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UNITED STATES

DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

MEMORANDUM TO CHIEF DESIGNING ENGINEER

SUBJECT: MECHANICAL COMPOSITION OF EARTH DAM MATERIALS

HYDRAULIC LABORATORY REPORT NO. .1

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by

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Under direction of

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MEMORANDUM TO THE CHIEF DESIGNING ENGINEER
(E. W. Lane, Research Engineer)

Subject: Mechanical Composition of Earth Dam Materials.

The following data was compiled from available engineering literature, Bureau of Reclamation records and other sources, in order to investigate the possibilities of mechanical analysis as a means of determining the suitability of available materials for the construction of earth dams. The mechanical analyses of a large number of earth dam materials have been compiled, classified and assembled in graphical form, and tentative conclusions drawn as to the limits of the mechanical composition suitable for the construction of earth dams using various methods of construction.

The dams were divided into two classes; rolled fill and hydraulic, including semi-hydraulic, fill. Nearly all of the available mechanical analyses fall into one of three classes; (1) Material for rolled fill dams, usually the analyses of samples for borrow pits; (2) Borrow pit materials for hydraulic or semi-hydraulic fill dams, and (3) Core materials of hydraulic fill and semi-hydraulic fill dams.

Rolled Fill Dam Material

On Table 1 is given some of the data on the rolled fill dams, together with the source of information from which the mechanical analysis data was obtained. The mechanical analyses are plotted on Figure 1. This diagram shows that a wide range of materials have been used in earth dams, with apparent success. The data at hand does not indicate any lower limit to the grain size of material suitable for rolled fill dam construction. In fact, dams have been successfully built with large proportions of clay. If the term "clay" used in the description of these dams is the same as that used by the Bureau of Soils, (which is the classification used for the sizes "fine gravel" and below, as shown on the Figure 1) these dams are composed of very much finer material than anything shown on the diagram. Steps are now being taken to secure samples of material from existing successful dams said to have a high clay content. It is entirely possible, however, that the term "clay" as ordinarily used differs considerably from the standard used on the chart. For example, the three samples averaged to obtain the line (No. 2) on the chart, representing the composition of Table Rock Dam material, were all described as "clay," although the average analysis shows only about 7% of clay, as defined by the Bureau of Soils. Sufficient knowledge of the materials represented by the analysis curves is not at hand to determine whether or not the mechanical analyses will throw any light on some properties of the material which affect their suitability as rolled earth dam materials, such as the ease of compacting, the tendency to stick to the roller, and tendency of the material to slough when saturated. The mechanical analysis cannot therefore be taken as the only criterion of suitability of earth dam materials. It obviously cannot indicate the presence of soluble substances in the dam material.

The diagram does give a rough indication of the maximum size of the materials suitable for the imprevious portions of earth dams. Line No. 9 shows the composition of the downstream portion of the Lahontan Dam, which was composed of clean, well-graded gravel. The material comprising the upstream portion of the dam (Line No. 8) was composed of a 50:50 mixture of the gravel shown by line 9 and silt. Extensive tests were made of the seepage rates through the two classes of material and the 50:50 mixture permitted a flow of only 1/3000th as great as gravel. Since the Lahontan Dam has been in use about 14 years, and has not shown an undesirable amount of seepage, it may be concluded that the 50:50 mixture represented by line 8 is suitable for the imprevious sections of earth dams, and that shown by line 9, which allows 3,000 times as much water to pass through, would not be suitable. Experiments were also performed on the material of the Cold Springs Dam. Line 15 represents the material of the downstream portion of the dam, which was 100% gravel. This material permitted even more seepage than that shown by line 9, and would therefore represent too coarse a material. Line 14 shows material composed of 80% gravel and 20% fine surface soil, which permitted a flow of about 1/2200th as great as that of line 15. Line 13 is for a material composed of 75% gravel and 25% fine soil, which permitted a flow of about 1/5000th that of the gravel alone. These materials are believed to be about the limit of material suitable for the imprevious sections of rolled fill dams.

