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THE STORAGE OF WATER IN EARTHEN RESERVOIRS.

BY SAMUEL FORTIER, M.CAN. SOC. C.E.

To be read Thursday, 8th October, 1896.

The large number of earthen reservoir embankments in use, the widely differing opinions held by engineers in regard to the best method of constructing them, and the fact that the subject has not heretofore been considered by the Canadian Society of Civil Engineers, must plead as an excuse for this paper.

Very many earthen embankments, chiefly known as tanks, have been built in India to store water for irrigation purposes. The high prices of structural materials, the inability to procure and operate modern machinery and the low wages paid to workmen have favored this kind of construction.

* It costs but little to build an earthen embankment of even large dimensions where the materials are abundant and convenient, and where laborers can be procured for eight cents a day for each man, four cents for each woman, six cents for a donkey and fifteen cents for a pair of bullocks. A structure requiring skilled labor and modern machinery, with coal at $20 per ton, timber scarce and iron and steel from $8 to $15 per cwt., would be much more expensive. These peculiar conditions may, in a measure, account for the 37,000 tanks to be found in Mysore, and the 53,000 in Madras, besides smaller numbers in the other presidencies. The past history, however, of these tanks, many of which were built centuries ago, seems to prove the suitability of this material to retain water, and where failures have occurred they were in nearly every case traceable to imperfect outlet conduits or to faulty design. +

Not only in India, but in all regions where the rainfall is insufficient to mature crops, and where water has to be artificially applied to make up for the natural deficiency, it is only a question of time when the storage of water becomes a necessity. In the Western States of the Union, for example, the average annual run-off from the drainage areas, not to speak of the flood discharges, is from five to ten times greater than the run-off during the dry period of summer, when it is most needed for the raising of agricultural products. It is thus evident that only a small percentage of the total water supply can be utilized without the aid of storage reservoirs. For many centuries these reservoir dams have been built of earth, and there is good reason to believe that in the centuries to come the same material will be used. Upon this assumption the irrigated countries of Cape Colony, Egypt, Spain, Italy and France, and on this continent those of South America, British Columbia, and two-fifths of the United States are, and will continue to be, more or less dependent upon earthen dams to conserve and equalize the flow of the scanty water supply.

In reference to the use of earthen dams to store water for domestic purposes, it may surprise some to learn that the increase in the number of water-works plants in Canada and the United States has been greater than that of railways. In 1830 there were in the United States only 31, and 58 years latter there were 1701, while in Canada during the same period the number increased from a few insignificant plants in the larger cities to 68 in 1888.* Since many water-works systems have each a number of earthen reservoirs, it is probable that the increase in the latter has been equally great.

The diversity of opinions among engineers on this subject is remarkable and difficult to explain. The wide differences in the kind and quality of the materials used may partially account for it, but apart from this, one is forced to conclude that the opinions held by many engineers regarding the best way to design and construct earthen embankments to impound water are erroneous. For any given case the problem is: to store with safety to life and property a certain volume of water, on a particular site, within walls of earth. The task seems easy and simple, but in its design and execution the plans and specifications from a dozen or more competent engineers would show great dissimilarities. The general form, content and particular dimensions might differ 100 per cent. One engineer would be willing to incur considerable expense in procuring clay for the entire embankment; another would use clay only as a centre core; while a third would reject it as the most treacherous material in existence for that class of work, and would build a homogenous wall of a mixture of fine and coarse materials. Some would specify that the materials be packed dry, others that they be dampened, while some would call for an abundance of water. In regard to lining or paving there would likely be as many different kinds recommended as there were specifications. Some would be positive that the structure would be insecure without a heavy masonry core wall, while the advocates of a homogenous embankment would consider it a waste of money.

The task of reconciling so divergent views is too great for the writer of this paper. The most that he can hope for is that the opinions herein expressed, the suggestions offered, and the consideration of a few practical features relating to reservoir dams and the storage of water may aid, in some measure, our younger brethren.

CHARACTER OF THE MATERIALS.

Earth dams are composed of varying proportions of gravel, sand, silt, clay, organic matter and water. The same ingredients which constitute the cultivated fields and their underlying strata are in nearly every case the most convenient and also the most suitable materials to use. A consideration, therefore, of the nature of the materials forming a reservoir embankment leads us directly to that of soils and subsoils. For this purpose, the physical and mechanical properties of soils are of much more importance than their chemical ingredients. It is not essential, for example, that we know the amount of potash, phosphorus or lime in any given case, but the size and weight of the grains, the amount of air-space they enclose, the percentages of air and water contained in these open spaces, and the effects produced by moisture, heat and frost, as well as the action of such forces as gravity, capillarity and evaporation, are of great importance. To such an extent is this true that one might say without exaggeration that the success of works of this character rests mainly upon the fact that they were designed and built in accordance with an intimate knowledge gained from a close study and carefully made tests of the physical properties of the materials. For twenty years and over men have been testing the physical qualities of iron, steel, cements and the various kinds of timbers, and this knowledge, when coupled with the correct application of the principles of mechanics, has given us our modern structures composed of a minimum amount of materials with a maximum of strength and efficiency. Reservoir embankments on the other hand have been built in most instances without the requisite knowledge, upon mere guess work, brawn and not brain predominating.

The site having been determined upon, samples of the underlying strata can best be obtained by test pits. They cost more than samples obtained by boring, but the additional information gained much more than compensates for the extra cost.

To avoid danger to workmen and shoring, the writer makes these pits elliptical. By having the majorax is, say 18 feet, and the minor about 6 feet, it is possible to dig with picks and shovels to a depth of 30 feet by leaving a b rm of 6 feet one-third the way down and a second berm of the same width two-thirds of the distance from the top. Samples can then be taken from each pit at every change in the formation. Sieves graduated from 5 meshes to the linear inch downwards in fineness to 10, 15, 20, etc, meshes may be used to grade the materials as to texture. When a portion of each of these graded samples is washed and afterwards examined by a good lenz, the size and mineral character of all the larger particles can be determined, whether lime, quartzite, slate, shale, etc. The finer particles of sand, silt and clay, or all less than say one-hundredth of an inch in diameter can be classified only by some mechanical soil separator like those invented by Doctors Hilgard and Osbourne.

The following classification as to the size of particles contained in soils and sub-soils is now used by most authors on soil analysis. The dimensions are given in both millimeters and inches :

• H. M. Wilson in 12th Annual Report U.S. Geol. Survey, p. 533.
• Proc. Inst. C. E. Vol. XXXIII. Gordon on the value of water in India.
• Eng. News. Vol. XXI.

