THE PRACTICE OF SOILS CONTROL ON HIGHWAY AND DAM CONSTRUCTION, U. S. FOREST SERVICE

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SYNOPSIS

The U S. Forest Service, Department of Agriculture, cooperates closely with Federal, college and commercial laboratories as well as with its own regional facilities, to obtain data on soils proposed as earth fill in structures requiring characteristics favorable to imperviousness and compaction. Rolled earth fill dams and more important roads fall in this class of construction.

Soils control—from its choice through its compaction in place—is practiced on as economical and simplified basis as is possible in the Service because of limited funds and the relative inexperience—prior to training on the site—of men in the Civilian Conservation Corps which constitutes the major construction organization. The field laboratory equipment is maintained at a minimum consistent with adequate control through the use of the Proctor Method of soils compaction and its key controls of "Maximum Dry Density, Optimum Moisture Content, and Penetration Resistance"

The U. S. Forest Service has practiced and practices soils control in the construction of its more important roads. In doing so, full realization is had of the infancy of the science of soil mechanics which embraces not only the character of soils but also their selection and behavior for engineering purposes prior to, during, and long after their placing and compaction.

Many of the Forest Service roads lead to recreational areas which owe their popularity to lakes. These lakes are, more often than not, the creations of man-made dams. And like the roads, these dams are often constructed of earth—carefully selected, tested earth—rigidly controlled in its placing and compaction during construction.

There is identity of purpose in the consideration and use of soils in roads and dams. Mechanical properties of strength and stability are sought, together with maximum densities of soils in place. Both types of structures must survive the impacts of forces great in magnitude and quite similar in character. Roads have their concentrated, superimposed pressures and live loads, their problems of mud and dust. Dams have their more uniformly distributed live loads of superimposed water, wave impact, and alternate submergence and exposure to atmospheric conditions. Complete stability and safety of the structure must be maintained in both cases. These identities of purpose and similarities in principles permit and justify the interchange of research data. Accordingly, while this paper concerns itself with the choice and control of soils in rolled earth fill dams within the Eastern Region of the Forest Service, it is equally applicable to its problems of road construction.

Since its inception, the Civilian Conservation Corps has been the principal construction organization of the Forest Service This labor source, inexperienced in general, has not created any unreasonable man-day limitations However, funds for the purchase of construction materials have been limited. Accordingly, it has been found desirable to choose that type of dam for which the designs can be standardized more effectively, which lends itself to greater facility of supervision by the few experienced construction men available in the CCC organization undertaking the construction of the project, and which will result in the greatest recreational and multiple-use returns for the minimum costs for construction materials.

The quest for a more easily standardized design has resulted, most often, in the choice of a rolled fill earth dam unless the physical characteristics of the dam site and the availability and abundance of masonry, concrete aggregates, and timber (logs) have been so advantageous as to recommend other types

The Proctor method (1)[1] of testing soils makes possible the standardization, within the many construction organizations, of the field testing and of the compaction of earth fill material. An engineer on the project, while inexperienced at first, can become well adapted to the work through proper initial training and through faithful application of principles during construction. He, in turn, can delegate certain minor test responsibilities to able enrollees.

Maximum stability of soils in dams is the result of proper selection, grading, and placing of the individual materials into a correctly designed section. Soil studies have resulted in the general conclusion that absolutely impervious dams are not attainable.

An entire section of uniform fill will cause the line of saturation through the dam to intersect the downstream slope of the fill above the natural ground line, that is, above the toe of the dam While the rate of percolation through this uniform section may be so small for highly impervious materials that the amount of percolating water would be negligible, a less impervious fill material would permit higher velocities that might cause "piping." "Piping" is the movement and displacement by jet action of small particles of material, within a dam or foundation section, caused by an excessive velocity of the percolating water. This is not an immediate action and becomes dangerous to the safety of structure only after the rate of flow has increased above a safe maximum.

The velocity required to move, by jet action, particles of silt (0 01 m.m.) is 1.94 ft per minute and particles of fine gravel (1.0 m.m.) is 19.4 ft. per minute. As a section consisting of graded materials can conceivably have such variations in permissible jet velocities it is desirable for the design to recognize the presence of the finer materials and the lower permissible velocities. Thus, with a factor of safety of 4, the permissible maximum "jet" velocity would be 0.5 ft. per minute in order to prevent the washing out of the silt. As actually all dam sections contain clay materials that are finer than silt, design practice would tend to limit the maximum permissible velocity to 0 25 ft. per minute. Laboratory tests of samples of clay to be used on dam construction indicate actual percolation velocities much smaller than the 0.25 ft. per minute.

That there is real danger in the phenomenon of piping is evidenced by the failure of Horse Creek Dam, about 30 miles from Denver, Colorado, from that cause on January 28, 1914 (2). It is of importance to note that failure of this approximately 55 ft. high dam was caused by piping within the fill section rather than within the foundation. There are many other instances of piping in either the fill sections themselves or in the foundation materials (2)

Sloughing in road and earth dam embankments is the result of piping, excess saturation of embankment materials, and of the creation of a contact plane having a low coefficient of friction.

