



British Geological Survey

ODA

TECHNICAL REPORT WC/94/62
Overseas Geology Series

UNCONSOLIDATED SEDIMENTARY AQUIFERS : REVIEW NO 5 - THE USE OF LABORATORY TECHNIQUES IN THE CHARACTERIZATION OF UNCONSOLIDATED SEDIMENTARY AQUIFER PHYSICAL PROPERTIES

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A Report prepared for the Overseas Development Administration under the
ODA/BGS Technology Development and Research Programme, Project 93/2

ODA classification :

Subsector: Water and Sanitation

Theme: W1 - Improve integrated water resources development and management
including systems for flood and drought control

Project title: Groundwater development in alluvial aquifers

Reference number: R5561

Bibliographic reference :

Bloomfield J 1994. Unconsolidated sedimentary aquifers : Review No 5 - the use of
laboratory techniques in the characterization of unconsolidated sedimentary aquifer
physical properties. BGS Technical Report WC/94/62

Keywords :

unconsolidated sediments; aquifer characterisation; physical properties; laboratory techniques

Front cover illustration :

Sigatoka River flood plain, Fiji

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UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSA's)

PREFACE

This review is one of a set of reports prepared as part of a project entitled "Groundwater Development in Alluvial Aquifers, Project No R5561 (BGS 93/2), under the ODA/BGS Technology Development and Research (TDR) Programme of aid to the developing countries. The project addresses all unconsolidated sedimentary aquifers (UNSA's) not only alluviums.

This particular review describes the application of geophysical logging techniques in boreholes drilled in unconsolidated aquifers.

This review is a compilation of existing knowledge. It is intended to be updated, as appropriate, following the results of research which will be carried out during the lifetime of the project, which is scheduled to run until 1996.

The project is funded by ODA as part of their research and development programme designed to improve living standards and conditions in the world's developing countries.

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 Hydrogeological Advisor to ODA
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A Guide to the sedimentology of unconsolidated sedimentary aquifers (UNSAs)

INTRODUCTION

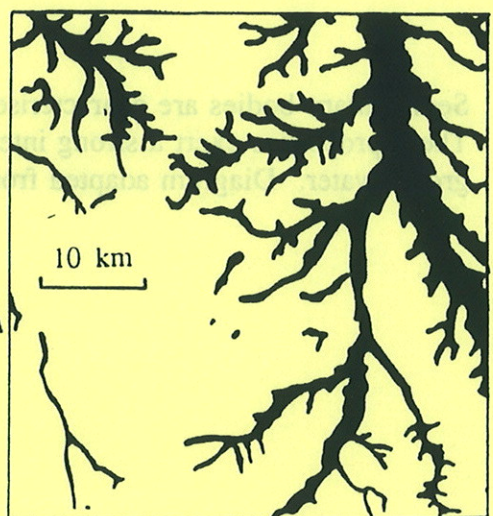
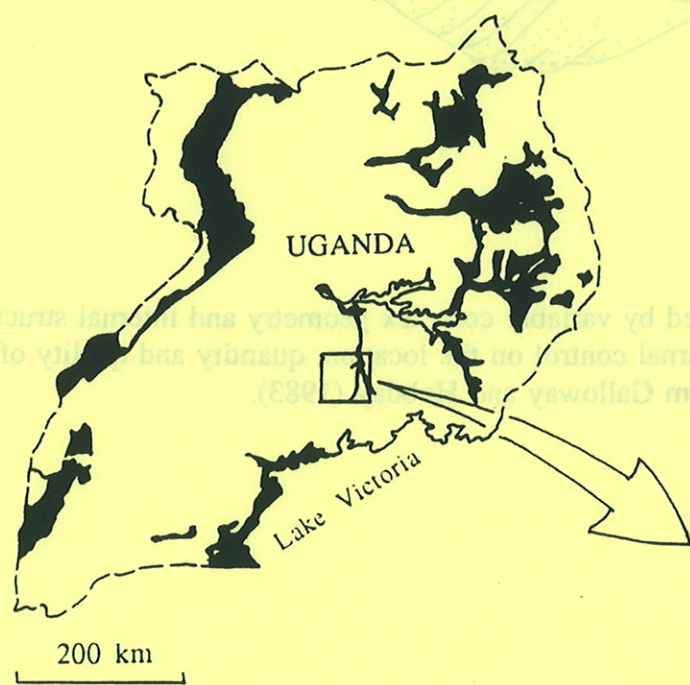
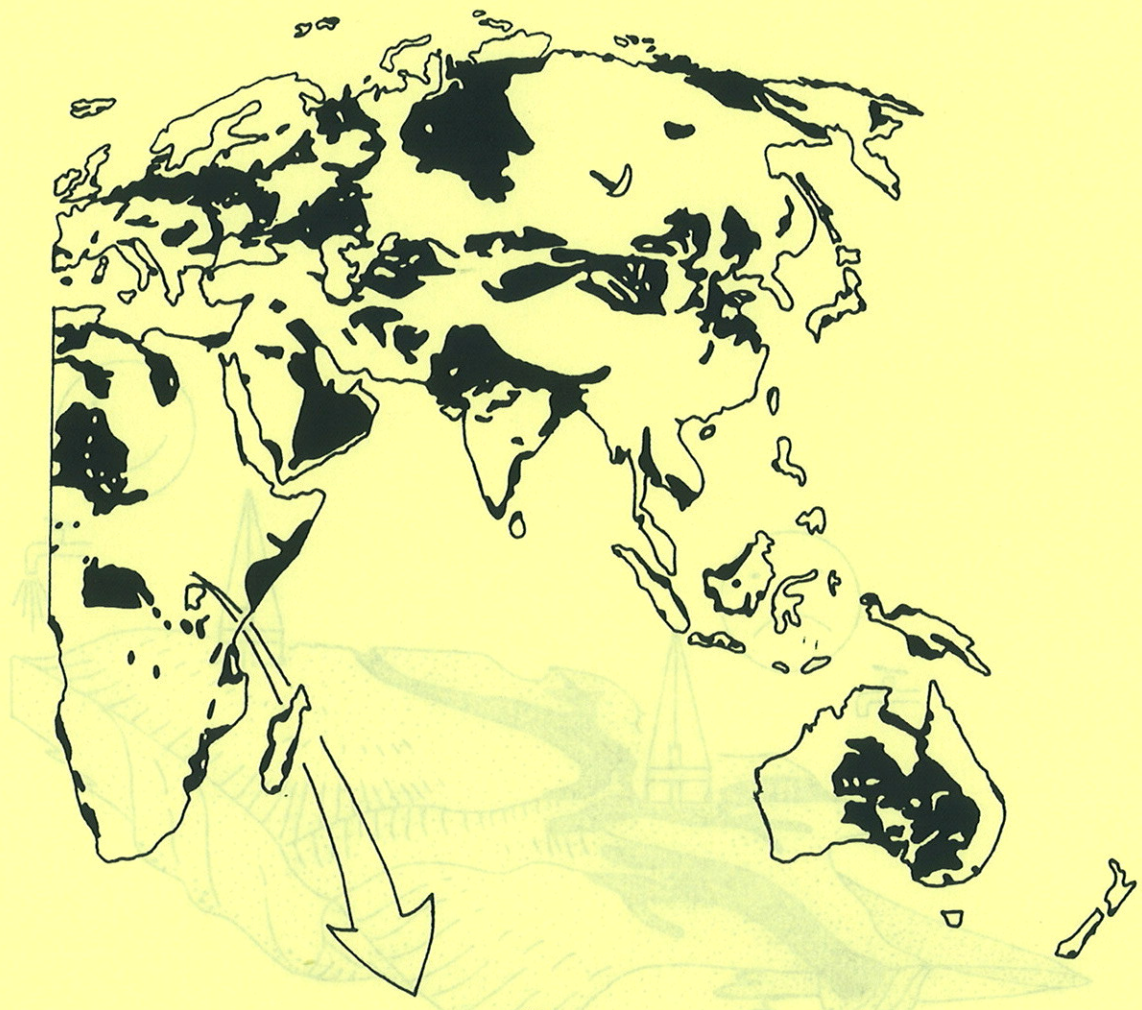
WHAT ARE UNSAs AND WHY IS IT IMPORTANT TO UNDERSTAND THEM?

UNSAs are unconsolidated sedimentary aquifers. These are the water-bearing strata within the swathes of unconsolidated sediment that mantle much of the earth's surface. There is no clear dividing line between UNSAs and aquifers in consolidated rocks, as lithification is a gradational process: deposits a hundred years old can be lithified, while some deposits 500 million years old are still essentially unlithified. However, for most purposes, UNSAs can be understood as deposits which have accumulated over the past few million years, that is during Quaternary and Neogene (late Tertiary) time. They are important sources of water in many parts of the world, and in particular constitute the only major sources of groundwater for vast areas throughout the developing world. In the influential text-book *Hydrogeology* by Davies and De Weist it says:

"The search for ground water most commonly starts with an investigation of nonindurated sediments. There are sound reasons for this preference. First, the deposits are easy to drill or dig so that exploration is rapid and inexpensive. Second, the deposits are most likely to be found in valleys where ground-water levels are close to the surface and where, as a consequence, pumping lifts are small. Third, the deposits are commonly in a favourable location with respect to recharge from lakes and rivers. Fourth, nonindurated sediments have generally higher specific yields than other material. Fifth, and perhaps most important, permeabilities are much higher than other natural materials with the exception of some recent volcanic rocks and cavernous limestones."

To date, though, few attempts have been made to understand the detailed internal structure of unconsolidated aquifers even though such knowledge may be crucial to the long term success of any water development project. This shortcoming is probably the reason why the operational lives of many water boreholes are frequently much shorter than expected.

Understanding of the internal structure or "architecture" of many types of sedimentary deposit has, however, advanced greatly over the past couple of decades. Part of this research has been academic, but much has been sponsored by the oil industry, so as to better predict the possible location of oil within sedimentary traps. Oil, like water, is most profitably located within bodies of relatively coarse-grained and porous sediment. Thus, there is obvious scope for applying this recently gained understanding to hydrogeological problems. Advances have also been made in the understanding of the geometry of complex "soft-rock" deposits by the application of appropriate combinations of investigative techniques, including remote sensing, rapid geophysical methods and new drilling techniques. The combination of these bodies of knowledge can provide a framework for locating and assessing UNSAs.



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Method Summary Sheet (Lab 2): Particle size analysis - sieve method

Method Summary Sheet (Lab 3): Particle size analysis - sedimentation method

Method Summary Sheet (Lab 4): Porosity determination - gas expansion method

Method Summary Sheet (Lab 5): Porosity determination - density methods

Method Summary Sheet (Lab 6): Pore size distribution - water desorption method

Method Summary Sheet (Lab 7): Pore size distribution - mercury intrusion method

Method Summary Sheet (Lab 8): Permeability measurement - falling head test

Method Summary Sheet (Lab 9): Permeability measurement - constant head test

Method Summary Sheet (Lab 10): Permeability measurement - oedometer test

1. AIMS OF THE REVIEW

This review is intended for field workers with limited experience of using laboratory data in the evaluation Unconsolidated Sedimentary Aquifers (UNSAs) and for staff who may be required to interpret physical properties laboratory data; it is not intended for use by specialist laboratory geoscientists. The aims of the review are

- to provide an overview of the available laboratory techniques for the hydrogeological characterization of UNSAs (supported by appropriate basic theoretical background),
- to note the applicability of the techniques described to given tasks and
- to direct the interested reader to more detailed reference texts.

It is not possible, or reasonable, to present full details of all experimental procedures since the general techniques described in this review will invariably have to be adapted for the specific purposes of a given site investigation.

2. BACKGROUND

Physical properties laboratory tests, *eg.* grain size analysis, porosity, permeability and capillary pressure tests, may be performed for a variety of reasons,

- to enable appropriate gravel packs and screen slot sizes to be chosen during the design of boreholes,
- to assess the degree of hydrogeological variability of a given aquifer,
- to obtain specific parameters for use in particular geotechnical calculations, *eg.* measurement of effective porosity for use in the calculation of storage coefficients or measurement of grain size distributions for use in the selection of appropriate borehole screens and in the estimation of permeability coefficients, and
- to validate, or establish correlations with field data, such as transmissivities obtained from pumping tests.

Physical properties laboratory tests routinely performed on consolidated aquifer materials are often identical to standard core analysis tests as used by the oil industry (*eg.* Worthington 1990, Worthington & Longeron 1991). However, tests performed on material from unconsolidated sedimentary aquifers are relatively uncommon, and the experimental techniques that are used owe more to the methods developed by soil scientists and engineering geologists (*eg.* Terzaghi 1943, Akroyd 1957, Black *et al.* 1965, BS5930 1981, Clayton *et al.* 1982, Klute 1986).

The equipment used in the laboratory investigation of unconsolidated materials may be of limited availability and can be expensive. In addition, many of the tests may require significant time from skilled or appropriately trained staff. Consequently, tests on unconsolidated materials can be expensive; they should only be undertaken for specific purposes (as outlined above) and they should be used only if they are believed to be cost effective within the context of the study being undertaken.

There are relatively few published works on the physical hydrogeological characteristics of non-indurated sediments. Davis (1969) has provided the most concise review to date of both field and laboratory measurements.

Table 2.1 (after Davis 1969) illustrates typical values of porosity, permeability and particle size data for a range of non-indurated sediment types. Porosities in non-indurated sediments are high (0.2 to 0.5) relative to consolidated materials, grain sizes may range over approximately five orders of magnitude, from 0.0001 mm diameter (glacial till and wind blown deposits, loess) to in excess of 10 mm diameter (beach gravels) and permeabilities of over eight orders of magnitude have been recorded (from less than 0.0001 mD for alluvial clays to greater than 10 000 mD for gravels).

Description of sample	Porosity (%)	Permeability (darcys)	Median diameter (mm)
CLAY			
marine	48.5	1.6×10^{-6}	0.0005
silty	41.1	1.1×10^{-4}	0.003
SAND			
marine	41.0	38.5	0.5
coarse, alluvium	41.0	2.2	0.5
medium, alluvium	42.9	0.6	0.32
fine, alluvium	42.4	0.27	0.14
SILT			
sandy	39.4	3.8×10^{-2}	0.059
clayey	34.1	5.5×10^{-3}	0.04
loess	50.0	0.33	0.02

Table 2.1 Laboratory and field observations of porosity and permeability for a range of unconsolidated materials (from Davis 1969)

Due to the large range in the hydrogeological physical properties of UNSAs a variety of types of test have been developed to measure any given hydrogeological parameter. For example, Section 5.4 describes three basic types of test that are

used in the laboratory measurement of permeability (the type of permeability test used for a given sample is dictated by a combination of equipment availability and the absolute permeability of the sample).

2.2 Review structure

This report has the following structure; the Preface, common to the entire series of BGS/ODA technical reports on unconsolidated sedimentary aquifers, briefly describes the worldwide occurrence of the aquifers and defines the scope of the UNSAs report series. Sections 1 and 2, present the background to, and outlines the aims of the present review of the use of laboratory techniques in the hydrogeological characterization of UNSAs physical properties. Section 3 briefly discusses the reasoning behind the laboratory methods described in this report and notes some of the practical problems associated with the quantitative measurement of hydrogeological parameters.

Section 4 gives details of methods and techniques used in the quantitative description of unconsolidated sedimentary aquifer materials in the laboratory and Section 5 gives details of laboratory hydrogeological measurement techniques. The latter section includes descriptions of porosity, capillary pressure and permeability tests. Where appropriate working definitions and brief theoretical background details are included to support the experimental descriptions. Throughout Sections 4 and 5 notes are made of references that give more detailed information on the experimental equipment and procedures, or of references that may be of use in data interpretation. Section 6 is a list of references cited in the text.

Method summary sheets have been included at the end of the text. These are intended to provide concise descriptions of the scope and use of each of the principal techniques described in this report. They also present brief illustrated descriptions of the experimental methods and give listings of key references associated with each of the procedures.

3. LABORATORY TECHNIQUES AND UNSAS

Laboratory techniques used in the evaluation of UNSAs can be broadly categorized into techniques used to describe the mineralogical and geometrical characteristics of the aquifer (*eg.* particle size and morphology or grain fabric) and techniques used to measure the hydrogeological physical properties of the aquifer. However, common aims for all laboratory methods can be identified and are described below. In addition, this section also gives details of error analysis and emphasises the importance of safe working practices.

3.1 Aims of Laboratory Techniques

The aims of quantitative laboratory tests on UNSAs are principally to assess the degree of hydrogeological variability of a given aquifer, and/or to obtain values for specific parameters and/or to validate, or establish correlations with field data.

As field conditions cannot be exactly replicated in the laboratory and because it is likely that sample structure will be modified by the time a sample has reached the laboratory all laboratory hydrogeological measurements should be regarded as relative (not absolute) observations that are some complex function of "in-situ" field values. If laboratory data is to be of use to the field hydrogeologist, geophysicist or the modeller it is important to identify and minimise the errors associated with laboratory measurements. The following sections briefly describe some of the possible sources of error in laboratory data, with particular reference to the problems associated with obtaining measurements from unconsolidated sediments.

3.1 Errors

Kempthorne & Allmaras (1986) present detailed discussions of the errors and variability associated with laboratory observations. Their discussions are illustrated with specific examples from the soil science literature. They note three sources of bias in laboratory data; scientific bias (bias introduced due to inadequacies in the specifications of the laboratory technique used), measurement bias (bias introduced by equipment errors) and sampling bias (bias introduced during the process of sample acquisition). Scientific bias in laboratory observations should be negligible if appropriate tests are used, consequently it is not discussed further.

The following sections present brief qualitative descriptions of measurement and sampling biases likely to be encountered in the laboratory characterization of UNSAs physical properties. However, if rigorous descriptions of the statistical treatment of measurement and sampling biases are required then the following are texts are recommended as introductions to the subject.

