FACTORS AFFECTING LABORATORY MEASUREMENT OF PERMEABILITY OF UNCONSOLIDATED GLACIAL MATERIAL[1]

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Introduction

Many noteworthy contributions have been made by scientific research on the flow of fluids through porous media. The work has been mainly in two categories, consolidated material and filtration materials, with less attention to unconsolidated water-bearing materials. Many of the same problems confront the worker in all three fields, and much of the information and many concepts are interchangeable. There are, however, certain problems in the study of unconsolidated water-bearing deposits which are not encountered in the study of either filtration or consolidated material. The consolidated material tends to be more uniform in character (excluding materials with secondary porosity). Filtration material may be sorted, stratified, and of varying shape to obtain the desired results or effects. In natural unconsolidated water-bearing material, a marked heterogeneity is usually encountered; therefore a more empirical approach is necessary in their study.

Properties of Sediments

Classification.—Numerous methods have been devised to describe and classify sediments. Some are extremely useful whereas others are of limited use and little practical value. A brief review of some of the criteria is necessary to ascertain those which are pertinent to the present study. Krumbein[2] says of the mass properties of sediments, "Just as the behavior and functions of a complex organism are the sum of the behavior and functions of the component cells, so also is the character of the aggregate sediment (or any other particulate substance) a summation of the characters of the individual particles or grains of which it is made."

Packing.—An important factor which exercises control over both porosity and permeability is packing. Graton and Fraser[3] have recognized two classifications of packing, systematic and random. They have recognized six basic patterns for systematic packing, which range from loosest to closest packing. Random or disorderly packing is far more common in nature and therefore of more interest to the hydrologist and geologist.

They further state[4] that haphazard packing being of higher porosity than tighter rhombohedral packing has a larger average size of voids;

[1] Published with the permission of the Chief, Illinois State Geological Survey, Urbana, Illinois and based, in part, upon Master's thesis, University of Illinois.

[2] Krumbein, W. C. and Pettijohn, F. S., Manual of sedimentary petrology, p. 498, D. Appleton-Century Company, New York, 1939.

[3] Graton, L. C. and Fraser, H. J., Systematic packing of spheres with particular relation to porosity and permeability: Jour. Geol. vol. 43, pp. 485-800, 1935.

[4] Op. Cit., p. 876.

therefore it has a higher permeability. Since most haphazard packing is systemless, the voids are generally of non-uniform size, producing a higher permeability than systematic packing of the same porosity.

Porosity.—Porosity is the percentage of pore space in the total volume of the sample, i.e., the space not occupied by solid mineral matter. Fraser[5] has listed the following seven factors which control the porosity

1. Absolute size of grain.
2. Non-uniformity in size of grain.
3. Proportions of various sizes of grains.
4. Shape of grain.

Factors of more general nature include:

5. Method of deposition.
6. Compaction during and following deposition.
7. Solidification.

Size.—Slichter[6] in his theoretical work came to the conclusion that the absolute size does not affect the porosity. The factor which has been overlooked is that spherical particles were used instead of natural grains. Actually as grain size decreases, friction, adhesion, and bridging become increasingly important because of the higher ratio of surface area to volume and mass. Therefore, the smaller the grain size, the greater the porosity. Lee and Ellis[7] made determinations on 36 samples ranging from coarse sand to silt with the following results in percentage of total voids: Coarse sand, 39-41 percent; medium sand, 41-48 percent; fine sand, 44-49 percent; fine sandy loam, 50-59 percent. The average of the thirty-six samples was 45.1 percent. Smaller particles were found to give values ranging from 50 to 95 percent.

The variety in grain size in proportion of various sizes and degree of assortment must be taken into consideration in any study of porosity. A mechanical screen analysis can best express these variations.

