penstocks at the dam that they gave no indication of the unrestricted flow of the Colorado.

The minimum flow was not sufficient to carry the load of the pumps, the lights, two street-car systems, and the motors for power plants in the city, and when this flow was decreased by the evaporation from the lake surface (3 square miles) the lake level sank rapidly.

The low stages of the water in 1899 can not be ascribed to a decreased annual rainfall but to a very irregular one. For the purpose of comparison, the rainfall at Austin since 1856, with the exception of the years 1882, 1883, and 1884, records for which are not obtainable, is given below.

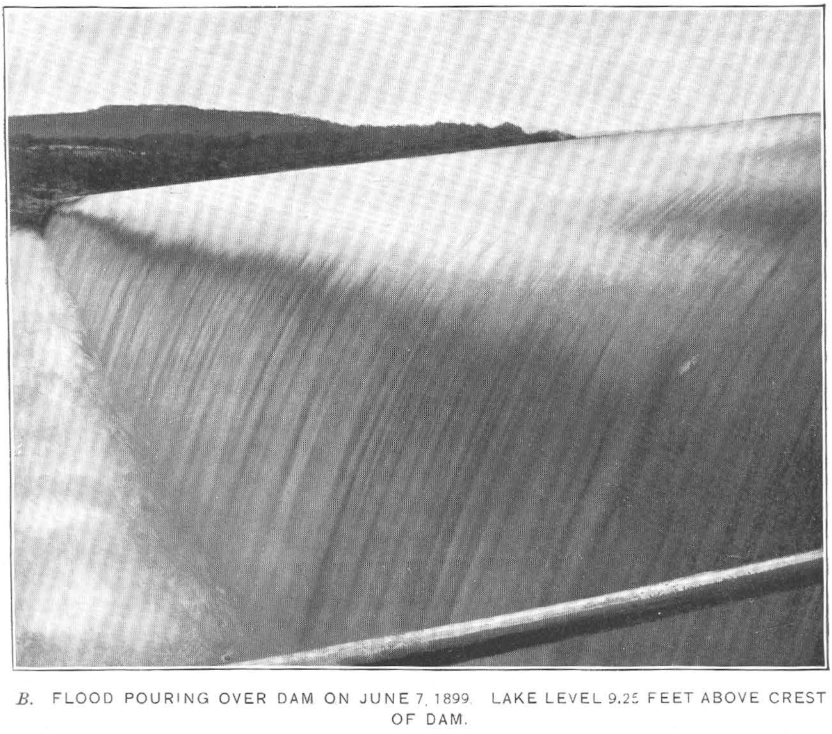
Rainfall at Austin, Texas.

Year.	Rainfall.	Year.	Rainfall.	Year.	Rainfall.
	Inches.		*Inches.*		*Inches.*
1856	19.6	1870	42.5	1887	23.5
1857	33.0	1871	30.1	1888	51.8
1858	36.4	1872	33.3	1889	43.2
1859	28.2	1873	43.4	1890	36.4
1860	29.6	1874	46.5	1891	37.1
1861	28.7	1875	29.3	1892	34.7
1862	22.2	1876	32.6	1893	16.3
1863	34.7	1877	41.8	1894	27.5
1864	25.2	1878	21.6	1895	31.9
1865	37.8	1879	18.3	1896	21.9
1866	40.5	1880	48.1	1897	28.1
1867	27.3	1881	25.3	1898	25.9
1868	40.1	1885	40.3	1899	28.0
1869	38.5	1886	32.4		

The rainfall of 1899 (28 inches) was greater than that of 1898, nearly equal to that of 1897, and greater than that of 1896; but the rainfall of that year (1899) was concentrated and not distributed like that of previous years. In 1899 very heavy rains fell in the months of April and June. In the latter month occurred the highest flood within the last twelve years.

In the discussion that arose over the proposition to change the cross section of the dam, as shown in fig. 3, the question of the amount of flow and its effect on the toe of the dam was considered. Mr. Frizell then brought to the attention of the engineering public the following proof of the formula of flow: Let H = the height of lake level above crest of dam; x = the part of this height that gives the velocity over the crest; Q = flow in second-feet; v = velocity in feet per second;

A. VIEW OF DAM FIVE MINUTES BEFORE FAILURE ON APRIL 7, 1900.



B. FLOOD POURING OVER DAM ON JUNE 7, 1899. LAKE LEVEL 9.25 FEET ABOVE CREST OF DAM.

l = length of crest; $H - x$ = depth of water on crest: Then $v = \sqrt{2gx}$ where $2g = 64.32$ feet; $\therefore Q = v (H - x) l = l (H - x) \sqrt{2gx}$. This must be a maximum, hence the derivative of Q with respect to x must be zero; hence—

$$O = l \sqrt{2g} \left[\frac{H - x}{2x^{\frac{1}{2}}} - x^{\frac{1}{2}} \right], \therefore x = \tfrac{1}{3} H, \therefore Q = 3.09\, l\, H^{\frac{3}{2}}.$$

In the case of the Austin dam, $l = 1091$, $\therefore Q = 3362\, H^{\frac{3}{2}}$.

The formula generally used to find the flow over crests is $Q = cl\, H^{\frac{3}{2}}$. With a view to testing the reliability of this formula and finding the coefficint c, in January and March, 1900, measurements of velocity were taken, with a small Price electric meter, by Mr. E. E. Howard, a senior in the engineering department of the University of Texas. The dam broke before the investigations were completed, but the following values of the coefficient c were found:

Tabular statement of values of coefficient c.

Date.	H.	h. (a)	v.	c.
1900.				
January 15	1.09	0.92	3.85	3.09
Do	1.09	.92	3.99	3.21
Do	1.09	.92	3.85	3.09
Do	1.09	.79	4.22	3.14
January 18	.72	.625	2.33	3.06
Do	.72	.625	2.33	3.06
Do	.72	.625	2.37	3.11
Do	.72	.625	2.29	3.00
Do	.72	.625	2.33	3.06
Do	.72	.625	2.33	3.06
Do	.72	.626	2.33	3.06
Do	.72	.625	2.29	3.00
Do	.72	.625	2.37	3.11
Do	.72	.625	2.29	3.00
Do	.72	.625	2.33	3.06
January 26	.42	.33	1.57	3.06
Do	.42	.33	1.61	3.13
Do	.42	.33	1.61	3.13
Do	.42	.33	1.61	3.13
March 28	1.44	1.04	4.95	3.32
Do	1.44	1.04	4.95	3.32
Do	1.44	1.04	5.01	3.36
Do	1.32	.96	5.27	3.33
Do	1.32	.96	5.18	3.26
Do	1.32	.96	5.27	3.33
Do	1.32	.96	5.18	3.26
Do	1.32	.96	5.27	3.33

a Depth of water on crest.

Floods of historic importance occurred as follows:

	Feet.
February, 1843	36
March, 1852	36
July, 1869	43
October, 1870	36
June, 1899	23
April, 1900	33

On July 3, 1869, began the longest and most uninterrupted rain ever known in Austin. It rained without stopping for about sixty-four hours, and the river rose to a height of 45 feet. The lower part of the city was overflowed and several people were drowned. The town of Webberville, 16 miles below Austin, was also overflowed, and Bastrop, 30 miles below, was inundated.

ECONOMIC ASPECT.

The population and taxable wealth of the city at various times is shown in the following table:

Population and taxable wealth of Austin, Texas.

Year.	Assessed valuation of real estate.	Assessed valuation of personal property.	Total assessed value.	Increase each year.
1889	$5,665,886	$2,324,757	$7,990,643	
1890	6,462,209	2,473,343	8,935,552	$944,909
1891	7,577,116	2,936,962	10,514,188	1,578,530
1892	8,054,405	2,719,318	10,773,723	259,635
1893	8,184,297	2,697,633	10,881,930	108,207
1894	8,384,429	2,640,342	11,025,368	144,335
1895	8,520,659	2,863,075	11,384,734	259,366

Before the issuance of the $1,400,000 of water and light bonds in 1890, the bonded indebtedness was as follows:

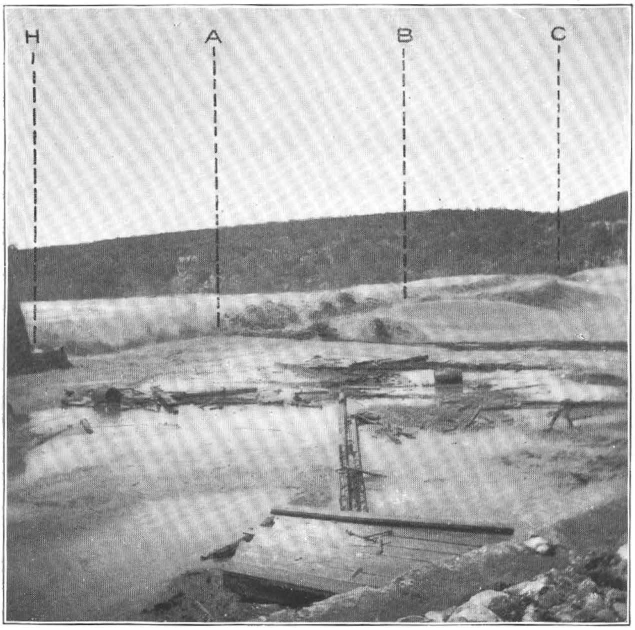
Six per cent bonds due in 1901	$12,500
Six per cent bonds due in 1905	40,000
Six per cent bonds due in 1925	72,500
Total	125,000

On May 5, 1890, the city authorized the issuance of $1,400,000 water and light bonds at 5 per cent. The first $400,000 were sold on October 15, 1890, to a syndicate of local capitalists at par and accrued interest. In April, 1892, the Union Trust Company bought $500,000 of the bonds at 95 cents on the dollar, and in 1893 Bernard Corrigan bought $62,000 of them at 95. Later, in 1893, $388,000 were sold at 92 and $50,000 at par.