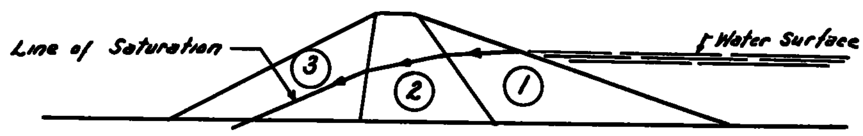
Piping can be minimized or eliminated by a careful choice of earth fill materials, through cut-off provisions in the foundations, and by the use of a correctly designed base thickness of such upstream-downstream magnitude that the velocity of flow through the foundation and fill materials will be reduced to a low rate and

[1] Numbers in parentheses refer to list of references at end

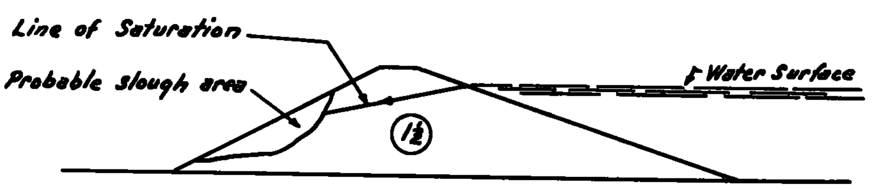
the finest particles will therefore not be dislodged.

As in road construction, clay in a dam acts as a "weak cement," binding together other desirable types of particles. Also as in roads, there is a maximum desirable limit for the clay contents in dams In the case of roads, the quantity of highly colloidal or sticky clay is kept at or below 15 percent. Less colloidal clay contents run up as high as 28 percent. For the purpose of this paper, a "highly colloidal" clay is one having more than 60 percent of its particles colloidal. In a "less colloidal" clay this proportion approaches 40 percent. In dams, the acceptable upper limit for clay contents has been found to be about 35 percent. The clay tends to maintain a high line of saturation which may cause sloughing and eventual failure of structure.

These known facts and the knowledge that total imperviousness is not possible have brought about cross-sectional designs which lower the line of saturation. The Forest Service generally prefers a cross-section having what might be called "progressive perviousness," in which the upstream third, or half, is of most impervious material; the center area of semi-pervious fill; and the remaining, or most downstream sectional area, of relatively pervious material having weight as its important characteristic. This section provides greatest obstruction to internal flow where that obstruction is logical. The small flow penetrating through the most impervious fill will then flow through the more pervious sec-



TYPE A



TYPE B

Figure 1. Fill Sections

1. Most impervious fill material.
1½. Quite impervious fill material.
2. Semi-impervious fill material.
3. Least impervious fill material.

tions, with a consequent drop in the slope of the line of saturation because there is a higher coefficient of permeability, a higher velocity of flow, and therefore smaller area. The line of saturation will intersect the base of the dam rather than the downstream slope, provided of course, that a sufficient upstream-downstream width of base is made available through correct design Figure 1, "Fill Sections," Type A, shows this type of section and the manner in which the line of saturation is lowered progressively in a dam. Type B represents relatively impervious fill in the section. In this type, sloughing is almost certain to occur eventually.

Just what types of soils are desirable; in what combination; and are these combinations obtained? These questions are in order. The desirable types of soils enter the picture as combinations rather than as individuals. When used alone, fine gravels; coarse, medium, fine and very fine sands; silt; and clays are not suitable for the construction of a rolled-earth dam The reason for this is the absence of one or more of the required qualifications of weight, stability, or water - tightness. Gravel provides weight; sand is porous but lacks stability; loam, containing a high percentage of organic matter, is relatively impervious but lacks stability and weight; silt and clay are quite impervious but also lack weight and stability and tend to swell and slump when saturated.

There may be some disagreement in the definition of "loam" and its interpretation with respect to road work and to dams. The Bureau of Chemistry and soils classification, commonly used in road work, does not stress the high organic content of loam. There are a sufficient number of authorities, however, who agree to its high organic content. Hanna and Kennedy (3) state that "Loam or earth, containing a high percentage of organic matter . . . ." Messrs. James F. Kemp and Frederick K. Morris (4) state: "Loam is a sandy or clayey soil mixed with humus" and "Humus is the carbonaceous matter produced by decaying organisms."

The Special Committee, Materials for Road Construction, Am. Soc. C. E. has proposed the following definition (5) "Loam: Finely divided earthy material containing a considerable proportion of organic matter."

It should be kept in mind that definitions for soils, as adopted by agronomists, geologists, and ceramists, can be in variance with engineers' definitions when applied to engineering problems (6).

