reached a height of 40 feet, the main culvert was crushed by the weight above it, and no longer served as a waste channel. At this stage, therefore, hydraulic filling was substituted by earth brought in by carts, by which means the fill was completed. But the dam always leaked badly, as might have been expected. With but a few feet of water in the pond there was a stream of 1 second-foot passing under the dam, issuing from the broken waste-box. This at first ran muddy, but afterwards diminished and became clearer as the result of sluicing in material from the hillside upon the upper toe of the dam. Later, when the pond was filled, there was more leakage through the material deposited by carts than through the stratified material that was sluiced into position.

After the second failure the building of a dam was abandoned, and the ravine was crossed with a flume.

The case is cited as an example of the misuse of a most favorable opportunity for building a permanent construction with the greatest possible economy and with the best of materials for lack of experienced and intelligent supervision. The work was done without an engineer, by a so-called "practical" contractor, upon whom fell the entire loss.

General Principles of Hydraulic-fill Dam Construction.—From the various experiences in actual works detailed in the foregoing pages, the general principles involved in successful dam building by the hydraulic process may be gleaned, or inferred by the careful reader, but to make these principles clear the conclusions of the author from his personal experiences and years of observation are summarized as follows:

Materials.—The material best adapted for hydraulic-fill dams is an admixture of rounded bowlders, of all sizes that can be transported with the water and grades available, gravel, sand and clay, the latter to comprise 10% to 30% of the whole. The rounded rocks roll more readily than angular stone, and create less wear and tear in the pipes or flumes used to transport them while the clay acts as a lubricant to assist in transporting the heavier materials.

The most difficult material with which to build such a dam is pure clay unmixed with sand, because it is unstable until the water conveying it is drained from the mass, and if the entire embankment is formed of clay its complete drainage and maturity to a solidified mass is a slow process. Shrinkage is much greater in clay than in all other materials, and there is greater likelihood of the opening of cracks during the process of maturing. The difficulties of maintaining the slopes during construction are also greatly increased by the absence of coarse materials on the slopes, as in the Lake Frances dam. However, as is truly said by a good authority, "Wet clay under pressure will part with its water even though the mass be entirely surrounded by that liquid," * and when finally consolidated, as it will become within a reasonable time after being deposited under water, it makes a dam which can have no superior for water-tightness and solidity.

The preferable use of clay in a hydraulic-fill is as a core between overlying, overlapping masses of sand, gravel, and rock, which rest upon the clay and exert such constant pressure upon it as to assist in squeezing out its surplus water, for which the porous rock affords required drainage. In this condition clay, no matter what its original character, whether it be a "fat" clay, subject to excessive shrinkage, or a clay which readily slacks when exposed to the weather, will mature and ripen to a condition where it will neither absorb water or permit of percolation through it. Surface clays and soils which are thoroughly weathered are preferable to deep-seated clays in beds of such depth as to have undergone few of the changes produced by the action of the elements. In the opinion of the author, fine sand, glacial flour, rock dust, or any finely-pulverized non-plastic material is really preferable to clay as core material for a hydraulic-fill dam, for the reason that when settled in water it is not subject to shrinkage or further settlement, and is practically impervious to water if the particles are fine enough to pass a 100-mesh sieve. A combination or admixture of clay and fine sand is still better and less subject to shrinkage than pure clay.

Stratification.—An important feature of construction is the avoidance of the deposit of the material in such a manner as to permit strata of coarse sand and gravel from passing through the dam, giving porous passages from side to side. This may be regulated and controlled by an even distribution of the material along the slopes, avoiding the formation of high cones, extending beyond certain safe limits toward the core, and by keeping the pond on the dam as high as possible at all times. It is observed that sand and gravel with a lubricant of clay will take a natural slope of 5% to 8%, but on passing into the quiet pool will drop and deposit at a slope of about 1 on 1, while the clay spreads through the water practically level.