Total receipts from bonds.

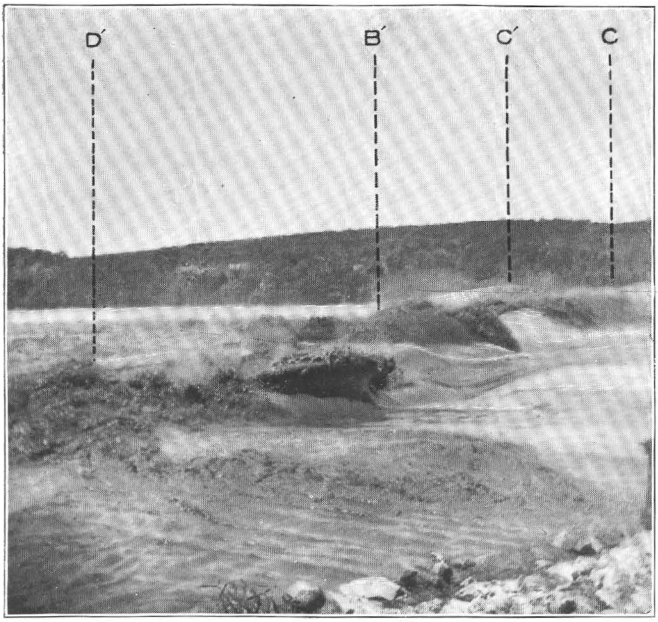
450 bonds, at par	$450,000
562 bonds, at 95	533,900
388 bonds, at 92	356,960
Total	1,340,860

The break in the head-gate masonry and the destruction of the first foundation of the power house caused an outlay of $97,000 above all expectations, and it was apparent that another issue of bonds would be necessary to complete the enterprise as originally contemplated.



A. VIEW THREE MINUTES AFTER FAILURE OF DAM.

A—B and B—C are portions of dam first broken; H—A is eastern part of dam (83 feet long on crest) left standing.



B. VIEW TEN MINUTES AFTER FAILURE OF DAM.

D′—B′ is broken portion of dam still standing; B′—C′ is western portion of break; C is end of western part of dam (456 feet long on crest) left standing.

Under the direction of the board of public works the following expenditures were made:

Disbursements.

Engineering expenses	$58,402.37
Dam	611,313.39
Electric-light dynamos	7,700.55
Electric-power generators	6,708.50
Belting	43.81
Power house	45,917.98
Penstocks, head-gate castings, etc	47,792.19
Draft-tube excavations	2,314.08
Pump foundations	658.66
Bonds	1,237.50
Head gates	2,122.60
Sluice pipes	2,420.19
Repairs on account of break	96,941.23
Wheels, pumps, etc	43,418.02
Countershafting, pulleys, etc	1,206.85
Water distribution system	158,081.04
Electrical distribution system	115,678.29
Railroad	87,431.90
Office expenses	10,170.03
Submerged lands	27,732.15
Head-gate masonries	46,934.17
Power-house foundations	11,527.60
Miscellaneous	5,375.74
Total	1,391,129.64

The board of public works was discontinued on the completion of the dam in 1893, and the city council then assumed control and managed the plant until the water and light commission was created by charter in 1897. At the time the board of public works was abolished there was due and unpaid on contracts the sum of $55,896.87. The water and light commission had exclusive supervision, management, and control of the waterworks system, the electric lights, the power plant, and all property, funds, and business belonging or pertaining thereto.

The $200,000 of bonds issued in 1895 were utilized in paying the $56,000 indebtedness left by the board of public works, and in completing the water and light system, with the exception of the reservoir. The reservoir was never built. After a site had been practically chosen it became evident that it would be necessary to filter the water of the lake, and upon the advice of Mr. Allen Hazen, of New York City, the sanitary engineer called in for consultation, it was determined to construct filtering galleries in the sand flats about 2 miles below the dam, and to transfer the pumps to a new pump house to be erected near the filters. These galleries, three in number, were in successful operation when the dam broke. The lower station was equipped with a 6,000,000-gallon pump and a 300-kilowatt synchronous motor, which cost $29,380. The filtering galleries and connections cost, in round numbers, $21,000.

No better idea can be given of the operation of the plant than to append a report for the twelve months ending November 30, 1899:

Earnings:	
Water	$40,369.39
Light	30,192.61
Power	12,777.14
Miscellaneous	1,206.86
Total	84,546.00
Collected in cash	67,298.12
Due by city	12,745.19
Garnisheed accounts	2,836.70
Due on bills, etc	1,665.99
Total	84,546.00

For the purpose of comparison, the receipts and expenditures for the last three years are here tabulated:

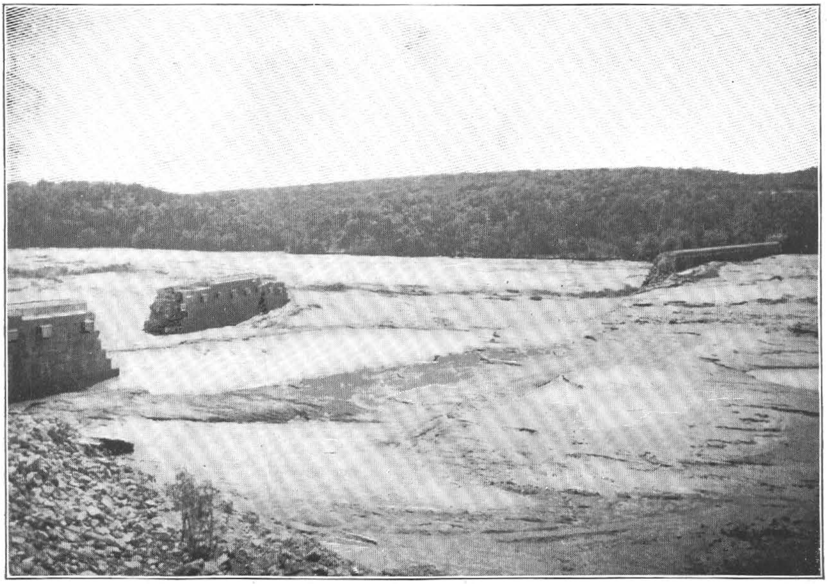
Receipts and disbursements of power plant at Austin, Texas.

Year ending—	Receipts.	Operating expenses.	Extensions.	Total disbursements.
November 30, 1897	$82,059.44	$36,709.07	$57,821.02	$94,530.09
November 30, 1898	93,651.05	36,239.32	38,724.54	74,963.86
November 30, 1899	82,927.43	39,742.31	34,711.95	74,454.26

SILTING UP OF LAKE McDONALD.

In 1890 cross sections of Colorado River were taken at sixteen stations, as shown in the tabular statement on page 38 and in fig. 6. The complete outline of the diagrams in fig. 6 represents the original cross section, the horizontal line being the water surface even with the crest of the dam and the shaded area showing the amount of silt that had been deposited up to February, 1900. All vertical dimensions are exaggerated three times over the horizontal dimensions. Cross sections were again taken for the United States Geological Survey in May, 1897, also in January, 1900. The silt deposited from 1893 to 1897 is represented by the lower shaded area, and that deposited from 1897 to 1900 by the upper shaded area.