TABLE I.

Conventional Names.	Size in M.M.	Size in inches.
Coarse gravel	– to 6	– to $\frac{1}{4}$
Gravel	6 to 2	$\frac{1}{4}$ to $\frac{1}{12}$
Fine gravel	2 to 1	$\frac{1}{12}$ to $\frac{1}{25}$
Coarse sand	1 to .5	$\frac{1}{25}$ to $\frac{1}{50}$
Medium sand	.5 to .25	$\frac{1}{50}$ to $\frac{1}{100}$
Fine sand	.25 to .05	$\frac{1}{100}$ to $\frac{1}{500}$
Silt	.05 to .01	$\frac{1}{500}$ to $\frac{1}{2500}$
Fine salt	.01 to .005	$\frac{1}{2500}$ to $\frac{1}{5000}$
Clay	.005 to .0001	$\frac{1}{5000}$ to $\frac{1}{25000}$

That the reader may get a clearer idea of the approximate proportions of gravel, sand, silt and clay in the soils commonly cultivated, the following table, compiled chiefly from the published works of Prof. Whitney is herein given. No. 1 is the red clay tile of the Potomac Valley near Baltimore, and No. 2 is a blue clay of the same locality used for making stoneware pipe. No. 3 is a 'clay' soil so-called taken from a truck field on James Island, S. Carolina. No. 4 is a heavy loam, from Hatfield, Mass., and No. 5 a close retentive soil. No. 6 is a sample of the lightest grade of sandy land of Southern Maryland. No. 7 and 8 are early truck land from the same State :

TABLE II.

No.	Kind of soil	Organic Matter.	Gravel.	Coarse Sand.	Medium Send.	Fine Sand.	Very fine Sand.	Silt.	Fine Silt.	Clay.
1	Red clay	6.24	0.00	0.00	0.50	2.63	9.62	25.13	13.44	42.34
2	Blue clay	2.61	0.00	0.00	0.29	1.27	8.93	20.16	!6.72	50.02
3	Clay land	1.62	0.00	0.54	1.03	83.20	3.22	3.22	3.58	3.59
4	Heavy loam	3.45	0.00	0.00	0.10	0.43	21.88	67.00	3.4!	2.61
5	Meadow land	4.75	0.00	0.00	0.05	0.50	32.64	49.32	5.46	6.79
6	Sandy land	0.24	0.45	10.33	46.29	20.15	8.17	7.11	2.29	4.77
7	Light truck soil	0.00	0.49	4.96	40.19	27.59	12.10	7.74	2.23	4.40
8	Gravelly loam	3.18	6.06	22.09	29.87	9.82	6.52	10.71	3.86	7.89

According to Schübler the average weights of one cubic foot of various soils as they exist in nature, are as follows :—

Dry silicious, or calcareous sand	110	pounds.
Half saud and half clay	96	"
Common arable soil	80 to 90	"
Heavy clay	75	"
Garden mould rich in vegetable matter.	70	"
Pe t soil	30 to 50	"

The difference in weight between a clay and a sandy soil for instance is due largely to the greater number of open spaces in the former and not to any material difference in the specific gravity of the grains.

A cubic foot of a very sandy soil contains about 40 per cent. by volume of air space, while a soil derived from limestone contains about 60 per cent. air space.

According to Whitney the percentage of open spaces in the following typical soils of Maryland are :—

TABLE III.

Light truck land	37.3	per cent.
Pine barrens chiefly sand	40.0	"
Sandy land	41.8	"
Wheat land	42.7	"
Tobacco land	50.0	"
Gummy land	58.5	"

Outside of the laboratory it is impossible to find soils completely saturated *i.e.* with all the spaces filled with water. These open spaces contain air and water in varying amounts. In dry soils there is a large proportion of air and a correspondingly small proportion of water, while in wet soils these proportions are reversed.

In irrigated regions where it is possible to control the soil moisture long experience has shown that the best crops can be raised when the open spaces contain nearly equal volumes of air and water. Thus the water-holding capacity of heavy clay soils is about 44 lbs. of water in every 100 lbs. of saturated soil and the most favorable condition for plant growth in such soils is when they contain from 16 to 24 lbs. of water in 100 lbs. of moist soil.

The following table gives the approximate number of grains in each classification of similar weights:

TABLE IV.

Fine gravel	1.4	grains.
Coarse sand	17.0	"
Medium sand	139.0	"
Fine fand	1370.0	"
Very fine sand	17360.0	"
Silt	274000.0	"
Fine silt	17280000.0	"
Clay	449280000.0	"

FORMING A COMPACT EMBANKMENT.

The belief is prevalent among laymen and engineers inexperienced in this kind of work, that any country road foreman who is familiar with the handling of earth, is qualified to superintend the building of earthen dams. They fail to understand the difference between an embankment capable of withstanding a load and one compact and stable enough to retain water. In highways, or railroad fills, little, if any, attention is given to packing the materials. The fill when completed is nearly as porous as the soils and sub-soils of which it is composed. When a cubic yard of earth is removed from the pit to the fill, its bulk is increased by about one and one-half in sandy soil to six per cent. in hard clay soil, and the subsequent shrinkage of from 5 to 15 per cent. finally reduces it from 90 to 95 per cent. of its original volume. But soils and sub-soils in their natural state contain from 35 per cent. to 60 per cent. by volume open space, and the ordinary highway, or railroad fills, are thus shown to be porous masses wholly unfit to impound water.

In the building of earthen dams something more is needed than the piling up of a mass of porous materials. The hydraulic engineer who desires to build a safe dam with a minimum amount of earth, must attend closely to the following features :—

1. The relative sizes of the grains.
2. The percentage by volume of open space.
3. The proportions of air and water contained in these open spaces.

4. The best mode of filling the interstices between the larger grains with the smaller grains.

5. The best mode of expelling the greater part of the air contained in the open spaces.

6. Making the embankment proof against the action of extreme drouth, or excessive saturation.

As the hydraulic engineer of the Experiment Station of Utah, the writer recently began to make some experiments on the best mode of compacting soils and sub-soils. On account of cold weather these experiments have not been completed, but enough has been done to show the general trend of the investigations.