Contact with Foundation.—The preparation of the foundations by stripping all loose and porous material from at least the center third of the base down to impervious bed-rock, hard-pan, or clay is the first essential to secure a satisfactory contact with the foundation. In case the base material should be of the least doubtful character or show in test pits that there may be porous strata beneath the stripped surface, one or more trenches, extending longitudinally parallel with the center

* "Clays, their Occurrence, Properties and Uses," by Heinrich Ries, Ph.D. New York, John Wiley & Sons, 1906.

line should be excavated to the depth required to give reasonable assurance of impermeability, or that the porous strata may have no direct connection with the reservoir above so as to permit of water passing beneath the dam. This trench should then be filled with a dense quality of concrete, and the core-wall carried a sufficient height above the stripped surface to enable the clay core material to envelop and form a bond with it as the plastic matter settles and consolidates. In some cases, as in dams of moderate height, not over 50 feet, the concrete may be omitted entirely and the trench allowed to fill with the natural puddle of the sluiced material. Where the foundation is clay, hard-pan, or rock overlaid to a considerable depth by permeable sand and gravel which would be expensive to excavate, a satisfactory joining with the impervious base may be made by driving a continuous line of sheet-piling from end to end of dam through all porous matter into the base material.

Should the hydraulic-fill be lacking in impervious material it is good modern practice to build a reinforced concrete core-wall through the body of the fill, founded on the sheet-piling below.

Concrete or Masonry vs. *Clay as a Core-wall.*—The essential difference between the practice of English and American engineers in the building of ordinary earth dams is that the former rely for water-tightness on a specially prepared puddle core-wall of clay in the center of the dam, deeply founded in a trench below the lowest surface, and carried up to the original surface in form of a widening wedge, which narrows thence to the top of the dam. American engineers, on the contrary, seldom use clay in this manner, either because of its scarcity and high cost of the quality desired, or for other constructive reason, but prefer a central core-wall of masonry or concrete backed on either side by the most impervious material available well rolled in layers. Investigations made of a number of these dams of the best American types a few years since revealed the fact that the core-walls are seldom water-tight. Mr. E. Sherman Gould, late M. Am. Soc. C. E., in commenting on the revelations of the borings made in various high earth dams during the investigation of the new Croton dam by Messrs. Croes, Smith, and Sweet, in 1901, says:* "It is to be feared that in many cases the masonry center walls of earth dams are built too light. They should be more than mere diaphragms: they should be *walls* in fact as well as in name. My own rule is to give the center wall a bottom thickness equal to one-quarter of the greatest depth of water in the reservoir, and to draw in by offsets 2 feet in every 10 feet of height. I would never

* *Engineering News*, February 9, 1902.

voluntarily reduce this thickness, although I might increase it, except perhaps to draw in more rapidly near the top in the case of a very high wall."

This expression represents the extreme of conservatism from the standpoint of the American engineer. The way in which masonry or concrete core-walls are regarded by English engineers is partly expressed by the language used by the late James Mansergh, F.R.S., when President Institution of Civil Engineers, in an address to the society, in which he said: "I am not sure that such a core may not be made from end to end of an earth dam, if very special precautions are taken by well rolling the bank to insure that *unequal settlement* or *surging* does not take place. *I have never yet ventured to try it*, but if I do not get nervous as I grow older, I may some day." Reginald E. Middleton, M. Inst. C. E., of London,* writes on this subject: "Where masonry alone is used, should there be any movement in the bank, the wall will be fractured, serious leakage may take place and the dam be so much weakened thereby that its unforeseen destruction may result, and it is exceedingly difficult to make a thin, or even a thick, masonry wall perfectly water-tight."

Hydraulic-fill dams offer a safe and satisfactory middle ground of compromise between the American earth dam with concrete core-wall or diaphragm and the English type of earth dam with its elaborate mixed and tamped puddle-wall of selected clay. By no other process can such a large proportion of the entire dam be made of puddle clay at practicable cost.

The apparent effect of hydraulic sluicing upon most soils, the natural process of sorting out the finer particles, is to produce a clay of marked uniformity. Mr. Joseph Morgan, consulting engineer, Cambria Steel Works, Johnstown, Pa., in making a series of analyses of core material from various hydraulic-fill dams in widely separated sections of the country, noticed a curious similarity between them, and first called attention to it in correspondence with the author. The analyses were practically identical, except in the absence of sulphur, with those of average English blue clays, which show the following ratio of constituents:

Silica	63.35
Alumina and iron	18.50
Lime	6.60
Sulphur	4.32
Loss by ignition	7.23
	100.00

† *Engineering Record*, March 29, 1902.

It would seem from these analyses that the natural result of the process is the automatic segregation and deposition of puddle clay of a quality equal to the best puddle-core material used in English dam construction, at a small fraction of the cost. This being true no other core-wall can possibly be required. There have been no failures of earth dams on record within the knowledge of the author due to the lack of water-tightness of the puddle-core.

The hydraulic process, therefore, affords the means of segregating and assembling the puddle-cores from all classes of soils, and when intelligently employed will make a safe dam from the most unpromising materials.