The water first flowed over the crest of the dam on May 16, 1893, at which time there were 83,556,000 cubic yards of water in the main channel of the lake up to the level of the crest of the dam; in 1897 there were only 51,889,000 cubic yards of water in the channel, the remaining 31,667,000 cubic yards (or 38 per cent of the original capac-



A. VIEW ABOUT TWO HOURS AFTER BREAK.

B. VIEW ONE HOUR AFTER BREAK.

ity) being silt. Estimated in depths on a square-mile base we have, in 1893, a volume of water equal to a depth of 80.9 feet, and in 1897,

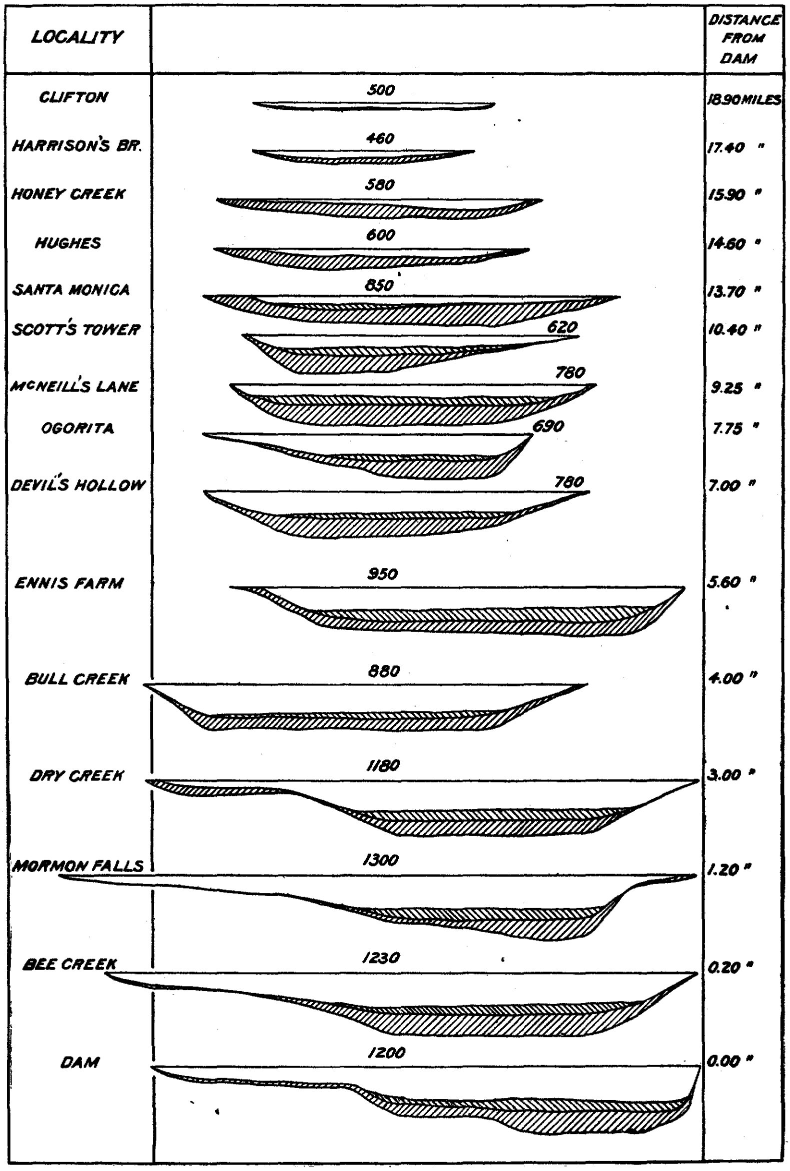


FIG. 6.—Cross sections of Lake McDonald, illustrating accumulation of sediment between 1893 and 1897 (illustrated by the lower shaded area) and between 1897 and 1900 (illustrated by the upper shaded area). The number above each section indicates its length, in feet.

four years later, we have a volume of water equal to a depth of 50 feet and silt to a depth of 30.9 feet, showing the average amount of silt deposited annually to be 7.7 feet, on a square-mile base.

The following table shows the maximum and mean depths of water for 1893 and 1900, the maximum and mean depths of silt for 1900, and the percentage of silting up at the respective stations:

Table showing silting up of Lake McDonald.

Station.	Maximum depth of water.		Maximum depth of silt, 1900.	Mean depth of water.		Mean depth of silt, 1900.	Amount of silting up to February, 1900.
	1893.	1900.		1893.	1900.		
Miles.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Per cent.*
0.0	66.0	39.0	27.0	40.1	27.5	12.6	31.2
0.2	67.0	38.0	27.7	37.6	26.5	11.1	32.2
1.2	63.8	35.5	28.3	30.6	21.7	8.9	30.2
3.0	56.0	31.5	24.5	33.4	21.5	11.9	38.8
4.0	47.8	31.5	19.0	38.0	23.5	14.5	37.9
5.6	47.5	27.5	23.0	36.7	23.0	13.7	42.0
7.0	47.0	22.0	26.0	36.3	17.4	18.9	56.3
7.75	44.8	20.5	25.0	30.7	15.4	15.3	56.3
9.25	40.4	13.4	29.0	30.8	10.2	20.6	66.9
10.4	40.9	13.5	27.4	27.2	7.9	19.3	71.8
13.7	29.4	9.8	26.0	20.3	5.5	14.8	78.9
14.6	24.0	12.5	16.0	17.2	9.0	8.2	50.4
15.9	16.6	12.0	15.0	13.2	10.0	3.2	60.0
17.4	13.2	9.5	7.0	11.2	8.8	2.4	30.0
18.9	7.6	5.0	2.6	5.6	3.9	1.7	33.0
20.0	3.7	2.2	1.5	2.8	2.0	1.8	35.0

The maximum depth of silt is not always equal to the difference between the maximum depth of water for 1893 and 1900, as the channel shifted at several points. This is very noticeable at station 13.7, known as the Santa Monica (or Sulphur) Springs station. The last column ("Amount of silting up," etc.) gives the ratio that the present cross section of silt bears to the original cross section of water. Thus at Santa Monica Springs (station 13.7) 78.9 per cent of the original cross section has filled with silt.

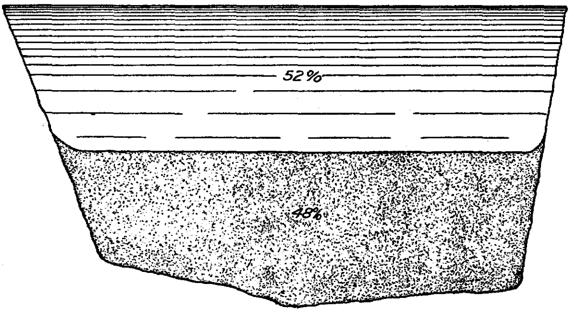


FIG. 7.—Generalized cross section of Lake McDonald, showing accumulation of sediment.

In February, 1900, there were 43,460,000 cubic yards of water in the main channel of the lake beneath the level of the top of the dam (equivalent to 42.1 feet on a square-mile base) and 38.8 feet of silt. Thus 48 per cent of the original storage capacity of the lake was at that time mud. Up to that date the average rate of deposit, on a square-mile base, was 5.8 feet per year.

A. VIEW ABOUT 350 FEET BELOW DAM, SHOWING WAVES THOUGHT TO BE DUE TO SECONDARY DAM FORMED BY DÉBRIS FROM WRECK.

B. POWER HOUSE OF AUSTIN WATER, LIGHT AND POWER COMPANY, ABOUT 2 MILES BELOW DAM.

In 1897 this silt, to within 2 miles of the head of the lake, was a fine, impalpable, absolutely gritless deposit, and where newly exposed would not bear an appreciable weight on its surface. The writer has often tried its resistance all along the lake, and an oar could be driven into it several feet with moderate pressure. Shovelfuls of it placed upon boards in a heaped-up mass would immediately settle and spread so that the upper surface was almost horizontal. A barrelful of it, when first taken up at Santa Monica Springs, soon spread out in a flat sheet. At the head and for about 2 miles down the lake the silt consisted of a sand which readily deposited when the velocity of the stream was checked by the waters of the lake. At occasional points below the head of the lake small bars of sand were found near the mouths of small canyons or creeks.

From March 15 to April, 1899, the water level of the lake was a

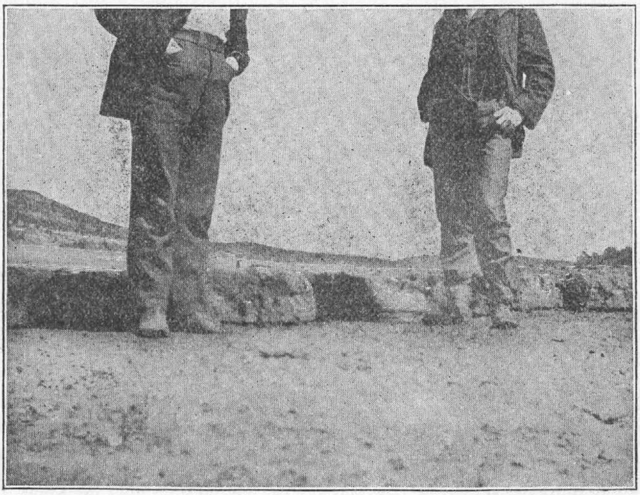


FIG. 8.—Layer of silt remaining on plateau after destruction of dam.

little more than 10 feet below the crest of the dam. The water again commenced flowing over the crest of the dam on April 21 and continued to flow over, at small depths, until June 7, when the river rose to a height of 9.8 feet above the crest of the dam. This flood continued until June 12, and its effect on the cross sections near the head of the lake was marked. The sections at stations 14.6, 15.9, 17.4, and 18.9 were scoured out 2 to 3 feet deeper than the sections of 1897, and at station 15.9 a sand bar was deposited on the inside (left) of the curve of the river, contracting the channel to less than half its former width.

The typical section illustrating the ratio of silt and water areas for the whole lake is about midway between stations 5.6 and 7.0, i. e., about one-fourth of a mile below the Chautauqua wharf. Fig. 7 illustrates this section, the vertical scale being magnified ten times.