Sand suitable for cement concrete was carted from a bank, placed under cover and allowed to remain for about two months until quite dry, when it was separated by graduated sieves into four grades—coarse sand, medium sand, fine sand, and very fine sand. In the same way bank gravel was obtained in two sizes. Grains that would pass through round holes one quarter of an inch in diameter and be retained by holes one-sixth of an inch, were classed as gravel, and the grains left between sieves one-sixth to one-twelfth inches were classed as fine gravel.

The silt was a mixture of vegetable matter and extremely fine sand. The clay was a brick fire clay and was air-dried, ground and passed through graduated sieves.

Boxes were made containing some even part of a cubic yard and graduated from bottom to top. The smallest box used was one foot in height and contained .01 cubic yard. The materials were poured into the boxes through a funnel five-eighths inches in diameter from a height of 0.85 ft., and the weight of each determined.

To determine the percentage of open space in each, a given volume was poured from a height of 0.85 feet into a known volume of water and the volume of water thus contained in the interstices gave the percentage by volume of open space.

In the following table the percentage by volume of open space in the clay is not given on account of its tendency to "swell" when immersed in water. Assuming the specific gravity of the solid particles of the clay to be 2.40, the percentage of open space would be about 0.65.

TABLE V.

Material.	Size inches.	Weight per cub. yard lbs.	Percentage by volume open space.	Temperature of materials.	Temperature of water.
Gravel	$\frac{1}{4}$ to $\frac{1}{6}$	2550	45.0	48° Fahr.	35° Fahr.
Fine gravel.. ...	$\frac{1}{6}$ to $\frac{1}{12}$	2275	45.7	48° "	35° "
Coarse sand.....	$\frac{1}{25}$ to $\frac{1}{50}$	2200	47.7	46° "	44° "
Medium Sand...	$\frac{1}{50}$ to $\frac{1}{100}$	2150	50.8	46° "	44° "
Fine sand.......	$\frac{1}{100}$ to $\frac{1}{500}$	2150	48.3	46° "	44° "
Very fine sand ..	$\frac{1}{500}$ to $\frac{1}{1500}$	2025	47.7	46° "	44° "
Silt.............	$\frac{1}{1500}$ to $\frac{1}{2500}$	1925	51.7	46° "	44° "
Clay............	$\frac{1}{2500}$ to $\frac{1}{15000}$	1380	....		

CLAY CONCRETE.

An embankment formed of gravel would be stable and unaffected by the actions of frost, drought, or moisture, but the 45 per cent. of open space in gravel would allow the water to pass through it. Sand would be more impervious but less stable and more affected by drought and excessive moisture. Soils containing a high percentage of organic matter might make an impervious embankment, but the necessary weight and compactness would be wanting. The same is true of all clays. Clayey soils are often styled heavy soils, but, as we have seen, such soils are the most porous and are capable of absorbing large percentages of water. The tendency of clay to swell when wet, and shrink and crack when dry, renders it a treacherous material for reservoir embankments when used alone.

Since there are serious objections to each class of the materials named when used alone, the writer has made a few tests of compactness with various mixtures of the above which he has termed *clay concrete*. The object sought being to mix sufficient silt or clay with the sand to more than fill all the open spaces in the sand, and to mix with the gravel a sufficient volume of sand and silt or clay to more than fill all the open spaces in the gravel.

The results of the tests are as follows:

CLAY CONCRETE No. 1.

Gravel	1.00 cubic yards.
Coarse sand	0.25 "
Very fine sand	0.27 "
Clay	0.43 "
Total	1.95 cub. yds.

(*a*) When No. 1 mixture was thoroughly mixed dry and poured from a height of 0.85 feet its volume was 1.546 cubic yards.

(*b*) When thoroughly mixed and tamped dry in one-tenth of a foot layers, its volume was 1.240 cubic yards.

(*c*) When poured slowly into water and mixed its volume was 1.26 cubic yards.

(*d*) When moistened sufficiently to form a stiff paste and tamped in one-tenth of a foot layers, its volume was 1.312 cubic yards.

CLAY CONCRETE No. 2.

Fine gravel	0.90 cubic yards.
Fine sand	0.56 "
Silt	0.42 "
Total	1.88 cubic yards.

(*a*) When No. 2 mixture was mixed dry and poured from a height of 0.85 feet its volume was 1.526 cubic yards.

(*b*) When mixed dry and thoroughly tamped its volume was 1,294 cubic yards.

(*c*) When mixed dry and poured from a height of 0.85 feet into water, mixed but not tamped, and the excess of water drained through holes covered with canvass in the bottom of the box, its volume was 1,256 cubic yards.

(*d*) When mixed dry and moistened with 0.277 cubic yards water at a temperature of 41 degrees Fahr. into a stiff paste and well tamped, its volume was 1.296 cubic yards.

CLAY CONCRETE No. 3.

No. 3 is identical with No. 2 except that 0.58 cubic yards of clay is substituted for 0.42 cubic yards silt.

Fine gravel	0 90 cubic yards.
Fine sand	0.56 "
Clay	0 58 "
Total	2.04 cubic yards.

(*a*) When No. 3 mixture was mixed dry and poured from a height of 0.85 feet its volume was 1.604 cubic yards.

(*b*) When mixed dry and well tamped, 1.324 cubic yards.

(*c*) When mixed dry and poured from a height of 0.85 feet into water, mixed but not tamped, and drained of excess water, its volume was:

1.432 cubic yards	after experiment.	
1.420 "	"	1 day.
1.360 "	"	2 days.
1.356 "	"	4 days.
1.324 "	"	15 days.

(*a*) When mixed dry and moistened with 0.307 cubic yards of water into a paste and well tamped, its volume was 1.348 cubic yards which shrunk but slightly in four days.

CLAY CONCRETE No. 4.

Fine gravel....	1.00 cubic yards.
Medium sand.........................	0.51 "
Silt	0.26 "
Total.........	1.77 cubic yards.

(b) When No. 4 mixture was mixed dry and tamped its volume was 1.26 cubic yards.

(c) When mixed dry and poured from a height of 0.85 feet into water, and mixed but not tamped, its volume was 1.204 cubic yards.

(d) When mixed dry and moistened with 0.30 cubic yards water into a stiff paste and well tamped, its volume was 1.212 cubic yards.