Limiting Height of Hydraulic-fill Dams.—The highest earth dam in the world, the San Leandro dam, near Oakland, California, is but 125 feet from base to crest, and this was partially constructed as to exterior slopes by the hydraulic-sluicing process. It is without masonry core-wall. Until within the past few years engineers have been inclined to consider 100 feet as about the safe limit of earth dams. The author does not subscribe to this doctrine, but believes that nature has given too many examples of glacial lakes many hundreds of feet deep formed by dams of moraine deposits to discourage the engineer from building earth embankments by the improved hydraulic process of any height desired, limited only by practical considerations of cost and time required for construction, provided suitable conditions are presented. E. Sherman Gould, M. Am. Soc. C. E.,* touched the keynote to this question in the following: "It would seem that whatever water gets into an earth bank must be introduced by simple soakage, *the pressure exercising but a slight influence upon the penetration beyond a small depth.* If this view be correct, then it appears reasonable to suppose that the greater the mass of earth the less danger of its being saturated by the water, which, as the area increases approximately as the square of the height, would lead to the conclusion that as far as soakage is concerned the higher the dam the less liability is there of general saturation."

In its applicability to the design and construction of high hydraulic-fill dams the author indorses the following editorial expression of *Engineering Record* (vol. 46, p. 121): "With reasonable care in founding an earth embankment upon such solid and impervious foundation as rock or its equivalent for such a purpose, and with other features so designed as to shut off absolutely the flow of water underneath and with a practically impervious bank, which it is perfectly practicable

* *Engineering News*, February 20, 1902.

to attain, guarded with pavements on both the up-stream and down-stream sides if advisable, *there seems to be no basis as yet on which a limiting height of earth dam may be placed.* The design of these structures has been born of conditions under which they have been imperative, as the expense of solid masonry work would have been prohibitive. They have served sound engineering purpose, and they point the way to further economical development of high dam construction under circumstances where earth embankments, or even earth embankments combined with rock-fill and other accompanying features of design are justifiable by the canons of the best engineering practice." In the author's opinion there is no limit, except one of cost, to the height to which it is possible and safe to build hydraulic-fill dams, provided they be made of sufficient dimensions to fulfill the simple requirement that frictional resistance to the passage of water shall be practically insuperable, or if water in moderate amount does find its way through the mass, that it shall be robbed of all velocity and power to transport any of the particles of the embankment with it, issuing clear as water issues from a filter.

Drainage.—The stability of hydraulic-fill dams as well as that of, all earth dams, depends to a large extent upon the proper drainage of the down-stream portion of the embankment. Unless the lower third of the foundation consists of gravel, loose rock, or other porous material, through which water will percolate freely, artificial drains should be provided to lead the water draining from the center third to the outer toe. These drains should not approach nearer the center than the line between the middle and outer thirds of the base, and they should be so prepared as to act in the nature of a filter, grading from fine to coarse, in a way to avoid displacement of the core material during the process of drainage and consolidation.

A covered gathering well at the head of each drain, to concentrate seepage, and so arranged as to force the water to rise in the bottom against a certain slight head, boiling up, as in a spring, can be recommended as an efficient and satisfactory device. The well should be surrounded with fine gravel and sand, and when properly made will always be found effective in preventing percolating water from washing out channels through the dam.

Hydraulic Fills on the Canadian Pacific Railway.—Further examples of the successful employment of hydraulic mining principles to the work of building embankments are to be found on the Pacific coast, but none more instructive than the extensive hydraulic fills made by the Canadian Pacific Railway in British Columbia, where trestles of great height are being supplanted by earth and gravel embankments made by the agency of water alone. The methods employed differ materially from those described in the foregoing pages, but will doubtless find frequent application elsewhere in irrigation-dam construction.

At trestle No. 374, near North Bend, in Fraser River Canyon, 110 miles east of Vancouver, there was required to fill a chasm an embankment 231 feet in height, containing 148,000 cubic yards. When visited by the writer in November, 1896, the fill had reached a height of 167 feet and contained 70,000 cubic yards, all of which had been put in place by the hydraulic process. The plant used consisted of 1450 feet of double-riveted sheet-steel pipe, 15 inches in diameter, 1200 feet of sluice-boxes or flumes, about 3 feet wide and the same depth, one No. 3 double-jointed "Giant" monitor with 5-inch nozzle, and a large derrick fitted with a Pelton wheel connected with the winding-drum of the derrick and operated by diverting the jet of water, used in piping the bank, upon the wheel when loads were to be hoisted by the derrick. The gravel bank where the material was obtained was 1130 feet distant from the center of the track, and from this pit the pipe was laid to an adjacent stream, 1450 feet, in which length the fall available was 125 feet. The sluice-boxes were laid on a grade of 11% for the first 425 feet, increasing to 25% the rest of the way. They were chiefly supported on trestles. These boxes, constituting a continuous flume, were paved with wood blocks on the lighter part of the grade, and with pieces of old railway rails, laid close together lengthwise of the flume, where the grade was heaviest.