Fig. 2 shows the configuration and geography of the lake formed by the dam. The river, as shown by fig. 1, for 200 or 300 miles, flows through a hilly country, from above Colorado City, on the Texas and Pacific Railroad, and in its course absorbs the waters of the Concho, the San Saba, the Llano, and the Pecan Bayou. All of the country drained by these tributaries is hilly, with the exception of a few miles along the head of the Colorado and the Concho.

When the break occurred the silt in the immediate vicinity of the dam would have flowed out had there been no water. Just above the part of the dam that gave way was a plateau whose surface was on an average about 18 feet below the crest of the dam. At the time of the break the lake level was 11 feet above the crest of the dam, making the depth of water on the plateau 29 feet. The torrent poured over this plateau with immense velocity, as shown in Pls. X and XI. The silt on the plateau was cut away with such swiftness that in three hours it was swept almost clean. Only a slight amount remained, as can be seen from fig. 8; the men are standing on the original soil of the plateau, the silt appearing behind them.

In the main channel the upper surface of the silt was 38 feet below the crest of the dam, giving, at the time of the break, a depth of water in the main channel of 49 feet. After the water level dropped below the plateau the current was confined to a narrow gorge. The flood continued in the main channel for several days. A week after the failure the silt along the shores of the former lake was cut into fantastic shapes by the currents of the river and those of many mountain gorges. The silt in contact with the dam undoubtedly increased the pressure against it, but that portion of the dam across the main channel where the silt was 28 feet deep and where the pressure was greatest was on a good hard rock foundation and successfully resisted it. There was practically no waterlogged drift in this silt; the soundings indicated mud bottom. The silt deposit kept the river at Austin muddy for months after the failure. (It is still muddy—November 1, 1900.)

Pl. VIII, *B*, is a view of the lake from Mount Bonnel, looking up the river, two weeks after the break, with the freshet still on. The extreme right-hand part of the curve is the mouth of Bull Creek.

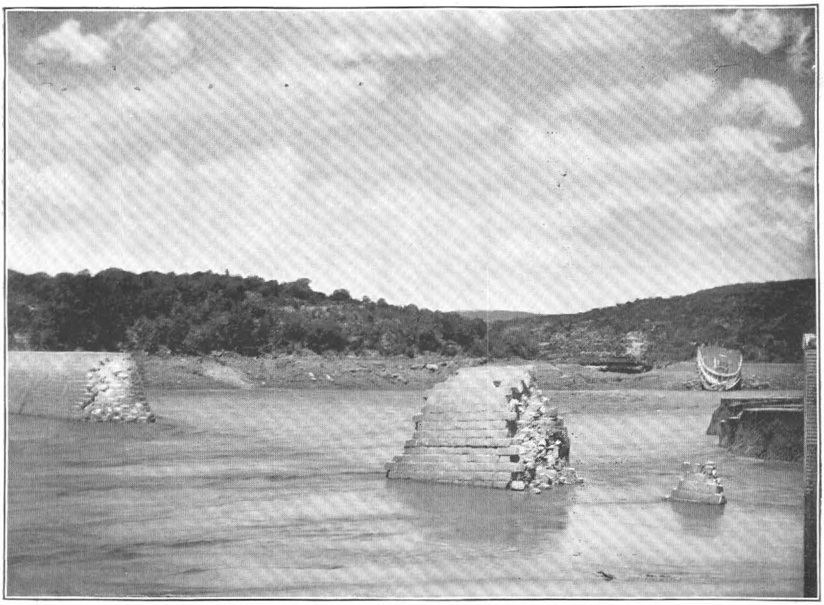
For purposes of comparison, the silting up of reservoirs is best reduced to heights and depths on a square-mile base. To derive an expression for the amount of silt deposited in a given time, let x equal depth, in feet, of silt deposited in a year by each foot of water in the reservoir, and let h equal the original depth of the reservoir. The depths of water are at the end of one, two, three, etc. n years:

First year, $h - h\,x = h\,(1-x)$;
Second year, $h\,(1-x) - h\,(1-x)\,x = h\,(1-x)^2$;
Third year, $h\,(1-x)^2 - h\,(1-x)^2 x = h\,(1-x)^3$;
Fourth year, $h\,(1-x)^3 - h\,(1-x)^3 x = h\,(1-x)^4$.

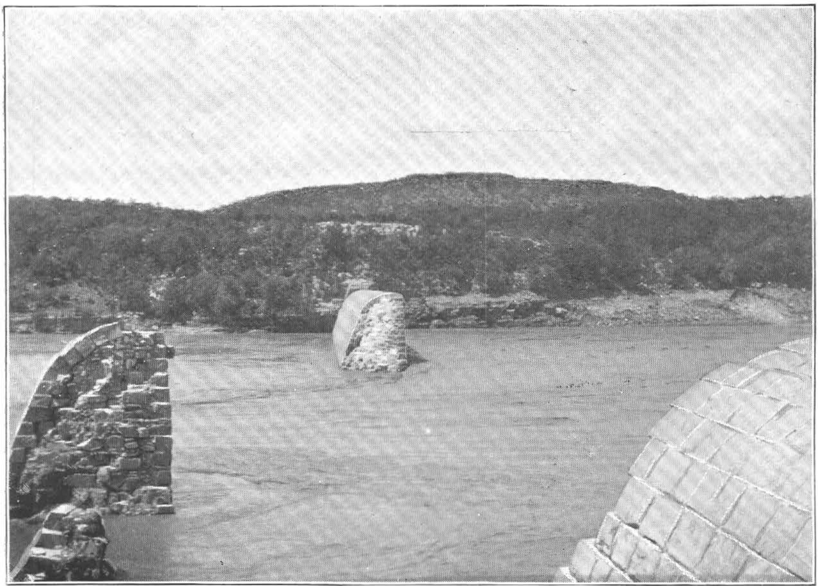
Hence, if we let d=depth of water in n years, we have $d=h\,(1-x)^n$.

In 1897 $h=81$, $d=50$, $n=4$; $\therefore\ x=0.1135$.

In 1900 we have $d=0.52h$, $n=6\frac{2}{3}$, $(1-x)^{\frac{20}{3}}=0.52$; $\therefore x=0.09343$.



A. VIEW UPSTREAM ONE DAY AFTER FAILURE OF DAM.



B. VIEW WESTERLY ALONG LINE OF DAM ONE DAY AFTER FAILURE.

For safety let us assume the least value of x; the following table gives the results for each year on that assumption:

Table showing silting up of reservoirs.

n years.	Amount of water, $d \div h$.	n years.	Amount of water, $d \div h$.
1	0.907	12	0.308
2	.822	13	.279
3	.745	14	.253
4	.676	15	.230
5	.612	16	.208
6	.555	17	.189
$6\frac{2}{3}$	.520	18	.171
7	.503	19	.155
8	.456	20	.191
9	.414	25	.086
10	.375	30	.053
11	.340	40	.020

These results will not be correct for any reservoir in which there is an appreciable current acting on the bottom of the basin, i. e., on the upper surface of the silt. In Lake McDonald the level of the water could sink to 10 feet below the crest of the dam and there would still be a fair current in the penstocks, as the bottom of the forebay was 12 feet below the crest. When this condition obtained, as it did during the months of March, April, and October, 1899, there was a current on the upper third of the lake. Unless the lake was drained by the three 3-foot pipes at the west end of the dam (which did not occur after 1893), it was not possible for the current under ordinary conditions to affect the silt in the lower two-thirds of the lake. The results of the table are illustrated in fig. 9.

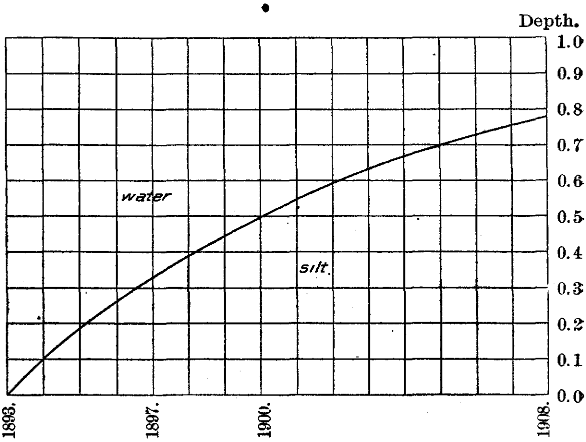


FIG. 9.—Curve illustrating progress of silting in Lake McDonald.

FAILURE OF THE DAM.

At Austin the Colorado emerges from a mountainous country which extends for a distance of over 200 miles in a northwesterly direction. The channel above Austin is for the most part a sinuous gorge held in by limestone mountains and hills. Austin is at the foot of a long range of mountains, 37,000 square miles of which afford a drainage area for Colorado River. The river is fed by the Perdinales, the

Llano, the San Saba, the Concho, and the Pecan Bayou. The configuration of the country is such that the water runs off rapidly into streams.