The line shown on Figure 1, labeled "Approximate limit of materials suitable for imprevious sections of rolled fill dams" is somewhat arbitrarily drawn, representing an effective size of 0.15 mm. and a uniformity coefficient of 40, the meanings of these terms being those used by Hazen; namely, (1) effective size; the diameter of grain compared with which 10% of material is smaller and 90% larger and (2) uniformity coefficient; the ratio of the size of grain compared with which 60% is smaller and 40% larger, to the effective size. This line represents materials finer than the gravels shown by lines Nos. 9 and 15, composing the downstream sections of the Lahontan and Cold Springs dams respectively, which were shown to be too porous. It shows coarser materials than line No. 8, the upstream section of Lahotan Dam, and about the same gradation as lines Nos. 13 and 14, which represent the top, center and downstream center sections of the

Cold Springs Dam, which are believed to represent about the upper limit of size of suitable materials, if a reasonably watertight dam is to be secured. For the porous material as frequently used in the downstream sections of dams to secure stability and drainage, there is no need of prescribing a limitation, for the material may be and frequently is, a rock fill including boulders of considerable size. The line given on Figure 1 does not represent a fixed limit beyond which a safe dam can not be built, but is believed to represent approximately the limits of material which can be used for dams of the cross sections oridinarily used to secure a dam without objectionable seepage.

Practically all dams seep more or less. The expense to which it is desirable to go to get an extremely watertight dam is a question of economics and depends largely on the value or cost of the stored water. Dams sometimes have quite large leakage through them, but as long as they show no tendency to slough, or there is no sediment or unusual quantity of soluble matter in the seepage water, no danger is involved. Ordinarily, however, one should aim at a practically watertight dam, as frequently the seepage is much more than expected. Considerable seepage is particularly likely to occur through the natural earth beneath or at the sides of the dam and the frequency of its occurrence indicates that more study should be given to its prevention than is commonly done.

Hydraulic Fill Borrow Pit Material

The analyses of borrow pit material for hydraulic fill dams is shown on Figure 2, and additional data and the sources of information regarding them is given on Table 2. The diagram shows that a wide range of material has been successfully used for hydraulic and semi-hydraulic fill dam construction. By hydraulic fill dams is meant those in which the earth is both transported to the dam and placed by the agency of water, while in semi-hydraulic fills the material is hauled by mechanical means and placed hydraulically. The data available is not sufficient to show that any difference exists in the requirements of material suitable for these two types of construction, and they have therefore been plotted on one diagram. Certain differences do exist, however. The maximum size of particle which can be handled by the hydraulic method, where the material passes through pumps, is limited by the size of the pump openings. On the Miami Conservancy Project, stones over 6½" diameter were screened out. Larger material is frequently used in semi-hydraulic fills. If there is a deficiency of fine material, it seems probable that a greater proportion of the fines coming from the borrow pit could be placed in the core by the hydraulic method than can be washed out of the material after it is dumped on the dam from cars in the semi-hydraulic process, since in the hydraulic process after the material passes through the flumes or pipes the fines are in suspension and do not deposit readily except in the core pool.

On the other hand, if there is an excess of fines, using the semi-hydraulic process, part of the fine material could be allowed to remain mixed with the coarser material in the outer section of the dam.

From the data available it is not possible to set a lower limit for the size of borrow pit material suitable for a hydraulic or semi-hydraulic fill dam. No analyses of borrow pit material are available for the dams which have failed during construction, and so far as known, no dam built by the hydraulic process has proved to be unsatisfactory after construction was completed.

In the case of the Swinging Bridge and Henshaw dams (Nos. 2 and 1) those in charge of construction believed the borrow pits to contain too much fine material, and some was wasted. At the Taylorsville Dam (not shown on Figure 2) 60% of the material was retained on a 100-mesh sieve, and considerable of the finer material was wasted. On the other hand, at the Somerset Dam, the borrow pit material of which was much finer than any of those just named, an effort was made to retain all of the fines, alum being used to settle out the very fine particles. The experience with this dam* indicates that a dam using very fine material can be built and maintained. It is not known whether or not fine material from the Saluda core is being wasted.

*Engineering News-Record, Vol 103, November 14, 1929, p. 769.