The desirable combination is one so proportioned that the pore space in the coarser sand is filled with finer grains of sand, silt, and clay; and the pore space in the gravel is filled with this new combination. It is possible to approximate closely this desirable combination; and according to Hanna & Kennedy (3), it is feasible to reduce the pore space to less than 15 percent of the total volume; and to secure a combination more stable and heavier than gravel and nearly as impervious as clay. It might be stated here that the Forest Service has found it necessary to resort to mixing only in a few cases. Tests of samples from available borrow pit sites have generally located a soil which has had the desirable qualifications.

The question on the desirable combination can best be answered by citing actual test results for two different soils. For the purpose of this paper, these two soils will be identified as "A" and "B" respectively.

	Soils	
	"A"	"B"
	%	%
Particles larger than 2 0 mm	7	
Sand (2 0 to 0 25 mm)	13	83
Sand (0 25 to 0 05 mm.)	28	4
Silt (0 05 to 0 005 mm)	32	4
Clay (smaller than 0 005 mm.)	20	9

For these soils, the following characteristics were obtained:

	Soils	
	"A"	"B"
Liquid limit	40	29
Plasticity index	12	5
Optimum moisture content	17 3%	11 7%
Penetration resistance at optimum moisture content	1100 lb. per sq. in.	Erratic
Permeability	0 0004 ft. per day	15 ft. per day

Soil "B" had been used quite successfully in road construction but the high percolation rate eliminated all consideration of it except for the downstream third or quarter section. Soil "A" on the other hand, by test and by use, proved to be excellent material for the upstream half or third of the structure.

These two samples of opposite characteristics illustrate the value of proper combinations and of laboratory tests of soils for rolled-earth dams. As has been stated hereinbefore, experience has shown that soils with greater than about 35 percent clay content are difficult to work and therefore undesirable.

The question may arise as to what practical use has been made of test results such as these. Every attempt has been made in the Forest Service to synchronize the field work with these laboratory results while encouraging, at the same time, the field organization's interest in, and appreciation of results. Simplicity has therefore been the objective in order to maintain field interest. It has been found that the use of the Rate of Percolation (Coefficient of Permeability), and the Plasticity Index brings about an acceptable choice of soils for dams.

It might be well here to review definitions of soil characteristics which play a major part in the choice and construction of fill material for either highways or dams:

"Liquid Limit" of a soil is the minimum moisture content at which 10 light shocks will close a tooled groove in a sample under standard test conditions.

"Plastic Limit" is the minimum moisture content that will enable a soil to be rolled in threads of ⅛ in. diameter on a glass plate without crumbling.

"Plasticity Index" is the difference between the Liquid Limit and Plastic Limit of a soil and denotes its "workability range."

"Moisture Content" is the percent of moisture in the soil expressed in terms of the dry weight of the soil particles.

"Coefficient of Permeability" is the rate of flow of water at a known temperature, usually between 60 and 68°F, through a soil sample when the soil is compacted at the optimum moisture content and under a known load.

The information available in the laboratory reports is plotted for the purpose of graphical representation of the test results as well as to facilitate field control. These curves are: first, density of wet soil (lb. per cu. ft.) versus moisture content in percent; second, density of dry soil versus moisture content; and third, bearing value by Proctor needle in lb. per sq in. versus moisture content. It is seen that moisture content is the abscissa in all cases. Hence it is of great importance in the control.

Figure 2, "Soil Control Curves," records the following curves of a typical soil.

1. Weight of wet soil (lb. per cu ft.) vs. moisture content (percent)
2. Weight of dry soil (lb. per cu. ft.) vs. moisture content (percent)
3. Bearing value (lb per sq. in.) vs. moisture content (percent)

The Plasticity Index of 10 in Figure 2 indicates a workability range of 10% and a soil classified as "medium plastic."

Construction specifications would not permit the use of this entire range of 10% and would specify a comparatively narrow workability range close to the Optimum Moisture Content.

The optimum moisture content is attained gradually as shown by the weight of dry soil curve of which moisture content is a function.

By virtue of a desirable and gradual approach to the optimum moisture con-

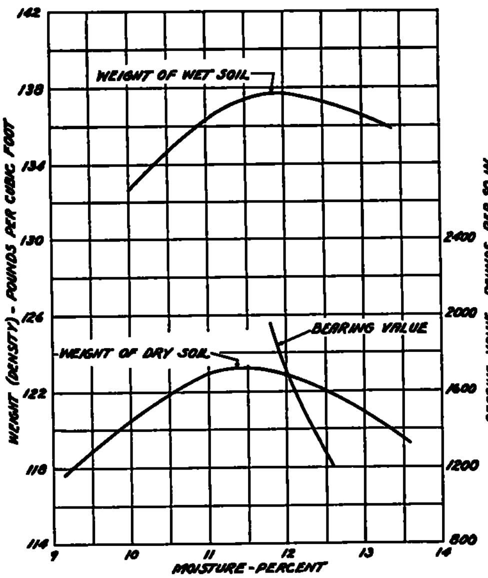


Figure 2. Soil Control Curves

Plastic limit = 18; plasticity index = 10.

$$\textbf{Dry density} = \frac{\textbf{Wet density}}{(100\% + \%\ \textbf{moisture})}$$

tent, it is possible to obtain a permissible range of bearing values through reasonable care and supervision in the field.