From 1 p. m. on April 6 to 4 a. m. on April 7 there was a rainfall of 5 inches at and in the vicinity of Austin, in a mountainous country and on ground already wet. In addition to this, tremendous rains fell all along the Colorado and its tributaries from Austin as far up as Llano, a distance of over 100 miles. The river rose rapidly, and by 10 a. m. on Saturday, April 7, it was apparent that the dam would be called upon to withstand the biggest flood since water first wetted its crest on May 16, 1893. At that hour the water level of the lake was more than 10 feet above the crest of the dam and it was rising nearly 2 feet an hour. The greatest previous flood height occurred at 9 p. m. on June 7, 1899, when the lake level was 9.8 feet above the crest of the dam. The water rose rather gradually throughout the day to its maximum level of 9.8 feet. Pl. IX, *B*, gives a view of the flood of June 7, 1899, taken when the lake level was 9.25 feet above the crest of the dam and the water level only 22 inches lower than that of April 7, 1900; and Pl. IX, *A*, is a reproduction of a snapshot picture taken with a small kodak five minutes before the dam broke. It shows conclusively that there was no drift in concentrated masses. Isolated logs and débris were passing, but they never came within 8 feet of the crest of the dam.

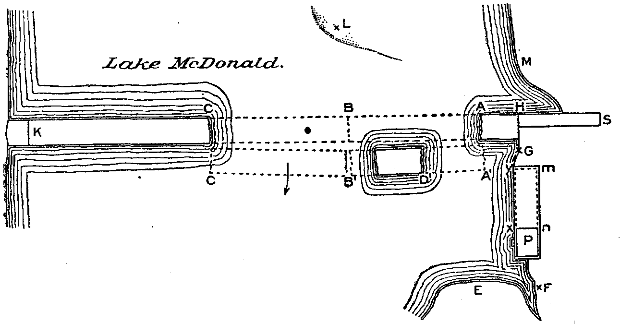
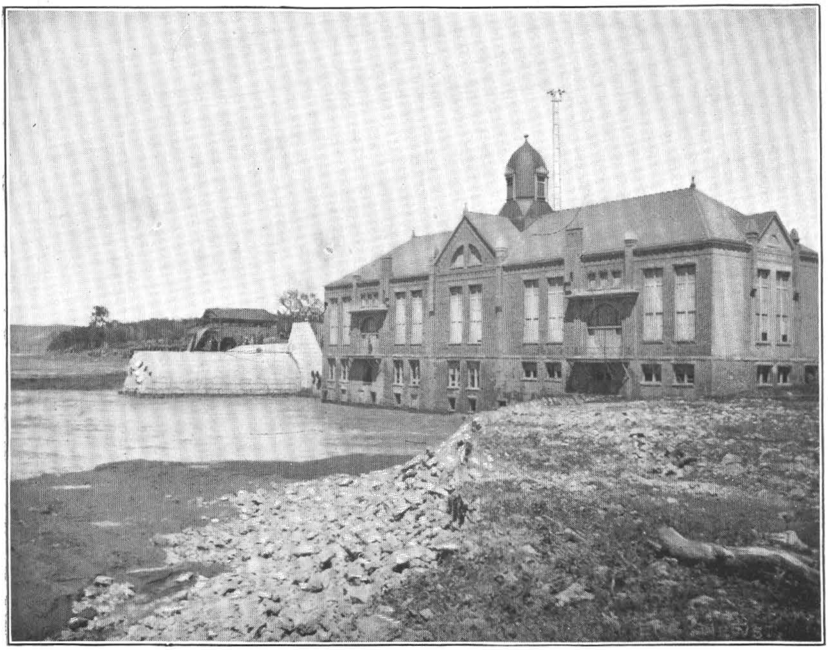
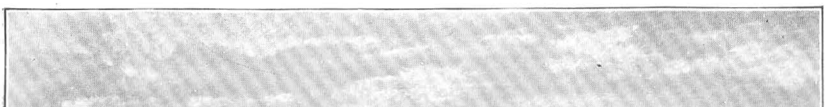


FIG. 10.—Plan showing break in dam April 7, 1900. KC is western part of dam (456 feet long on crest) left standing; HA is eastern part (83 feet long on crest) left standing; AB and BC are portions of dam first broken; xymn is dynamo room at power house; P is pump room; L is point from which view shown in Pl. XV, *A*, was taken; F is point from which view shown in Pl. XIII, *A*, was taken; G is point from which view shown in Pl. XIII, *B*, was taken; M is point from which view shown in Pl. XI, *A*, was taken; E is point from which view shown in Pl. IX, *A*, was taken; HS is bulkhead; B′C′ and D′A′ are portions of dam that broke and disappeared 45 minutes after break; B′D′ is the broken portion of dam still standing; S is point from which view shown in Pl. XI, *B*, was taken.

At 11.20 a. m. on April 7, when the lake level had reached a height of 11.07 feet above the crest of the dam, the dam gave way at the point marked B in fig. 10, about 300 feet from the east end of the dam. Observers at E, F, and H all agree in their testimony that it first opened at B, and as though the mad current had simply pushed its way through the structure. Sooner than it takes to write these words the two sections AB and BC, each about 250 feet long, were shoved or pushed into the lower positions A′B′ and B′C′, about 60 feet from



A. VIEW OF POWER HOUSE ABOUT TWO HOURS AFTER FAILURE OF DAM.



B. WRECK OF POWER HOUSE.

their former positions in the dam. There was not the slightest overturning. After the warning break at B, the water over the part ABC was seen to rise several feet, and the next instant the pent-up waters were pouring over the sections A′B′ and C′B′.

The view shown in Pl. X, *A*, was taken at 11.23 a. m., or three minutes after the failure. The parts may be identified by comparing Pl. X, *A*, with fig. 5 and with the sketch plan, fig. 10, the view shown in Pl. X, *A*, extending slightly beyond C in fig. 10. By 11.30 a. m. the lake level had fallen to the crest of the dam, and the sections A′B′ and B′C′ were seen to be upright, each still a solid mass, complete, unbroken, and intact, except for the scaling off of the granite facing from the downstream side, occupying a position practically parallel to the dam, a view of which is shown in Pl. X, *B*, a snapshot taken ten minutes after the break. To the casual observer the detached portions at this time had the appearance of having been erected in their new positions by the original contractor. The crests of the sections A′B′ and B′C′ were about on a level with their original positions, except at C, where the crest was slightly higher, giving B′C′ a slight longitudinal dip toward the power house. Measuring along the crest the break left 456 feet of the dam (KC in fig. 10), at the west end and 83 feet (AH) at the east end still standing unaffected.

As soon as the sections were broken out and moved to the positions A′B′ and B′C′, the partially pent-up waters rushed through the gap, those held back by CK producing a strong current in the direction of the power house. This current struck the wall of the power house almost on a level with the floor of the pump room (about 12 feet below the crest of the dam), crushed in all of the windows on the west side, flooded all of the lower stories, and caught and drowned five employees and three small boys. Two of the employees miraculously escaped by climbing through a belt hole in the dynamo room (x y m n, fig. 10). These workmen were pumping water from the lower portions of the power house.

At 12 o'clock, forty minutes after the break, the broken section B′C′ turned over toward the dam and disappeared beneath the torrent, and the eastern end of the section A′B′ was broken up and engulfed. This left about 100 feet (B′D′), which was shifted slightly out of its parallel position. This section (B′D′) was cracked from the crest as far down as could be seen. Sometime during Saturday night the smallest portion of this 100-foot section was swept away. The picture reproduced in Pl. XI, *A*, was taken from the top of the bulkhead at 2 p. m. on Saturday, April 7.

At 12.05 a. m., Sunday, April 8, the northern two-thirds (x y m n, fig. 10) of the west wall of the power house gave way and fell, taking with it the roof over the dynamo room and wrecking the corresponding part of the east wall. The power house was 198 feet by 54 feet, and had a total height on the river side of 112 feet. The walls were of brick, except the first 20 feet, which were constructed of dressed granite rocks about 2½ feet by 5 feet by 3 feet. The dynamo floor (x y m n, fig. 10) was about on a level with the crest of the dam. The floor of this room extended as a gallery over the pump room (P) in which the big duplex pumps were located.

