CHAPTER III.

MASONRY DAMS.

THE character of structure which appeals most effectively to the majority as worthy of confidence in its ability to withstand water-pressure and the action of the elements for ages is unquestionably the masonry dam, founded on solid rock and built up as a monolith between the natural rock buttresses of a gorge, with Portland-cement mortar. Such a structure invariably commands greater respect and confidence in the public mind than any other. It may not in certain cases actually be safer from overturning or better able to resist the strains and forces tending to rupture it than well-built dams of wood, earth, or loose rock, but it usually has the appearance of strength; and the moral effect of a dam of that character upon the public, as well as upon investors in securities dependent upon the stability of dams and the permanence of the water-supply retained by them in reservoirs, is one which cannot be disregarded.

That masonry dams are not built in every site is due to the fact that the foundations are not always suitable, and surrounding conditions oftentimes render their cost prohibitive.

Masonry dams are distinct from buildings, arched bridges, and other masonry structures in that the best class of masonry as ordinarily applied and used is not best adapted to dam-construction. Cut-stone masonry or ranged ashlar, while more expensive and of greater strength, is not so suitable for masonry dams as random rubble, laid regardless of beds or courses, homogeneous concrete, or a combination of large irregular masses of stone embedded in concrete—a rubble-concrete,—either of which is much cheaper. The strains in a dam are in various directions, whereas ranged ashlar, laid in horizontal courses, is best adapted to resist the forces acting perpendicular to those courses, and not those having the same horizontal direction. The dam should therefore be made as nearly homogeneous and monolithic as possible, and the stones used thoroughly interlocked in all directions, avoiding the horizontal courses of ordinary cut-stone masonry.

While masonry dams have been built antedating the Christian era, and some very notable ones were constructed in Spain for irrigation-storage more than three hundred years ago, it is only within the past fifty years that the correct theories of the strains to which such structures are subjected, and the proper proportions to be given them to secure stability under all conditions, have been reduced to some degree of mathematical certainty. The Spanish dams built in the sixteenth century were massive blocks of masonry, almost rectangular in form, containing a large surplus of material beyond actual requirement, but so unscientifically disposed as to produce maxima pressures dangerously near the point of crushing.

The French engineers who were required by the French Government to prepare plans for high masonry dams for the control of floods on torrential rivers in southern France about fifty years ago, were the first to advance new ideas and practical theories on the principles that should govern the design of these structures. M. Sazilly prepared a paper on the subject in 1853, and a few years later the matter was more fully elaborated by M. Delocre, on whose formula were drawn the plans for the great Furens dam, 183.7 feet high. In 1881 Prof. W. J. M. Rankine, the noted English engineer, was called upon to report on the best form of masonry dam to be built for the city of Bombay, India, and investigated the question in a thorough mathematical way, producing a form of profile which is recognized as one of the most logically correct in its conformity to all requisite conditions. He established as one of the governing principles that no tensile strains should be permitted in any part of the masonry, and that therefore the lines of resultant pressure, with reservoir either full or empty, should fall within the inner third of the dam at all points. The acceptance of this principle carries with it as a necessary sequence that the maxima pressures will fall below safe limits, whereas if the dam be designed with regard to safe limits of pressure alone the structure may be so slender as to carry the lines of pressure far beyond the center third and thus set up dangerous tension in the masonry.

Other prominent English engineers who have investigated the subject are Mr. Guilford L. Molesworth and Mr. W. B. Coventry.

Mr. H. M. Wilson, Assistant Hydrographer, U. S. Geological Survey, in his "Manual of Irrigation Engineering," devotes a long chapter to an admirable discussion of masonry dams, while the most recent American treatise is the elaborate work entitled "The Design and Construction of Dams," by Edward Wegmann, C.E., of which the fifth edition was issued in New York in 1907. Mr. Wegmann has rendered invaluable service to the profession in the investigation of the difficult problems involved in the design of masonry dams, and in simplifying the mathematical formulæ for computing the economical safe proportions of such structures.

The general principles to be considered in designing such a dam are briefly as follows:

(1) That it must not fail by overturning.

(2) That it must not slide on its foundation or on any horizontal joints.

(3) That it must not fail by the crushing of the masonry or the settlement of its foundation.

(4) That it must be equally safe from excessive pressure upon the masonry whether the reservoir be full or empty.

(5) That certain known safe limits of crushing of masonry of the class to be used shall not be exceeded.