Griffiths (1967) gives a detailed description of the use of statistical techniques in the quantitative characterization of sediments (topics covered include sampling and grain size, shape and fabric measurement) and Davis (1986) provides a comprehensive but readable review of statistical and data analysis techniques (*eg.* sequence analysis and map analysis) with illustrations using geological examples.

3.1.1 Experimental bias

The aim of any hydrogeological laboratory technique is to obtain reproducible observations under specified laboratory conditions. A suite of tests performed following the same procedures and under the same conditions (with identical experimental errors) will be internally consistent. The absolute accuracy of the resulting data set is then a function of the experimental measurement errors.

Experimental measurement errors can be quantified and should be minimised. For example experimental measurement errors associated with the determination of sample porosity by the pycnometer method are entirely determined by the accuracy of the balance used to weigh the pycnometer. To minimise the measurement errors associated with this technique a balance of the appropriate scale range with the minimum associated weight measurement error should be used.

Most of the experimental techniques described in this report are relatively simple (with the exception of techniques such as x-ray diffraction and mercury injection capillary pressure determination), and may involve a few basic measurements, *eg.* sample dimensions, sample weight, viscosity or temperature. Consequently, experimental bias may be expected to be minimal. If scientific and experimental biases are minimal sampling bias may be expected to be the most significant bias introduced into laboratory hydrogeological observations of UNSAs.

3.1.2 Sampling bias

Petersen & Calvin (1986) provide a detailed discussion of the theory of soil sampling that is also applicable to the sampling of UNSAs. They recognise four typical sampling regimes; the judgement sample, the simple random sample, the stratified random sample and the systematic sample.

Judgement samples are those where something is known about the population under investigation and this information is used to obtain a "representative" sample, as a result these samples are biased. Simple random samples are obtained by a variety of techniques that dictate the random selection of samples from an entire population while stratified random samples are obtained at random from sub-populations within an entire population. Finally, systematic samples are obtained according to a regular or predetermined selection procedure, *eg.* at regular depth intervals down a borehole.

The frequency of sampling required to characterize any parameter will depend on the magnitude of the variation within the population under investigation, *ie.* the more heterogeneous the porosity distribution in an UNSAs the more samples are required to define the heterogeneity.

Due to the diverse nature of the hydrogeological parameters discussed in this report it is not possible to describe all the possible types of sampling biases that can be introduced into laboratory data. Where biases are likely to be encountered these are noted in the appropriate subsections of Sections 4 and 5, however the most significant sample biases encountered in the hydrogeological evaluation of UNSAs physical properties are briefly discussed below.

There are two types of sample bias commonly encountered during laboratory evaluation of unconsolidated sediments; bias introduced by

- disturbance of sample structure and
- unrepresentative samples due to poor sampling techniques.

By the time samples of unconsolidated sediments reach the laboratory they have inevitably undergone some degree of structural change. These structural changes are of little consequence for tests such as grain size analyses where samples are required in a disaggregated form, but they can be of critical importance to the result of porosity, pore size distribution and permeability tests.

Many fine grained sediments may undergo significant compaction during sampling. Smearing of soft sediments can occur at core edges where they are in contact with thin walled borers and clay rich samples, if allowed to dry, can flake or crack.

For samples with grain sizes greater than that of a fine to medium grained sand it is likely that only disaggregated samples will be obtainable. However, for finer grained materials disturbance of sample structure can be minimised by a combination of the use of appropriate field techniques, careful sample handling and good laboratory practices.

If an appropriate sampling scheme, *eg.* a simple random or a stratified random sampling scheme, has been adopted samples should in principal be representative of the population from which they have been taken. However, samples collected for use in grain size analyses are particularly prone to being unrepresentative.

During collection of disaggregated material at the drill site fines may easily be washed out (this problem is particularly acute when sampling a relatively coarse grained material with a fine matrix), conversely, during the sampling of relatively coarse grained aggregates it is possible to collect insufficient coarse material to adequately characterize the grain size distribution.

These problems are discussed in more detail later, however if samples are to be collected for grain size analysis the operator should be satisfied that the samples are representative.

3.2 Good laboratory practices

Good laboratory practices are essential to the efficient and safe running of a physical properties laboratory. Gale & Hoare (1991) set out a clear series of guidelines covering sample documentation, sample storage, equipment use and maintenance, chemical handling and measurement techniques specifically applicable to the testing of unconsolidated aggregates. Their appendices contain guidelines for laboratory safety and refer to UK safety legislation, they also contain useful references on safety procedures. Workers should be familiar with and comply with the appropriate national or state safety legislation.

4. SAMPLE DESCRIPTION METHODS

The following sections outline some basic principals behind the quantitative description of lithological and physical characteristics of unconsolidated sediments and provide a brief introduction to the extensive literature. Topics covered include mineralogical description of unconsolidated sediments, sample colour description and the geometrical characterization of unconsolidated sediments through grain size analysis and grain morphology and fabric description.

4.1 Mineralogical description

Mineralogical descriptions may be required as part of a hydrogeological investigation of an unconsolidated aquifer. These should be performed in a manner similar to standard petrographic analyses of consolidated, or lithified geomaterials. There is a plethora of standard petrographic texts and reference works, this section is intended to act only as a very brief introduction to the literature.

Carver (1971) and Hutchinson (1974) give detailed accounts of the use of optical polarizing microscopes, photomicrography, modal analysis, mineral separation for heavy mineral analysis and a variety of more sophisticated techniques. Both texts include extensive lists of references.

Tucker (1981) presents a concise introduction to the petrological description of sedimentary rocks. After an introduction that reviews basic concepts and methodologies terrigenous clastic sediments (coarse and fine grained), limestones, evaporites and a variety of less common lithotypes such as volcanoclastic sediments are described. Gale & Hoare (1991) provide a state of the art review of the characterization of (quaternary) regolith, including the lithological analysis of gravel-grade particles. They also include as an appendix a useful precis of the physical properties of the more common rock forming minerals. Cady *et al.* (1986) present a comprehensive review of the petrographic analysis of soils. Deer *et al.* (1982) is a standard mineralogy reference text.

Perhaps the most problematic minerals to identify, and those which may well be of particular interest to the hydrogeologist, are the clays. Clays are a mineralogically diverse group of platy or sheeted hydrous aluminosilicate minerals. They are important in the process of ion exchange, but in addition a number of clays, such as the smectite montmorillonite, have the ability to absorb/desorb large quantities of water. Changes in the degree of water saturation of such clays is often associated with substantial changes in volume.

The identification of clay minerals is usually performed by x-ray diffraction of the less than 2 μm component of a mineral assemblage. This technique is widely used in sedimentary petrology and in the analysis of soil mineralogy and chemistry (Whittig & Allardice 1986). The technique is expensive and is unlikely to have general application to UNSAs evaluation, however the following is a brief outline of the methodology.

4.1.1 X-ray diffraction techniques

The principals of x-ray diffraction have been discussed extensively (*eg.* Wormald 1973, Klug & Alexander 1974, Cullity 1978). The technique relies upon the detection of diffraction patterns generated by the interaction of x-rays with the regular crystalline structure of clay lattices. The phenomenon of diffraction involves the scattering of x-rays by atoms of a crystal and the reinforcement of the scattered rays in specific directions away from the crystal. As different mineral phases have unique interatomic distances each will give rise to a unique array of diffraction maxima.

Clay samples to be analyzed are in the form of fine powders, individual crystals of which are randomly oriented with respect to the primary beam of monochromatic x-rays. Due to the large number of crystals there is always a sufficient number of crystallites oriented so that every set of lattice planes will be capable of diffraction, *i.e.* the powder is equivalent to a single crystal rotated about all possible crystallographic axes. If more than one mineral phase is present in the powder discrete diffraction maxima will be obtained for each phase. The diffracted rays are recorded on a cylindrical photographic plate behind the sample.

Successful identification and quantification of clay mineral species requires complex polymineralic aggregates to be fractionated according to particle size, which in turn is only achieved if the samples have been dispersed by removal of flocculating and aggregate-cementing agents. In addition, since expansive phyllosilicates can retain different amounts of interlayer water, depending on the nature of their interchangeable cations, the clay samples need to be treated so that they are homoionic (this involves saturation with an ion exchange complex). A detailed account of procedures employed in sample preparation and in obtaining x-ray diffractograms is given in Hutchinson (1974).

4.1.2 Sample Colour

The rational description of sample colour is particularly important in the description of fine grained sediments. In some circumstances field logging of a sequence of fine silts or muds may rely almost entirely on the colour of the material. The following section gives details of the most widely used colour classification scheme for geomaterials.

The colour of geomaterials is a function of their mineralogy, geochemistry and grain size distribution. The main controls on colour are the concentration of organic matter, degree of pyrite content and of the oxidation state of the material. Red and purple colours are due to the presence of ferric oxide (hematite), which usually occurs as grain coatings and as complex intergrowths with clay minerals. Green colouration indicates the absence of hematite, organic matter and iron sulphides and results from the presence of ferrous iron associated with illite and chlorite. Other colours such as olive and yellow are commonly due to the mixing of green clay minerals with darker organic matter. It is essential that an objective scheme of colour classification be used in the description of geomaterials. The most commonly adopted scheme is the Munsell system (see Folk 1969, Nickerson 1976, Gale & Hoare 1991 for detailed descriptions of the classification scheme and its applications). The classification is based on three coordinates, hue, value and chroma which constitute an approximately spherical colour solid (Figure 4.1) and which can be combined into a numerical notation.

Hue is the dominant base colour, the Munsell classification recognises 100 hues arranged into five principal hues, red (R), yellow (Y), green (G), blue (B) and purple (P) and five intermediate hues, *eg.* yellow red (YR). Rocks commonly occupy the range R-YR-Y. Within a given hue the colour intensity increases from 0 to 10, *i.e.* yellow-red hues become more yellow in the YR range from 10R (OYR) to 10YR (OY) with 5YR in the middle of the range.

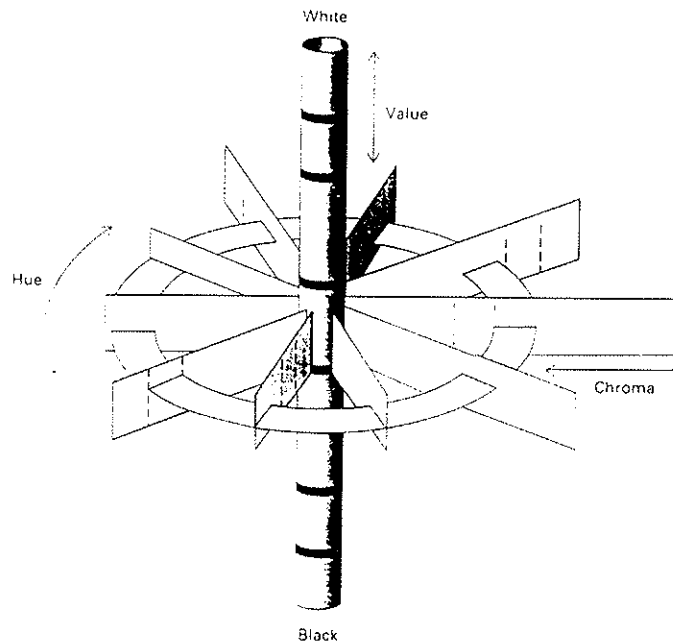


Figure 4.1 The Munsell colour solid. Value is plotted as the vertical axis, with hue and chroma plotted in the horizontal plane. Most geological materials plot in the range of hues 10R to 5Y (see text for details).

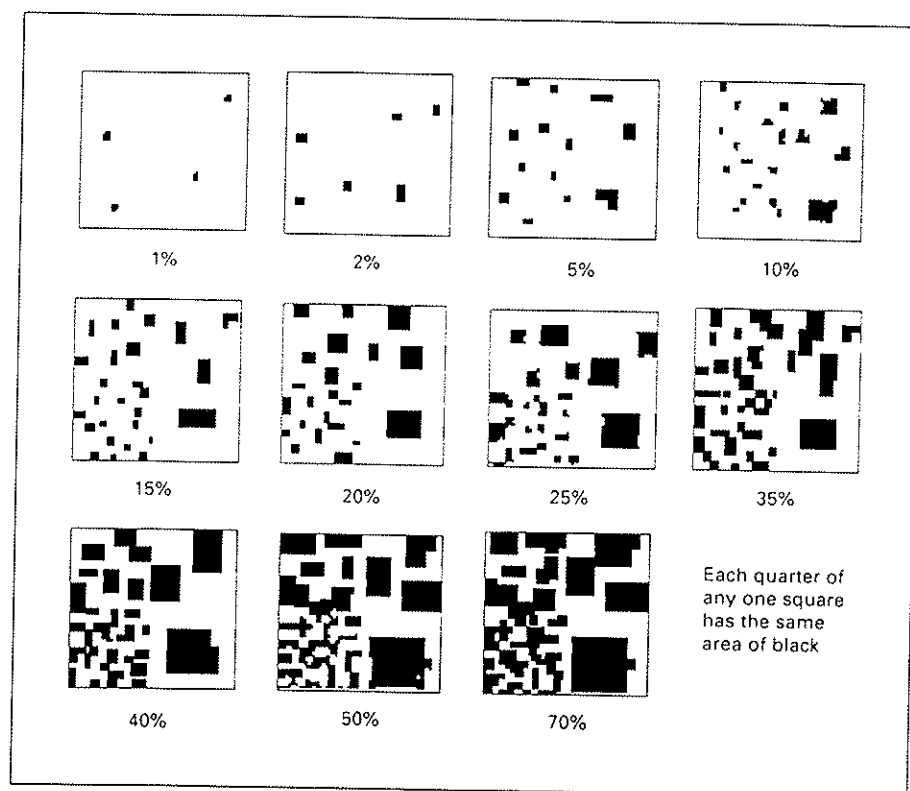


Figure 4.2 Chart for the visual estimation of the proportion of mottle in a geological material. Each quarter of any one square has the same proportional area of black (from Gale & Hoare 1991, after Hodgson 1974).

Value is a measure of the luminosity, brightness or proportion of black or white of a given colour. It constitutes the vertical axis of the colour solid and is represented in Munsell notation by a number between 0 (absolute black) and 10 (absolute white), 5 signifies an intermediate grey. An example of value notation as applied to a yellow-red rock would be as follows, 10YR 4/. Chroma indicates the intensity or strength of the colour, ie. the proportion of pure colour to neutral grey. Chroma constitutes the horizontal axis of the Munsell colour solid and varies from 0 for a neutral grey to 20 for a fully saturated colour (a value never approached by natural unconsolidated materials). An example of chroma notation as applied to a yellow-red rock would be as follows, 10YR 4/4.

To enable rapid and easy identification of the hue, value and chroma of materials Munsell soil colour charts are available (Anon 1975), these contain 199 colours in seven charts covering hues from 10R to 10Y. Unconsolidated aquifer materials may have a mottled appearance, in such cases charts are available (eg. Figure 4.2) to enable visual estimations of the proportion of mottles (Hodgson 1974).

4.2 Geometrical characterization of unconsolidated materials

There are three principal elements to the geometrical characterization of unconsolidated sediments; particle or grain size analysis, grain morphology and grain fabric descriptions. The results of particle or grain size analysis have been extensively used in the hydrogeological evaluation of non-indurated materials and consequently grain size analysis methods will be described in some detail. Methods of grain morphology and grain fabric analysis are also briefly discussed.

4.2.1 Particle size analysis

There are a variety of definitions of particle size, eg. linear dimension, volume diameter and the hydraulic-equivalent diameter.

For particles large enough to measure directly the linear dimension can be defined using the length of one of the three major particle axes. Volume diameter is the diameter of a sphere with an equivalent volume to the particle under consideration. This is commonly approximated by a nominal diameter D_n , where D_n is the cube root of the product of the three major axes. The hydraulic-equivalent diameter is usually taken to be the diameter of a sphere of quartz density ($\sim 2650 \text{ kg m}^{-3}$) which has the same terminal settling velocity in a fluid as the particle under consideration.

Techniques of particle size analysis as applied to geological materials are well established. The following sections review a number of grain size classification schemes and describe standard data presentation formats. They describe sample preparation procedures, sieve and sedimentation techniques and discuss the application of grain size analysis data to the hydrogeological evaluation of UNSAs.

There are a number of methods that are unlikely to be widely applicable in the evaluation of UNSAs. For example optical methods are unlikely to be of use

because of the possible diversity in grain sizes within a given sample and due to difficulties in optically resolving fine grains. Consequently, they are not considered in this review (optical methods are discussed in detail in an excellent book on quantitative stereology by Underwood 1970). Similarly, transmission electron microscopy (TEM), scanning electron microscopy (SEM), electrical sensory zone (Coulter counter) methods, turbidimeters and x-ray centrifuges have all been used to generate particle size analysis data. These methods are unlikely to be suitable for use in the analysis of UNSAs, however further information on these techniques can be found in Allen (1981).

Grain size classification schemes

A number of grain size scales have been proposed and adopted, one which is commonly used is the Udden-Wentworth scale (Udden 1914, Wentworth 1922). The Udden-Wentworth scale, illustrated in Table 4.1, divides sediments into seven grades, *i.e.* clay, silt, sand, granules, pebbles, cobbles and boulders (sands and silts are subdivided into five and four subclasses respectively). The term gravel, not included in the Udden-Wentworth scale, is usually applied to loose sediments coarser than sand grade (2mm).