In addition to the information similar to that shown in Figure 2 and which is plotted from soil tests of all samples, the Forest Service has used and uses, in conjunction with these curves, valuable data available in Public Roads Administration's subgrade classifications, mechanical analysis curves, and in the Lee band (7) method of establishing the limits for ungraded materials suitable for impervious sections for rolled fill dams.

In the field, a laboratory is set up for the testing equipment and work. Samples of soils are taken from the actual "in-place" rolled-earth at least once each day. These samples are dried and weighed in order to check on the compacted soil's agreement with the curve data. The moisture content of the fill is controlled by sprinkling the material or by further spreading and harrowing to permit evaporation of any excess moisture. Layers up to 8 in. thick, before rolling, are used.

The field laboratory density tests supplement and verify the results of the Proctor needle with which tests are made frequently during the placing and rolling of the fill The standard for the penetration—for which the field strives—is that shown on the curve as the penetration resistance at optimum moisture content, which latter is synonymous to maximum dry density. It is herewith stressed that the use of the Proctor needle alone is not considered sufficient as the only test. It is, however, the most practical and the quickest way to obtain field checks

The steepness of the "Bearing Value" curve of Figure 2 shows that an appreciable variation in that value can occur before there is material variation from the maximum dry density and optimum moisture content. Accordingly, if the actual field tolerance of the bearing value —as determined by the Proctor needle— is restricted to a reasonable plus or minus variation from the value corresponding to the optimum moisture content, a very close adherence to the maximum dry density and optimum moisture contents will result. This is true in principle unless the slope of the "Bearing Value" curve is less than that of the "Weight of dry soil-moisture content" curve within the pertinent section.

While the average size of a Forest

Service dam project in general precludes the setting up of an expensive field testing laboratory, such expenditures would be found desirable were it not for the close cooperation between field organizations and regional, federal, college, and commercial laboratories. These excellent facilities have been, and are available for the most detailed primary tests which provide data for curves and tabulations for construction organizations and which, in turn, control the moisture and density factors during construction.

The amount of field testing equipment is maintained at an economical minimum consistent with adequate field control.

The desirable minimum equipment is as follows.

Penetration needles, $\frac{1}{10}$ sq. in and $\frac{1}{20}$ sq in. areas (with replacements.)

$\frac{1}{30}$ cu ft cylinder (4 in. diameter, $4\frac{1}{2}$ in. deep) with detachable base plate

$5\frac{1}{2}$ lb. rammer, face 2 in. in diameter (area 3 sq. in)

Scales: $\frac{1}{2}$ oz. to 30 lb. limits.

Balance: $\frac{1}{10}$ g to 100 g. limits.

Evaporation dishes or pans.

Tyler sieves

Stove for drying samples.

The heavy construction equipment is typical of earth moving projects. Sheeps foot rollers are used singly, in tandem, or abreast.

Forest Service experience has proven that the selection and control of soils for rolled fill dams are definitely justified.

Great benefit is derived from the field organization's interest in the soils work. This interest has encouraged the adoption and continued use of methodical construction. Carelessness has been reduced to a minimum. The morale of the construction personnel is high because they see what they are doing, why it is being done, and because they know that they have striven, not in vain, for highly commendable results. They know and take pride in their knowledge that the selection and control of soils for rolled earth fill dams is of the greatest importance in their building of a worthy monument through work well done.

To date the majority of dams in the Forest Service have not exceeded 35 ft. in height—from streambed to top of fill —and 700 ft. or more in total length. It has been found that recreational facilities, public demand and the cost of materials and of construction are satisfactorily met with in dams not exceeding these dimensions.

It is true, however, that the use of correct principles in design and construction are as important for smaller dams as they are in larger structures. There are as many, and often more problems to be solved in the design and construction of the smaller projects because permissible maximum costs, more often than not, dictate both design economy and construction methods.

Figure 3 shows a completed rolled earth fill dam in the Moshannon State Forest, Clearfield County, Pennsylvania.

Much time and effort have been expended by the Forest Service in the construction of rolled earth fill dams. A considerable number of lakes from 3 to 75 acres or more in surface area are now serving as recreational areas. As an intrinsic proof of the recreational value of such lakes, figures show that numerous recreational areas have each provided enjoyment to between 50,000 to 100,000 persons during a comparatively short season of three months.

A very great number of the Forest Service lakes have been possible only because dams can be built of earth. But earth alone is not sufficient. There must also be selection and control; and patience with and sincerity in these principles. Only then will there be unity and completeness.