Water, sewer, and gas mains are laid in trenches excavated in materials somewhat similar to those which may be used in earth dams. Of trenches for water mains the writer has superintended the filling in of over 100 miles. Formerly, city engineers required the trenches in all public streets to be filled in in three inch layers and well tamped. In the three systems of water works recently constructed by the writer in this State, permission was granted to fill the trenches under water instead of tamping the earth in thin layers. The method followed was to keep separate while excavating the road metal, gravel, or paving, and the ordinary earth. After the pipe was laid in the trench and caulked, care was taken to tamp sufficient earth beneath, and at the sides of the pipe to give it a continuous and uniform bearing; then earth bridges were thrown in at intervals to prevent floatation and the trench partially filled with water from the hydrants or from irrigating canals. The ordinary earth was then plowed, shovelled, or scraped into the water and the road metal or gravel placed on top.

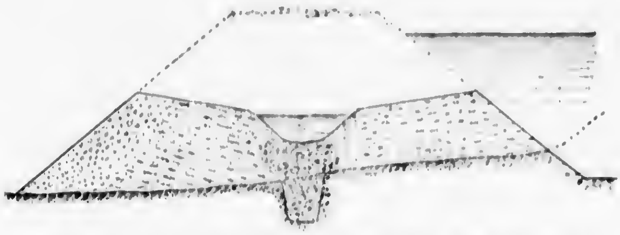
Trenches filled with dry earth and tamped invariably settled more or less after a heavy rainstorm, but trenches filled under water, although quite soft for a few days, behaved much better and seldom settled.

The foregoing statement does not apply to clay soils since it requires too long for the wet mass to become sufficiently dry to bear up the weight of a horse.

There is every reason to believe, however, that trenches filled with clay placed under water in the manner indicated, would, when freed of the excess moisture, be more stable and less liable to subsequent changes.

In building a distributing reservoir for Ogden City, Utah, the writer adopted a mode of compacting the materials somewhat similar to that outlined in filling in trenches under water. The location was below the old beach line of Lake Bonneville, a name given by geologists to the large fresh water lake of which the present Great Salt Lake forms only a small remnant. The materials were, for the most part, fine sand, with an occasional stratum of coarse gravel, cobblerock, clay or silt. The capacity of the reservoir is 7,000,000 U.S. gals., width of embankment at flowline 30.5 ft., water slopes one and one-half to one, outer slopes two to one, depth of water 20 feet.

After removing the surface soil a trench from 4 ft. to 6 ft. wide and 6 ft. deep was dug along the entire centre line of the proposed embankment. The base of the embankment was then formed and allowed to slope slightly towards its center. Instead of filling in the trench at once, it was allowed to remain nearly full of water, and it became the origin of a canal in the center of the entire embankment. The most impervious material was deposited on the inner half of the embankment, while the cobble rock and more porous material were deposited near the outer edge. The inner, and to some extent, the outer half of the embankment, was built up in layers, moistened and packed in the usual manner. The central portion was built up by emptying the wheelers at each edge of the canal and shovelling the material into the water. Fig. 1 shows a sketch of the partially completed reservoir embankment.



The mode of compacting reservoir embankments, almost universally followed by American engineers, is to specify that the earth shall be spread evenly over the surface in layers of from 4 to 6 inches in depth, then moistened and rolled with grooved rollers weighing from 100 to 300 lbs. per inch of tread. In most instances the number of times each layer is rolled is left to the decision of the engineer, but some specify a minimum roller travel in miles for each 1000 cubic yards excavated.

Opinions differ as to the amount of water to use. In gravel puddle, or what the writer has termed, clay concrete, in which the percentage of clay is small, a large amount of water can be used with good results. This mixture unquestionably makes the safest embankment.

To those who persist in using chiefly clay, it may be said that the addition of water to moisten the layers is of doubtful benefit. The effect of water on comparatively dry clay is to increase its bulk, and no amount of rolling will make it quite so compact as it would be if rolled to the same extent in a dry state.

In reference to compacting materials by depositing them under water, as was done on the Ogden reservoir, by means of a canal in the center, the reader will note that this method is applicable only to gravel puddle or clay concrete containing less than 25 per cent. clay. A higher percentage of clay would render the embankment so soft that it could not be traversed by teams, but the method is particularly well adapted to earth containing either no clay or very little.

In so far as the author knows, this method has never been tried before. If the reader, however, compares tests No. 1c, No. 2c, No. 3c, and No. 4c, with corresponding tests (*b*) and (*a*), he will find that, when the percentage of clay is small, as compact a mass can be made by simply pouring the earth into water and mixing as by moistening with water and thoroughly ramming.

It is, however, from practical experience rather than from the few preceding experimental tests, that the writer bases the following conclusions :

1. Earth deposited under water is freed from the greater part of the air confined in the open space.

2. Earth containing grains of different sizes packs better under water than in air.

3. Embankments built of dry earth, or earth moistened and packed, are more liable to be injuriously affected by capillary action than embankments, or portions of embankments, built under water.

4. Making provision during construction for a canal holding water in the center of the embankment, is a practical test, before completion, of the safety of the structure.

5. Most of the advantages of a center core are gained by this mode of construction without the disadvantage of having distinct lines of separation between an earth and a masonry wall.

6. Where water is abundant and easily applied, the middle portion of earth dams can be more cheaply compacted under water than by sprinkling and rolling.

THE DIMENSIONS OF RESERVOIR EMBANKMENTS.

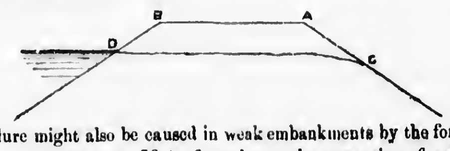
The proper widths and slopes to adopt in the building of earthen dams cannot as yet be determined by mathematical calculations. Our knowledge of soil physics is too meager to admit of limiting the amounts of materials used to the same extent as one would in the construction, for example, of a railroad bridge, or a roof truss. The dimensions in each particular case must be left to the good judgment, practical skill and the knowledge gained from experimental tests of the designing engineer.

The character of the materials, the purposes for which water is stored, and the natural conditions surrounding each site differ so widely, that it is impossible to lay down precise rules. Generally speaking, however, the dimensions of each embankment will depend to a greater or less extent upon the following conditions:—

1. The danger to life and property in case of failure.
2. The depth of water to be impounded.
3. The height and force of the waves.
4. The angle of repose of the materials.
5. The pressure which the materials can safely withstand.
6. The necessity of a roadway on top of the embankment.
7. The slope paving.
8. The imperviousness of the materials.
9. The existence of a center core.
10. The manner of construction.