Masonry dams may resist the thrust of water-pressure either by their weight alone or by being built in the form of an arch, which will transmit the pressures to the abutments. The first of these two classes of structure is called the gravity dam. The second is the arch dam, and it may be either of the gravity type in arched form, or it may depend upon its arched form alone. In either case the weight of the dam must be borne by the foundations, and these must be of the best quality of solid bed-rock. Everything of a friable nature should be removed, and the excavation so made as to leave the surface rough, to avoid the possibility of the dam sliding on its base. The maxima pressures permissible should not exceed 15 tons per square foot, and may require to be as low as 6 tons per square foot. For very high dams it is essential that they should diminish in thickness as the top is approached, else the masonry might be crushed and fail of its own weight. This consideration suggests the simple triangle as theoretically correct, with certain modifications. The thrust of the water tends to overthrow the dam by revolving it around its lower toe, and hence there is such a concentration of water-pressure and weight of masonry at that point as to necessitate a sufficient width of base to confine the resultant of these forces inside the outer toe-line of the wall, and avoid the crushing of the masonry by distribution of the strains over a greater area. If the hypothenuse of the right-angle triangle were presented to the water as the upper face of the dam, the forces acting perpendicular to that face would give the wall greater stability from overturning, if the structure were considered as a rigid body incapable of being crushed. On the contrary, if the vertical side of the triangle be presented to the water, the dam, while less liable to be overturned, is more capable of resisting fracture or crushing, the pressures are more evenly distributed over its base, and the foundations less likely to yield.

While the simple triangular form of dam, of such base-width that the lines of pressure with reservoir full or empty fall within the inner third, amply fulfills the requisite conditions to resist the quiet pressure of water, in practice it is necessary to give a certain definite width to the top of the dam to enable it to resist wave-action and ice-thrust. In dams 50 feet high or less this top width need not exceed 5 feet; for dams 100 feet high the width need not be more than 10 feet, and for a height of 200 feet a width of 20 feet is considered ample. Greater widths are given where the top of the dam is to be used as a roadway. The crest of the structure should also

be raised a certain elevation above the highest water-level to provide for extreme floods. This superelevation will necessarily be governed by the size of the spillway provided and the area of watershed tributary, but ordinarily it should be limited to about 15 feet at the extreme.

High reservoir dams erected across large streams, where conditions do not easily permit of the construction of a spillway to carry the water around them and it is necessary to permit the passage of floods over their crest, are subjected to shocks due to the weight of water falling upon the toe of the dam, which cannot be computed accurately and for which no formulæ have been deduced. In cases of this kind it is customary to allow a substantial addition to the dimensions given by the theoretical profiles deduced from the formulæ for gravity dams under quiet pressure, and to provide a water-cushion at the toe of the dam by the erection of an auxiliary wall a little distance below. The lower face of the dam should also conform as closely as possible to the natural curves assumed by the falling water.

Curved Dams.—While there is an essential general agreement among engineers as to the theoretical profile best adapted for gravity dams, there is a wide difference of opinion as to the effect of the value of the arch in adding stability to the dam. That such structures can and do successfully transmit pressures laterally to the abutments is proven by the Bear Valley, the Zola, and the Sweetwater dams (Fig. 148), the three highest and most noted types of arched dams in existence. The Bear Valley and Zola dams are so slender in profile as to be absolutely unstable were they built straight, while the Sweetwater dam, though more nearly approaching the gravity type, is of such proportions as to be theoretically unstable as a gravity dam,

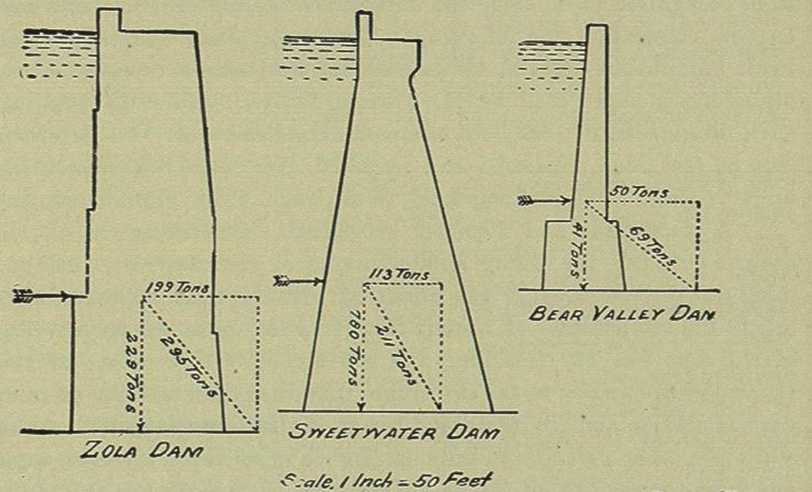

FIG. 148.—COMPARISON OF PROFILES OF ZOLA, SWEETWATER, AND BEAR VALLEY DAMS.

although it has successfully withstood the shocks of an enormous flood pouring over its crest for nearly two days.