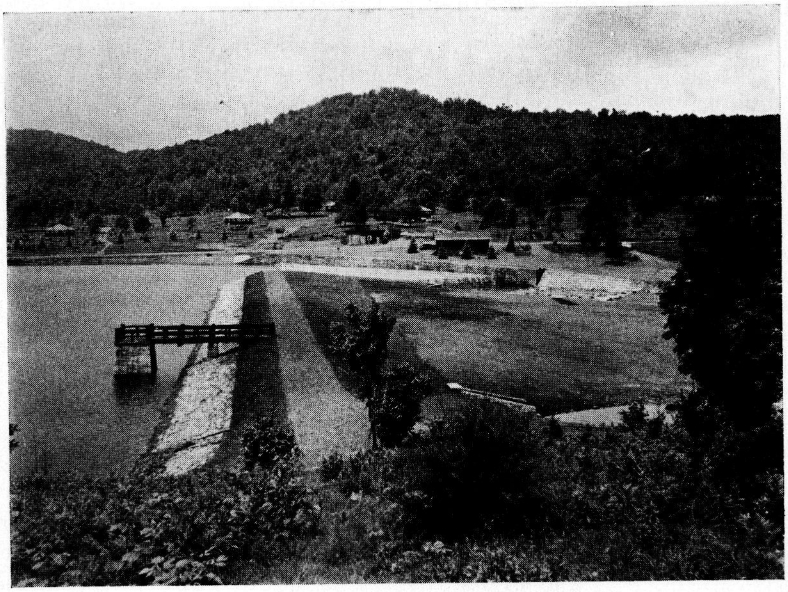


Figure 3. Parker Dam

Location: Moshannon State Forest, Clearfield County, Pennsylvania.
Type: Rolled Earth fill.
Size: 20 ft. by 660 ft. (at top of fill).

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(3) Hanna & Kennedy, "Design of Dams" First Edition, page 345.
(4) American Highway Engineers' Handbook—Arthur H. Blanchard, Editor-in-Chief, page 105.
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(6) "Low Dams" National Resource Committee, page 237.
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DISCUSSION ON SOILS CONTROL ON HIGHWAYS AND DAMS

Mr. M. B. Arthur, *United States Forest Service:* This paper has very appropriately pointed out the major requirements for the design and construction of relatively low earth dams which best meet the combination of conditions of size, service requirement, cost and construction procedure which are encountered in the Forest Service. Mr. Ronka's statements were made to cover mainly the Eastern Region but they are applicable in a general way to the Forest Service domain from the Rocky Mountains eastward. The majority of these dams, which number into the hundreds, have been built with Civilian Conservation Corps cooperation. Funds for purchase of construction materials have been limited, the labor has been inexperienced in dam work and the local technical supervision has also usually been without previous experience both in dam construction and in soil compaction methods.

As explained in the paper, the requirements for recreational waters have been best met by relatively small structures, seldom exceeding 35 ft. in height although there are some notable exceptions. In some instances the watersheds are so small that they can be expected to yield only enough runoff to keep the water in the reservoir fresh and usable during the hot, dry summer months of the recreation season and it is therefore quite essential that such dams be designed and built to a high degree of imperviousness.

The local technical supervision of the work during construction is usually done by young engineers with little or no experience in soil testing or compacting methods and the designs are therefore standardized as much as possible so that only minor problems will be left to their decision. It has become rather common practice in the design of these low dams to assume a conventional cross-section using slopes of three-to-one on the upstream side and two and one-half to one or two to one on the downstream side and to then search for soils which meet the relatively rigid requirements of this design.

Occasionally a soil is found which is in the boundary zone between pervious and impervious designation which can be used for the entire embankment section with the aid or a rock fill or other free-draining device along the downstream toe to insure adequate drainage. As Mr. Ronka points out in his paper, the use of a single soil which is moderately impervious tends to produce a condition of saturation at or close to the face of the embankment somewhere above the toe. This may or may not be a source of danger in a low dam, depending on the nature of the soil and the rate of percolation. Such danger as exists is not so much from piping as it is from sloughing or shear failure. Inasmuch as the embankment design should be such that it is stable when in a saturated condition as analyzed using factors of internal friction and cohesion which have been determined by laboratory test of samples of the soil, the danger of shear failure is measurable, leaving the matter of sloughing at the toe as the only indeterminate element. The cause of sloughing is the fact that the saturated soil between the ground line and the point where the line of saturation emerges from the dam is under mild hydrostatic pressure, and this pressure tends to dislodge it. As previously stated, the way to avoid it is to use a rock blanket or tow fill, or a subsurface drain which will lower the water level and relieve the pressure.