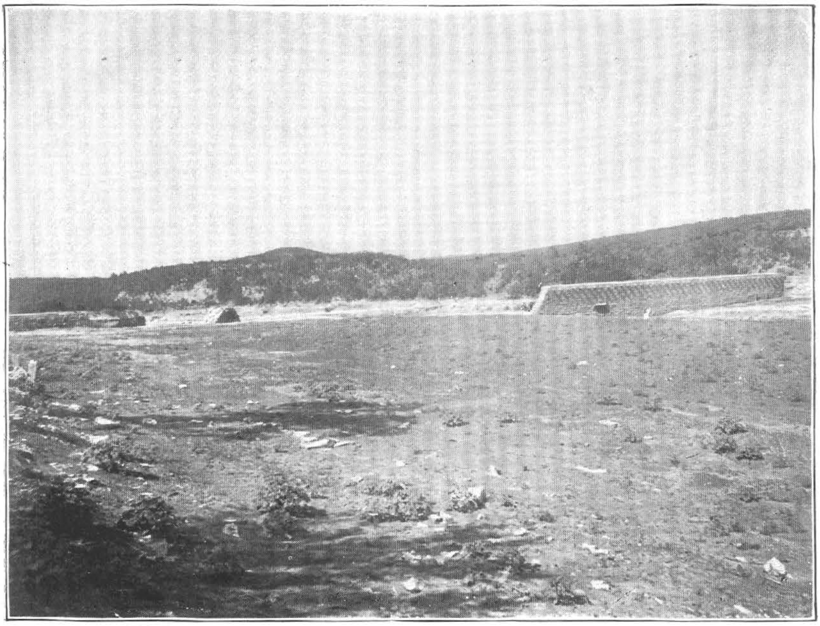
The broken sections moved back about 60 feet and the toe rested on the shore line of the tailrace. The impact and the resultant compressive stress on the stones on the curved face tore the granite facing loose from the core in several places. The section was stripped of its facing stones in the third course from the top as far down as could be seen, a distance of fully 30 feet. Some of the top granite stones of the section were loosened in their beds by the break and were carried away by the current.

Specimens of the cement of the core have been examined and these have been found to be first class in every particular. In some places breaks occurred through limestone rubble and the adhering cement, showing that the strength of the joint was superior to that of the limestone.

The behavior of the granite facing indicates very clearly that it was easily pulled off by the immense forces brought into play. The impact cracked the section along an irregular surface about 42 feet below the crest.

There was not sufficient continuity between the rubble core and the granite facing. There were slight irregularities in the line of contact between the granite and the rubble, but when subjected to the powerful forces of the water pressure the two separated at many places. In a few cases isolated granite blocks on the curved crest were forced from their beds, as shown by the dark spot on the curved crest in Pl. X, *B*.

The maximum depth of the water near the dam was only 38 feet below the crest. Thus at the time of the break the total depth was a little more than 49 feet. The lake had silted up from the original bed-rock bottom in the main stream exactly 30 feet. Had there been no silt a much larger volume of water would have passed and the results have been more disastrous at and below the dam. While this silt would flow, it was sluggish and served to retard the current, thus prolonging the flood several hours (it actually continued, with great velocity, for nearly two days). Within twenty-four hours the river level had fallen more than 40 feet, but this only served to confine the flood to the main channel, with little diminution of velocity. At 3.20 p. m., four hours after the dam broke, the water level had dropped 30 feet and was at the high-water mark of the old channel, cutting the banks both above and below the dam. Below the dam the alluvial banks reached a height of 64 feet above the toe of the dam. This whole mass was in a few hours cut back 40 feet. The effect of this continuous flood on the silt deposited in the lake since 1893 is considered under the heading "Silting up of Lake McDonald," page 36.



A. WESTERN PORTION OF DAM REMAINING AFTER BREAK.

B. PORTIONS OF BROKEN DAM BROUGHT DOWN BY FLOOD.

It is almost certain that the dam failed by sliding. It seems that at a point 300 to 400 feet from the east end the limestone upon which the dam rested was of a friable nature. Mr. Frizell realized this, and it was stated to be a part of his plan, had he continued in charge of the work, to reenforce the bottom of the river just below the dam by a cement foundation about 100 feet wide by 600 feet long; it was also contrary to his purpose to have the water of the tailrace run along the toe of the dam.

In order to ascertain whether any of the foundation of the dam remains in the broken gap, soundings were made in June and in the latter part of October, 1900. Three lines (A, B, and C) of soundings were made parallel to the upper face of the dam, namely, at 2, 16.5, and 42 feet, respectively, from the upper face. A cord was tagged every 20 feet, and the soundings were made with a sharpened three-fourths-inch iron rod. Stations were taken west to east. The following table shows the result of the soundings, the depth being measured from the crest of dam. When the October soundings were made the water surface was 56.1 feet below the crest of the dam. The rod soundings were added to this to give the depth recorded in the table.

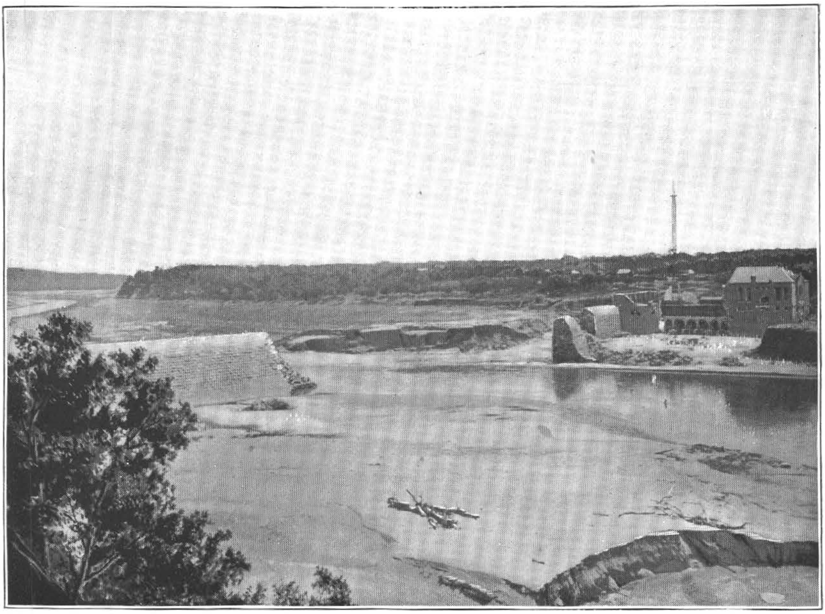
Result of soundings taken at Austin dam site in June and October, 1900.

Station.	Line A.		Line B.		Line C.	
	Depth in feet.	Bottom.	Depth in feet.	Bottom.	Depth in feet.	Bottom.
60					Water's edge.	Dam.
40					63.1	Solid rock.
20					67.9	Do.
0	Water's edge.	Dam	Water's edge.	Dam	68.4	Mud.
20	73.5	Solid rock.	69.1	Solid rock.	69.5	Solid rock.
40	69.5	do	69.1	do	70.1	Do.
60	69.9	do	70.1	do	70.9	Do.
80	70.6	do	71.1	do	71.3	Do.
100	71.1	do	72.6	do	72.5	Do.
120	72.3	do	72.6	do	72.4	Do.
140	a 72.6	do	72.9	do	72.6	Do.
160	a 72.3	do	73.1	do	73.5	Do.
180	a 71.9	do	72.1	do	73.1	Do.
200	a 71.3	do	71.1	do	71.3	Sand.
220	a 70.9	do	69.1	do	71.0	Rock.
240	a 68.1	do	68.9	do	69.6	Mud.
260	Deep sand.		67.1	Mud	68.1	Gravel.
280	do		63.6	Gravel	67.9	Mud.
300	Water's edge.		63.1	do		Loose rock.
320						Water's edge.

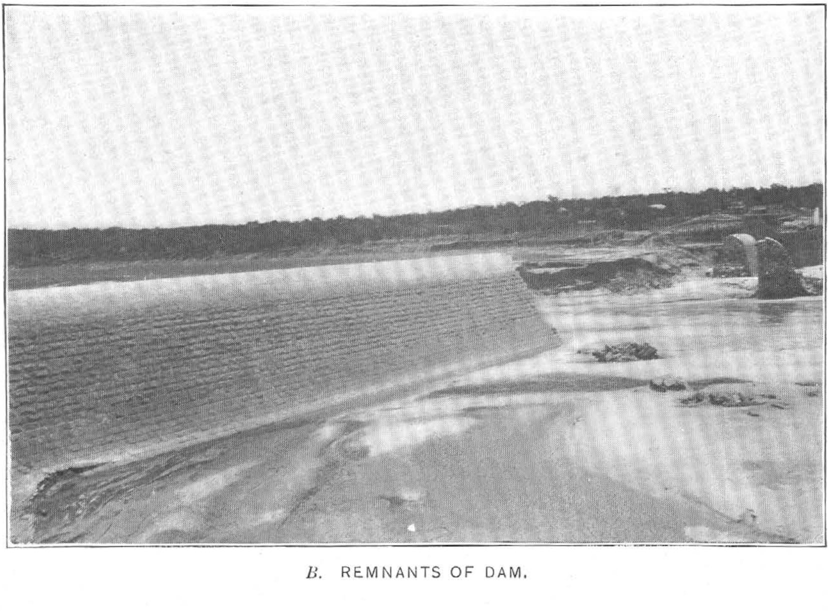
a Sand was found, but the sounding rod was driven through to solid rock.

If we remember that the height of the dam above the rocky bed of the river was 66 feet, and that the foundation was not (except as noted on the next page by Mr. E. W. Groves), even with its toe-hold, more than 68 feet below the crest, a glance at the foregoing table will convince anyone that no part of the foundation in the western 300 feet of the broken section remains. From the present ordinary eastern water's edge a large sand bank extends along the entire eastern section still remaining. Soundings were not made through this 30-foot sand bank, but the crest of the big section of the dam, shown in all of the views of the broken part, is only 4 feet lower than the crest of the portion standing, which indicates very clearly that its foundation went with it, as it is resting practically in the old tailrace, whose bed was lower than the bed of the dam.