The fineness of the material allowable is influenced somewhat by the rate which it is expected to build the dam, the decision to waste fine material in the case of the Henshaw Dam being influenced by the fact that it was expected to build the dam very rapidly. To indicate roughly the maximum size of material which will make a tight dam, a line has been drawn on Figure 2, labeled "Approximate upper limit of size for tight dam." This line is somewhat arbitrarily drawn, having an effective size of 0.12 mm. and a uniformity coefficient of 60. This places it finer than the Conconnuly Dam, which permits considerable seepage, although not enough to in any way endanger the structure. This dam was built in 1910, when the construction of hydraulic fill dams was not as well understood as now. The fine material was only sufficient to form a core which is thin as compared with dams more recently constructed. The Tieton Dam contains a concrete core wall, and the fact that it is practically watertight does not prove that the puddle core itself is sufficient. The Dwinnell Dam (No. 3) was also constructed of coarse material. Before construction, it was expected that the volume of fine material would be insufficient, but this was not found to be the case. It is probable, therefore, that the material of this dam represents about the upper limit of suitable material for a hydraulic fill dam. The analysis shown by line No. 3 does not include the large stones and boulder, and if these were included the proportion of these larger particles, judging from a photograph of a dam, would be sufficient to cause the line to fall fairly close to the limit set. It is probable that with more uniform material; i. e., a lower uniformity coefficient, a somewhat larger effective size would be allowable than shown by the limiting line on Figure 2, since this condition would give a greater proportion of fine material, and therefore a greater thickness of core. However, the data at hand is not sufficient to establish this hypothesis. As remarked in the discussion of rolled fill dams, this line should not be regarded as a definite limit, but as an approximate relation applying to dams of ordinary cross section.

Hydraulic Fill Core Material

Considerable data was secured on the composition of the core material of hydraulic fill and semi-hydraulic fill dams. On Figure 3 the analyses are shown graphically. The materials of successful dams vary over a wide range, the finest showing 50% coarser than 0.024 mm. and the coarsest 50% larger than 0.35, or a ratio of size of 1:14.6. The material forming the core of the Calavaras Dam (No. 16), which sloughed during construction due to the failure of the central core to consolidate with sufficient rapidity, is shown to be much finer than any of the others. The Calavaras Dam was built prior to the construction of most of the other dams shown, and its failure, together with that of the Nexcaxa Dam, caused the constructors of a number of dams to waste some of the fine material from their cores. This is particularly true of the Taylorsville Dam (No. 9), which, next to the Calavaras, had the finest core, even with much of the very fine material removed. Fines were also intentionally wasted at the Swinging Bridge Dam (No. 14) and the Hanshaw Dam (No. 12). In the latter case the core material is quite coarse, but this was believed to be necessary to secure consolidation of the core at a sufficient rate to permit a rapid construction of the dam. As previously stated, however, all fine material possible was retained at the Somersed Dam (No. 20) with apparently no bad effects.

It is not possible to determine with exactness the lower limit of size for safe core material. The line on Figure 3 labeled "Probable Limit of Safe Core Material," is somewhat arbitrarily placed roughly parallel to and indicating particles slightly smaller than those of the Taylorsville Dam core (No. 9). Although a dam might safely be built with finer core material than indicated by the line, especially if the rate of progress was slow, for ordinary progress rates, material finer than the limit indicated would hardly be conservative practice unless tests of the rate of consolidation were especially favorable.

No data is available to show the upper limit of core material sizes from the standpoint of safety of the dam, but as the material reaches a certain size seepage through the dam, if built with the customary cross section, begins to assume undesirable proportions. The Soft Maple Dam (No. 17) was built of nearly pure sand, and showed considerable leakage. As the water passing through is perfectly clear no concern is felt for the safety of the dam. The line labeled, "Possible limits of satisfactory core material" is drawn passing through the point representing 65% passing a 100-mesh sieve, and below the lines for the Bridgewater Dam (No. 4), the Henshaw Dam (No. 12), and the Dwinnell Dam (No. 5), all of which have satisfactory cores. Information is not available on the results at the Sherman Dam (No. 18). According to Mr. Albert S. Crane, who has had extensive experience with hydraulic fill dams with cores ranging in fineness from that at the Saluda Dam (No. 1) to the Soft Maple Dam (No. 17), "Almost any material, 65% of which passes a 100-mesh sieve, makes a satisfactory core." It is, therefore, believed that in at least some cases cores coarser than this have been found to be unsatisfactory, and the line is drawn through this point, although the results at the Sherman Dam (No. 18) may have been satisfactory. Mr. Crane also states that of the dams with which he has been connected, the composition of the Bridgewater Dam (No. 4) is the best.