Failures of embankments by piping have been much less frequent in recent years, notwithstanding the fact that the past decade has undoubtedly witnessed the greatest wave of earth dam building that the country has ever known. Piping is a condition of what may be termed "erosive percolation" and might occur in almost any soil if it were not compacted to sufficient density. The modern conception of the moisture-density relation and the general acceptance of moisture control practices in rolled fill construction operations has resulted in securing of higher and more uniform embankment densities with proportionately less chance for piping to occur. There continue to be occasional cases of failure from piping through the foundation or around the abutments due to failure to detect and remove highly pervious soil veins or strata. One of the most recent of these was the failure of the Big Dry Creek Dam near Jordon, Montana on March 13, 1939, after it had been in service only a few months.

The use of the term loam is of course largely a matter of definition, but since it has been included in the widely accepted schedule of descriptive values of the Bureau of Chemistry and Soils, it seems futile to attempt to discard the term and with it the system of classification because someone else defines loam as a soil which contains organic matter. Obviously, engineers, whether they be interested in soils for roads, for dams or for foundations, are concerned only with mineral soil. Non-mineral soil, or that which contains roots, litter, or other organic material, can as well be termed humus, topsoil, or some term acceptable to the agronomist, but as this material is always excluded from engineering use, the engineer need not quibble about what it shall be called. He should, on the other hand, work for the retainment of the term loam as defined in the Bureau of Chemistry and Soils classification because it has definite merit therein.

TABLE 1

Degree of Impermeability	Range of k in ft per min
Very impervious	<0 0002
Moderately impervious	>0 0002 <0 01
Moderately pervious	>0 01 <0 2
Very pervious	>0 2

When speaking of the coefficient of permeability of a soil, we refer of course to a determination made in the laboratory using a small sample of soil. The use of this factor quantitatively in an attempt to compute probable percolation losses in the completed dam involves a somewhat complicated mathematical procedure and furthermore, the coefficient of the soil in place in the embankment is not necessarily the same as for the laboratory sample. This is because of the fact that the small sample can be placed in the test compartment as an isotropic mass, whereas the process of building embankments in rolled layers results in a definitely anisotropic mass in which the mean coefficient of permeability in a horizontal direction will be somewhat greater than in a vertical direction.

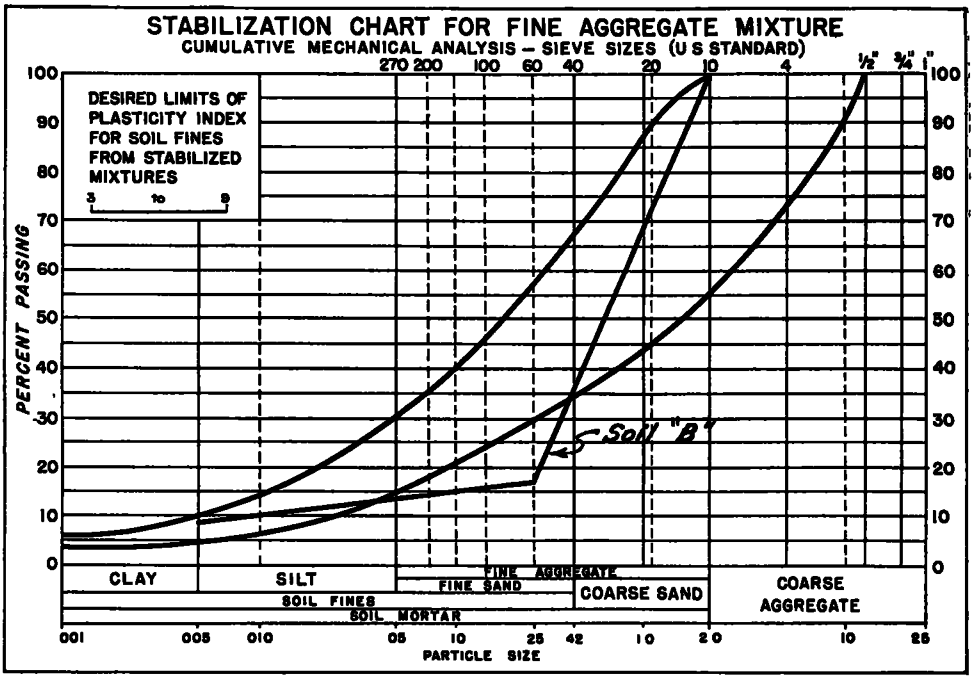
It is possible to evaluate and correct the coefficient determined in the laboratory so that a reasonably close computation of the percolation loss through an embankment and its foundation can be made, but the percolation loss through the average low dam is not of sufficient significance to require such refined procedure. It is ordinarily enough to determine the laboratory value and use it to classify the soil as to relative impermeability, that is, to determine whether the soil is most suitable for the upstream, the central, or the downstream zone of the embankment.

There are no sharp lines of demarkation between very impervious, moderately impervious and pervious soils, since these are relative terms, but it may be interesting to record here what may be considered approximate ranges of permeability, k, for these terms. These are given in Table 1.