The Udden-Wentworth scale is a geometric scale graduated in millimetre units (*i.e.* 1, 2, 4, 8, 16 *etc.*), but it is commonly converted to an arithmetic scale (*i.e.* 1, 2, 3 *etc.*) of phi (ϕ) units, where $\phi = -\log_2 S$ and where S is the grain size in millimetres. Commonly, phi class intervals in the sand range are at quarter phi intervals. Conversion tables for mm to phi units are available (Page 1955).

Other grain size classifications have been adopted as standards by a variety of organisations, *eg.* International Soil Science Society (ISSS, Yong & Warkentin 1966), U.S. Department of Agriculture (USDA Soil Survey 1975), Canada Soil Survey Committee (CSSC, McKeague 1978) and the American Society for Testing and Materials (ASTM 1985). These classifications usually correlate names such as gravel, fine gravel or medium sand, to specific particle size ranges or ASTM sieve number or size ranges (openings in inches). These classification schemes are illustrated in Table 4.2.

The grain size terms defined in the Udden-Wentworth scale can be used to describe sediments with unimodal grain sizes, however, most sediments have distributed grain size ranges. Consequently, it has been necessary to develop descriptive classification schemes for these material. The classification schemes have usually been based on a ternary system of the relative proportions of either sand, silt and clay or gravel, sand and silt/clay. Perhaps the most widely adopted is the classification of Folk (1954), as illustrated in Figures 4.3a and 4.3b.

mm	phi	Class terms
256	-8	boulders
128	-7	cobbles
64	-6	
32	-5	pebbles
16	-4	
8	-3	
4	-2	granules
2	-1	
1	0	sand
0.5	1	
0.25	2	
0.125	3	
0.0625	4	
0.0312	5	silt
0.0156	6	
0.0078	7	
0.0039	8	clay

Table 4.1 The Udden-Wentworth scale. The table presents the phi unit to millimetre conversion and the associated particle size nomenclature. Although the finest size category shown is that of fine clay and the largest is that of boulder there are no theoretical size limits to the classification.

PARTICLE SIZE LIMIT CLASSIFICATION					
		USDA	CSSC	ISSS	ASTM (UNIFIED)
0.0002	ASTM SIEVE NUMBER OR SIZE (OPENINGS / INCHES)	CLAY	FINE CLAY	CLAY	FINES (SILT AND CLAY)
0.001			COARSE CLAY		
0.002		SILT	FINE SILT	SILT	
0.003			MEDIUM SILT		
0.004					
0.006			COARSE SILT		
0.008					
0.01		VERY FINE SAND	VERY FINE SAND	FINE SAND	
0.02		FINE SAND	FINE SAND		
0.03		MEDIUM SAND	MEDIUM SAND	COARSE SAND	
0.04					
0.06	COARSE SAND	COARSE SAND	MEDIUM SAND		
0.08	VERY COARSE SAND	VERY COARSE SAND			
0.1	FINE GRAVEL	GRAVEL	GRAVEL	COARSE SAND	
0.2	COARSE GRAVEL			FINE GRAVEL	
0.3					
0.4	COARSE GRAVEL				
0.6	COBBLES			COBBLES	COBBLES

Table 4.2 Comparison of particle size limits, ASTM sieve number or size (openings in inches) and nomenclature according to several current classification schemes. USDA - US. Department of Agriculture classification, CSSC - Canada Soil Survey Committee classification, ISSS - International Soil Science Society classification and ASTM - American Society for Testing and Materials classification (after Gee & Bauder 1986).

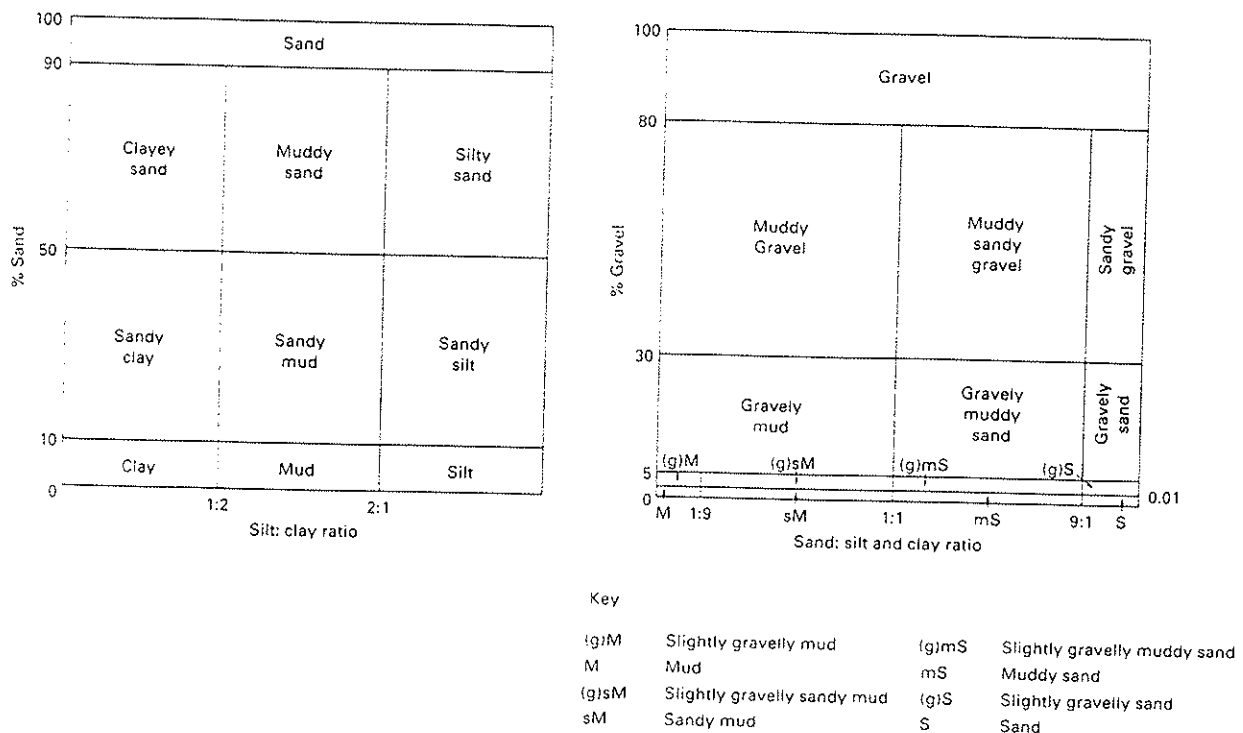


Figure 4.3 Nomenclature for sediments with distributed grain sizes (after Folk 1954). a, particle size classification for materials of sand grade and finer (<2.00 mm) and b, particle size classification for materials of a coarser grade than sand grade (>2.00 mm).

Graphical presentation of grain size distribution data

Particle size analysis data may be plotted as frequency distributions (Figure 4.4), however it is usually plotted as size distribution curves (geologists) and as USDA (United States Department of Agriculture) soil texture plots (soil scientists). McBride (1971) provides a concise review of the graphical presentation of grain size distribution data.

Particle size distribution curves are plots of the cumulative percentage of particles less than a given particle size plotted against the log of the "effective" particle diameter, where the cumulative percentage is plotted on either an arithmetic frequency scale or on a probability frequency scale. Examples of such plots and the corresponding frequency distribution are given in Figures 4.4. By convention the grain size is plotted as decreasing along the abscissa (x-axis).

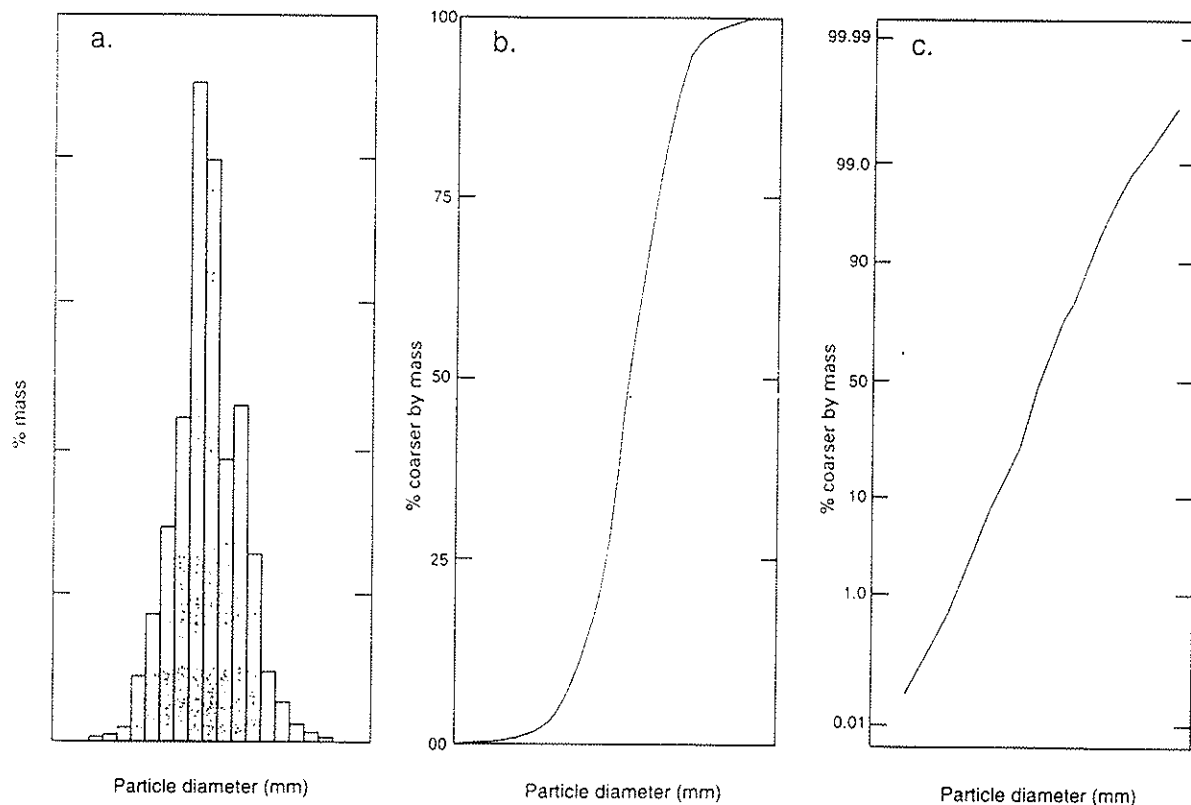


Figure 4.4 Illustration of a typical particle size distribution plotted a as a histogram, b as a cumulative frequency distribution (arithmetic scale) and c as a cumulative frequency distribution (probability frequency scale) (after Tucker 1981).

The standard deviation of the distribution (in phi units) can be used as the basis of a verbal classification for the degree of sorting (Folk & Ward 1957). Similarly skewness and kurtosis have verbal classifications associated with the form of the grain size distribution (Folk & Ward 1957). These classifications are detailed in Table 4.3. Charts for visual estimation of the degree of sorting are available, Figure 4.5 is an example from Tucker 1981, after Pettijohn *et al.* 1973).

The USDA soil texture plots are triangular plots, used in the classification of soils, where the percentage of clay grade material is plotted vs the percentage of sand grade material (Figure 4.6).

Standard Deviation (phi-units)	Category
<0.35	Very well-sorted
0.35 to 0.49	Well-sorted
0.50 to 0.99	Moderately-sorted
1.00 to 1.99	Poorly-sorted
2.00 to 3.99	Very poorly-sorted
≥ 4.00	Extremely poorly-sorted

Skewness (psi-units)	Category
-1.00 to -0.31	Very negative (coarse)-skewed
-0.30 to -0.11	Negative (coarse)-skewed
-0.10 to 0.09	Nearly symmetrical
0.10 to 0.29	Positive (fine)-skewed
0.30 to 0.99	Very positive (fine)-skewed

Kurtosis (phi-units)	Category
<0.67	Very platykurtic
0.67 to 0.89	Platykurtic
0.90 to 1.10	Mesokurtic
1.11 to 1.49	Leptokurtic
1.50 to 2.99	Very leptokurtic
≥ 3.00	Extremely leptokurtic

Table 4.3 Nomenclature associated with the description of grain size distributions. a, verbal scale for degree of grain size sorting (standard distribution of the phi scale frequency distribution). b, verbal scale for skewness and c, verbal scale for kurtosis (after Folk 1957).

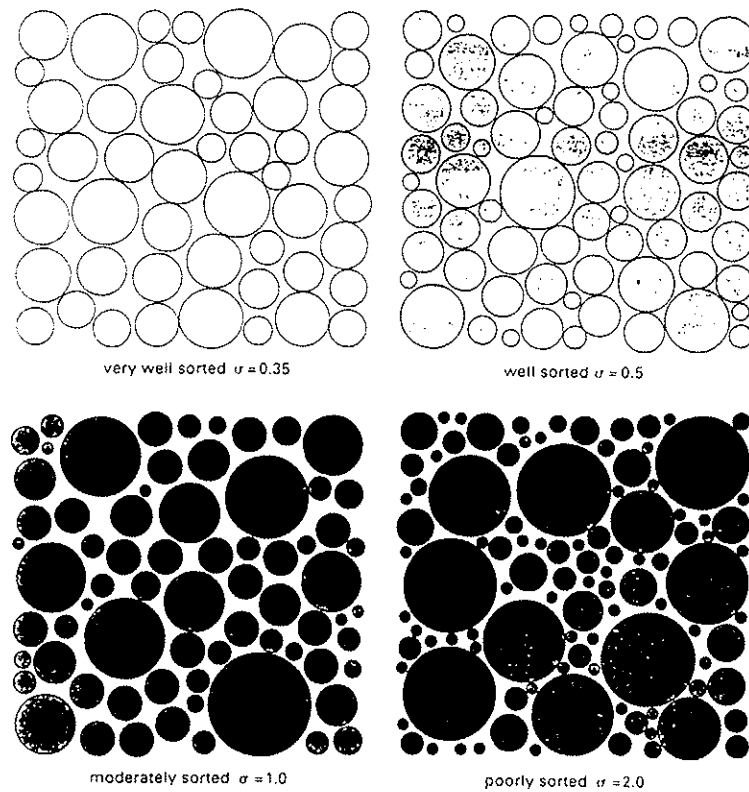


Figure 4.5 Example of a chart for the visual estimation of the degree of grain size sorting, where degree of sorting is defined in terms of the standard deviation (σ) (from Tucker 1981, after Pettijohn *et al.* 1973)

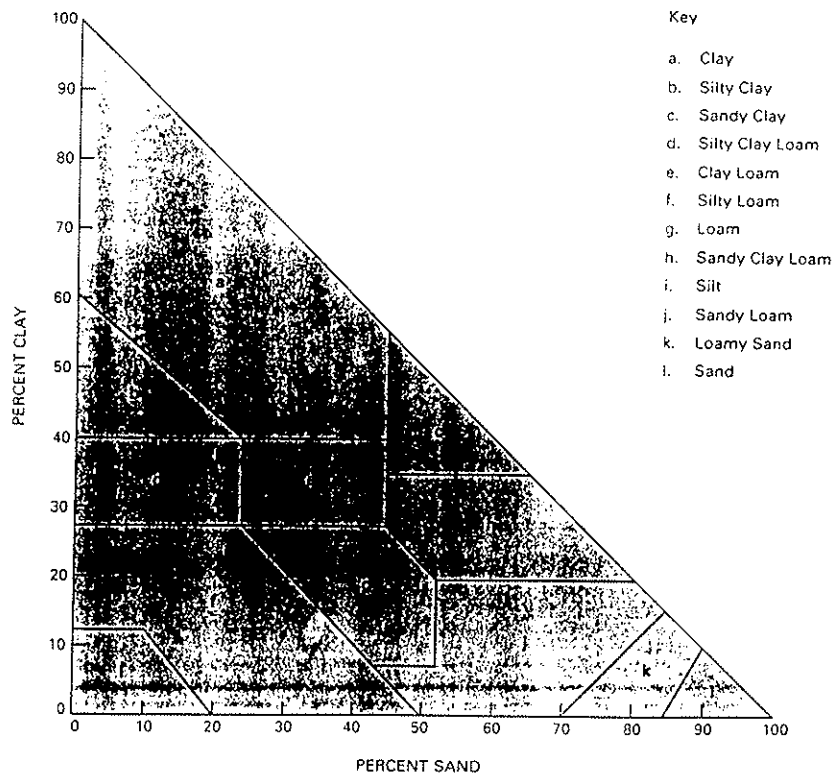


Figure 4.6 USDA soil classification chart (after Gee & Bauder 1986)

Preparation of samples for grain size analysis

Sample preparation procedures are an important precursor to grain size analysis. Preparation procedures will vary greatly according to

- the nature of the sample being analyzed (*eg.* soil or clean sand, coarse grained or fine grained),
- the grain size analysis technique being used (*eg.* sieve or sedimentation analysis) and
- the degree of sample consolidation.

The three basic types of sample preparation procedures are chemical pretreatment (primarily used in the analysis of soils), mechanical disaggregation and subsampling (primarily used in the analysis of sediments) and dispersion techniques (usually used in the treatment of fine and very fine grained aggregates prior to sedimentation grain size analysis).

Chemical pretreatment

Ingram (1971) and Gee & Bauder (1986) present extensive reviews of chemical pretreatment procedures for soil samples. As standard soil grain size analysis methods usually require soil particles to be dispersed in an aqueous solution chemical pretreatment and dispersion techniques are usually run concurrently.

Common soil science chemical pretreatments include the removal of organic matter (typically using sodium peroxide), the removal of iron oxides (*eg.* hematite) and carbonate cements (the latter being removed by acidification of the sample with hydrochloric acid) and the removal of soluble salts (*eg.* sodium, calcium and magnesium chlorides and carbonates). Sophisticated pretreatments are more important in the study of structurally, mineralogically and chemically complex soils than in relatively clean loose sands therefore care should be taken to match the appropriate pretreatment to each sample type to be studied.