Hazen,[8] in his experimental soil work, devised a method of gaining a simple quantitative expression of the degree of uniformity which he calls the uniformity coefficient. This is the ratio of the diameter of a grain that has 60 percent by weight of the sample finer than itself to the diameter of a grain that has 10 percent finer than itself. Results of other workers[9] have shown that the values used by Hazen are not always applicable to all types of material. However, the variation is so slight that it does not seem necessary to change the values. Hazen further noted that uniformity coefficient would range from a value of 1, if all particles were of the same size, to 20 or 30 for heterogeneous material; that is, the coefficient increases as porosity decreases. A rough estimate of the open spaces can be made from the coefficient of uniformity. Sharp-grained materials having uni-

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[5] Fraser, H. J., Experimental study of the porosity and permeability of clastic sediments: Jour. Geol., vol. 43, p. 916, 1935.

of natural unconsolidated deposits.

[6] Slichter, C. S. Theoretical investigation of the motion of groundwaters: U.S.G.S., Nineteenth Annual Report, 1897-98.

[7] Lee, C. H. and Ellis, A. J., Geology and groundwaters of the western part of San Diego County, California: U.S.G.S., Water Supply Paper 446, pp. 121-23, 1919.

[8] Hazen, Allen, Some physical properties of sands and gravels with special reference to their use in filtration: Mass. State Board of Health, 24th Ann. Rept., p. 50.

[9] Terzaghi, Karl and Peck, R. B., Soil mechanics in engineering practice, pp. 21-22, John Wiley and Sons, 1948.

formity coefficients below a value of 2 have nearly 45 percent open space as ordinarily packed, and sands having coefficients below 3 as they occur in banks, or artificially settled in water, will usually have 40 percent open spaces. With more mixed materials the closeness of packing increases until, with a uniformity coefficient of 6 to 8, only 30 percent open space is obtained, and with extremely high coefficients almost no open space is left. With round-grained water-worn sands the open space has been observed to be from 2 to 5 percent less than for sharp grains of similar size.

Permeability. — Permeability as defined by Tolman[10] is the capacity of water-bearing material to transmit water, measured by the quantity of water passing through a unit cross-section in a unit time under a 100 percent hydraulic grade. Many factors influence the permeability, including size of interstitial openings, continuity of openings, surface tension, capillarity, size of grains, absolute viscosity of fluid (in centipoises), and dissolved gas. It is beyond the scope of this paper to delve into all the hydrologic aspects, but they should be recognized. Although dependent on porosity, there is no direct ratio between porosity and permeability. Terzaghi and Peck[11] have stated that "when a soil is compressed or vibrated, the volume occupied by its solid constituents remains practically unchanged, but the volume of voids decreases; as a consequence the permeability of the soil decreases."

[10] Idem, p. 114.
[11] Idem, p. 44.

With openings of capillary and sub-capillary size the molecular attraction of water molecules is sufficient to "lock" the water in the interstitial spaces.

Surface tension of fluids.—Surface tension in fine-grained sediments exercises important control. It has been estimated by King[12] that the surface area in a cubic foot of sand composed of particles 0.02 millimeter in diameter is about 50,000 square feet. It is apparent that a considerable amount of water can be contained as a thin film on the surface of the grains of such fine material, and that molecular cohesion causes any remaining interstitial space to be filled with captive water. It can be demonstrated that in a given volume of material in which all factors other than size remain equal, the total interstitial space varies inversely with the size of the interstices. A half-inch sphere has one-fourth the surface area of a one-inch sphere, but a container of one cubic inch capacity will hold eight half-inch spheres which in effect doubles the interstitial surface.

Shape.—The shape of particles is known to affect both porosity and permeability, but thorough quantitative work on this aspect has been meager.

Shape studies.—Shape studies[13] were conducted to see whether a measurable quantitative relationship exists between shape, porosity, and permeability. An arbitrary scale[14] was set up based upon three shapes,

[12] King, F. H., A text of physics of agriculture, Madison, Wis., p. 124, 1900.
[13] Wadell, H., Sphericity and roundness of rock particles: Jour. Geol., vol. 41, pp. 310-331, 1933.
[14] Rittenhouse, Gordon, Analytical methods as applied in petrographic investigation of Appalachian Basin, U.S.G.S., Circular 22, March, 1948.