But to return to the matter of selection of embankment soil, the most common practice is, as described in this paper, to divide the cross-section into two or more zones, with the zone of least impermeability on the downstream side Fortunately suitable soils can be found in many localities so that the problem is to locate the borrow pit areas, instruct the project engineer on methods of identification of the accepted soils, provide him with the laboratory test results needed to guide him in the compaction operations and caution him to seek assistance if any of these factors varies so that the desired results can not be obtained. Frequently it turns out that sources of approved soil from the borrow pits run out or change to soil of different characteristics so that the laboratory is called on to test and approve additional samples from other sources. Our projects are as a rule not large enough to justify setting up of a complete soils laboratory in the field so the major part of the testing is done in a regional laboratory, the field equipment being limited to that needed to control the moisture and density factors during construction.

According to the Bureau of Chemistry and Soils classification which is commonly used in highway work, Mr. Ronka's Soil "A" which he regards as highly satisfactory, is on the border line between loam and clay-loam. It is interesting to see that Soil "A," under the Public Roads Administration's sub-grade classification, this curve gives a valuable indication of the uniformity of grading, the density and the permeability of the soil. These curves may be typed in six classifications, as illustrated in Figure 2. (See also D. M. Burmeister, Assoc. M Am. Soc. C E., Trans , Vol. 65, No. 8, Part 2.)

Type I. Represents a soil composed largely of a single grain size, such as might be suitable for a filter sand.



LIQUID LIMIT ------ PLASTIC LIMIT ------ PLASTICITY INDEX ------

Figure 1. Stabilization Band

would fall into the A-5 zone, whereas Soil "B" which is not desirable for dams, is in the favorable A-1 zone. Soil "B" however, would not be acceptable for the minus ten fraction of a stabilized road surface mix, being deficient in fines in the middle range of the band. (See Figure 1.)

In determining the suitability of a soil for dam use, considerable help can be gained from a study of the mechanical analysis curve as plotted on the usual semi-log scale. The slope and shape of

Will have low density, high permeability and poor compacting qualities.

Type II. A soil with good distribution of grain sizes conforms to this S-shaped pattern. It can be compacted to good density and usually to give a low permeability coefficient.

Type III. This represents a straight line distribution with uniform amounts of all sizes, which will be less dense and more permeable than Type II. It is an undesirable grading.

Type IV. This is typical of a mixture of two soils, as a coarse aggregate and a silt or clay, both deficient in the middle grain sizes. It can often be compacted to high density and impermeability but may lack stability depending on the nature of the fine fraction.

Type V. Represents a soil in which fine sizes predominate so that its nature is determined by the character of the fines. It will usually have a lower density rating than Type II.

Type VI. This curve, based on the Talbot formula for maximum density grading, is representative of the artificial mixture of soils for road subgrade stabilization. High density and low permeability are assured. This type will be rarely encountered in a natural state.

Another criterion for determining the suitability of a soil for dam embankment use is by application of the mechanical analysis curve to the so-called Lee Band.[1] If the curve falls within the limits of the band, Figure 3, and if it also conforms to the general shape and slope of the limiting lines, it will usually be acceptable for rolled fill use. Mr. Ronka's Soil "A" meets these requirements, being just below and approximately parallel to the upper limit line. Soil "B," on the other hand, cuts diagonally across the band, and would be considered as not meeting the criterion. Curves "C" and "D" represent other soils which have been used successfully. Soil "C" is a granitic clay from the eastern slope of the Rocky Mountains. It gave a Proctor dry density value of 122.5 lbs. per cu. ft. and permeability of 0.0013 ft. per day. Soil "D" is a sandy loam from northern Georgia which gave a dry density of 117.8 lb.