Mechanical disaggregation and subsampling

The principal aim of mechanical disaggregation and subsampling procedures is to obtain representative samples in a state ready for grain size analysis (either by sieving or sedimentation analysis). This initially requires

- adequate volumes of bulk sample material to be obtained,
- efficient but non-destructive sample disaggregation procedures and
- rigorous subsampling methods.

When sampling relatively coarse materials for grain size analysis it is difficult to determine what mass of material is sufficient to provide a representative sample. Gale & Hoare (1991) present a detailed discussion of the problem. The American Society for Testing of Materials (1987) has established a scheme where minimum

sample mass is proportional to the diameter of the largest clast in the material, while the recommended British Standards Institution (1985) procedure relates minimum sample mass to the diameter of the largest clast raised to the power 2.75. Gale & Hoare (1991) recommend the adoption of a scheme developed by Church *et al.* (1987). Church *et al.* (1987) showed that

- a minimum of 100 particles is required in each half phi-unit fraction to obtain a stable measure of the proportion of an entire sample and
- that the largest particle in the coarsest stable size fraction constitutes approximately 0.1% of a total sample mass (Figure 4.7).

Church *et al.* (1987) proposed that the latter observation is a suitable criteria for minimum sample size. Gale & Hoare (1991) recommend that due to the very large sample masses required for samples with large maximum particle sizes the 0.1% criterion should be adopted for maximum particle sizes of up to 32 mm and a 1.0% criterion for particle sizes in excess of 32 mm.

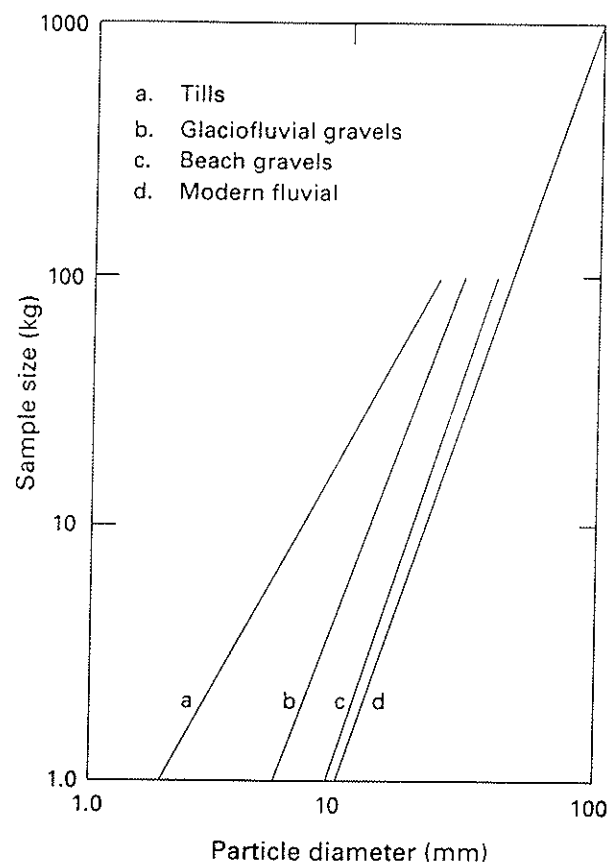


Figure 4.7 Minimum sample mass required to obtain a reproducible measure of particle size distribution as a function of maximum particle size for ancient tills, glaciofluvial and beach gravels and for modern fluvial gravels (from Gale & Hoare 1991).

Coning and quartering or sample splitters should be used to reduce excessive sample masses to suitable masses for sieve analysis (see Ingram 1971 for details of procedures).

Simple mechanical disaggregation procedures require that the sample is initially dried in air or in an oven at 40° C (higher temperatures can bake clays and make their mechanical disaggregation problematic). Clumps of the sample can then be broken by hand, in a pestle and mortar or a wooden rolling pin (Ingram 1971). Grains should become disaggregated but individual grains should not be broken.

Gale & Hoare (1991) provide a detailed discussion of practical procedures associated with the subdivision of samples with distributed grain sizes. They recommend that a split be made at 63 μm , so that relatively coarse material can be obtained for sieve analysis and relatively fine material can be obtained for sedimentation analysis.

Dispersion

If sedimentation techniques are to be used samples are required to be dispersed in aqueous solutions. Gee & Bauder (1986) provide a detailed review of the available techniques. These include the use of electronic mixers with specially designed paddles, air-jet stirrers and reciprocating shakers. Dispersion may also be achieved with ultrasonic baths. This latter technique is commonly employed in conjunction with chemical dispersants (Kubota 1972, Mikhail & Briner 1978).

Sieve grain size analysis

Various standard test procedures are available for sieve grain size analyses, *eg.* American Society for Testing and Materials (ASTMS 1985), however it is essential that the sieving procedures used are suited to the type of material being investigated. For example methods suitable for the investigation of clean gravels with relatively unimodal grain sizes, such as river or beach gravels, are not necessarily be suitable for matrix rich gravels (Gale & Hoare 1991).

To perform a basic sieve analysis some form of mechanical shaking device and a set of sieves with the appropriate range of mesh apertures are required. A nest of sieves is built up using the desired mesh sizes with the coarsest screens at the top and the finest screens at the bottom. The disaggregated material to be sieved is placed in the top sieve. A lid is placed on the top sieve to prevent loss of fines from the top sieve during shaking and a pan placed below the lowest sieve.

The nest of sieves is then firmly secured to a shaker and shaken for a nominal time, usually 10 to 15 minutes. Once sieving is complete the contents of each sieve are emptied and weighed. Care should be taken to remove all material, either by tapping the sieve on the rim and/or by using a soft nylon sieve brush. The contents of the pan at the base of the nest of sieves should also be weighed. Weight percentage by size fraction and cumulative weight percentage by size fraction can then be calculated. Ingram (1971) gives details of practical procedures for the handling, cleaning and calibration of sieves.

Sedimentation analysis

Sedimentation analysis depends on the relationship between grain settling velocity and grain diameter. Settling velocity, v , is related to spherical diameter as follows,

$$v = (\rho_s - \rho_l) X^2 / (18\eta) \quad 4.1$$

where X is the particle diameter, ρ_s is the particle density, ρ_l is the liquid density and η is the fluid viscosity.

This relationship, a form of Stoke's Law, may be applied to sedimentation analysis when

- the particles have reached their terminal falling velocity (a fraction of a second for particle within the applicable size range),
- the particles are smooth, rigid spheres that do not interact with each other (particle concentrations of less than 1%),
- the fluid is of infinite extent (side wall effects in sedimentation vessels of 4 cm diameter or greater are negligible),
- particles must be less $0.5 \mu\text{m}$ in diameter (to prevent Brownian motion effects) and must not be greater than $50 \mu\text{m}$ (above this limit there is turbulence in the fluid during grain settling and Stoke's Law breaks down).

In practice sedimentation techniques are used on grain size fractions up to $62.5 \mu\text{m}$ (lower size limit of sand), since errors introduced by possible turbulence effects are minimal and as geological particles are not ideally smooth or spherical X is taken to be an "equivalent" hydrodynamic grain diameter.

There are two basic methods of sedimentation analysis, the pipette method and the hydrometer method. Detailed descriptions of the equipment and chemical reagents used and of the experimental procedures employed in each type of test are given in Galehouse (1971), Gee & Bauder (1986) and in Gale & Hoare (1991). The following sections are brief descriptions of the basic principals and methods used in pipette and hydrometer tests.

The Pipette method

Grain size can be calculated from a modified form of Stoke's Law (Gee & Bauder 1986) using the pipette method. The method requires samples of a suspension to be removed from known depths (h) at known times (t).

A sample is placed in a cylindrical container and distilled water (and a chemical dispersant if required) is added to make up to a volume of 1 litre. The cylinder is covered and the solution left to stand and equilibrate for several hours. Following equilibration the suspension is stirred by hand with an up and down motion for a

minimum of 30 seconds. On completion of stirring the temperature of the suspension and the time are noted.

After an appropriate time has elapsed a pipette is placed into the suspension to a suitable depth, which is recorded, and a 25 mL sample of the suspension is removed. The 25 mL sample is placed in weighing bottle, the water is evaporated, the clay dried in an oven at 105 C, cooled in a desiccator and finally weighed. The type of pipette commonly used in the sampling procedure is a closed Lowy pipette mounted in an adjustable supporting clamp (Figure 4.8), pipet suction is supplied by a vacuum line. Gee & Bauder (1986) give full details of calculation procedures.

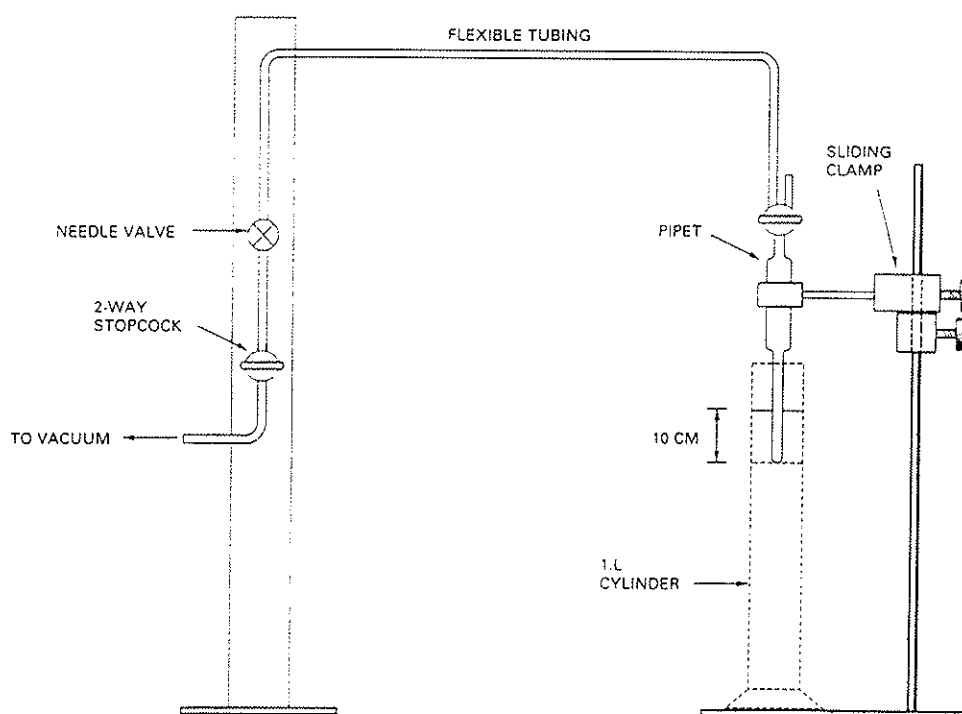


Figure 4.8 Schematic illustration of pipette stand and apparatus configuration for sedimentation analysis (after Gee & Bauder 1986).

The Hydrometer method

The hydrometer method requires density measurements to be taken using a calibrated hydrometer.

The hydrometers used in the tests are type H hydrometers, as illustrated in Figure 4.9. A solution of distilled water and chemical dispersant (if required) is made up in a 1 litre sedimentation cylinder (the cylinder should be approximately 35 cm tall to take the hydrometer). The hydrometer is placed in the blank solution to determine the base hydrometer-scale reading.

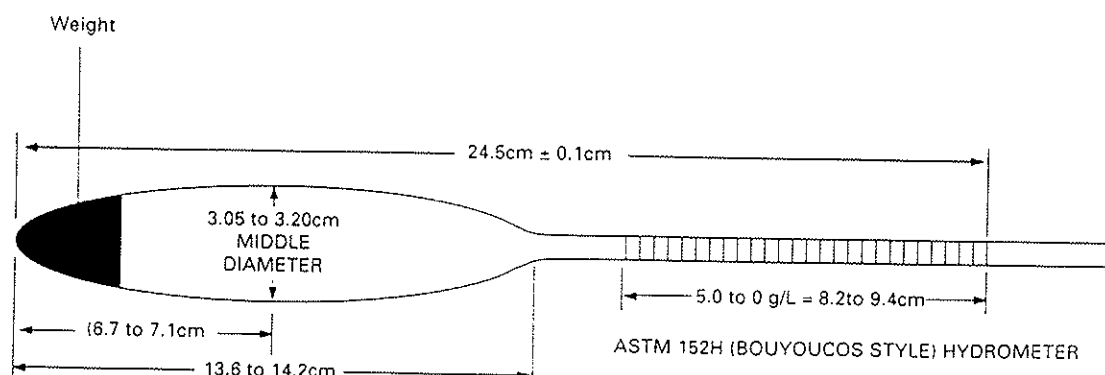


Figure 4.9 Schematic illustration of an ASTM type H hydrometer as used in sedimentation tests.

Approximately 40 g of sample are placed in a beaker, water and chemical dispersant are added and the mixture allowed to stand overnight. The sample then undergoes physical dispersion (either using an electric mixer or automatic shaker, see Gee & Bauder 1986 for details) and is finally placed in a litre cylinder and made up to a volume of one litre with distilled water.

The suspension is allowed to thermally equilibrate and stirred for at least 30 seconds with an up and down motion. When mixing is complete place the hydrometer in the cylinder and take the initial density measurement. Remove and clean the hydrometer. Repeat density measurements should be obtained at suitable time intervals. Gee & Bauder (1986) suggest suitable timetables for density observations and describe how particle sizes are calculated using the density observations.

Interpretation of grain size analysis data

Accurate grain size analyses are an important step in successful borehole design in UNSAs. The choice of appropriate gravel pack sizes and screen slot sizes depends on the quality of grain size distribution data. Herbert (1994) gives full details of how grain size distribution data should be used in borehole design.

Grain size distributions are commonly used to obtain rough estimates of hydraulic conductivity or permeability, this section is a brief review of a number of methods that have been adopted. However, it should be noted that the relationships described in this section should be used with great caution. The relationships are generally based on empirical observation of specific materials or on theoretical considerations; the empirical studies are not entirely representative of all unconsolidated sediments and many natural sediments may depart significantly from the assumptions used in the formulation of the theoretical models. *There is no substitute for the direct field measurement of transmissivities or of the measurement of the permeability of laboratory samples.*

An early empirical relation established by Hazen (Freeze & Cherry 1979) predicts the following power law relationship between hydraulic conductivity, K , and effective grain size, d_{10} ,

$$K = Ad_{10} \quad 4.2$$

where d_{10} is the grain size of the 10% by cumulative weight of particles. If K is in cm/s and d_{10} in mm then A in Eqn. 4.2 is equal to 1. Freeze & Cherry (1979) note that this relationship was originally determined for sands with unimodal grain sizes but can provide rough but useful estimates of hydraulic conductivity for aggregates in the fine sand to gravel range.

Krumbein & Monk (1942) established an empirical relationship between permeability and mean geometric grain diameter using synthetic samples composed of reconstituted sands with controlled grain size distributions. They found that

$$k = bd^2e^{-a\sigma} \quad 4.3$$

where k is the permeability (Darcy units), d is the geometric mean diameter (mm), σ is the geometric standard deviation of the grain size (in phi units) and a and b are constants.

Other empirical studies have established correlations between median grain size and the logarithm of the sample permeability (*eg.* Johnson 1963). Masch & Denny (1966) developed a more sophisticated scheme for determining permeability from grain size distribution curves by taking into account the entire form of the curves. They obtained a series of grain size distribution curves for samples prepared from unconsolidated sand. Using a measure of dispersion about a median diameter (the inclusive standard deviation of Folk 1955) they were able to establish an empirical correlation between the median grain size (in phi units) and permeability measurements as a function of the inclusive standard deviation of the grain size distribution. This relationship is illustrated graphically in Figure 4.10.

Egboka & Uma (1986) have shown that hydraulic conductivities calculated from grain size distributions for sediments from the Ajali formation of Nigeria were in good agreement with the results of pumping tests.

Theoretically derived relationships have been used to predict hydraulic conductivity from grain size distribution data, the most widely known being the Kozeny-Carmen equation (see Bear 1972 or Dullien 1979 for discussion). The Kozeny-Carmen equation requires porosity values as it predicts that permeability is a function of both fluid properties (*i.e.* viscosity and density), sample porosity, and grain surface area (a function of the grain size distribution).

Grain size distributions have also been used to predict the hydraulic properties of soils (Bloemen 1980 and Arya & Paris 1981 used the results of grain size analyses to predict water retention and unsaturated hydraulic conductivity in soils).

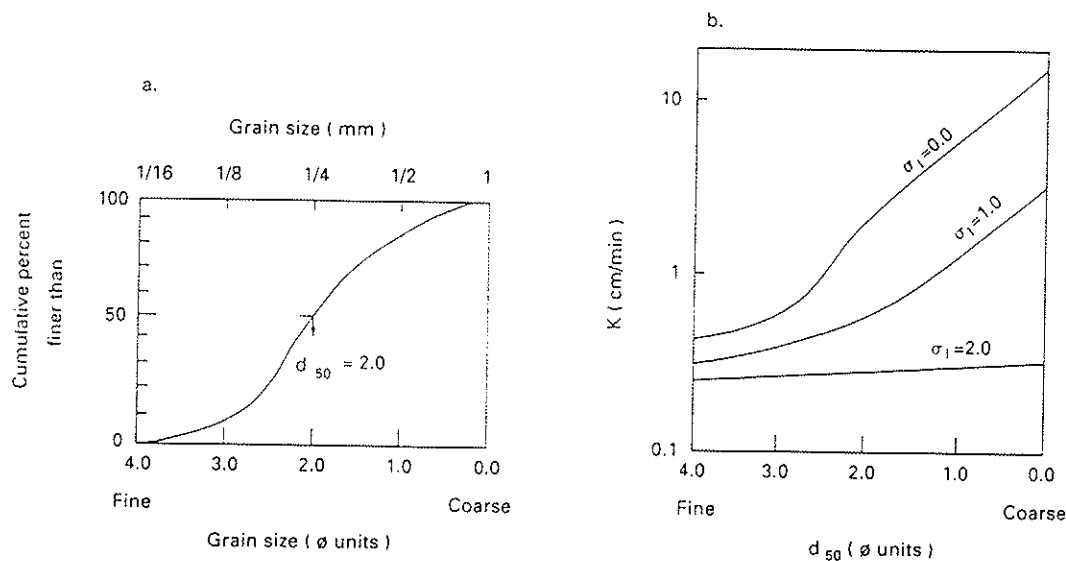


Figure 4.10 Masch & Denny (1966) scheme for determining permeability from grain size distribution data. a typical grain size distribution plot for an unconsolidated sand, where $\phi = 2.0$ at d_{50} , and b plot of permeability as a function of d_{50} grain size (in ϕ units) contoured for cumulative grain size distribution standard deviations.