M. Delocre has said that a curved dam will act as an arch if its thickness does not exceed one-third of the radius of its upper face, while another eminent French engineer, M. Pelletreau, considers that it will so act provided the thickness be not greater than one-half the radius. Mr. J. B. Krantz maintains that a radius as small as 65 feet is essential to permit a dam to act as an arch and transmit water-pressure to the sides. All engineers appear to agree that the mathematics of curved dams are extremely uncertain, and irreducible to a satisfactory demonstration. It is undoubtedly true that in a narrow gorge a considerable saving of masonry might be made by constructing the dam as an arch, with equal stability to one of gravity type built straight. M. Delocre is of the opinion that in no situation is it necessary for a curved dam to be of greater thickness at any point than the width of the valley at that height. The principle now generally adopted as safe is to make the structure strong enough to resist water-pressure by its weight, and curve the form as an additional safeguard.

The curving of all dams of whatever length or height regardless of whether they may act as an arch or otherwise for the purpose of enabling them to better resist the tendency to vertical cracks due to variations in temperature, especially in countries subject to climatic extremes, is coming to be recognized as of sufficient importance to lead to its general adoption. In this connection the following quotation is taken from the remarks of Prof. Forchheimer of the Aix la Chapelle Polytechnic School, Germany, in discussing a paper read by Mr. George Farren, before the Institution of Civil Engineers, in 1893, on "Impounding Reservoirs."* Referring to a dam 82 feet high, plastered and rendered over with two coats of asphalt, built by Prof. Intze in Remscheid, Westphalia, Prof. Forchheimer says:

"A backward and forward movement, amounting to $1\frac{1}{16}$ inches, occurred during the filling and emptying of the reservoir, and the movement due to temperature was almost as great as this. The latter was due less to the temperature of the air than to direct solar radiation. The crest of this dam was 460 feet long and was arched with a radius of 420 feet. One side was exposed to the sun longer than the other, and the more exposed part moved to and fro seven-eighths of an inch in the course of the year, while the other part moved only one-eighth of an inch, the crest expanding one nine-thousandth of its length, or five-eighths of an inch. In arched dams such movements do no harm, but in straight dams these phenomena are objectionable. As dams are usually built during the warmer seasons of the year, the masonry has a tendency to contract in the colder weather. In a curved dam this can take place by movement of the structure without cracking, but not in a straight dam. . . . If the temperature is lowered

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* Proc. Inst. Civil Eng., vol. cxv. p. 156.

10° C. (50° F.) and it is not free to contract, tension amounting to between 140 and 280 pounds per square inch is set up, which is greater than the mortar will stand. . . . That a straight, or almost straight, wall incurs considerable danger of fracture is shown by practical experience. The dams of Habra, Grands-Cheurfas, and Sig, in Algiers, have broken, and in that of Hamiz a tear occurred during the first filling. The Habra dam broke in December, and the Grands-Cheurfas and Sig dams gave way in the month of February. The Beetaloo dam, in Australia, also developed a crack one-eighth of an inch wide in the middle of winter without any apparent cause. The Mouche dam, Haute Marne, a structure 1346 feet long and about 100 feet high, exhibits clearly the dangers attending straight dams. In the winter of 1890–91, when the temperature varied between – 10° C. and – 20° C. (14° to – 4° F.) and the water-surface was 10 feet 8 inches below the normal level, seven vertical cracks appeared in the dam, situated at uniform distances of about 160 feet apart. They were widest at the top, and died out about 37 feet below the normal water-level. Their aggregate breadth was $2\frac{7}{8}$ inches. The cracks gradually closed as the temperature rose, and by the end of February, 1891, four of them had completely vanished, while the others had perceptibly contracted."

It has been the observation of the writer that all curved dams are free from cracks, but that straight reservoir walls are quite certain to crack. The tendency of the water-pressure is to close any cracks that may appear where the dam is curved, and a curved dam is able to take up the movement due to temperature, without cracking, even though the pressure may not cause the arch to come in action. The inference is that every masonry dam should be built in the form of an arch, whatever its profile may be, for the avoidance of temperature cracks.