Fig. 1.—Selected pebbles used as a guide in shape studies.

rounded, semi-rounded, and angular. Three specimens were picked from the samples and photographed. This photograph (fig. 1) was used as a guide in further grain counts.

A piece of metric cross-section paper placed between two pieces of lucite served to delineate a given area. Small portions of a sieved sample were placed on the ruled piece of lucite and examined under a microscope. Grains within a given area were counted and an estimate was made of the percentage of each of the three shapes. A less rapid but more accurate method would be to make counts from photomicrographs.

Methods of Analysis

It can be readily seen that to the hydrologist permeability is much more important than porosity. A sediment which possesses porosity but not permeability is useless as an aquifer.

Numerous graphical and statistical methods have been devised by various workers in an attempt to analyze sediments. A review and appraisal is desirable to ascertain which of these methods is pertinent to the present problem.

Mechanical size analysis.—Two common and widely used statistical devices are the histogram and the cumulative curve. There are certain limitations and variations attendant to these methods, some of which are discussed below. Udden[15] was among the first workers in the field of sedimentation to use histograms. He observed that histograms of sediments varied considerably according to the type of sediment involved. Beach sands have well defined modes whereas glacial till fractions are widespread and irregular and often bi-modal. One of the greatest difficulties involved in the use of the histogram is caused by the choice of class intervals used in an analysis, i.e., its shape varies according to the particular class limits which are chosen. It is therefore quite possible to construct two very unlike histograms from the same sediment merely by using different class intervals. The basic difficulty with the histogram is that it appears to illustrate continuous frequency distribution as though it were made of discrete classes. Hence the histogram may not furnish much visual information about the frequency distribution considered as a continuous variation of size.

The use of the cumulative curve was prompted by the difficulties encountered in the histogram. This curve remains fairly constant regardless of the class limits used, whereas the histogram is definitely affected by a choice of class limits. Thus the cumulative curve is a much more reliable index of the nature of continuous distribution of particles of sediment. Another advantage of

[15] Udden, J. A., The mechanical composition of wind deposits, Augustana Library Publications, No. 1, 1898.

this curve is the ease with which other statistical data may be derived from it.

Size analysis coefficients.—One of the most valuable measures is that of the median, which is the mid-point in size distribution of the sediment of which one-half by weight is composed of particles of smaller diameter than the median and one-half is composed of particles larger than the median. This is readily obtained from the cumulative curve by noting the diameter at the intersection of the 50 percent line and the curve. This value is used in the recommendations for well screens by the Illinois State Geological Survey.

Skewness, or the measure of the degree of asymmetry of the cumulative curve, has been recommended by some as a method of ascertaining the sorting; that is, a positive skewness indicates that a preponderance of the sample lies on the coarse side of the median. A negative skewness would indicate the opposite. The use of skewness currently has little practical application, mainly because relatively little is known of this character of sediments. Sampling errors, selective transportation, and other factors often manifest themselves as skewness.

Effective size was a term developed by Hazen[16] in his work on filtration sands to designate the diameter of the size particle of which they were 10 percent of the sample by weight smaller and 90 percent by weight larger. Although this measurement was derived for use on a certain sediment, it has with some modifications been quite generally accepted. The effective size is readily obtained from the cumulative frequency curve by ascertaining the point at which the 90 percent line intersects the curve. Hazen justified the choice of effective size upon his observations that the finest 10 percent of a sample has as much effect on the properties as the coarsest 90 percent.

Trask[17] has proposed a method of expressing the measure of the average quartile spread, the coefficient of sorting. It is determined by the square root of the third quartile diameter divided by the square root of the first quartile diameter. This method eliminates the size factor, that is, differences in coarseness between samples or units of measures have no effect on the coefficient of sorting. This method gives a relative idea of the sorting in terms of well sorted (less than 2.5), medium sorted (about 3.0), and poorly sorted (4.5 or more), but fails to give an accurate quantitative measure.