4.2.2 Grain morphology

The morphology of grains in unconsolidated materials may have a significant effect on the degree and nature of porosity (see discussion on grain packing, Section 4.1), but the rigorous measurement of individual grain forms is a slow procedure. Consequently, the analysis of grain morphology is likely to be of limited practical value in the evaluation of UNSAs. Pryor (1971), Pettijohn *et al.* (1973) and Tucker (1981) provided an introduction to the extensive literature on the morphology of sedimentary grains. The following brief comments are largely taken from these sources.

Grain shape, roundness and pivotability are the three principal grain form parameters. Grain shape is defined in terms of a grain's spacial geometric form and roundness describes the degree of sharpness of the grain's corners and edges. Pryor (1971) defined pivotability as a measure of the motion response of a grain to a set of standard physical conditions in a gravity-driven system. Qualitative descriptions may be applied to grain shape, such as needle-shaped, irregular, globular or lozenge-shaped, however it is more useful to describe grain shape in terms of rigorously defined parameters, such as sphericity, flatness ratio, roundness ratio and elongation indices (Pryor 1971). Figure 4.11 illustrates a fourfold classification of sedimentary grain shape adopted by Tucker (1981). Qualitative terms such as angular, subangular and rounded may be used to describe roundness and a variety of charts are also available for the visual comparison of roundness (Figures 4.12). However, quantitative roundness parameters have also been defined, *eg.* Wadell (1933), Wentworth (1933) and Cailleux (1947). Pivotability is a somewhat esoteric concept that has been investigated by a number of sedimentary petrologists but is of no practical interest to the field hydrogeologist.

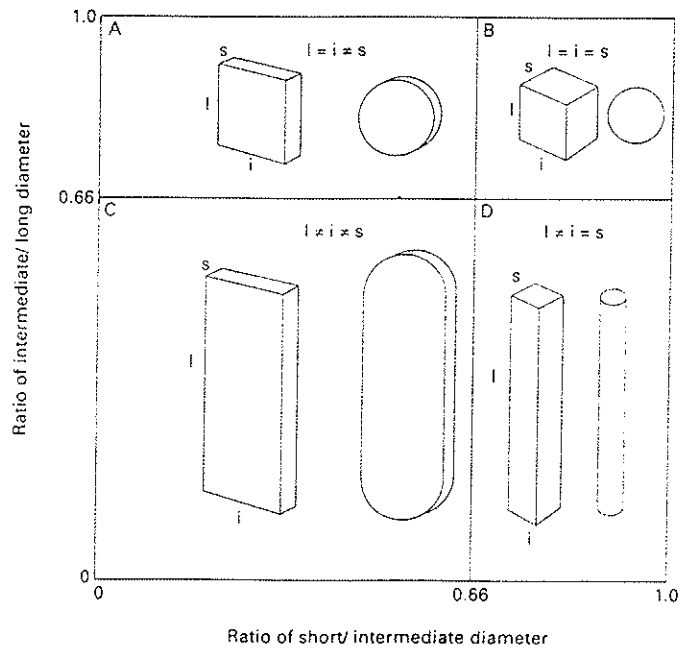


Figure 4.11 Illustration of the four principal classes of sedimentary grain shape. The classification is based on the ratios of the long (l), intermediate (i) and short (s) diameters or axes of grains. The four classes defined in the figure are A : oblate (tabular or disc shaped), B : equant (cubic or spherical), C : bladed and D : prolate (rod shaped). Within each class an example of a well rounded and a very angular grain are given (after Tucker 1981).

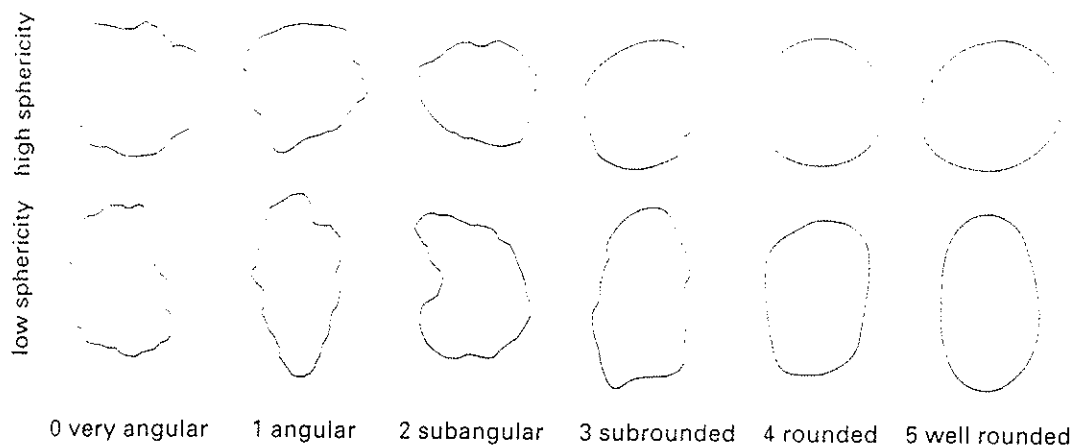


Figure 4.12 Chart for the visual comparison of roundness (from Tucker 1981, after Pettijohn *et al.* 1973).

4.2.3 Grain fabric

Grain fabric when applied to sedimentary materials, whether consolidated or unconsolidated, refers to the characteristic orientation and packing of the grains. Strong grain fabrics are not restricted to any particular grain size range although they tend to be associated with high energy depositional environments. Such fabrics may cause significant heterogeneities in transmissivity values in unconsolidated aquifers.

Although there is an extensive sedimentological literature on the interpretation of grain fabrics and sedimentary structures in terms of sedimentary environments (see Tucker 1981 for a concise overview) quantitative correlations between grain fabric and the *permeability* of unconsolidated materials have not been established.

4.2.4 Grain morphology and grain fabric in mudrocks

It is usually not possible to identify grain morphology or fabric in fine terrigenous clastic sediments or mudrocks, however textures and structures within these material may be hydrogeologically important. Preferred orientation of clay minerals and micas parallel to bedding are the commonest textures and may be detected in thin section by areas of common extinction. The preferred grain orientation gives rise to fissility, or the ability of mudrocks to split along smooth planes. A second planar feature in mudrocks which may cause anisotropy of hydraulic characteristics is lamination. This is principally due to variations in grain size or compositional changes.

5. HYDROGEOLOGICAL PHYSICAL PROPERTIES METHODS

The following sections present reviews of laboratory measurement techniques that may be applicable to the investigation of the hydrogeological physical properties of unconsolidated sedimentary aquifers. The techniques reviewed include porosity, pore size distribution, permeability and compaction measurement techniques.

5.1 Porosity

Variations in the effective pore volume, pore size distribution and the configuration or distribution of pores within unconsolidated aquifers are of primary importance in determining aquifer hydrogeological characteristics.

Precise quantification of these variables, particularly pore configuration, under laboratory conditions is highly problematic due to the commonly disturbed nature of the pore structure as a consequence of sampling and material handling. However, total effective porosity and pore size distributions may be measured experimentally.

Lawrence (1977) and Danielson & Sutherland (1986) have provided detailed reviews of current experimental soil science porosimetry techniques and Dullien (1979) has presented both a detailed discussion of the problems associated with the description of porosity and pore size distributions and a discussion of the complex relationship between porosity and fluid transport processes.

Total porosity (also called voidage), ϕ_t , is the proportion of the bulk volume of a sample occupied by pore or void space. Porosity may be either interconnected or effective pore space, where pore space forms a continuous phase within the sample, or it may be non-interconnected or isolated, where pore spaces are dispersed throughout the sample. The non-interconnected void space cannot contribute to the transport of fluids through the porous sample. Effective porosity is commonly denoted by ϕ . The following values of porosity, after Davis (1969) and Freeze & Cherry (1979), are typical total porosities for a variety of unconsolidated aquifer materials; gravel 0.25 to 0.4, sand 0.25 to 0.5, silt 0.35 to 0.5 and clay 0.4 to 0.7.

5.1.1 Theoretical porosity

The effect of grain sorting on porosity in natural unconsolidated aggregates has already been noted, however where a material consists of unconsolidated particles of a regular nature (*i.e.* where shape parameters and/or size distributions can be prescribed) the density or porosity of the material is amenable to theoretical analysis.

Particle packing is controlled by the shape of the particles in the pack, their size distribution and their ordering (regular or irregular). If particles are uniform spheres in a regular order it is possible to specify packing rules to define porosity, whereas in disordered packs of uniform size spheres the bulk porosity will be a complex function of the average number of contacts per sphere. Unlike the regular position of particles in a regular packing arrangement the position of particles in a disordered pack will be described by a probability density function.

Dullien (1979) has described the variation in porosity of aggregates as a function of packing. The "loosest" common regular packing is the cubic pack with a coordination number (points of contact per sphere) of 6 and a mean bulk porosity of 0.47, the "densest" regular packing is the rhombohedral pack with a coordination number of 12 and a mean bulk porosity of 0.26. Random packing porosities vary from 0.44 for very loose random packing (*eg.* sedimentation of equal sized spheres), through 0.37 to 0.39 for poured random packing (*eg.* when equal sized spheres are poured into a container) to porosities of 0.36 to 0.37 for close random packing (*eg.* when a randomly packed bed is shaken down vigorously).

5.2 Experimental determination of effective porosity

There are various experimental techniques that may be used in the determination of porosity;

- Optical methods
- Helium gas expansion method
- Density methods

- Water desorption method
- Mercury injection method

Optical methods rely on the equality of volume and areal fractions; it can be shown that the porosity of a sample is equal to the areal fraction of pore space in a section of the sample (Underwood 1970). Porosity may be determined from peels or from thin sections of samples that have been impregnated with resin, wax or Wood's metal.

When impregnated samples are used the interconnected and non-interconnected pore spaces may be distinguished, since only the interconnected or effective pore space will be accessed by the resin, wax or metal. However, small pore sizes are difficult to resolve optically. Consequently, porosities determined by optical methods may differ significantly from other methods.

The gas expansion method requires measurements of changes in gas pressure during a series of gas expansions into a porous sample, by applying Boyle's law effective porosity can be calculated. Finally, density methods may be used to give total porosity measurements if the bulk density of the sample and the density of solids within the sample can be measured.

The water desorption and mercury injection methods are commonly used to measure pore size distributions, however they may also be used to obtain an effective porosity value. The water desorption method requires the controlled suction of water from a soil sample under the action of gravity through a porous plate.

The mercury injection method requires the hydrostatic pressure of mercury in an evacuated flask containing both a sample of the porous material and mercury to be increased, commonly to pressure in excess of 10,000 psi. During pressurization mercury is forced into the evacuated effective pore spaces in the sample; the total volume of intruded mercury is then equated with the total effective porosity of the sample.

5.2.1 Optical methods

Sample porosity may be determined from any representative two dimensional surface or image, *ie.* flat outcrop surface such as a pit wall, sawed hand specimen, thin section or acetate peel, using the principal of modal analysis by point counting. This standard petrographic technique is described in detail by Hutchinson (1974). However the successful application of optical techniques is reliant on the adequate resolution of sample porosity. Commonly small pores are not recognised by this method. An additional problem is that of differentiating between isolated and effective porosity. To ensure measurement of only effective porosity hand specimen samples must be impregnated with coloured resins prior to thin sectioning (Stanley 1971, Hutchinson 1974).

5.2.2 The gas expansion method

The gas expansion method is based on Boyle's law of volume-pressure relationships. Assuming constant temperature, a given amount of gas (moles) confined at a pressure P_1 , in a given volume (V_1), when allowed to expand (P_2) into a new volume (V_2) will satisfy the following equality,

$$P_1 V_1 = P_2 V_2 \quad 5.1$$

Danielson & Sutherland (1986) provide a detailed description of the apparatus and experimental procedures employed in the gas expansion method.

Two basic types of apparatus can be used, a variable volume gas pycnometer and a constant volume gas pycnometer (Figure 5.1). Each consists of a sample chamber and a reservoir chamber. When the variable volume system is used the volume of the reservoir chamber may be changed following sealing of the system, the consequent change in pressure in the sample chamber is then measured. When the constant volume system is used the reservoir and sample chambers are isolated and contain gas at a different pressure, the change in the gas pressure in the sample chamber is then monitored when the two chambers are pneumatically connected.

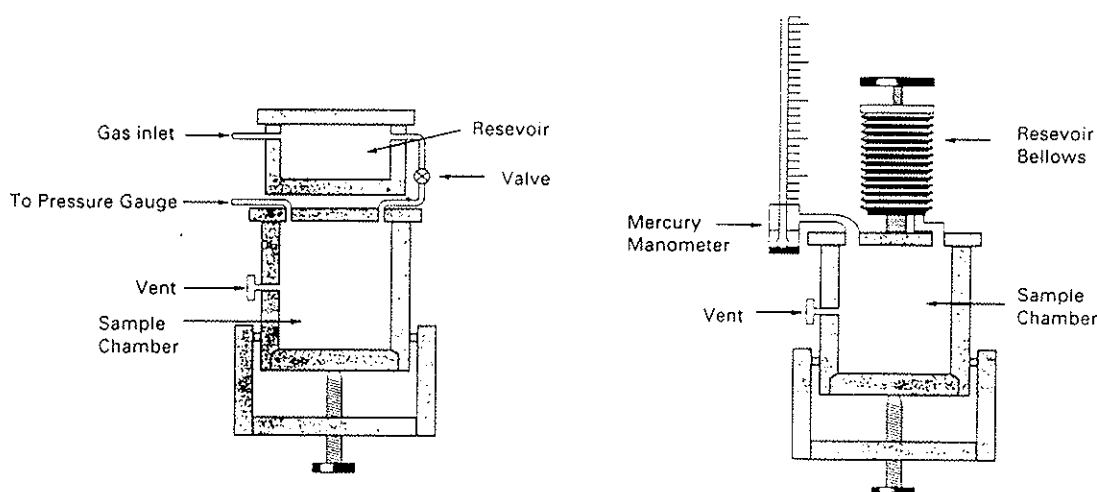


Figure 5.1 Schematic illustrations of the two principal types of gas pycnometer. a, the variable volume pycnometer and b, the constant volume pycnometer (after Danielson & Sutherland 1986).

Using the variable volume system porosity is calculated as follows; as $P_1 V_1 = P_2 V_2$ and as $V_1 = V_2 + \Delta V$ (where ΔV is the change in volume of the system following compression it can be shown that,

$$V_2 = P_1 \Delta V / \Delta P \quad 5.2$$

where ΔP is the change in gas pressure associated with the change in the volume of the system. Assuming no leaks in the system (and a constant temperature) P_1 is the atmospheric pressure when the system is sealed, ΔP is measured using a pressure gauge as the volume of the system is changed. If V_2 is obtained with and without a sample in the sample chamber the difference between the two measurements is the volume of solids (and liquids) in the sample chamber. This when subtracted from the bulk sample volume gives the effective porosity of the sample.

Using the constant volume system porosity is calculated as follows; the volume of gas in the sample chamber, V_c , is given by the sum of the pressure-volume products of the chamber and the reservoir system after they are pneumatically connected, *ie.*

$$V_c P_c + V_r P_r = (V_c + V_r) P \quad 5.3$$

where P is the pressure of the system following pneumatic connection and the subscripts c and r refer to the sample chamber and reservoir respectively. If Eqn 6.3 is solved for P_c we obtain

$$V_c = (P_r - P) V_r / (P - P_c) \quad 5.4$$

As with the variable volume method the volume of solid (and liquid) in the sample is given by the difference in V_c as determined with and without the sample in the chamber. The sample porosity is then calculated given the bulk volume of the sample.

5.2.3 Density methods

Total porosity, S_t , may be calculated if the particle density, ρ_p , and the bulk density, ρ_b , are known. The ratio ρ_b/ρ_p is the fraction of the total volume occupied by solids therefore this value subtracted from unity gives the fraction of the total volume occupied by pores, *ie.*

$$S_t = (1 - \rho_b/\rho_p) \quad 5.5$$

The following sections detail experimental techniques used to measure particle and bulk density in unconsolidated materials.

Particle density determination

Particle density is the ratio of the total mass of particles to their total volume (excluding interparticulate pore spaces), it is conventionally expressed in grams per cubic centimetre (g cm^{-3}). Particle density may be required in the determination of sample porosity or for grain size analysis, *eg.* in sedimentation experiments. Particle mass is measured by weighing the sample and sample volume is calculated from the mass and density of water (or other fluid) displaced by the sample. There are two standard laboratory methods for measuring particle density, the pycnometer method (ASTM 1958) and the submersion method (Blake & Hartge 1986b).

Pycnometer method

A pycnometer (also known as a density bottle or specific-gravity flask) is a glass bottle with a ground glass stopper that is pierced lengthways by a capillary opening. Flasks of 25, 50 or 100 mL capacity are generally used in density measurements. The pycnometer method for measuring particle density is commonly used by soil scientists. A detailed description of the technique is given by the American Society for Testing and Materials (ASTM 1958), Blake & Hartge (1986b) also provide a description of the technique and include a discussion of its practical application to the measurement of soil particle density.