Top Width.—When teams are used to convey the materials the smallest top-width must be at least six feet, since it requires that space to prevent horses, and particularly mules, from crowding. It is usually desirable to have a roadway paved with rolled gravel and a fence around the reservoir, in which case a top width of twelve feet or more would be required. Where stability and security alone are concerned the top-width depends upon the elevation of high water.

High Water Line.—In cold climates like those of Canada and the Northern States, it is important that the high water line be kept below the frost line in the upper portion of the dam. Failures have been caused by the earth freezing in the trapezoidal section A B C D Fig. 2, which elevated the section sufficiently to allow the water to pass along the division line C D.



Failure might also be caused in weak embankments by the formation of ice at the flow-line. If the force due to the expansion of a stratum of ice were to be exerted at D against a frozen mass A B C D, it might be sufficient to disturb the upper part of the embankment and endanger the whole structure.

In both cold and warm climates there is the danger of waves overtopping the embankment. The maximum height of waves which may occur on the surface of any reservoir of known dimensions may be roughly estimated by Stephenson's formula $H = 1.5 \sqrt{F} + (2.5 \sqrt[4]{F}.)$ in which H is the height of the waves in feet and F the fetch or distance in nautical miles through which the waves act. According to the above formula the heights of waves on ordinary reservoirs would vary from two to three feet. On the smallest the waves would be more than 2 feet high and seldom more than 3 feet on the largest. It is evident, therefore, that this formula does not apply to small surfaces of water, but as the error is on the side of safety, and since the top of even small reservoirs should be raised at least two feet above high water, the formula can be trusted to give approximate results.

Breadth of Embankment at the Flow-Line.—The practice of the writer for years in designing the cross-sections of reservoir embankments has been to determine first the breadth at the flow-line. Then through the extremities of this distance converging lines can be drawn to suit the angle of repose of the material and other necessary conditions. Great differences exist as to this dimension. While writing this article there lie before the author the descriptions of five reservoirs each 30 feet deep, and their respective breadths at the flow-line are 28 ft., 34 ft., 40 ft., 45 ft., and 53 ft. After making ample allowance for a difference in the quality of the materials, there should not be a difference of nearly 100 per cent. in the widths of the embankments, providing the work in each case has been carefully done.

With a view to unifying the results and economizing material, the writer obtained by circular letters, private correspondence and otherwise, descriptions of about 100 reservoirs located in nearly every State of the Union. Out of the hundred 75 were chosen as typical of existing conditions, and their depths of water and breadths of embankment at the flow-line were plotted on cross-section paper.

The co-ordinates for each of the 75 reservoirs were the abscissa (x) which represented the breadth in feet of the embankment at the flow-line, and the ordinate (y) which represented the depth in feet of the water in the reservoir. The curve formed by joining all the points was so nearly that of a straight line that the following equation of a straight line was adopted.

$$y = x - 5.$$

For outer and inner slopes of 2 horizontal to 1 vertical and with the top of the embankment from 2 to 6 ft. above the flow-line, the above empirical formula gives top-widths and flow-line widths for depths of water from 10 feet to 45 feet as follows:

TABLE VI.

Depth of water in reservoir.	Outer slope.	Inner slope.	Top width.	Distance between top of embkt. and surf. of water.	Breadth at flow-line.
Ft.			Ft.	Ft.	Ft.
10	2 to 1	2 to 1	7	2	15
15	"	"	8	3	20
20	"	"	11	3½	25
25	"	"	14	4	30
30	"	"	19	4	35
35	"	"	22	4½	40
40	"	"	25	5	45
45	"	"	31	6	55

In impounding water to a depth greater than 40 or 50 feet safe construction requires the introduction of berms. Thus in a reservoir 60 ft. deep, there should be near the middle of each slope a berm of 5 or 6 ft. in width, and when we deduct the width of these two berms, the top width is limited to about 30 ft., while the formula still holds approximately true.

Outer and Inner Slopes.—Regarding the 75 typical reservoirs referred to on a preceding page, it may be here stated that their inner slopes varied from a maximum of 4 to 1 to a minimum of 1 to 1, and averaged 2.61 to 1, while their outer slopes averaged 2.1.

TABLE VII.

Outer slopes.	Inner slopes.
2 reservoirs 1 to 1	2 reservoirs 1 to 1
23 " 1½ " 1	23 " 1½ " 1
2 " 1¾ " 1	2 " 1¾ " 1
41 " 2 " 1	31 " 2 " 1
1 " 2¼ " 1	1 " 2¼ " 1
3 " 2½ " 1	1 " 2¾ " 1
3 " 3 " 1	11 " 3 " 1
	2 " 4 " 1
75 Res's aver. 2 to 1	75 Res's aver. 2.61 to 1

It is evident from the foregoing that American practice in adopting slopes to earth embankments does not often vary from 2 horizontal to 1 vertical.

No unprotected earth slope will long withstand the action of waves, even on a 3 to 1 incline, and since some kind of paving is necessary, a

2 to 1 slope of suitable materials and properly constructed is preferable to one flatter. In paving with hydraulic cement concrete, the cost can be considerably lessened by adopting a 1½ to 1 slope on the water side without lessening to any extent the strength or efficiency of the embankment.

PROTECTING THE INNER SLOPE.

To prevent the destructive effects of waves, ice and frost, to facilitate the removal of silt and aquatic vegetation, to prevent animals from burrowing into the bank, and in many cases to prevent percolation through the bottom and sides, some kind of paving is usually required.

The following brief notes obtained by circular letters describing the mode of paving and the materials used in more than thirty reservoirs of the Union will give the reader a fairly correct idea of existing conditions :

WATER WORKS RESERVOIR, 47 FEET DEEP.

Charlottesville, Va.

"Inside slope of dam is paved 12 ins. thick with ordinary stone rip-rap."

E. F. HARRIS, *Supt.*

LAKE MONTEBELLO RESERVOIR, 31 FT. DEEP.

Baltimore, Md.

"Inside slope is rip-rapped with broken stone for a distance of 2 feet above and 3 feet below the flow-line."

WM. BENTHALL, *Ass't Engineer.*

TATNUCK BROOK RESERVOIR, 30 FT. DEEP.

Worcester, Mass.

"Paved 24 ins. thick at top and 18 ins. thick at bottom of inside slope with field stone of large size, having interstices filled with smaller stones."

FRED. A. MCCLURE, *Supt.*

WATER WORKS RESERVOIR, 16 FT. DEEP.

Grand Rapids, Mich.

"Bottom of reservoir is paved 12 ins. thick, inside slope from 12 inches at bottom to 2 ins. at top with cobble stone laid in cement concrete. Frost has loosened some of the cobble stones at the water line."