On April 8, 1896 (four years before the dam failed), in a letter to the mayor, Mr. Frizell called attention to the fact that dangerous abrasion might occur near the point mentioned, i. e., 300 to 400 feet from the east end. The waters of the tailrace followed the toe of the dam fully 600 feet and were discharged through a narrow neck 45 feet wide, at an average depth of 2.8 feet during the day and about 3 feet at night when the full power was on. In March, 1899, the writer, with Mr. H. K. Seltzer, made soundings along the toe of the dam between this narrow neck and the power house. At or near the point where the break occurred the bottom was not reached with a rod 5.3 feet long, even when the hand holding it was thrust at least 2 feet below the surface. The water surface of the tailrace was then 2.5 feet below the toe of the dam. This makes the bottom of the tailrace more than 9.5 feet below the top of the toe of dam. The tailrace near the dam passed over a shoal-like formation and entered the tailrace pond about 50 feet from the east end of the dam. Between this point and the narrow neck alluded to the tailrace was bounded by the toe of the dam and an elliptical shore line. Its maximum width was 125 feet, its narrowest width (at the neck) 45 feet. It was at this neck that many measurements of flow were made during 1888 and 1889 for the United States Geological Survey. In March, 1899, simultaneous measurements were made of the tailrace at this neck and of the forebay; and while the flow through the tailrace exceeded that in the forebay, the difference was not greater than could be accounted for by the fluctuations of flow caused by increased demands on the street-car service. Early in 1899, when the lake level was 10 feet below the crest of the dam, the writer urged some of the authorities to shut off all power some night at 12 o'clock, and after the tailrace water had run off to have the flow measured in order to ascertain the leakage, if any; but there were difficulties which prevented the stopping of the works. It is probable that there was no leak under the dam from the lake. Water from the lake going under the dam would have been under a head of 66 feet, and would have emerged with a velocity of



A. BROKEN DAM, SHOWING IN FOREGROUND SAND BAR LEFT IN MAIN CHANNEL.



B. REMNANTS OF DAM.

more than 64 feet per second, which would have cut away the limestone foundation in a few hours.

Mr. E. W. Groves, who was connected with the work, as an engineer, from the preliminary surveys to the completion of the dam, states that for the first 150 feet from the east bluff very good rock was found; that at that point a fault 75 feet wide was encountered, in which there was no semblance of stratified rock, most of the material being adobe or pulverized rock, with an occasional streak of red clay; that the excavation in this space was carried down 8 or 10 feet in the upstream trench, and the trench widened from 4 feet to 10 or 15 feet; that the fault extended to an indefinite depth; that from the west edge of the fault the foundation rock was poor for 350 feet, and that a supplementary protection was added to the upstream side opposite the fault by dumping clay along the face of the dam.

The limestone formation in the vicinity of the dam consisted of alternately hard and soft strata. The outcropping in Bee Creek (just above

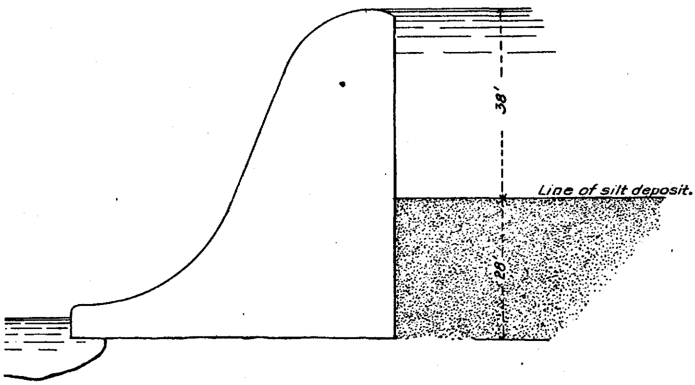


FIG. 11.—Cross section showing undermining of toe of dam.

the dam), that at Taylor's lime chute (about a half mile above the dam), and that through which the excavation was made to repair the head-gate masonry are all of that character. The soft strata could be handled without a pick and often with a shovel, but the hard strata was composed of a fairly good quality of limestone. In its western part the dam rested on one of these hard stratas. During a freshet in 1892 the overfall cut through this hard strata, tore up large pieces (some of them 10 feet long, 4 feet wide, and 2.5 feet thick and of 7 to 8 tons weight), and deposited a whole quarry in a confused and irregular pile about 150 to 200 yards farther down the river. These stones remained in that location until the big freshet of June 7, 1899, when they were carried away.

The foregoing facts are necessary for a proper understanding of what follows. In 1897, Mr. J. G. Palm, one of Austin's leading citizens and a cashier of the oldest national bank in the city, while fishing along the toe of the dam, ran his fishing pole under the toe for a

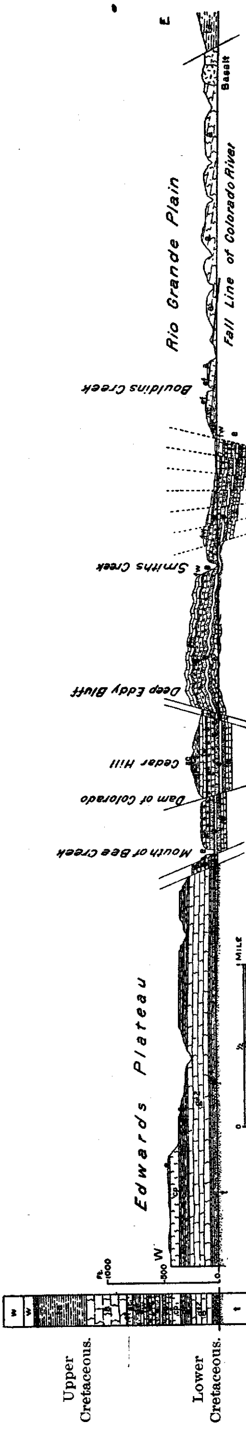


FIG. 12.—Geologic section east and west along Colorado River at Austin, Texas, showing Balcones zone of faulting. ta, Taylor formation; a, Austin chalk; ef, Eagle Ford shales; sc, Buda (Shoal Creek) limestone; dr, Del Rio clays; fw, Fort Worth limestone; e, Edwards limestone; cp, Comanche Peak limestone and Walnut formation; gr, Glen Rose formation; t, Travis Peak formation.

distance of 6 feet. This shows conclusively that either the water flowing along the tailrace had scoured out the foundation under the toe of the dam or the overfalling water had undermined it. A large percentage of the water flowing over the east half of the dam at ordinary height reenforced the tailrace waters and produced a strong current along the toe of the dam for more than half its length. It has now been proved, by actual measurements, that the toe was cut under at some place, as shown in fig. 11. In speaking about the matter Mr. Palm said that he often wondered why the toe did not break off. This undermining of the toe left the dam exposed to the pressure of the water, and it became only a question of which was the stronger—the water or the friction between the dam and its bed.

In regard to the geologic formations, the following is quoted from a letter of Mr. Robert T. Hill, of the United States Geological Survey, in the Engineering News of May 3, 1900:

In the plateau country, which begins about a mile above the present site of the dam, the strata are firm and horizontal, and the river flows over ledges of firm and solid rock, which would have made a suitable and durable foundation for the construction. Just below this point, and within a belt of country upon which the dam is located, the strata are excessively jointed and faulted, constituting what is technically known as the Balcones fault zone, as shown in [fig. 12]. The geological formation is also different, consisting of the limestones of the Edwards formation, which are exceedingly porous and soluble, while to the west of the fault zone the strata are less soluble and more durable. The action of the subterranean waters upon the Edwards limestone results in dissolving it into caverns and crumbling strata, even where at the surface it appears perfectly solid and durable. Furthermore, artesian springs of great volume and pressure well up the joint planes and fissures in this formation. The site of the dam chosen crossed the river subparallel to one of the most conspicuous fault lines, at the northern (eastern) end of which, after the excavation and construction had well advanced, a spring of the character mentioned developed, which greatly endangered the tie-on at the end and cost many thousands of dollars to circumvent. * * * Had the dam been located less than 2 miles above the present site, this structural condition would have been avoided.

A second geological consideration in the construction of the dam, and one to which sufficient attention was not, in my opinion, paid, was in the choice of material. Within 60 miles of Austin by rail are some of the most superb granite quarries in the world. This material was used to face the dam, but its center was built of the same soluble limestone as that previously mentioned, which was obtained from a quarry at the mouth of Bee Creek on the south (west) side of the river, less than half a mile from the dam. An examination of the face of the quarry shows the character of the material taken from it for use in the dam, and a glance is sufficient to show that its solubility was such as to render it utterly untrustworthy.

Mr. J. P. Frizell, after an examination of the preceding statements, adds that the location at Mormon Falls, 2 miles above the chosen site, presented points of decided superiority over the locality selected, but the board of public works thought that location inconsistent with the purposes of the improvement. Mr. Frizell does not consider that the solubility of the rock had any bearing on the failure, and sees no reason to doubt that the immediate cause was the undermining on the downstream side, caused by the abrasive action of the current and the constant stream of water coming from the power house and flowing along the toe of the dam on its way to the open channel of the river. A progressive weakening is attested by the fact that during the preceding year the dam had withstood a flood substantially as great as the one in which it failed. The toe of the dam, which was left without support by the undermining, contained granite blocks of more than 6 tons weight.