Krumbein and Monk[18] conducted experiments on unconsolidated glacial sediments to determine the effect of size perameters on permeability. The results of their work are of little value in this study because their samples were artificially compounded to fit a predetermined curve, that is, the sieve separates were mixed so that the mean and standard deviations could be varied at will.

Drilling and sampling techniques. The technique in obtaining well samples varies greatly from the techniques used in other methods of sam-

[16] Idem, p. 432.

[17] Trask, P. D., Origin and environments of source sediments of petroleum: Nat. Research Council, Rept. Comm. on Sed., pp. 67-76, 1932.

[18] Krumbein, W. C. and Monk, G. D., Permeability as a function of size perameters of unconsolidated sand: Amer. Inst. Min. Met. Eng. Inc., Petroleum Technology, July, 1942.

pling. It is impossible to remove the material of well samples in an undisturbed condition. Material which has slumped from higher levels in the well bore often contaminates the samples, and drilling bits often pulverize or otherwise disintegrate particles, thus distorting their true magnitude.

The type of drilling tools, the methods used, the size (diameter) of the hole, and the type of well (test hole or producing well) must be considered in the study of any given sample.

Most wells are drilled by one of three different methods—rotary, cable tool, and reverse hydraulic. Certain characteristics of each method merit discussion.

Cable tool or percussion drilling is accomplished by repeated raising and dropping of a bit and a heavy string of tools suspended on a cable or by driving casing and cleaning out the debris as the casing is forced downward, or often by a combination of the two operations.

It is difficult to obtain representative samples from cable tool bore holes. The upper portions are often drilled "dry," that is, with just enough water to facilitate drilling and bailing operations. When a water-bearing sand is encountered, the bore hole is loaded with fluid to, or in excess of, hydrostatic balance with the formation in order to prevent heaving. Heaving can cause drilling difficulties as well as contamination of samples. The constant influx of sand from a heaving formation makes it difficult or impossible to ascertain the true position and character of the water-bearing zone. Excessive disintegration of material is often caused by certain operations of the drilling procedure. Casing set with a drive shoe tends to disturb the formation, and failure of the bailer to remove cuttings exposes them to repeated blows from the drilling bit. The importance of a good and experienced driller cannot be overemphasized. It is generally the driller who collects samples, and the validity of the samples is largely dependent on his care, knowledge, and experience.

In rotary drilling, mud is of prime importance. Many holes drilled in glacial drift utilize as drilling mud the clay material found in the upper portion of the drift, adding only water. When sandy zones are encountered, additional fine-grained material, such as bentonitic clays, must be added by the driller to maintain the mud at the proper weight and viscosity and to remove the cuttings. In some cases, lime, cement, or other materials may be added to increase viscosity or weight.

Care in removing samples is necessary. A device similar to a wire box is generally used to slow up the flow of mud sufficiently to allow even the finer parts of the sample to settle before the sample is removed.

Hole size is an important consideration in the study of well samples. For example, in the large diameter wells drilled for the Illinois Water Service Company, a larger percentage of coarse particles were brought up and a larger percentage of fine particles were washed away than in the 4-inch rotary test holes drilled on the same sites.

As would be expected, information from a test hole tends to be more reliable. More care is taken in sam-

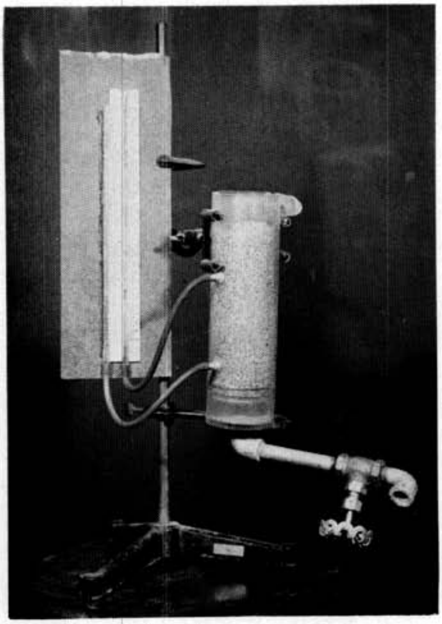

FIG. 2.—Device for measuring permeability of unconsolidated material.

pling and in other techniques. In most final wells, production is the ultimate goal. Large diameter wells produce so much material that a considerable disposal problem results, and it would be necessary to conduct a regular sample splitting procedure in order to obtain a representative sample.