Mr. H. M. Wilson says:* "An additional advantage of the arched form of dam is that the pressure of the water on the back of the arch is perpendicular to the up-stream face, and is decomposed into two components, one perpendicular to the span of the arch and the other parallel to it. The first is resisted by the gravity and arch stability, and the second thrusts the up-stream face into compression, which has a tendency to close all vertical cracks and to consolidate the masonry transversely. An excellent manner in which to increase the efficiency of the arch action in a curved dam is that employed in the Sweetwater dam. This consists in reducing the radius of curvature from the center towards the abutments. The good effect of this is to widen the base or spring of the arch at the abutments, thus giving a broader bearing for the arch on the hillsides. The effect of this is seen in projections or rectangular offsets made on the down-stream face of the dam, the center sloping evenly, while the surface is broken by

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* Manual of Irrigation Engineering, pp. 390, 391.

steps when it abuts against the hillside. . . . Though the cross-section of a curved dam may unquestionably be somewhat reduced, it would be unsafe to reduce it as much as has been done in the case of the Bear Valley and Zola dams, though these have withstood securely the pressures brought against them. It might with safety be reduced to the dimensions of the Sweetwater dam, thus saving largely in the amount of material employed."

In recent years a number of independent investigations have been made by engineers in different parts of the world in the attempt to determine by experiments with models of dams made of various materials the character and distribution of the stresses on masonry dams. In 1904 Mr. L. W. Atcherley, Stud. Inst. C. E., assisted by Karl Pearson, F.R.S.,[*] prepared two model dams of a fairly heavy wood cut to the profile which had been used in an actual construction of a dam considered to be mathematically correct in its lines.

In one case the model was divided into a series of horizontal strata and in the second case into a series of vertical strata. In the first case the pull representing the water pressure was communicated by a cord to a stiff lath which bore on the ends of the horizontal strata through two longitudinal strips of india-rubber tube; the attachment of the cord being one-third up the lath and the cord adjusted to pull in a direction perpendicular to the front of the model, so that the resultant force was applied at a point corresponding to the center of pressure of the water. In the case of the model stratified vertically, much the same arrangement was adopted, except that the pull of the cord was applied directly to the first vertical stratum, which included the battered front. The angle of friction of the wood strips on each other varied from 25° to 30°, and a shearing strength more nearly corresponding to the masonry was obtained by pasting tissue paper round the battered fronts and curved flanks of the models.

The weight of a section one foot wide of the dam from which these models were reproduced was 505,000 pounds, and the corresponding water pressure 312,500 pounds. The weight of the horizontally stratified model was 12.40 pounds and of the vertically stratified model was 13.85 pounds. The corresponding value for the pulls representing the water pressure would therefore be 7.70 pounds and 8.57 pounds respectively. Trusting merely to the friction of the wood on wood, the model made up of horizontal layers slid on its base at 5.70 pounds pressure, and the one vertically stratified opened up at the third section from the tail

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[*] *Vide* a monograph "On some Disregarded Points in the Stability of Masonry Dams," Drapers Company Research Memoir. London, 1904.

or up-stream toe, and then the whole thing sheared with a pressure of only three pounds. When the models were strengthened for shearing resistance by tissue paper, as described, the respective pulls corresponding to the water pressure before collapse were 6.5 and 4.2 pounds.

The conclusions drawn from these experiments were that a dam collapses first by the tension on the vertical sections of the up-stream toe; that shearing of the vertical sections over each other follows immediately on this opening up by tension, and that the shear on the horizontal sections is also a far more important matter than was generally supposed. In the case cited from which the models were prepared there probably exist considerable tensions in the masonry amounting to 3 or 4 tons per square foot.

In commenting on these experiments in a commendatory way, Sir Benj. Baker, K.C.B., Past President Inst. C. E., described experiments he had made with models of dams made of jelly with horizontal and vertical lines drawn upon the side to show the location of distortion produced by applying pressure. These indicated that the elastic deformation of the dam was transmitted into the rock on which it was resting for a distance equal to half the height of the dam before it became undetectable. In discussing the paper of Charles S. R. Palmer, M. Inst. C. E., on the Coolgardie Water Supply, in which the construction of the Helena River dam is described,[*] Sir Benjamin Baker refers to experiments he had made with a number of stiff jelly models of the Assouan dam, with a view to determining some of the problems involved in the contemplated increase of height of the dam. He did not agree entirely with the conclusions reached by Messrs. Atcherley and Pearson. He concluded his discussion by saying:

"The result of experience so far with thermometers buried in the masonry of dams confirmed the common sense view that the different portions of masonry built during the year at varying temperatures settled down finally to uniform temperature in the interior of the dam, while the face-work was affected even by diurnal changes; so that internal strains exist in a dam as in a large unannealed casting. Whatever theory mathematicians might evolve, engineers would not be relieved from the obligation to use no material for dams which would not stand, say 50 tons per square foot in compression and 10 tons per square foot in tension without splintering, and in some cases concrete dams might probably with advantage be partially reinforced with steel bars."