One of the most serious difficulties here encountered—and each locality develops its special problems—was the fact that about 50% of the materials in the gravel-pit was such as to be classed as cemented gravel; 20% consisted of bowlders, too large to pass through the flume and requiring to be hoisted out of the way and piled up by the derrick; while but 30% was loose gravel, of the character best adapted for the work. Notwithstanding these disadvantages the results accomplished are quite remarkable, as the entire cost of the work, including the plant, was but $5089, an average of 7.24 cents per cubic yard. The entire force employed consisted of eight men, disposed as follows: 1 piper at the monitor, 1 man at the head of the sluice-boxes and in the pit, 2 on the flume, "driving" the material along to prevent choking, 3 on the dump, distributing the material and making brush mattresses for the slopes, and 1 foreman, a carpenter, chiefly engaged on general repairs of flume and overseeing the work. The time occupied was as follows: sluicing, 95.3 days; removing bowlders from the pit, 50.4 days; repairing flume and plant, 13.5 days; total, 159.2 days of 10 hours of the entire force. The total number of yards moved, divided by the actual working-time when sluicing was in progress, gave an average of 738 cubic yards per day of 10 hours, or at the rate of 1771 cubic yards per 24 hours. The water used was approximately 11 cubic feet per second, or 550 miner's inches under 4-inch pressure (440 inches under 6-inch pressure), the duty performed being 3.22 yards per 24-hour inch under 4-inch pressure, or 4.02 cubic yards per inch under 6-inch pressure, which latter is the unit of measure most commonly used in the hydraulic mines.

Had the gravel-bank been free from large bowlders, the work could have been done in two-thirds of the time actually occupied, and had the pressure been greater and the gravel all loose instead of being partially cemented, requiring the use of explosives to loosen it, the duty of the water, on the high grades available for the flume, should have been increased more than threefold, as the ratio of solids carried was only about 5% of the volume of water used. An understanding of all these conditions suggests what might be accomplished by this method with a perfect combination of circumstances, viz., water under pressure of 400 to 500 feet head, loose materials in abundance for washing, freedom from rocks of large size, and heavy grades to the dump.

In building the embankment no provision was made for draining off the water down through the center, but it was allowed to pour over the slopes, which were protected from erosion by brush and tree-tops woven in alternating layers along the edges of the fill. Old track-ties and poles were also used with the brush. In addition to this protection it was necessary to exercise care to prevent the water from concentrating in channels or from reaching to the sides or flowing down the hill over the natural surface. By keeping the sides of the fill as nearly level as possible the water was spread in a thin sheet over the face-slopes and reached the bottom of the embankment without washing or doing injury. The slopes are remarkably true and uniform, and the embankment was packed very hard, particularly near the end of the sluice, where the gravel had dropped from a considerable height to the dump below.

The device employed for handling the bowlders in the pit by water-power was ingenious and effective, and was similar to those in common use in hydraulic mines, where water under pressure is turned at will upon a tangential water-wheel with peripheral buckets. This wheel, being attached to a winding-drum, the wire hoisting-rope leading from the derrick boom is rapidly wound up and the load handled at will. A friction-brake with long lever gave the operator perfect control of the load and enabled him to lower it as swiftly or as gently as desired. Sharp turns in the flume were made by vertical drops of 2 feet at the angle, and two turns of 90° each were thus successfully made.

Bowlders with one or two square feet of face would sometimes stop rolling, and if not quickly started would cause a jam and overflow, endangering the flume on the gravel hillside. Hence it was necessary to employ two "drivers" to patrol the portion of the flume where the grade was lightest, to keep all such stones in continuous motion. On the heavier grade, however, no such attention was necessary.