A clean dry pycnometer is weighed in air (W_a), it is then filled with approximately 10 g of sample material and the pycnometer and sample are weighed (W_s). The pycnometer is then carefully filled with de-aired, distilled water so that no air remains in the flask and the pycnometer and its contents are weighed again (W_{sw}). The pycnometer is emptied, cleaned, filled with distilled water and reweighed (W_w). Finally, the density of the distilled water is measured (ρ_w). Particle density, ρ_p , can then be calculated from the following expression;

$$\rho_p = \rho_w (W_s - W_a) / [(W_s - W_a) - (W_{sw} - W_w)] \quad 5.6$$

where

- ρ_w = density of water (g cm^{-3})
- W_s = weight of pycnometer and sample (g)
- W_a = weight of air filled pycnometer (g)
- W_{sw} = weight of pycnometer sample and water (g)
- W_w = weight of water filled pycnometer (g)

Submersion method

The submersion method has been described in detail by Blake & Hartge (1986b). A sample of material to be tested is placed in a weighing dish (of known weight, W_d) and the dish and sample weighed in air (W_{sd}). They are then placed on a weighing frame submerged under distilled water and the combined weight of the weighing dish and sample are recorded under water (W_{sdl}). The sample is then removed from the weighing dish and the weight of the dish under water is recorded (W_{dl}). Finally, the density of the distilled water (ρ_l) is measured. Particle density, ρ_p , can then be calculated from the following expression;

$$\rho_p = \rho_l (W_{sd} - W_d) / [(W_{sd} - W_d) - (W_{sdl} - W_{dl})] \quad 5.7$$

where

- ρ_l = density of water (g cm^{-3})
- W_{sd} = weight of sample and dish (g)
- W_d = weight of dish (g)
- W_{sdl} = weight of sample and dish under water (g)
- W_{dl} = weight of dish under water (g)

The pycnometer method provides the more accurate measure of particle density, however the submersion method is an easier procedure and measurements can be

made on a series of samples relatively quickly. Blake & Hartge (1986b) noted that using the pycnometer method a weighing error of 1 mg on a 10 g sample would lead to an error in calculated particle density of 0.0003 g cm^{-3} , whereas the submersion method may be expected to have a standard error of approximately 0.005 g cm^{-3} .

Bulk density determination

The bulk density of porous materials, ρ_b , is the ratio of the total mass of solids to the bulk volume of the sample where the bulk volume includes both the volume of the solids and of the interstitial porosity, it is conventionally expressed in grams per cubic centimetre (g cm^{-3}). Bulk density measurements are used in the calculation of porosity and void volume (when particle densities are known). Bulk density of a given material will vary with pore structure and in unconsolidated materials is closely related to packing density and consequently grain shape and grain size distributions.

Bulk density measurements require the weighing of samples of known volume. Soil scientists have developed three general techniques for measuring the bulk volume of unconsolidated soils without disturbing the samples pore structure, these are the core method, the clod method and the excavation method (Blake & Hartge 1986a). Each of the methods differ in the way the samples are obtained and each is suited to particular types of unconsolidated material. The core method is typically applied to relatively fine grained homogeneous soils with moderate water contents (wet soils and dry soils are not amenable to this sampling technique). The clod method may be used where it is possible to obtain a representative clod of the material and excavation methods are used extensively in the study of bituminous and gravelly materials.

Core method

A cylindrical metal sampler is pressed or driven into the unconsolidated material so that the pore structure is not damaged or modified, and a sample of known volume is removed. The sample can then be weighed.

There are a variety of core sampler designs, the most commonly used consists of a thin walled cylindrical metal sleeve with an inner, removable sample cylinder. The removable cylinders are designed to obtain unconsolidated cores without significant damage to the sample pore structure and also to be used to transported cores without further damage. Such cores may then be used in the laboratory for pore size distribution or hydraulic conductivity tests.

Excavation method

The excavation method is described in detail in ASTM (1958). Using this method bulk density is found by excavating a quantity of material, weighing it and determining the volume of the excavation. The volume of excavated material may be found either by filling the hole with a measured volume of sand or by inflating a balloon in the excavation with a measured volume of water. In both cases care must be taken not to compact the material adjacent to the excavation. Blake & Hartge (1986a) note that if the excavation is done with care and that if it is of a

regular shape then direct measurement of the excavation dimensions may be used to calculate the volume.

Clod method

The clod method has been developed by soil scientists and may have only very limited application, it is described in detail by Blake & Hartge (1986a). The method requires a coherent, representative clod to be obtained. The mass of the clod is obtained by weighing the sample and the volume obtained by coating the clod in a water repellent substance (such as a resin) and then performing a fluid displacement test (submersion method).

5.3 Pore size distributions

Pore size distribution is the probability density function giving the distribution of pore volume by a characteristic pore size. Pore sizes can only be directly measured using thin sections and optical techniques, but these techniques are generally slow and unsuitable for hydrogeological studies. The commonly adopted methods for the measurement of pore size distributions rely on indirect measurements of volume of water (forcibly) drained or volume of mercury (forcibly) intruded as a function of the applied pressure difference.

The accurate quantification of pore size configuration and distribution in unconsolidated sediments is highly problematic, primarily due to the likely changes in pore structure imposed during sampling (Lawrence, 1977, presents a detailed discussion of the extensive problems associated with the handling and preparation of consolidated fine textured soil samples for pore size distribution measurement). Consequently, laboratory pore size distribution data should be interpreted with due regard for the possible errors associated with the observations.

The following sections briefly describe water desorption and mercury intrusion methods, the principal laboratory techniques that are used to investigate pore size distributions (Lawrence 1977, Danielson & Sutherland 1986).

5.3.1 Water Desorption method

The water desorption method requires a water saturated sample to be drained in a stepwise manner. The volume of water drained in each step is measured and can be equated to the volume of pores drained. If the size range of the drained pores during each step can be calculated the pore size distribution can be defined. Theoretically the largest pores drain first and the drainage of any given pore is determined by the largest radius of an opening to a neighbouring larger, previously drained, pore.

Capillary theory states that for a cylindrical capillary containing a water-air interface the pressure difference (ΔP , in pascals) across a meniscus in the capillary is proportional to the surface tension of the water (σ , in J m⁻²), the contact angle (θ , in degrees) and the radius of the capillary (r_p , in m), i.e.

$$\Delta P = 2\sigma r_c^{-1} = 2\sigma \cos\theta r_p^{-1} \quad 5.8$$

where r_c is the radius of curvature of the meniscus. If the contact angle is assumed to be zero degrees, *i.e.* the water is assumed to be perfectly wetting, then Eqn 5.8 reduces to

$$\Delta P = 2\sigma r_p^{-1} \quad 5.9$$

where r_p is considered to be the equivalent pore radius.

Forced drainage under an applied differential pressure causes the radius of curvature of air-water interfaces to decrease. When this radius decreases to the effective radius of a given pore that pore will drain. At equilibrium all pores with an effective radius less than the curvature of the air-water interface will remain water filled. Consequently, by applying Eqn 5.9 the volume of pores with an effective pore radius greater (or less) than a given size can be measured as a function of the applied differential pressure.

Danielson & Sutherland (1986) give a detailed account of the apparatus (including calibration), experimental procedure and calculation of pore size distribution curves using the water desorption method. The following comments are based on their review.

The experimental apparatus, illustrated schematically in Figure 5.2, consists of a saturated sample placed on a water saturated porous (ceramic) plate at the top of a drainage funnel containing water and mercury. Danielson & Sutherland (1986) recommend that the sample is contained in a metal or plastic cylinder (usually the sample cylinder that was used during the field sampling and core handling).

Suction is applied to the sample by draining mercury from the stopcock at the base of the drainage funnel. Measurements of the relative heights of x, y and z (see Figure 5.2) are then taken and used to calculate water suction, volume of drained water at each equilibrium step and consequently pore size distributions. Figure 5.3 (from Daniel & Sutherland 1986) gives examples of two pore size distribution plots for a typical clay soil and a typical sandy loam soil.

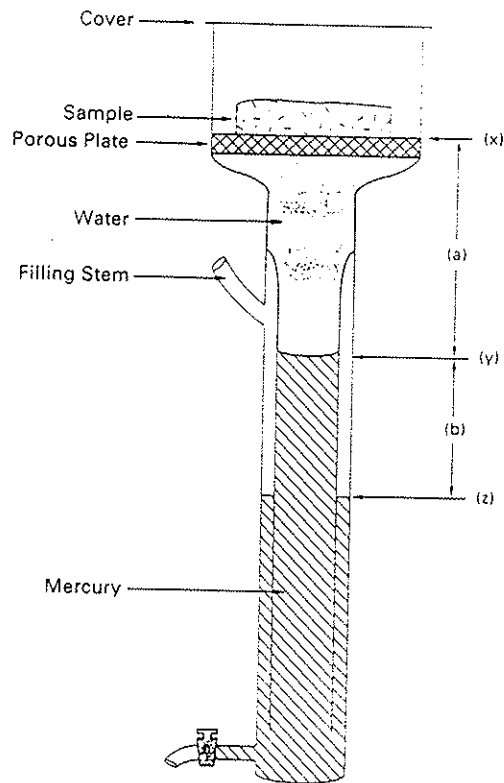


Figure 5.2 Schematic illustration of the porous funnel apparatus used for determining pore size distributions in soils by the water desorption method (after Danielson & Sutherland 1986).

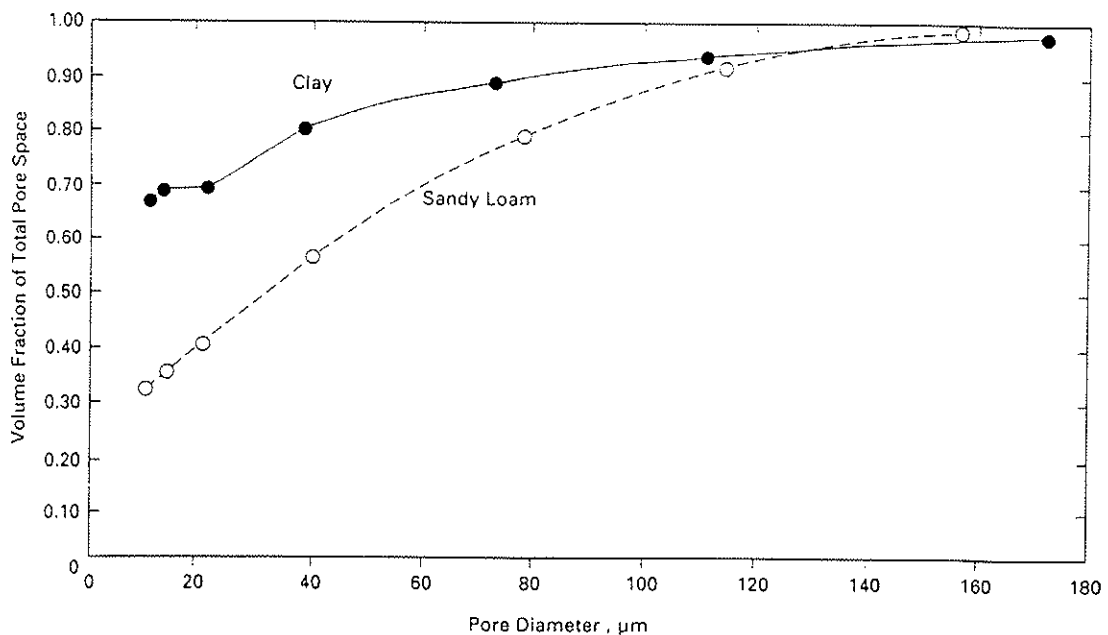


Figure 5.3 Examples of two typical pore size distribution curves obtained using the water desaturation technique. Typical pore size distribution curves for a clay and sandy loam soil are shown (after Danielson & Sutherland 1986).

5.3.2 Mercury intrusion

Mercury intrusion porosimetry has been extensively used in the study of pore size distributions in consolidated geological materials and it has also been applied to the study of clays and soils, *eg.* Sills *et al.* (1973, 1974), Lawrence (1977) and Ragab *et al.* (1992).

As with the water desorption method the mercury intrusion technique is based on capillary pressure theory. However, since mercury is non-wetting with respect to geological materials, *i.e.* it has a contact angle of greater than 90° , it will only enter pores under pressure. The pressure required to intrude mercury into pores is a function of contact angle, surface tension pore geometry and pore size and is given by Eqn 5.8.

The basic experimental procedure is as follows. A dry sample is placed in a glass penetrometer, which is in turn sealed in a glass bell jar containing mercury. The bell jar, and sample, are then evacuated. Once an adequate vacuum has been obtained the tip of the penetrometer stem is lowered into the mercury in the bell jar and the vacuum slowly relieved. This forces the mercury to flood the penetrometer and surround the sample. No intrusion takes place at this stage. The penetrometer stem is removed from the mercury once it is fully primed.

Pressure is then applied to the mercury in the penetrometer stem (usually via a hydraulic oil system) either in discrete steps or at a constant rate (scanning porosimeter). This causes the mercury to intrude into the sample pores. The volume of intruded mercury is measured by monitoring the change in length of the mercury column in the stem of the penetrometer.

Pressure and intrusion volume readings can then be used to calculate equivalent pore sizes from the standard capillary pressure relationship of Eqn 5.8. Danielson & Sutherland (1986) give a brief description of the experimental apparatus and procedure and a more detailed discussion of potential sources of error in the technique.

Note that the mercury injection technique can be used to apply greater hydrostatic intrusion pressures than the water desaturation method can apply drainage suction. Consequently, the mercury injection method may be used to measure smaller pores than are accessible using the water desaturation technique.

5.4 Measurement of permeability

Laboratory measurements of permeability should be an integral component of any detailed characterization of an aquifer, and are of particular importance in the assessment of the degree of hydrogeological heterogeneity. However, potentially large and unconstrainable errors may be introduced into laboratory measurements on UNSAs materials and consequently laboratory permeability studies may be of only limited use in UNSAs evaluation.

This section briefly defines hydraulic conductivity and permeability, notes the limitations of laboratory permeability measurements and then reviews the three basic types of permeability tests likely to be used in the investigation of UNSAs.

Hydraulic conductivity, K , is a measure of a materials ability to transmit water and has the dimensions of velocity (*eg.* m/year, mm/sec). Hydraulic conductivity is defined by Darcy's law, which states that under isothermal conditions, the apparent velocity of one dimensional flow is directly proportional to the hydraulic gradient, *ie.*

$$q = -K(\theta) \delta H / \delta z \quad 5.10$$

where q is the volume flux density or apparent velocity (*ie.* the volume of liquid passing through a unit cross-sectional area in unit time), $\delta H / \delta z$ is the gradient of the hydraulic head H , and $K(\theta)$ is the hydraulic conductivity as a function of the water saturation, θ . The driving force is expressed as the negative gradient of the hydraulic head. The hydraulic head is composed of the gravitational head, z , and the pressure head, h , *ie.*

$$H = h + z \quad 5.11$$

Permeability, also known as the coefficient of permeability, k , has the dimensions length squared (*eg.* mm²) and is related to the hydraulic conductivity as follows;

$$k = K\mu / \rho g \quad 5.12$$

where g is the acceleration due to gravity, μ is the viscosity and ρ is the density of the fluid.

However, it should be noted that Darcy's law is not universally valid for all liquid flow through porous media, since it can be shown that Darcy's Law is only applicable when inertial forces acting on the permeant are negligible with respect to the viscous forces acting on the permeant.

Davis (1969) has shown that coefficients of permeability for non-indurated sediments may exceed eight orders of magnitude, from greater than 10 000 Darcies for beach gravels to less than 0.0001 Darcies for alluvial clays (and that the permeability of UNSAs can be broadly correlated to the particle size distribution of the sediment, *eg.* Figure 5.4. See also Masch & Denny 1966, for an investigation of the effect of grain size distribution on permeability of unconsolidated sediments).

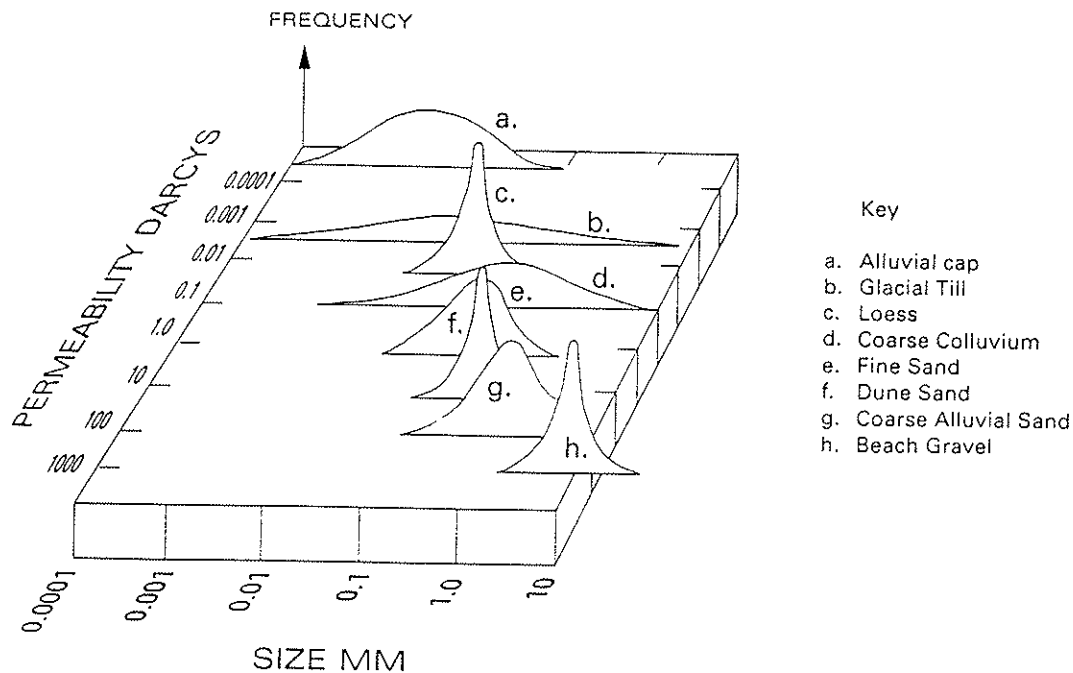


Figure 5.4 Schematic illustration of typical particle size distributions as a function of permeability for a variety of UNSAs (after Davis 1969).