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[*] Proc. Inst. C. E., vol. clxii, p. 125.

More recently, in 1905, experiments have been made on stresses in dams by means of India-rubber models, by John Sigismund Wilson and William Gore, Assoc. M. M. Inst. C. E., who exhibited their model at the Institution in July of that year. A series of weights hung to the base of the model represented gravity, and other weights suspended from cords passing over pulleys and leading to bearings on the up-stream face represented water pressure. The models were made to represent dams with 125 feet of water against them and having a top width of 8 feet, at a height of 4.5 feet above the flow line.

These experimenters confirmed Messrs. Atcherley and Pearson in finding tensile stresses in the up-stream toe of the dam, notwithstanding that they were designed with the lines of pressure well within the middle third, and conclude that to eliminate tensile strains it is desirable to either give greater super-elevation, wider top width, or make the upstream face vertical, so as to bring the center of gravity nearer to the wetted face, or to increase the section materially and back the dam with an embankment of earth on the reservoir side.

Experiments with models of dams made of "plasticine," a kind of modelling clay, were recently made by Sir John W. Ottley, K.C.I.E., M. Inst. C. E., and Arthur W. Brightmore, D. Sc., M. Inst. C. E. The model was 30 inches high, with a base of 26 inches and a length of 12 inches. It was moulded in a frame with plate-glass sides, which were ruled vertically and horizontally with lines scratched on both the glass and the plasticine, and made to coincide. Slight clearance was given between the glass and the model, so that there was no lateral friction to support the clay. Actual water pressure was applied through a thin rubber bag made to fit the face of the dam.

The results of these experiments will shortly be published in the Proceedings Inst. C. E., but it may be stated that they confirm in a general way the conclusions reached by the experiments with rubber models.

These various investigations serve to emphasize the fact that the engineering profession is not fully satisfied with the profile types of dams as they have been evolved by previous mathematical computation, but is still striving to reach a more conclusive and satisfactory solution of the intricate and indeterminate problems of the stresses on masonry dams. Meanwhile the ultra conservative ones pile up masses of materials to greater and greater volumes, and a few of the bolder ones build daring structures that appear to defy all theories of stability.

AMERICAN DAMS.

Old Mission Dam, San Diego, Cal.—The first masonry dam built in California of which there is any record was erected in 1770 by the Jesuit Mission Fathers. It was constructed across the San Diego River, 13 miles above its mouth, at the lower end of El Cajon Valley, where the stream cuts through a dike of porphyry. It was built for impounding and diverting water for irrigation and domestic use at the San Diego mission 4 miles below. It was 244 feet in length, 13 feet in thickness, and about 15 to 18 feet high. Fig. 149 is a recent photograph of the old dam in its present condition, half buried in trees and driftwood. The view is taken below the main outlet-sluice. The water was conveyed to the mission through an open masonry conduit, lined with semicircular tile or half-pipes. The cement used in the dam was made from limestone possessing hydraulic properties, quarried near the dam. The dam, though still in existence, has been disused for half a century past. It shows evidence of having been damaged by floods and repaired at various times. The manual labor of construction was done by Indians, of whom no less than 1600 neophytes were at one time supported at the mission. Considering the quality of the materials and labor available, and the torrential nature of the river, which it has resisted, as evidenced in the photograph by the driftwood piled up against it, the masonry is of excellent grade.

El Molino Dam.—A few years after the erection of the Old Mission dam of San Diego the Jesuit Fathers constructed a masonry wall of similar size about 10 miles east of Los Angeles, the purpose of which was to control and raise the level of a natural lake and impound it for use in irrigation at the Mission San Gabriel. The dam is located on what is now known as El Molino rancho, the name being derived from the fact that the priests here built a mill, whose massive walls are still intact, for grinding corn and wheat, the power for which was derived from water gathered from springs that issued from the hillside and fed the lake. The mill was a little above the level of the crest of the dam, and the water from the wheels flowed into the reservoir, where it was caught for use in the valley below. The dam was straight in plan, about 200 feet long, and 15 feet high at the center. The masonry is of superior character and is still in perfect state of preservation, although it has not been in service as a dam for many years past.

The Sweetwater Dam.—This structure is located in the Sweetwater River, 7 miles above the mouth of the stream and 12 miles southeast of the city of San Diego, California, and was built in 1887–88 by the San Diego