In this discussion no consideration has been given to the effect of colloids on the various materials. This is largely due to the fact that no data on the proportion of colloids present in any of the dam materials is given. Since colloids have particle sizes below limits variously assigned between 0.003 and 0.00[illegible] mm., in most of the materials considered they were not present in large quantities. The subject of colloids and their effect on permeability is indefinite and much further knowledge of their properties is desirable. It is hoped that further investigations along the line of colloids will be made, especially with reference to dam material, which will throw more light on their effect.

TABLE 1

Data on Rolled Fill Dams

Dam	Location	Condition	References	Remarks
Point of Rocks	Colorado	Not known	Eng. Rec., Vol. 64, July 15, 1911, p. 72.	
Table Rock	South Carolina	In use	Eng. News-Rec., Vol. 101, July 26, 1928, p. 147	Partial failure, not due to character of earth used, which was very satisfactory.
Schofield or Pleasant Valley	Utah	In use	Description in Eng. News-Rec., Vol. 100, pp. 827, 864 & 872, also Vol. 101, p. 915. Analysis from Reclamation Bureau records	Partial failure, not due to quality of earth fill.
Red Butte Canyon	Utah	Under construction	Data from Reclamation Bureau records	
Cle Elum	Washington	Construction authorized	...ditto...	
Hyrum	Utah	Proposed	"	
Echo	Utah	Under construction	"	
Lahontan	Nevada	In use since 1915	"	
Rock Canyon	Colorado	Constructed, 1925	Data from Colorado State Engineer	Flood control, no water stored yet.
Cold Springs	Oregon	In use since 1908	Eng. News, Vol. 57, Mar. 7, 1907, p. 250, Trans. Am. Soc. C.E., Vol. 74, 1911, p. 43.	

TABLE 2

Data on Hydraulic and Semi-Hydraulic Fill Dams.

Dam	Location	Type	Condition	References	Remarks
Henshaw	California	Hydraulic	Built in 1923	Eng. News-Rec., V. 91, Aug. 30, 1923, p. 342.	
Swinging Bridge	New York	"	Recently constructed	Proc., Boston Soc. C.E., May 1929.	
Dwinnell	California	"	...ditto...	Western Cons.News, V.4, Feb.25, 1929, p. 96	
Davis Bridge	Vermont	Semi-Hydraulic	In service since 1924	Water Works, Mar.1925, p.505; Eng. News-Rec., V.103, Nov.14, 1929, p.770.	
Somerset	Vermont	" "	In service since 1913	Eng. News, Vol.71, June 4, 1914, p. 1236; Eng.News-Rec., V.103, Nov. 14, 1929, p.770	
Conconnuly	Washington	Hydraulic	In service since 1910	Trans.Am.Soc.C.E., V.74, p.64 & 72; Eng. Rec., Vol.59, 4/3/09, p.370.	
Paddy Creek	North Carolina	Semi-Hydraulic		Trans.Am.Soc.C.E., Vol.83, 1919-20, p.1181.	
Linville	North Carolina	" "		Trans.Am.Soc.C.E., Vol.84, 1921, p.345; Hydro-Elec.Handbook, Creager and Justin, p.249.	
Tieton	Washington	" "	In service since 1925	Eng. News-Rec., V.97, Sept. 30, 1926, p.544; also Bureau of Reclamation records.	
Saluda	South Carolina	" "	Under construction	Data from Mr. Albert S. Crane.	
Magic	Idaho		Built in 1909	Hydro-Elec.Handbook, Creager and Justin, p.249.	
Germantown	Ohio	Hydraulic	Completed about 1921	Trans.Am.Soc., C.E., V.85, 1922, p.1181.	Flood control reservoirs
Englewood	Ohio	"	...ditto...	...ditto...	...ditto...
Lockington	Ohio	"	... " ...	... " ...	"

TABLE 2 (Continued)