H. A. COLLAR, *City Engineer.*

INDIAN CREEK RESERVOIR, 50 FT. DEEP.

Boise, Idaho.

"Inside slope rip-rapped with basalt 18 inches thick."

CHAS. L. SWAIN, *Engineer.*

STORAGE RESERVOIR, 65 FT. DEEP.

Amsterdam, N.Y.

"Face of dam is rip-rapped 1½ feet deep, hand placed. Frost never affects rip-rap. Don't believe in paving."

S. E. BABCOCK, *Engineer.*

STORAGE RESERVOIR, 15 FT. DEEP.

Rochester, N.Y.

"A berm five feet wide at middle of slope; rip-rap below berm; paved with stone above. Paving laid on gravel lining a few inches thick."

E. KUICHLING, *Chief Engineer.*

DISTRIBUTING RESERVOIR, 17 FT. DEEP.

Rochester, N.Y.

"On bottom of reservoir 4 inches of gravel spread over surface of clay puddle 12 to 18 inches thick hauled from brick yard. Rip-rap 24 inches thick below berm. Stone paving 18 inches thick above berm."

E. KINCHLING, *Chief Engineer.*

SCHUYHILL RIVER RESERVOIR, 13 FT. DEEP.

Conshohocken, Pa.

"12 inches cement concrete on bottom, 4 inches brick on 12 inches cement concrete on slopes. Concrete composed of 1 cement, 3 sand, 5 broken trap rock."

W. E. FERRIER, *Supt.*

WATER WORKS RESERVOIR, 30 FT. DEEP.

Sherburne, N.Y.

"Paved with stone 12 ins thick set at an angle of about 60°. Space filled with gravel."

W. E. DAVIS, *Supt.*

STORING AND RECEIVING RESERVOIRS.

New Bedford, Mass.

"The inside slope of storing reservoir dam is protected by a paving of large sized boulders. The inside slope of the receiving reservoir has a lining of granite blocks 1 foot thick."

R. C. P. COGGESHALL, *Supt.*

WATER WORKS RESERVOIR, 15 FT. DEEP.

Waltham, Mass.

"Bottom and water slopes paved with granite slabs 12 inches thick, laid dry as closely as possible."

L. BROWN, *Supt.*

Hartford, Conn.

"We have six reservoirs from 20 to 41 feet deep, paved wirh stones about what two men can lift, placed close together and filled in with smaller stones."

HENRY A. AYERS, *Supt.*

LOW SERVICE RESERVOIR No. 2, 21 FT. DEEP.

Portland, Oregon.

"Paved with brick coated with ¼ inch California asphalt laid flatwise in paving pitch."

J. HENRY SMITH.

EASTON LAKE RESERVOIR No. 2, 51 FT. DEEP.

Bridgeport, Conn.

"Cobble rip-rap 24 inches thick at bottom of slope and 15 inches at top."

S. G. STODDARD, Jr., *Engineer.*

WATER WORKS RESERVOIR, 47 FT. DEEP.

Covington, Ky.

"The water slopes are revetted with stone blocks 12 inches thick, laid in cement on a foundation of broken stone 12 inches deep."

W. H. GLORE, *Supt.*

WATER WORKS RESERVOIR, 26 FT. DEEP.

Erie, Pa.

"Bottom of reservoir puddled with 18 inches of brick clay put on dry and rolled solid every three or four inch course. Paved with brick laid flat on bottom (2 inches thick) and laid on edge on sides (4 inches thick) with cement after being laid."

WM. HINNEL, *Sec.-Treasurer.*

BIRMINGHAM RESERVOIR, 42 FT. DEEP.

Birmingham, Ala.

"Rough sand stone rip-rap 12 inches thick."

W. J. MILNER, *Supt.*

STORAGE RESERVOIR, 24 FT. DEEP.

Peoria, Ill.

"6 inches of concrete laid on bottom in about 10 foot squares separated by two rows of brick placed on edge. Water slopes lined with brick 8 inches thick. Frost in winter occasionally cracks the bricks at the water surface.'

DABNEY H. MAURY, *Supt.*

CHERRY VALLEY RESERVOIR, 35 FT. DEEP.

"The inside slope of the dam is covered with rubble paving from 12 to 24 inches in thickness, covered with about 6 inches of selected hard pan to fill the interstices in its surface."

J. C. HANCOCK, *Supt.*

CACHE LA POUDRE RESERVOIR, 30 FT. DEEP.
LARIMER AND WELD " 22 " "

Northern Colorado.

"Inside slope of both reservoirs rip-rapped with mountain sandstone 1 foot thick laid on 2 feet of gravel."

ED. BAKER, *Engineer.*

GREELY, Colo.

WATER WORKS RESERVOIR, 14 FT. DEEP.

Ann Harbor, Mich.

"Slopes protected by rubble or cobble stone."

CHAS. E. GREEN.

MARLETTE LAKE RESERVOIR, -- FT. DEEP.

Virginia City, Nevada.

"Front of dam paved with rubble. Stone and ice sometimes displace or disarrange the rubble but not seriously."

J. B. OVERTON.

STORAGE RESERVOIR, 25 FT. DEEP.

Southington, Conn.

"The water slope of the dam was covered 18 inches in depth with small broken stone, over which was laid a paving of large stone 15 ins. in depth."

J. H. MCKENZIE.

Figures 3, 4, 5, 6 and 7 show typical forms of slope paving and include all the kinds common to modern practice.

Fig. 0, not shown, is an illustration of the use of brush or willows tied together and anchored by means of galvanized wire. The small private irrigating reservoirs of Western America are frequently protected from wave action by wheat straw held down by strands of barbed wire. Occasionally brush and stones or slag are used.

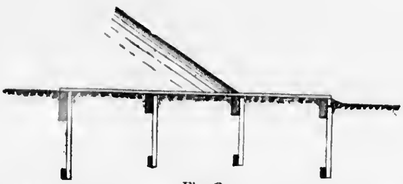


Fig. 3.

Figure 3 was designed by the author as a temporary expedient for the Ogden Distributing Reservoir until a more permanent paving could be put down. It was laid five years ago and has fulfilled all purposes so well that the owners have now no intention of substituting it. Red pine boards extend 3 feet above and 6 feet below the flow line along the slope and are nailed to joists 3x8 imbedded in the bank and anchored at intervals in the manner shown.