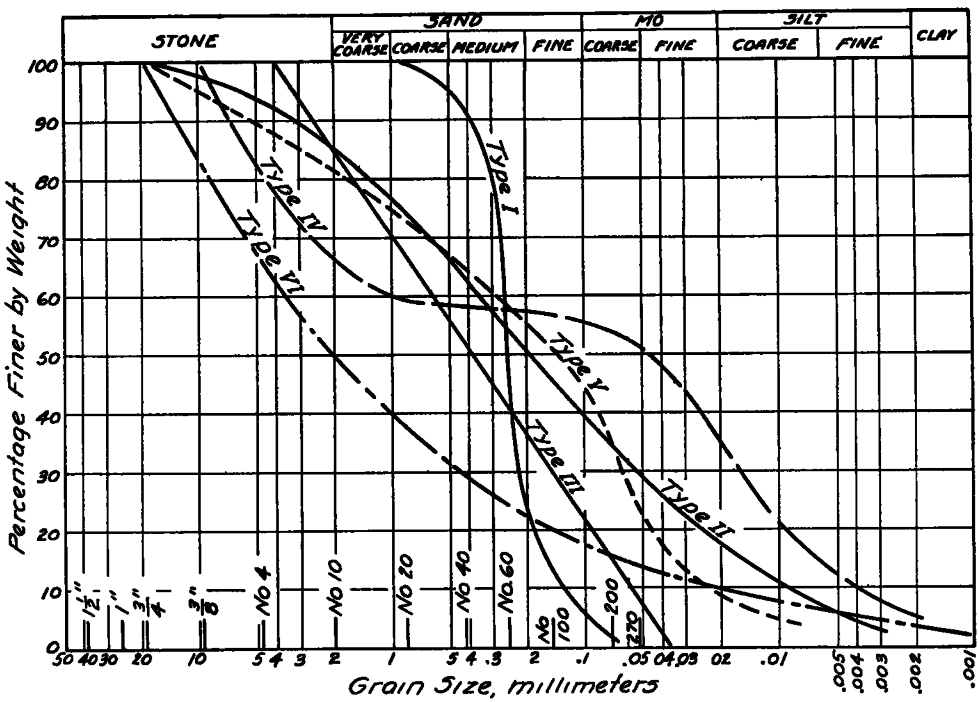


Figure 2. Types of Grading Curves

[1] Chas. H Lee, "Rolled Fill Earth Dams", *Proceedings* Am. Soc. C. E., Sept. 1936.

per cu. ft. The permeability of this soil is not available but it is unquestionably well within the safe limit.

There is little doubt that for dams 20 or even 30 ft. high, a study of the mechanical analysis curve in relation to the type significance will provide all information necessary for an experienced soil technician to determine which soils may be used without further test, which ones are unsuitable and which ones should be investigated and tested further before being accepted or rejected. Knowledge of the geological origin of the soil is also helpful in determining or predicting its behavior under use.

For larger dams, it is generally recognized that the procedure in preparation of the embankment design should be reversed. That is, instead of using a standard cross-section and hunting for soils which can be used in it, the better approach is to make a soil survey to determine the types and volumes of soils which are available for use and then to choose a stable cross-section which makes the most economical use of the available soils. By using flatter slopes, wider bases and by introducing internal drainage devices, it is possible to build a successful dam out of almost any soil but of course the cost of using a conveniently located soil of poor grade may exceed that of bringing in a more desirable one from a greater distance. The answer to such a problem is one of economic design study.

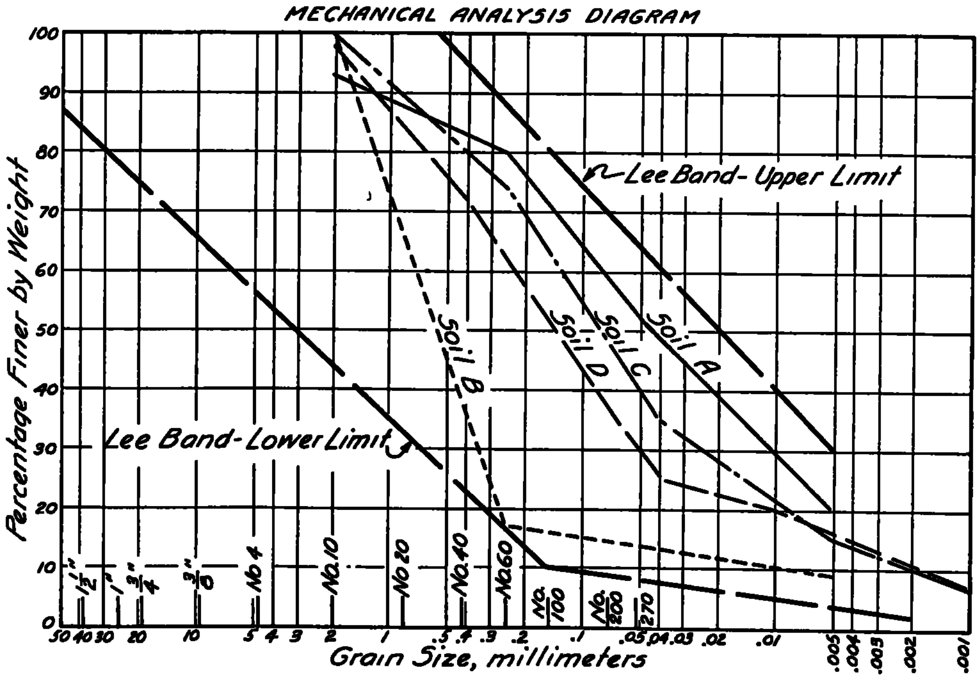


Figure 3. Lee Band

In recent years we may have been unnecessarily exacting in our selection and placing of soils in rolled earth dams, but if so, the error has been on the side of safety and caution and is no doubt justifiable in that we have been working with new tools and new knowledge As we become more accomplished in their use we will no doubt make better use of them to guide us to more economical yet adequately safe dam construction.