RESULTS OF STUDIES

Permeability. — Samples used in the permeability experiments were composite samples derived from the entire water-bearing portion of University of Illinois Well No. 10. A limited number of readings were taken on 60- and 80-mesh sands and BB shot. It was of interest to note the slight variation between loosest and closest packing in the case of the 60- and 80-mesh separates. When wet samples were introduced into the permeameter containing water, they settled in a state of closest packing and any attempts to lower the permeability were fruitless.

Permeability testing.—Permeability was measured by allowing water under a 100 percent gradient to pass through a sample of known cross section and height, and measuring the amount which was passed in a given time. A permeameter was constructed of a lucite cylinder with an inside diameter of approximately 6.4 cm. and a length of 30 cm. A disc of lucite was bonded to the bottom of the tube and tapped for a ⅜ inch street *el* to which was connected a gate valve. Approximately one inch from the bottom of the tube a piece of 60-mesh wire was placed between two rings of lucite and reinforced with hardware cloth. Above this screen two openings were tapped 10 cm. apart and connected to manometer tubes which were mounted on a board with metric scales (fig. 2).

The major problem was obtaining uniform and accurate readings. To accomplish this a system of "average readings" was devised. Material was introduced into the tube in a steady stream until the top manometer opening was covered. No attempt was made to pack the material further. Water was then introduced into the tube from the top until a steady stream was obtained at the outlet, at which time a reading was taken. This first reading was taken immediately after a continuous flow was obtained through the gate valve, and recorded the permeability of the material in loosest packing.

After the permeability of the material was obtained in a condition of loosest packing a "Vibra-Tool" was used to jar the material into the closest packing possible. The flow of water was stopped during the packing process to prevent the possibility of channeling. When the closest packing possible was obtained another reading was taken. The average of the two readings was then calculated, which, in the opinion of the writer, represents most closely the original permeability of the material in place in the ground. This conclusion was reached after it was demonstrated that it was possible to produce in the laboratory both looser and closer packing than a sediment possessed in nature. By using an average of loosest and closest packing it was possible to obtain more uniform results than could be obtained by attempting to pack each sample to a uniform standard.

Several experimental readings were made in order to develop a standard procedure which would give uniform results. It was found that false results could be obtained by surging the column of sediment and allowing a relatively complete sorting to take place in the tube. Channeling was common when higher velocities were used. These channels, when developed, allowed water to flow through the column of material in a quantity far greater than in unchanneled material.

The necessity for a gate valve to control the rate of flow of water through the column of material became apparent immediately. Materials of high permeability allowed turbulent flow to develop, introducing error into the results. A high rate of flow also allowed sorting and channeling to occur, causing intolerable errors. Several readings were taken on one sample allowing different amounts of water to flow through the tube in a given time; in all cases the results were well within the limits of probable error. It was then decided to use as low a rate of flow as would register a head on the manometer gauges, thus minimizing any effects due to turbulent flow or sorting.

Hydrologic tests.—A non-equilibrium formula for determining permeability and transmissibility by well pumping tests has been developed by Theis[19] and others. This formula has been applied to a number of well tests in Illinois and apparently gives a relatively reliable indication of the permeability and transmissibility of glacial drift aquifers in place. The values so obtained are controlled by the local natural variations in porosity and permeability (and packing) plus whatever changes may have been caused by drilling and development techniques at the particular site. In one instance in the Champaign-Urbana area, the calculated transmissibility based upon the Theis formula lies about half way between the limits of permeability determined in the laboratory for maximum open packing and maximum closed packing determined with materials from the well. Other cases indicate that the aquifer transmissibility based upon such pumping tests can always be expected to be within such limits, but that the production from a well cannot be predicted from laboratory analysis.