It is on record that the breaking down of this unsupported toe was imminent, in which event each of these stones would become a millstone (propelled in such a flood by some 2,000 horsepower) in the work of grinding the friable rock bottom and extending the undermining. At the wooden dam across Connecticut River at Holyoke, Massachusetts, an action of this kind became threatening in 1866. A pit 20 feet deep had formed on the downstream side of the dam. This danger was met by the construction of a massive apron of crib work filled with stone, which prolonged the duration of the structure more than thirty years, or until the construction of the present stone dam. At Austin the engineer had in contemplation from the beginning an analogous work, viz, an extension of the massive apron by a bed of concrete, to be applied as soon as the abrasive action had made sufficient progress to indicate the character and extent of the work required for its suppression.

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1895.

Sixteenth Annual Report of the United States Geological Survey, 1894-95, Part II, Papers of an economic character, 1895; octavo, 598 pp.

Contains a paper on the public lands and their water supply, by F. H. Newell, illustrated by a large map showing the relative extent and location of the vacant public lands; also a report on the water resources of a portion of the Great Plains, by Robert Hay.

A geological reconnoissance of northwestern Wyoming, by George H. Eldridge, 1894; octavo, 72 pp. Bulletin No. 119 of the United States Geological Survey; price, 10 cents.

Contains a description of the geologic structure of portions of the Big Horn Range and Big Horn Basin, especially with reference to the coal fields, and remarks upon the water supply and agricultural possibilities.

Report of progress of the division of hydrography for the calendar years 1893 and 1894, by F. H. Newell, 1895; octavo, 176 pp. Bulletin No. 131 of the United States Geological Survey; price, 15 cents.

Contains results of stream measurements at various points, mainly within the arid region, and records of wells in a number of counties in western Nebraska, western Kansas, and eastern Colorado.

1896.

Seventeenth Annual Report of the United States Geological Survey, 1895-96, Part II, Economic geology and hydrography, 1896; octavo, 864 pp.

Contains papers on "The underground water of the Arkansas Valley in eastern Colorado," by G. K. Gilbert; "The water resources of Illinois," by Frank Leverett, and "Preliminary report on the artesian waters of a portion of the Dakotas," by N. H. Darton.

Artesian-well prospects in the Atlantic Coastal Plain region, by N. H. Darton, 1896; octavo, 230 pp., 19 plates. Bulletin No. 138 of the United States Geological Survey; price, 20 cents.

Gives a description of the geologic conditions of the coastal region from Long Island, N. Y., to Georgia, and contains data relating to many of the deep wells.

Report of progress of the division of hydrography for the calendar year 1895, by F. H. Newell, hydrographer in charge, 1896; octavo, 356 pp. Bulletin No. 140 of the United States Geological Survey; price, 25 cents.

Contains a description of the instruments and methods employed in measuring streams and the results of hydrographic investigations in various parts of the United States.

1897.

Eighteenth Annual Report of the United States Geological Survey, 1896-97, Part IV, Hydrography, 1897; octavo, 756 pp.

Contains a "Report of progress of stream measurements for the calendar year 1896," by Arthur P. Davis; "The water resources of Indiana and Ohio," by Frank Leverett; "New developments in well boring and irrigation in South Dakota," by N. H. Darton, and "Reservoirs for irrigation," by J. D. Schuyler.

1899.

Nineteenth Annual Report of the United States Geological Survey, 1897-98, Part IV, Hydrography, 1899; octavo, 814 pp.

Contains a "Report of progress of stream measurements for the calendar year 1898," by F. H. Newell and others; "The rock waters of Ohio," by Edward Orton, and "A preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian," by N. H. Darton.

1900.

Twentieth Annual Report of the United States Geological Survey, 1898-99, Part IV, Hydrography, 1900; octavo, 660 pp.

Contains a "Report of progress of stream measurements for the calendar year 1898," by F. H. Newell, and "Hydrography of Nicaragua," by A. P. Davis.

WATER-SUPPLY AND IRRIGATION PAPERS, 1896-1900.

This series of papers is designed to present in pamphlet form the results of stream measurements and of special investigations. A list of these, with other information, is given on the outside (fourth) page of this cover.

Survey bulletins can be obtained only by prepayment of cost, as noted above. Money should be transmitted by postal money order or express order, made payable to the Director of the United States Geological Survey. Postage stamps, checks, and drafts can not be accepted. Correspondence relating to the publications of the Survey should be addressed to **The Director, United States Geological Survey, Washington, D. C.**

WATER-SUPPLY AND IRRIGATION PAPERS.

1. Pumping water for irrigation, by Herbert M. Wilson, 1896.
2. Irrigation near Phœnix, Arizona, by Arthur P. Davis, 1897.
3. Sewage irrigation, by George W. Rafter, 1897.
4. A reconnoissance in southeastern Washington, by Israel C. Russell, 1897.
5. Irrigation practice on the Great Plains, by E. B. Cowgill, 1897.
6. Underground waters of southwestern Kansas, by Erasmus Haworth, 1897.
7. Seepage waters of northern Utah, by Samuel Fortier, 1897.
8. Windmills for irrigation, by E. C. Murphy, 1897.
9. Irrigation near Greeley, Colorado, by David Boyd, 1897.
10. Irrigation in Mesilla Valley, New Mexico, by F. C. Barker, 1898.
11. River heights for 1896, by Arthur P. Davis, 1897.
12. Water resources of southeastern Nebraska, by Nelson Horatio Darton, 1898.
13. Irrigation systems in Texas, by William Furguson Hutson, 1898.
14. New tests of pumps and water lifts used in irrigation, by O. P. Hood, 1898.
15. Operations at river stations, 1897, Part I, 1898.
16. Operations at river stations, 1897, Part II, 1898.
17. Irrigation near Bakersfield, California, by C. E. Grunsky, 1898.
18. Irrigation near Fresno, California, by C. E. Grunsky, 1898.
19. Irrigation near Merced, California, by C. E. Grunsky, 1899.
20. Experiments with windmills, by Thomas O. Perry, 1899.
21. Wells of northern Indiana, by Frank Leverett, 1899.
22. Sewage irrigation, Part II, by George W. Rafter, 1899.
23. Water-right problems of the Bighorn Mountains, by Elwood Mead, 1899.
24. Water resources of the State of New York, Part I, by George W. Rafter, 1899.
25. Water resources of the State of New York, Part II, by George W. Rafter, 1899.
26. Wells of southern Indiana (continuation of No. 21), by Frank Leverett, 1899.
27. Operations at river stations, 1898, Part I, 1899.
28. Operations at river stations, 1898, Part II, 1899.
29. Wells and windmills in Nebraska, by Erwin Hinckley Barbour, 1899.
30. Water resources of the Lower Peninsula of Michigan, by Alfred C. Lane, 1899.
31. Lower Michigan mineral waters, by Alfred C. Lane, 1899.
32. Water resources of Puerto Rico, by H. M. Wilson, 1900.
33. Storage of water on Gila River, Arizona, by J. B. Lippincott, 1900.
34. Underground waters of a portion of southeastern S. Dak., by J. E. Todd, 1900.
35. Operations at river stations, 1899, Part I, 1900.
36. Operations at river stations, 1899, Part II, 1900.
37. Operations at river stations, 1899, Part III, 1900.
38. Operations at river stations, 1899, Part IV, 1900.
39. Operations at river stations, 1899, Part V, 1900.
40. The Austin dam, by Thomas U. Taylor, 1900.

In addition to the above, there are in various stages of preparation other papers relating to the measurement of streams, the storage of water, the amount available from underground sources, the efficiency of windmills, the cost of pumping, and other details relating to the methods of utilizing the water resources of the country. Provision has been made for printing these by the following clause in the sundry civil act making appropriations for the year 1896–97:

Provided, That hereafter the reports of the Geological Survey in relation to the gaging of streams and to the methods of utilizing the water resources may be printed in octavo form, not to exceed 100 pages in length and 5,000 copies in number; 1,000 copies of which shall be for the official use of the Geological Survey, 1,500 copies shall be delivered to the Senate, and 2,500 copies shall be delivered to the House of Representatives, for distribution. [Approved June 11, 1896; Stat. L., vol. 29, p. 453.]

The maximum number of copies available for the use of the Geological Survey is 1,000. This number falls far short of the demand, so that it is impossible to supply all requests. Attempts are made to send these pamphlets to persons who have rendered assistance in their preparation through replies to schedules or who have furnished data. Requests specifying a certain paper and stating a reason for asking for it are granted whenever practicable, but it is impossible to comply with general and indiscriminate demands, such as to have all of the series sent.

Application for these papers should be made either to Members of Congress or to

THE DIRECTOR, UNITED STATES GEOLOGICAL SURVEY, WASHINGTON, D. C.