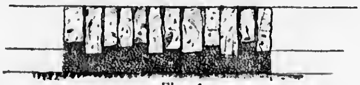


Fig. 4.

Figure 4 is typical of the most common kind of paving.

The foundation should be, in every instance, a compact, impervious and stable bank, on the inner slope of which is spread a layer of gravel or broken rock of sufficient depth to prevent the water from washing away the earth beneath. Upon this porous layer is laid the stone pitching or rip-rap, which may vary in depth from 1 to 2½ feet, depending upon the height of the waves and the action of ice and frost, the interstitices of the stone pitching being filled with gravel spalls or broken stone.

Fig. 5.

The usual form of cement concrete paving is shown in Figure 5, consisting of a layer of screened gravel or broken rock well rammed, upon which is laid the requisite thickness of concrete. For a short distance, both above and below the flow-line, stone-pitching laid in cement mortar upon a thin layer of cement concrete should be substituted for the cement concrete paving.

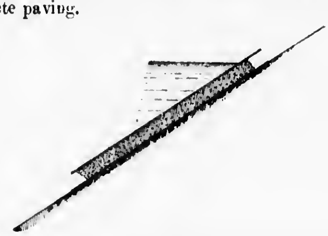


Fig. 6.

Figure 6 shows a portion of a slope paved with asphalt concrete. This concrete is composed of clean sand, gravel and liquid asphalt in about the following proportions:

Gravel....	70	per cent. by weight.
Sand.......	30	" "
Liquid asphalt.....	10-15	" "

The sand and gravel are heated to a temperature of over 300 fahr. and mixed with the liquid asphalt at a slightly lower temperature.

It is put on hot in a manner similar to street paving and varies from 1 to 4 inches in thickness.

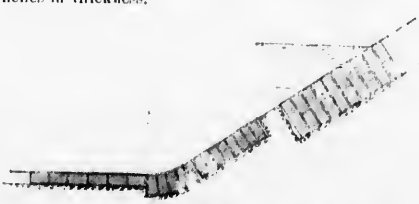


Fig. 7

Figure 7 shows a paving formed of brick and asphalt. The brick on the bottom may be laid flatwise, on the lower portion of the slope 4 inches and near the flow line 8 inches in thickness. To prevent the brick from absorbing moisture a thin layer of asphalt mortar, composed of 90 per cent. by weight of clean sand mixed with 10 per cent. by weight of liquid asphalt, is first spread over the rammed gravel; the brick are then dipped in hot asphalt, and after being laid grouted with the same material. A thin surface coating of asphalt of about $\frac{1}{8}$th of an inch in thickness completes the lining.

In discussing the relative merits and demerits of each type of paving represented above, little need be said of the first two named, since the early decay of both willows and lumber render periodical renewals necessary.

Many failures are recorded of stone pitching or rip-rap, but in nearly every instance they were caused by the washing away of part of the embankment immediately beneath the rip-rap. Under ordinary conditions wash can be prevented by placing a sufficient thickness of gravel or broken rock back of the pitching and carefully filling all interstices of the latter with coarse sand and gravel. The general success which has attended this kind of paving does not warrant, in the opinion of the writer, the following severe censure from the pen of Samuel McElroy C.E. of Brooklyn, N.Y.:

"The only way to protect an earth reservoir bank, or floor, is to keep it dry; otherwise pressure, storm wash, motion, leakage, frost or animals may weaken and destroy it.

"Dry work, properly laid, requires much more time for selection and fitting than cement work, for the same section and slope; it requires a better class of stone throughout; and the cost of hydraulic cement mortar, in itself, does not add more than \$1.20 per cubic yard, or about the cost of the cement mortar, to that of dry work, for the same stone. At Ridgewood we paid \$1.50 for the dry stone lining, and \$2.50 for similar wall in cement with full joints. The repair accounts of dry walls on various public works has been a formidable item.

"Experience also shows that a well puddled and brick covered reservoir floor would have prevented some costly bottom leaks and ruptures.

"In a Report on the Hudson River and Champlain Canal Improvement, made to the State Engineer of New York in 1867, I had occasion to show that a solid masonry canal slope wall one-third to one, with 4½ feet concrete footing and 30 inch wall could be built and coped for less than the 1¼ to 1 dry slope wall, which has been an endless cause of wash, rupture and repair along the entire canal system of the State.

"If the experience of our reservoirs similarly lined was collected it would certainly end their construction, as it would similar constructions for mill power races, dams and other faces exposed to wash and frost.

"For both Brooklyn reservoirs the following specification was adopted:

"The inside slopes to be carefully puddled for two feet in depth, then covered with a substantial layer of cement mortar and gravel (concrete), not less than three inches thick, over which a wall of brick masonry shall be built eight inches thick to the embankment top, and covered with a flag coping not less than three feet wide, by five inches thick. The bottom of the apartments to be similarly puddled and covered with best paving brick laid on their edges and carefully grouted.

"In the Ridgewood case this theory was fully confirmed by negative experience. A change in the direction took place in 1856, and some changes in plan in 1857. The slope lining was thus specified:

"The water slopes, unless otherwise directed, to be paved with a well laid stone paving one foot thick, the stone used to be sound and of proper shape to make neat and compact work; and openings between said stone to be well pinned and packed; to be equal in every respect to the receiving reservoir of the Croton work. The paving to be laid on a bed of gravel or small stones.

"A considerable length of slope was lined under this specification, under Mr. Kirkwood's personal inspection, as a pattern for the rest; it was as cheap for the sub contractors to use 15 to 18 inch stone, and the wall was thus laid, with about five inches of small stone backing. When about seven feet of water was pumped into the eastern division in 1858, the wave wash cut the embankment behind the wall so rapidly that the water was drawn down, the injured sections repaired, and the entire lining carefully filled in with cement, grout and pointing.

"This involved a change in the dry wall of the new Croton reservoir, then under contract, to cement stone masonry. The Mount Prospect reservoir, built according to the original specifications, illustrates to-day its advantages. For convenience of construction, however, it is best to increase the concrete thickness and reduce that of the puddling."

In the case of the Ridgewood reservoir, cited by Mr. McElroy, 5 inches of broken stone behind rip-rap is too thin to prevent wash. Again in the paving for the Brooklyn reservoirs, which he recommended, it is not good practice to lay cement concrete on clay, since the weight of the water which may accumulate back of the lining, or the liability of both clay and water freezing, will loosen and break the concrete.