In the summer of 1894 the railway company made a similar fill of 66,000 cubic yards, at the crossing of a stream called Chapman Creek, the average cost of which was 7.5 cents per cubic yard, of which 3.2 cents was for plant. The actual work of sluicing was but 1.78 cents per cubic yard. In this case also, it was necessary to use explosives to loosen the gravel and prepare it for washing.

In 1897–98 the same company made a similar fill at the crossing of Mountain Creek, in the Selkirk Mountains, requiring 400,000 cubic yards. (See Fig. 141.) The total length was 10,086 feet over all, with extreme depth of 154 feet. The fill was carried up on a slope of 1½ to 1. Between Aug. 10 and Nov. 1, 1897, over 65,000 cubic yards were sluiced in place, at the following cost:

Mattresses	$1370.79
Sluicing labor	1195.96
Maintenance and repairs	678.90
Superintendence and tools	385.05
Total	$3630.70

This gives the average cost of the first 65,000 cubic yards at 5.59 cents per yard. Including a proportion of the plant, the average was less than 8 cents per cubic yard of embankment. The work was done in about 60 working days of 10 hours each, and the average was nearly 1100 cubic yards per day. The water was delivered to the nozzle of the monitor under a head of 160 feet, the diameter of nozzle being 5.5 inches. The volume was therefore 15.75 second-feet, or 787 miner's inches. The ratio of water to gravel was as 19 to 1 and the duty of the water was nearly 4.2 cubic yards per 24-hour inch under 6-inch pressure. The sluice-boxes had a grade of 8%. The water-supply was brought in a flume, 4 feet wide, 2 feet high, 2 miles long, built on a grade of 20 feet per mile. The entire plant, including roads, camp, stables, flume, pipe-line 1200 feet long, sluice-boxes 600 feet in length, etc., cost $10,038.40. Considerable expense was caused by snow and land-slides, which damaged the plant.

The trestles were filled beginning at the banks of the stream and working back each way. On the made bank thus formed masonry piers were constructed, and a steel bridge of five spans was built over the main stream between them.

The work has been planned and executed under direction of H. J. Cambie, Chief Engineer Pacific Division, Canadian Pacific Railway, and his Chief Assistant Engineer, Edmund Duchesnay, of Vancouver, B. C., by whose courtesy the data concerning the work have been supplied.

The class of work done on the Canadian Pacific Railway described in

the foregoing pages is identical with that which is required in dam-construction with similar materials, and the processes employed will be recognized by engineers as distinctly applicable in a treatise on the subject of hydraulic dam-building, the only difference being that in railway fills no attention is paid to such a distribution of materials as will secure the water-tightness of the bank and free drainage of percolating waters on its exterior surface.

Hydraulic Fills on the Northern Pacific Railway.—The cheap and effective transportation of earth, gravel, rock, and sand and their deposit in embankment by water at a cost far below all other feasible methods, is the main principle involved, and this principle has been given further demonstration on a large scale on the Northern Pacific Railway, in the State of Washington, during the years 1895–96–97. No less than fifteen high and dangerous trestles on the Cascade Mountain division have been replaced by hydraulic-made embankments of earth, gravel, and loose rock, washed from the adjacent mountainsides. The total amount of material thus moved aggregates 606,750 cubic yards, the average cost of which was 6.39 cents per cubic yard; or 5.82 cents for labor and 0.57 cents for materials. The lowest cost of any of the fills was 3.38 cents per cubic yard, everything included.

The average cost of 377,000 cubic yards was 4.79 cents per yard, of which the detailed cost per cubic yard was as follows, figures which may be of special interest to those contemplating similar undertakings:

Sluicing and building side levees	3.89 cents per yard.
Hay used in side levees	0.09 " " "
Tools	0.08 " " "
Lumber and nails	0.22 " " "
Labor building flumes	0.44 " " "
Engineering and superintendence	0.11 " " "
Total	4.79 " " "

This work was done in the midst of a dense forest, where the ground to be sluiced had to be cleared, and stumps and roots necessarily interfered with the loosening of the material. All of the 377,000 yards were carried and deposited by water brought to the pits by gravity. In one case, however, that of bridge 191, the water was supplied by pumping and 42,250 cubic yards were moved by water thus lifted at an average cost of 13.5 cents per cubic yard, the dêtail of which was as follows:

Sluicing and building levees	10.81 cents per yard.
Hay used in side levees	0.21 " " "
Tools	0.14 " " "
Lumber and nails	0.12 " " "
Labor building flumes	0.14 " " "
Coal used in pumping	1.87 " " "
Engineering and superintendence	0.20 " " "
Total	13.50 " " "