Dam	Location	Type	Condition	References	Remarks
Taylorsville	Ohio	Hydraulic	Completed about 1921	Trans. Am. Soc., C.E., V.85, 1922, p.1181.	Flood control reservoirs
Huffman	"	"	...ditto...	...ditto...	...ditto...
Alouette	British Columbia	Semi- "	Completed about 1926	Eng. News-Rec., V.96, Apr. 29, 1926, p.696	
Calavaras	California	Hydraulic		Hydro-electric Handbook, Creager and Justin, p.249.	
Soft Maple	New York	"	Completed about 1925	Eng. News-Rec., V.94. Jan. 29, 1925, p.180 Data from Creager & Crane.	
Sherman	Massachusetts	Semi- "	In service since 1927	Eng. News-Rec., V.98, April 28, 1927, p.681 Data from Mr. Albert S. Crane	
Terrace	Colorado	Hyd. Fill		Eng. Rec., Vol.64, J Eng. Rec., Vol. 64, July 15, 1911, p.72.	
Bee Tree	North Carolina	Semi-Hydr.		Data from Mr. Albert S. Crane.	
Blue Ridge	Tennessee	" "	Under construction	Data from Mr. Albert S. Crane.	

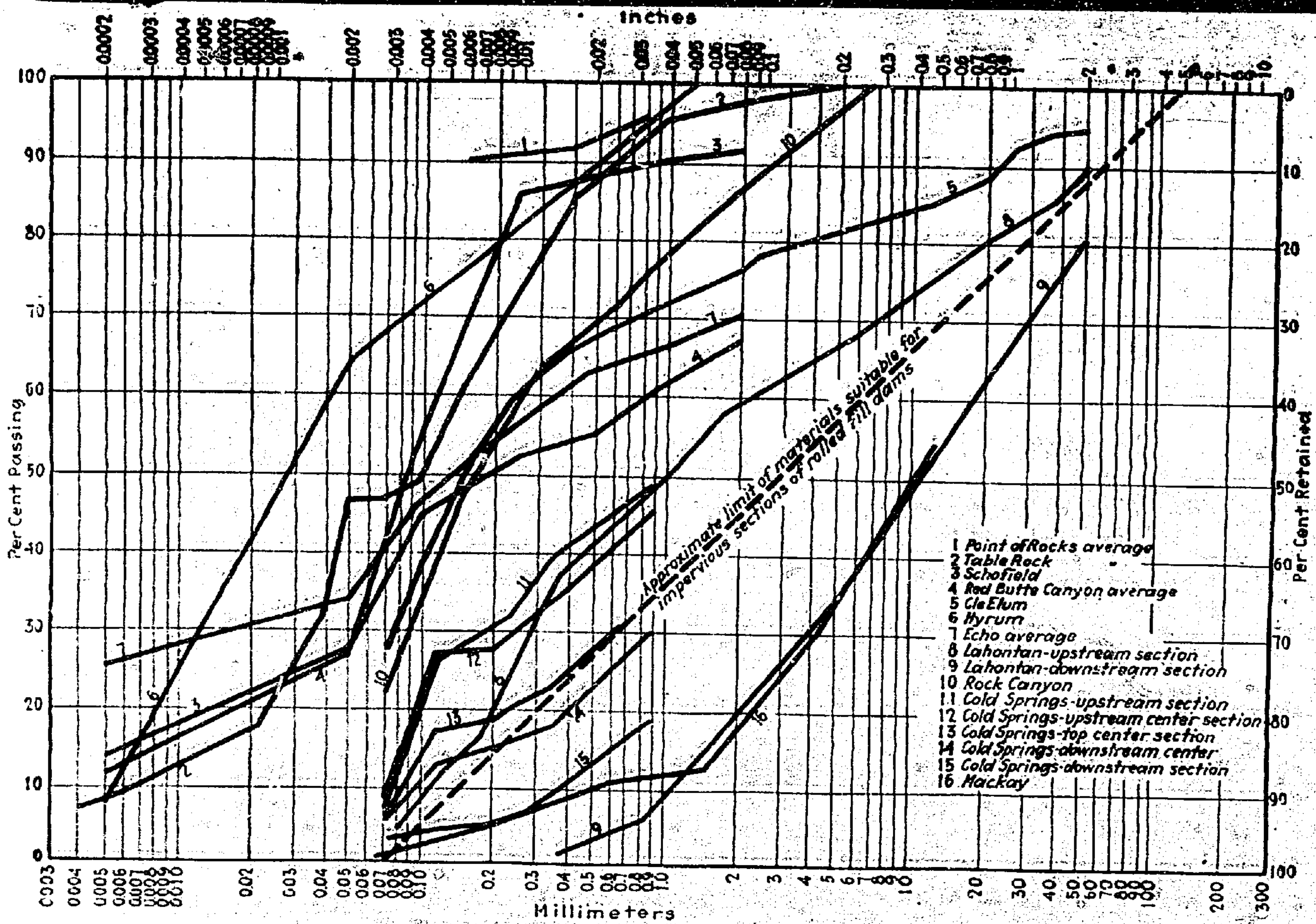
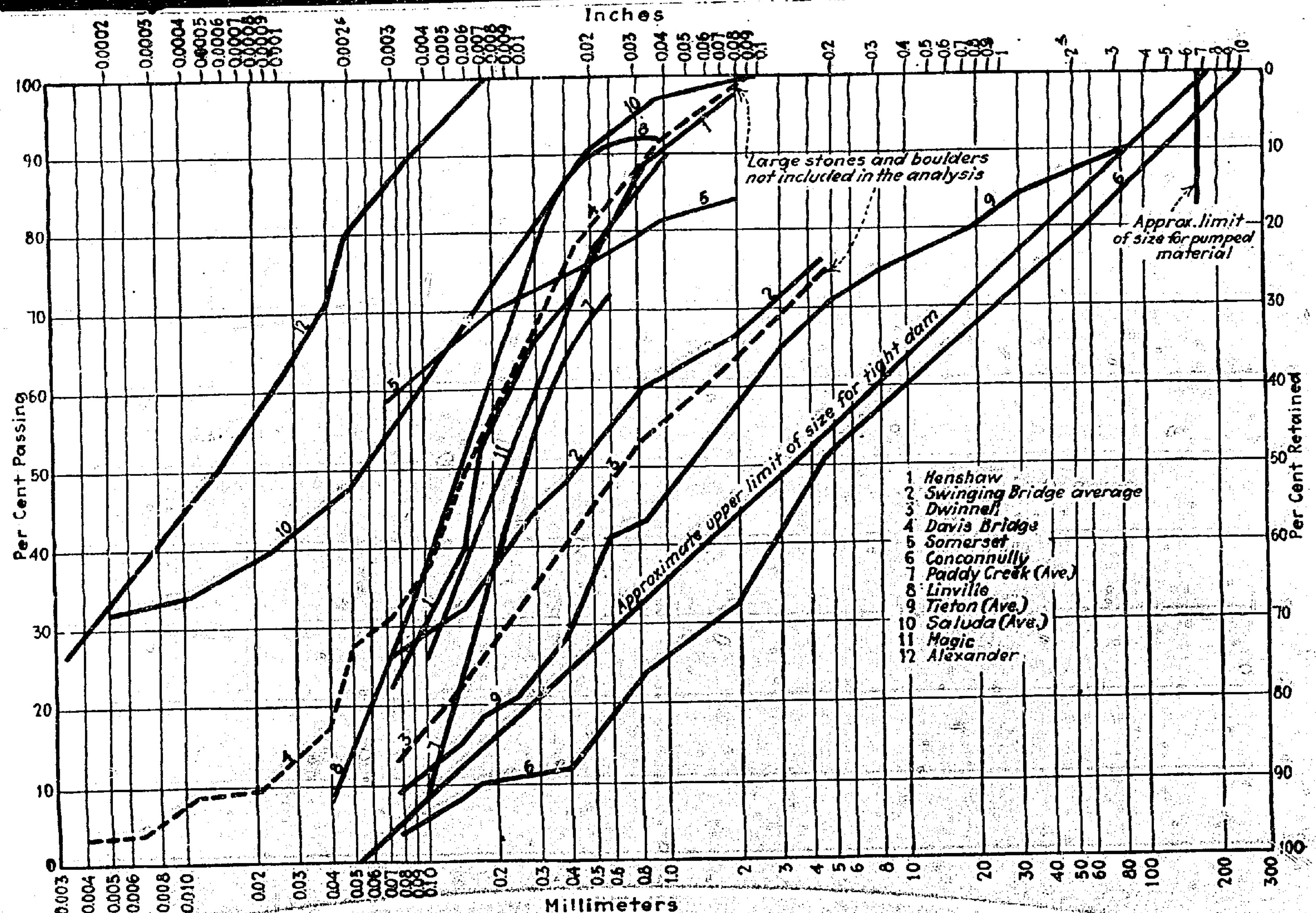


FIG. 1—MATERIALS OF ROLLED-FILL DAMS
Upper size limit suggested is somewhat coarser than the upstream material of the Lahontan Dam.