Water slopes lined with cement concrete fail usually in one of two ways; either the foundation is insecure or the bank settles. Quite often a layer of clay is first put down with no intermediate porous stratum of gravel or small stones, and when the water is rapidly drawn down in the reservoir the wet mass of clay is liable to slump and carry with it the concrete lining.

Engineers and superintendents frequently build reservoirs in earth and line the inner slopes and bottom with cement concrete before the banks have properly settled and without first thoroughly soaking the interior walls. In a properly made bank there will be no subsidence to speak of, but to pave a reservoir without first allowing the water to remain up to high-water mark for days and even weeks, is to invite failures.

The Cemetery Hill reservoir of Colorado, built in 1886-87 by the writer as engineer-in-charge, in accordance with plans and specifications prepared by chief engineer Allan, was not lined until 1890. In the spring of that year it was paved with Portland cement concrete, of which the greatest thickness did not exceed four inches. Five years later (1895) the writer examined the lining and found no failures, not even a crack. He attributes the success of this paving to the stable condition of the banks and to the water soaked state of the interior.

In the vicinity of Beaver Brook, Colorado, the farmers can get no water from wells, and they obtain their domestic supply from the irrigating canals in summer which is run into cisterns lined with cement mortar or concrete. After many failures the writer suggested that they soak the bottom and sides of the newly excavated cisterns for weeks, then remove the water, ram gravel over the entire interior and line with cement concrete. It was found that a much thinner coating would suffice when the foundation was prepared in the manner just described.

The toughness, elasticity and imperviousness of asphalt concrete render it a suitable material for reservoir lining. It has, however, one serious defect which engineers have not yet been able successfully to overcome. A hot sun, or warm weather, will cause it to slide down the slope.

In the kind of paving shown in Fig. 6 the thin coating of asphalt mortar which complетly surrounds the paving brick renders the lining impervious and difficult to crack, while the rigidity of the brick prevents the wall from sliding upon its base. Stone rip-rap based on a thin coating of asphalt concrete can be substituted for the brick, and the entire wall well grouted with asphalt mortar.

CORE WALLS.

In the New England states perhaps 85 per cent of all the earthen dams now in existence have been built with core walls of puddled clay, masonry, or concrete. In California, the Rocky Mountain Region and as far east as Pennsylvania and New York, masonry core walls are seldom introduced.

About a year ago, the writer sent the following questions to a large number of hydraulic engineers and water works superintendents:

Ques. 1. If the reservoir dam is built with a center core, state the materials used and mode of construction.

Ques. 2. Give the following dimensions of the center core, bottom width at original surface, top width, depth of base below original surface, width of base at bottom, height over all.

Ques. 3. Does the water in your opinion percolate through the inner portion of the embankment to the center core?

Ques. 4. Speaking generally, do you think the additional security gained by a concrete or masonry core justifies the extra expense?

The replies received to the above queries were so conflicting that it was impossible to harmonize the opinions expressed. If a classification were attempted it would be something like the folllowing:

(1) Those who consider a masonry core wall essential.

(2) Those who consider any kind of a core wall an element of weakness and a useless expenditure of money.

(3) Those who would insert a masonry core wall as an additional safeguard in all important structures, the failure of which might endanger life or property.

(4) Those who would be guided entirely by the quality of the materials and the conditions connected with each case.

The chief advantages of a masonry core wall are:

(1) It prevents animals from burrowing holes through the embankment.

(2) It may prevent percolation.

The chief disadvantages are:

(1) The additional cost.

(2) The unequal settling of unlike materials of different density and weight.

(3) The liability of the earth in the upper part of the embankment becoming saturated and increasing the pressure on the wall much beyond the designed limit.

(4) The tendency of the wall to crack on account of the expansion and contraction due to changes of temperature, presence of water back of the wall, or on account of the unequal settling.

It has always seemed to the writer that the advantages to be gained from a masonry core wall are in no measure commensurate to the disadvantages arising from its use. A 12 inch brick wall laid in cement mortar will prevent the burrowing of animals as effectively as a concrete wall 6 ft. in thickness. Besides, it is doubtful if there is an animal in existence which will burrow, for the sake of the pleasure to be derived from the exercise, through a well made gravel puddle. In the Western States cement concrete costs per cubic yard in place from \$6 to \$7, while earth suitable for earthen dams can be conveyed in wheel scrapers, puddled and rolled, for from 12 to 20 cts. per cubic yard. A yard of concrete is thus equivalent to nearly 45 yards of puddled earth. The most pronounced advocate of concrete core walls will hardly dare maintain that the relative utility of equal volumes of a concrete wall and the adjacent earthen embankment is as 45 to 1.

In considering the safety of earth dams with masonry or concrete heart walls, the late James B. Francis assumed that the full hydrostatic head would be exerted against the wall, and that as the wall alone was wholly inadequate to sustain this pressure, the earth on the down stream side had to be made of sufficient weight to resist the total pressure.

Desmond Fitzgerald, in describing the high earth dams recently constructed under his supervision for the Boston Water Works, lays down a similar assumption. One embankment is 65 ft. high, has an inner slope of 2 to 1, an outer slope of 2 to 1 and $2\frac{1}{2}$ to 1, a berm 6 ft. wide on each side, and a concrete core wall 10 ft. thick at the base and 2 ft. at the top. "In considering," he says, "the stability of this kind of an embankment, we must assume that the full head of the reservoir is carried to the core wall."

The writer fails to see the benefits to be gained by this process of reasoning based on such an assumption. In the first place, hydraulic engineers are nearly unanimous in the opinion that the inner part of the embankment should be the most impervious, and that if it cannot be homogeneous in structure the materials should be so placed that the imperviousness of the inner part should change gradually to the porosity of the outer. In following this practice it would be impossible in all well executed structures for the full head, or any head of water, to be exerted against a center wall.

If the intention is to place all the impervious material near the center and next to the core wall, the design is one of the worst that can be conceived. In such an embankment there is a porous mass of earth next to the water, through which the later can readily seep or percolate, then a heart wall encased in clay puddle much too weak to sustain the hydrostatic pressure, and back of this a second porous mass of earth too weak in itself to retain the impounded water.

This method of retaining water reminds the writer of the city engineer of a Western city who built a stand pipe of brick, and, to be doubly safe, lined its exterior with thin sheetiron plates. When the water was first turned in it never rose to the full head, but burst the brick and afterwards the thin sheetiron.

In impounding water one most depend wholly upon one particular class of material to sustain the pressure and prevent seepage and percolation.