Several factors govern the amount of water which may be derived from

[19] Idem, pp. 519-524.

a formation. Of these, proper development of the well is of great importance. In sand and gravel strata it is quite possible to over-develop a well to a point where a failure is caused in the "roof" or overlying formation. If the overlying formation is composed of clay or extremely fine sand, this material will enter the well bore, causing the material near the well to be clogged and reduced in permeability. Over-development may also cause a bridging of the fine particles between the larger ones. This condition can be generally remedied by surging, and is not considered as detrimental to the yield as roof failure.

Under-development may also cause a low yield. This occurs when insufficient pumping and surging fails to cause relatively complete sorting.

Size range of the particles and thickness of the formation have great effect on the yield of a well, as noted above. Material with great uniformity of particle size will not yield much more water after development than before.

The amount of water available and the diameter of the well are important factors in determining the yield of a well. If there is sufficient water, it is possible to utilize large diameter wells which are capable of transmitting larger quantities of water to the surface than wells of smaller diameter. A thick formation for obvious reasons is capable of containing more water than a thin one.

The factors concerning the development of wells are largely dependent on the skill and experience of the driller. In any study it is important to take cognizance of this factor.

In the shape studies conducted by the author, it was possible to determine accurately the percentage of rounded, semi-rounded, and angular grains in any given sample. However, in any consideration of porosity and permeability, the indeterminate factor of packing still remains. When dealing with uniform spherical particles Graton and Fraser[20] have shown that there are six types of systematic packing, and that porosity and permeability are definitely related to packing. Instead of dealing with six combinations as in the ideal case, it appears that in glacial drift, which is neither uniform nor spherical, an infinite number of combinations of packing can exist. Due to the extreme variability of size and shape, classification as to packing is meaningless. Therefore, any attempt to predict porosity and permeability of a finished well from laboratory samples by any mathematical or experimental process is impracticable.

Summary and Conclusions

Experimental procedure in attempting to produce uniform permeability readings illustrated very clearly that the permeability determinations in the laboratory are not indicative of the actual permeability in the formation surrounding the well bore. An experienced driller, by properly developing a well, causes its yield to differ greatly from those indicated by laboratory permeability results.

The development of a well consists of increasing the permeability of the formation in the vicinity of the well bore, which may be done by pumping and surging to remove the

[20] Idem, pp. 785-800.

fine particles from the vicinity of the well bore. The coarser sand or gravel remain behind the screen in the well bore. The entire water-bearing formation for a wide area around the well is made more uniform in grain size, affording the greatest possible voids for the water to pass through. In proper development the size of the particles gradually decreases with distance from the well bore, and the particles become firmly lodged together and stabilized so that no further change occurs. It appears impossible to predict accurately the amount of water which may be derived from a well treated in such a manner, although experienced drillers can often make remarkably accurate estimates.

After due consideration of existing studies and in the light of the present study, it becomes apparent that there is no way to evaluate quantitatively and accurately the effects of such features as roundness, size, shape, porosity, and permeability in a heterogeneous or non-uniform material with respect to its ability to produce water. In all previous works of this nature the material studied was either artificial or the original character of the natural sediments was altered to conform to desired conditions. While these studies are of academic interest they have been found to be of small value to the practicing groundwater geologist.

The use of compound samples was considered best because the production figures computed for a water well represent only the production obtained from the entire section rather than production from any single stratum.

It is concluded that the use of grain shape in predicting the yield of a formation is not practical because the effect of shape on permeability is exceeded by the effects of grain size and the manner of packing. In evaluating the factors which control porosity, permeability, and well productivity from glacial drift aquifers, it is apparent that for any given texture the effect of packing is of sufficient magnitude to minimize the effects of all other factors, so that the primary influence on an aquifer's productivity are the original conditions of deposition and its subsequent history as affecting its packing.

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