Upper size limit is between the material used in the Tieton Dam and that of the Conconnully Dam.

FIG. 2—BORROWPIT MATERIALS OF HYDRAULIC-FILL DAMS

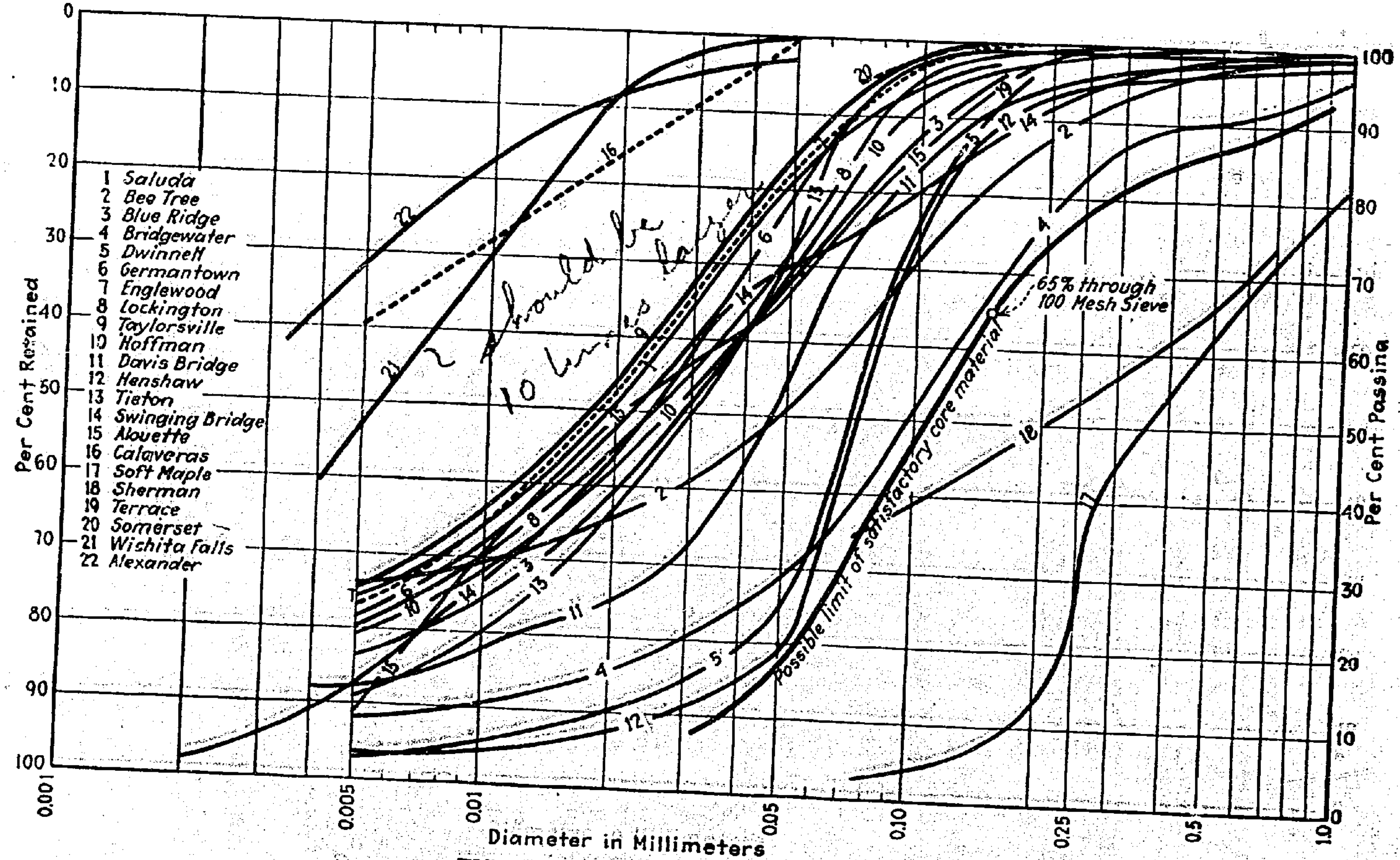


FIG. 3—ANALYSES OF CORE MATERIALS
Upper size limit is close to that of material of Bridgewater Dam.