5.4.1 Note on errors associated with permeability measurements

Care should be taken in the interpretation of the results of constant head, falling head and oedometer tests on UNSAs materials. The tests give only a guide to the coefficient of permeability and at best give relative values. Five significant reasons can be identified for the lack of absolute accuracy in permeability tests performed on unconsolidated samples, these may be summarized as follows;

- Difficulty in ensuring in-situ sample structure has been maintained. For a sample to be undisturbed not only sample density but also sample structure must be preserved. In practice all unconsolidated samples are disturbed to some degree and coarse grained samples are particularly likely to be substantially disturbed.
- Representativeness of laboratory scale sample. The hydrogeological behaviour of an unconsolidated sedimentary aquifer may be influenced by structural or fabric features that are not represented at the laboratory sample scale.
- Use of artificial or synthetic permeant. The use of artificial permeants such as deionized water may effect the nature of water adsorbed on the surfaces of relatively fine grained particles such as clays. This may potentially lead to chemical reactions, *eg.* adsorption/desorption of water, solution or precipitation of mineral phases and possible clay swelling. Each of these processes may significantly alter the sample permeability.

- Lack of ability to measure horizontal permeabilities. Laboratory measurement of the permeability of sample material removed from a vertical orientation will be of little use if flow in the field is predominantly horizontal or subhorizontal.
- Lack of comparability between laboratory and field values of total, pore water and effective pressure.

5.4.2 Measurement techniques

A variety of methods for determining permeability have been described in the literature. All require samples to be held in metal or plastic cylinders so that one dimensional flow can be measured. Ideally relatively undisturbed samples should be used in these tests. *The use of samples reconstituted from loose or disaggregated materials should be avoided* since it is unlikely that packing and pore structures achieved in the laboratory will equate to in-situ field packing and pore structures that developed as a consequence of a flowing depositional medium. Thin-walled cylinders are commonly employed as sampling tools, these cylinders then serve as sample holders during the tests (see Blake & Hartge 1986a).

Klute & Dirksen (1986) present a detailed discussion of the choice of test fluid used in permeability measurements. This may be particularly important in complex soils where a variety of biological, chemical and physical processes may be dependant on the nature of the permeant. For example if swelling clays (Madsen & Muller-Vonmoos 1989) are present the water chemistry may significantly effect measured hydraulic conductivities (Rolfe & Aylmore 1977). Generally, if formation brine, or synthetic formation brine, are not available then deionized or distilled water should be used as permeants. Despite the variety in detail of permeability tests three principal types of can be recognised (each type of test is briefly described in the following sections);

- The falling head permeameter
- The constant head permeameter
- The oedometer test.

The use of a particular type of test is not only determined by equipment availability but also by the permeability of the material to be investigated. Table 5.1 (after Klute & Dirksen 1986) illustrates the range of permeabilities that are commonly investigated by each of the three techniques.

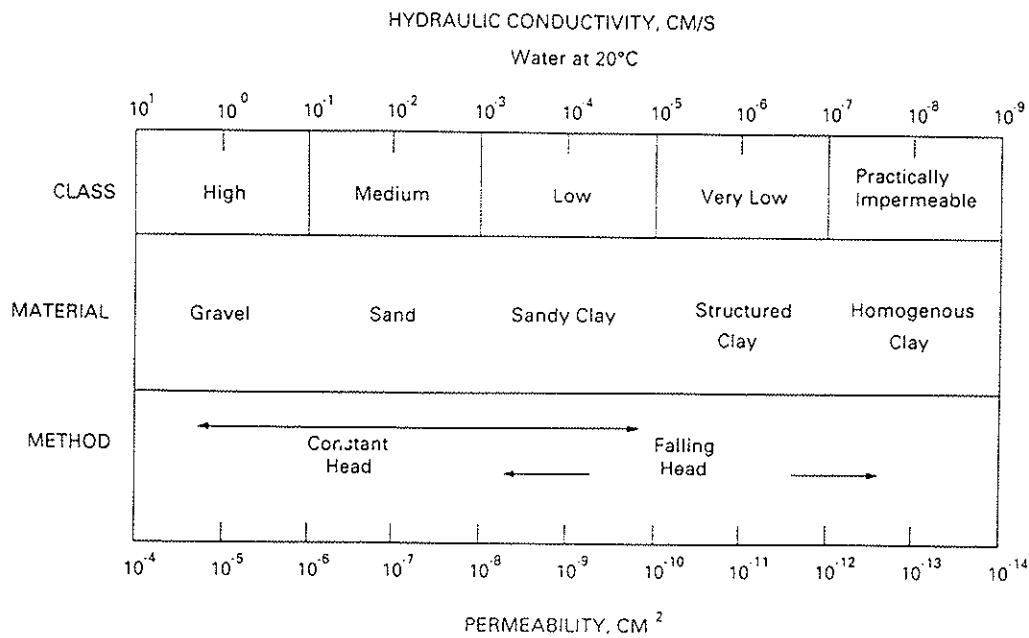


Table 5.1 Illustration of the range of hydraulic conductivities (and equivalent permeabilities) for various non-indurated materials and the methods used in their investigation.

5.4.3 The falling head permeameter

The falling head permeameter is usually used to determine the coefficient of permeability for relatively fine grained, or relatively impermeable, undisturbed materials. Although they may vary in detail the general construction of a falling head permeameter is as follows.

Coarse filter screens are placed at the upper and lower ends of the sample container (typically a U4 sampling tube), the base of the sample is placed in contact with a water reservoir and the top of the sample is connected to a glass standpipe of known cross-sectional area. The standpipe is filled with de-aired water. A schematic diagram of a typical falling head permeameter is shown in Figure 5.5.

As the water seeps through the sample the change in height of water in the standpipe above the base reservoir level with time is recorded. Permeability can be calculated knowing the sample dimensions (area and length) and the change in height of the water column with elapsed time. The test can be repeated with a range of standpipes of different diameter to obtain an average calculated coefficient of permeability.

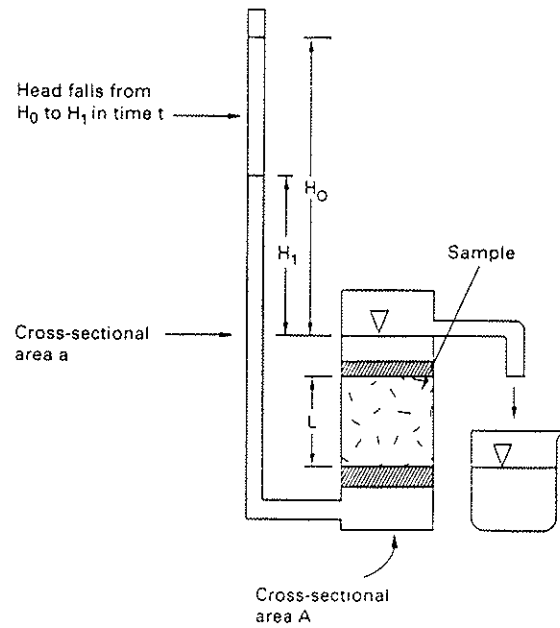


Figure 5.5 Schematic illustration of a falling head permeameter used for measuring hydraulic conductivity. H_0 is the initial hydraulic head at time t and H_1 is the final hydraulic head at t_1 . (after Freeze & Cherry 1979).

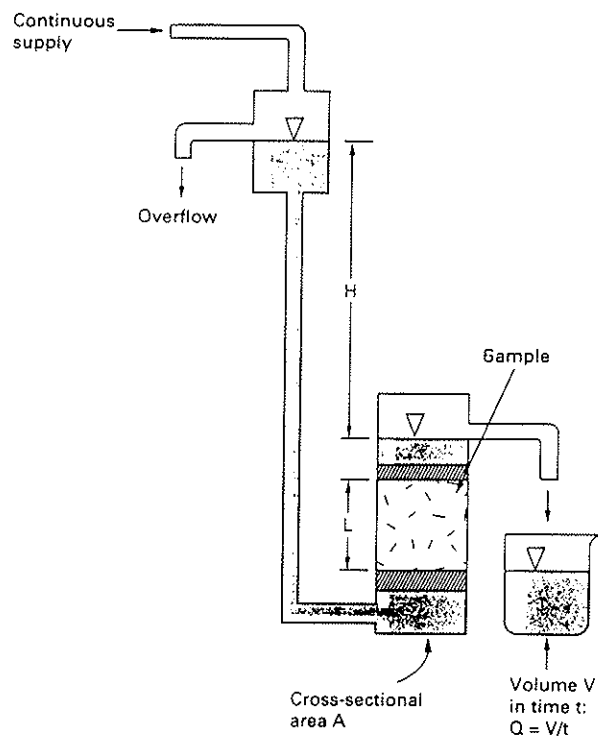


Figure 5.6 Schematic illustration of a constant head permeameter used for measuring hydraulic conductivity, where H is the constant hydraulic head. (after Freeze & Cherry 1979).

5.4.4 The constant head permeameter

The constant head permeameter is usually used in the determination of the coefficient of permeability for relatively coarse grained, or relatively permeable undisturbed materials. The general construction of constant head permeameters is essentially similar to the one outlined in the following section, however they may vary significantly in detail, particularly as to the methods of obtaining a constant head.

The sample is placed in a constant head permeameter coreholder. The coreholder consists of a cylinder, commonly made of perspex, with (at least) two access ports along its length. These ports permit the loss of head across a fixed length of sample to be measured. Coarse wire mesh filters are fitted to the upper and lower ends of the sample and a constant head supply of water is connected to the top of the sample. A schematic diagram of a typical constant head permeameter is shown in Figure 5.6.

Before measurements can be made it is essential that a constant head has been achieved. Constant head has been achieved when the flow rate can be shown to be constant and when the heads from the two tapping points are constant. Once a constant head has been achieved the flow rate and the difference in the level of water in two standpipes attached to the tapping points are measured. Permeability can be calculated knowing the cross sectional area of the sample in the coreholder, the flow rate, the difference in the level of the two standpipes and the distance between the two tapping points.

5.4.5 The oedometer test

The oedometer, or consolidation, test is usually used in the determination of the coefficient of permeability of very fine grained, or relatively impermeable undisturbed materials such as clays. Permeability may be calculated from consolidation tests following a theory developed by Terzaghi (1943) which states that the compressibility of a saturated sample under a given load is inversely related to the coefficient of permeability under that load. The following section describes the general construction of a typical consolidometer and briefly details standard experimental procedures. More detailed descriptions of experimental apparatus and procedures can be found in Lowe *et al.* (1964) and Bryant *et al.* (1975).

The consolidation of large samples is commonly performed in a hydraulic oedometer (Figure 5.7), also known as a consolidometer or Rowe cell (Rowe & Barden 1966). The sample is laterally constrained in a cast bronze ring, at the top by a porous sintered bronze plate and at the bottom by a metal base plate containing porous ceramic ports. Vertical stress is applied typically through a pleated bellows-like rubber membrane. Pore water pressure can be controlled through a top drain connected to the porous sintered brass plate and monitored via a pore pressure transducer fitted to the porous ceramic port at the base of the sample.

Hydraulic oedometers offer very flexible specimen drainage configurations; standard tests provide vertical drainage measurements, however, substitution of porous lower plates are lateral ports horizontal drainage (and consequently permeability) may also be obtained. Hydraulic oedometers are available for specimens of 76 mm, 152 mm and 254 mm in diameter (samples typically have a diameter to thickness ratio of approximately 2.5:1 to 3.5:1).

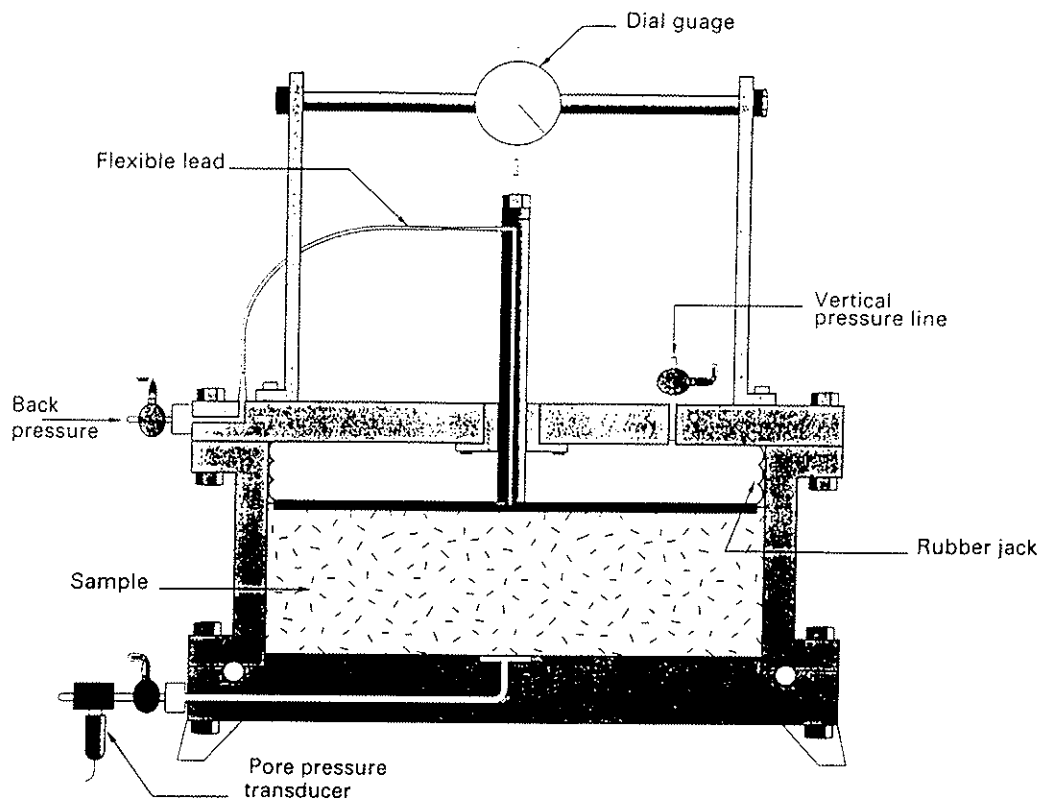


Figure 5.7 Schematic illustration of a hydraulic oedometer (after Rowe & Barden 1966)

By measuring the change in sample porosity as a function of applied pressure and by obtaining time-compression curves as a function of applied pressure the coefficients of volume change and consolidation can be calculated respectively. If the density of the water or other saturant is known then sample permeability can be calculated (see Bryant *et al.* 1975 for details of time-compression curve fitting procedures and for details of the permeability calculation).

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Method Summary Sheet (Lab1)

Title : *Quantitative sample description - Mineralogical description.*

Scope and use of method :

Mineralogical descriptions are generally of limited use in the hydrogeological evaluation of unconsolidated sedimentary aquifers. Descriptive methods include standard petrographic methods, colour description and x-ray diffraction techniques. A combination of these and related methods can be used to establish lithological descriptions of a sedimentary sequence and may be of use in the initial evaluation of UNSAs sedimentary depositional environments. Use of specific mineralogical description techniques in the hydrogeological evaluation of an UNSA is generally limited to the identification of hydrogeologically significant mineral assemblages (such as swelling clays) using x-ray diffraction methods. However, this is a relatively costly procedure that requires relatively sophisticated equipment.

Method summary :

Standard petrographic descriptions should be performed on hand specimens and thin sections (using optical microscopes). All hand specimen sample colour descriptions should be made with reference to the Munsell colour notation. X-ray diffraction techniques should be used for the identification of clay fractions.

Key Reference(s) :

Cady, J G, Wilding, L P & Drees, L R (1986) Petrographic microscope techniques. In : Klute, A (ed) *Methods of Soil Analysis* (second edition). Part 1, Physical and mineralogical methods. Agronomy No. 9. 185-218. Pub. American Society of Agronomy and Soil Science Society of America. Wisconsin USA

Folk, R L (1969) Toward greater precision in rock-colour terminology. *Geol. Soc. Am. Bull.* **80**, 725-727

Hutchinson, C S (1974) *Laboratory handbook of petrographic techniques*. Pub. Wiley-Interscience, New York USA

Tucker, M E (1981) *Sedimentary Petrology*. Pub. Blackwell Scientific, Oxford UK

Whittig, L D & Allardice, W R (1986) X-ray diffraction techniques. In : Klute, A (ed) *Methods of Soil Analysis* (second edition). Part 1 Physical and mineralogical methods. Agronomy No. 9. 331-362. Pub. American Society of Agronomy and Soil Science Society of America. Wisconsin USA

Method Summary Sheet (Lab2)

Title : *Particle size analysis - the sieve method.*

Scope and use of method :

In any hydrogeological investigation of an unconsolidated sedimentary aquifer the most useful geometrical parameter to measure is the particle size distribution. Estimates of permeability (and transmissivity) and crude estimates of porosity may be obtained from such measurements. *A knowledge of particle size distribution is also essential in the construction of effective well screens.*

The sieve method is generally used to obtain particle size distributions from samples, or sub-samples, containing particles with a minimum grain size of $63\ \mu\text{m}$. Below this grain size sedimentation techniques should be employed.

Method summary :

A nest of sieves is built up using the desired mesh sizes with the coarsest screens at the top. The sample is put in the top sieve. A lid is placed on the top sieve to prevent loss of fines and a pan placed below the lowest sieve. Secure the nest of sieves to a mechanical shaker and shaken for a nominal time (usually 10 to 15 mins). The contents of each sieve and the lowest pan are weighed and the weight percentage or cumulative weight percentage by size fraction are calculated.

Key Reference(s) :

Gale, S J & Hoare, P G (1991) *Quaternary sediments*. Pub. Belhaven Press, London

Ingram, R L (1971) Sieve analysis. In : Carver, R E (ed) (1971) *Procedures in sedimentary petrology*. 49- 67. Pub. Wiley-Interscience, New York USA

Method Summary Sheet (Lab3)

Title : *Particle size analysis sedimentation method*

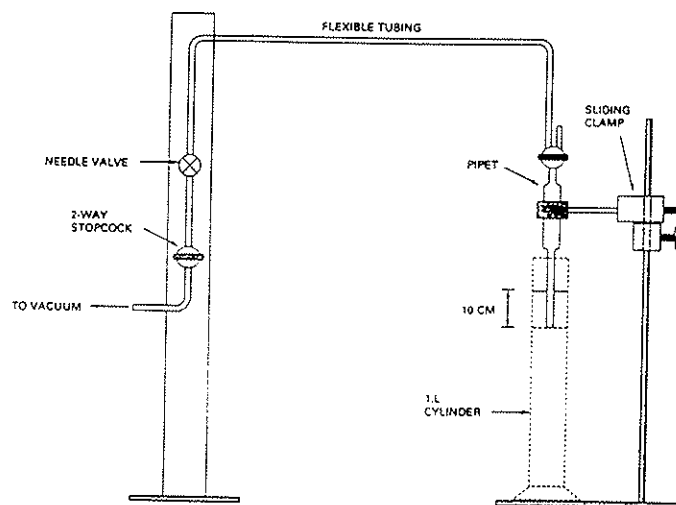
Scope and use of method :

In any hydrogeological investigation of an unconsolidated sedimentary aquifer the most useful geometrical parameter to measure is the particle size distribution. Estimates of permeability (and transmissivity) and crude estimates of porosity may be obtained from such measurements. *A knowledge of particle size distribution is also essential in the construction of effective well screens.*

The sedimentation method is generally used to obtain particle size distributions from samples, or sub-samples, containing particles with a maximum grain size of $63\ \mu\text{m}$. Above this grain size sedimentation techniques should be employed.

Method summary :

There are two sedimentation methods both require an aqueous suspension to be prepared. The hydrometer method requires density measurements to be taken using a calibrated hydrometer at suitable time intervals. Particle size distributions can then be calculated. The pipette method requires the use of a Lowy pipette to obtain samples of the suspension at suitable time intervals. These samples are dried and the clay fraction weighed. Particle size distributions can be calculated using the weights.



Schematic illustration of pipette stand and apparatus configuration for sedimentation analysis
(after Gee & Bauder 1986)

Key Reference(s) :

Gale, S J & Hoare, P G (1991) *Quaternary sediments*. Pub. Belhaven Press, London

Gee, G W & Bauder, J W (1986) Particle-size analysis. In : Klute, A (ed) *Methods of Soil Analysis* (second edition). Part 1, Physical and mineralogical methods. Agronomy No. 9. 383-411. Pub. American. Society of Agronomy and Soil Science Society of America. Wisconsin USA

Method Summary Sheet (Lab4)

Title : *Porosity determination - gas expansion method.*

Scope and use of method :

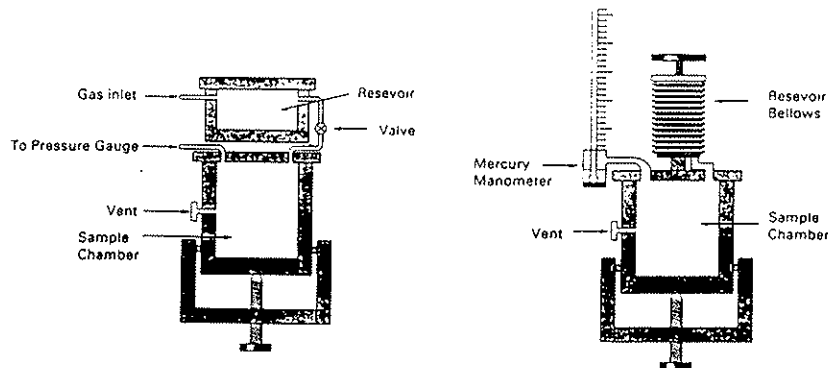
Porosity determination is an important component of any hydrogeological investigation of an unconsolidated sedimentary aquifer since storage coefficients and transport phenomena are dependent on the distribution of porosity within an aquifer.

When coherent samples, commonly soil samples, with undisturbed structures are available then porosities can be determined using the gas expansion method. The technique is not applicable to coarse grained non-indurated sediments (sediments which are generally incohesive) and it is not applicable to soft or friable non-indurated sediments where pore structure is likely to be significantly modified during sampling.

The technique provides an accurate measure of porosity in appropriate samples, however it requires specialist equipment (gas pycnometers) which may not be readily available.

Method summary :

The sample is sealed into a sample chamber and gas (usually helium) expanded from a reservoir of either constant or variable volume. The pressure of the gas before and after expansion is recorded and used to calculate sample porosity.



Schematic illustrations of the two principal types of gas pycnometer. a, the variable volume pycnometer and b, the constant volume pycnometer (after Danielson & Sutherland 1986)

Key Reference(s):

Danielson, R E & Sutherland, P L (1986) Porosity. In : Klute, A (ed) *Methods of Soil Analysis* (second edition). Part 1, Physical and mineralogical methods. Agronomy No. 9. 1443-461. Pub. American. Society of Agronomy and Soil Science Society of America. Wisconsin USA

Method Summary Sheet (Lab5)

Title : *Porosity determination - density methods.*

Scope and use of method :

Porosity determination is an important component of any hydrogeological investigation of an unconsolidated sedimentary aquifer since storage coefficients and transport phenomena are dependent on the distribution of porosity within an aquifer.

Density methods are used to determine the porosity of UNSAs samples when gas expansion methods are not available or when gas expansion methods are not suited to the available material. Generally, density methods are used on less cohesive UNSAs materials than gas porosity determination methods.

The techniques are relatively easy to perform and require the minimum of equipment (eg. balances and density bottles). Consequently, they are relatively inexpensive.

Method summary :

Porosity measurement by density methods requires particle density and bulk densities to be obtained. Particle density is obtained by Archimedes principal (by using a pycnometer or density bottle or by weighing submersed samples). Bulk density can be found by weighing a sample of known volume. Volumes may be obtained by cutting core of known dimensions, by excavating material from a pit of known size or in the case of soil obtaining a clod of known dimensions.

Key Reference(s) :

Blake, G R & Hartge, K H (1986a) Bulk density. In : Klute, A (ed) *Methods of Soil Analysis* (second edition). Part 1, Physical and mineralogical methods. Agronomy No. 9. 363-376. Pub. American. Society of Agronomy and Soil Science Society of America. Wisconsin USA

Blake, G R & Hartge, K H (1986b) Particle density. In : Klute, A (ed) *Methods of Soil Analysis* (second edition). Part 1, Physical and mineralogical methods. Agronomy No. 9. 377-382. Pub. American. Society of Agronomy and Soil Science Society of America. Wisconsin USA

Method Summary Sheet (Lab6)

Title : *Pore size distribution - water desorption method.*

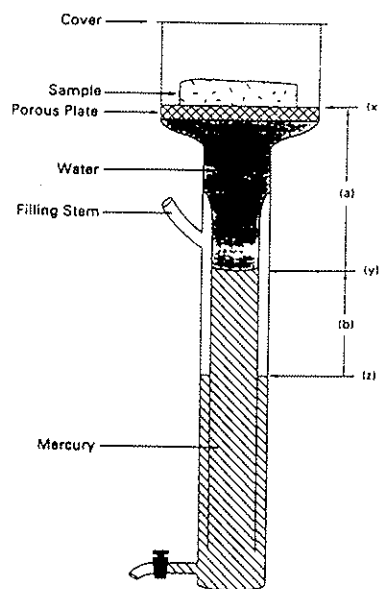
Scope and use of method :

Pore size distributions are of relatively limited use in the hydrogeological investigation of unconsolidated sedimentary aquifers. They are principally obtained in order to study the capillary pressure effects within *UNSA*s.

The water desorption method can only be used to obtain pore size distributions when coherent samples, commonly soil samples, with undisturbed structures are available. The technique is relatively sophisticated, and although the equipment required is relatively inexpensive it may be of limited availability.

Method summary :

A sample, saturated in formation or synthetic brine, is placed on a porous plate above a column of brine. A suction is applied to the sample so that the sample partially drains until equilibrium is achieved. Another increment of suction is then applied and a new equilibrium obtained. The suctions and volumes of drained water are recorded and used to calculate the pore size distribution.



Schematic illustration of the porous funnel apparatus used for determining pore size distributions in soils by the water desorption method (after Danielson & Sutherland 1986).

Key Reference(s) :

Danielson, R E & Sutherland, P L (1986) Porosity. In : Klute, A (ed) *Methods of Soil Analysis* (second edition). Part 1, Physical and mineralogical methods. Agronomy No. 9. 1443-461. Pub. American. Society of Agronomy and Soil Science Society of America. Wisconsin USA

Lawrence, G P (1977) Measurement of pore sizes in fine-textured soils: a review of existing techniques. *J Soil Sci.* 28, 527-540

Method Summary Sheet (Lab7)

Title : *Pore size distribution - mercury intrusion method.*

Scope and use of method :

Pore size distributions are of relatively limited use in the hydrogeological investigation of unconsolidated sedimentary aquifers. They are principally obtained in order to study capillary pressure effects within UNSAs.

Unlike the water desorption method the mercury injection method can be used to obtain pore size distributions from both coherent samples and relatively incohesive samples (providing pore structures within the samples are relatively undisturbed during sampling). The technique is relatively sophisticated, the equipment required is of very limited availability and consequently the tests are relatively expensive.

Method summary :

The mercury injection method is commonly semi-automated. A sample of material to be analyzed is placed in a penetrometer which is then flooded with mercury. The penetrometer containing the sample is pressurized using a hydraulic system, typically to 50,000 psi. During pressurization the mercury progressively intrudes the sample pore space. The volume of intruded mercury and the applied hydrostatic pressure are continually monitored and used to calculate the pore size distribution.

Key Reference(s) :

Lawrence, G P (1977) Measurement of pore sizes in fine-textured soils: a review of existing techniques. *J Soil Sci.* **28**, 527-540

Method Summary Sheet (Lab8)

Title : *Permeability measurement - falling head test.*

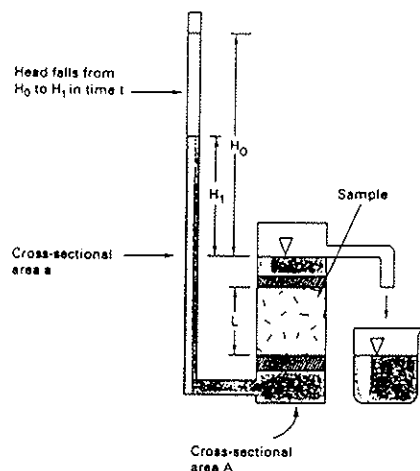
Scope and use of method :

Laboratory permeability measurements are generally used to assess the degree of hydrogeological variability of a given aquifer and to obtain values to validate or establish correlations with field data. However, they may be of limited use in the evaluation of unconsolidated sedimentary aquifers due to the problem of obtaining undisturbed core. *This test should not be employed on re-constituted loose material.*

Falling head permeameters require core with relatively undisturbed pore structure and are used to measure the permeability of samples with relatively fine grain sizes, eg. fine sands or structured clays. The technique is relatively simple and the equipment readily available, consequently the tests are relatively inexpensive.

Method summary :

Coarse filter screens are placed above and below the sample. The base of the sample is placed in contact with a water reservoir and either the top or the bottom of the sample is connected to a standpipe filled with de-aired water. A head is established across the sample and as water seeps through the sample the rate of change in the height of the water in the standpipe is recorded. Sample permeability can be calculated if standpipe and sample dimensions are known.



Schematic illustration of a falling head permeameter used for measuring hydraulic conductivity. H_0 is the initial hydraulic head at time t and H_1 is the final hydraulic head at t_1 . (after Freeze & Cherry 1979).

Key Reference(s) :

Freeze, R A & Cherry, J A (1979) *Groundwater*. Pub. Prentice-Hall, New York USA

Method Summary Sheet (Lab9)

Title : *Permeability measurement - constant head test.*

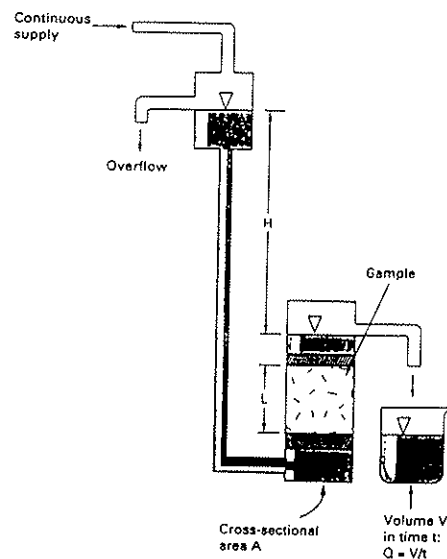
Scope and use of method :

Laboratory permeability measurements are generally used to assess the degree of hydrogeological variability of a given aquifer and to obtain values to validate or establish correlations with field data. However, they may be of limited use in the evaluation of unconsolidated sedimentary aquifers due to the problem of obtaining undisturbed core. *This test should not be employed on re-constituted loose material.*

Constant head permeameters require core with relatively undisturbed pore structure and are used to measure the permeability of samples with a variety of grain sizes, eg. gravels to fine sands. The technique is relatively simple and the equipment readily available, consequently the tests are relatively inexpensive.

Method summary :

Coarse filter screens are placed above and below the sample. The base of the sample is placed in contact with a water reservoir and the top and the bottom of the sample are connected to standpipes. A constant head of de-aired water is maintained in the upstream standpipe via a system of continuous supply to a tank with an overflow. Once a constant head (H) has been obtained between the two standpipes permeability can be calculated using H , the flow rate and the sample dimensions.



Schematic illustration of a constant head permeameter used for measuring hydraulic conductivity, where H is the constant hydraulic head (after Freeze & Cherry 1979).

Key Reference(s) :

Freeze, R A & Cherry, J A (1979) *Groundwater*. Pub. Prentice-Hall, New York USA

Method Summary Sheet (Lab10)

Title : *Permeability measurement - oedometer test.*

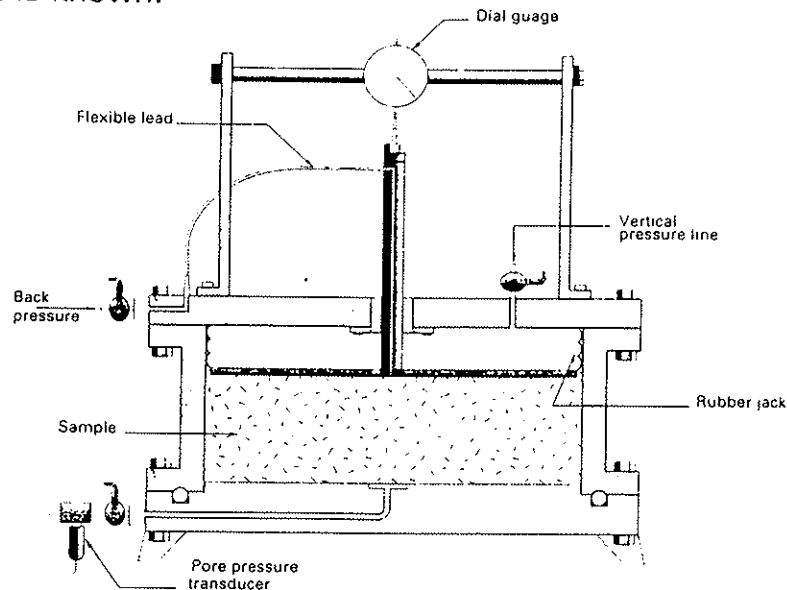
Scope and use :

Laboratory permeability measurements are generally used to assess the degree of hydrogeological variability of a given aquifer and to obtain values to validate or establish correlations with field data. However, they may be of limited use in the evaluation of unconsolidated sedimentary aquifers due to the problem of obtaining undisturbed core. This test should not be employed on re-constituted loose material.

The oedometer test requires core with relatively undisturbed pore structure and is typically used to measure the permeability of homogeneous clay samples.

Method summary :

The water or brine saturated, disk shaped, sample is placed in the hydraulic oedometer with a porous plate placed the sample and the whole assembly sealed in by a rubber jack. The sample is then pressurized using the rubber jack. By measuring the change in sample porosity as a function of applied pressure and by obtaining time-compression curves coefficients of volume change and consolidation can be calculated. Permeability can be found using these coefficients if the density of the saturant is known.



Schematic illustration of a hydraulic oedometer (after Rowe & Barden 1966)

Key Reference(s) :

Rowe, P W & Barden, L A (1966) A new consolidation cell. *Geotechnique* 21, 273-328

Terzaghi, K (1943) *Theoretical soil mechanics*. Pub. John Wiley & Sons, New York

