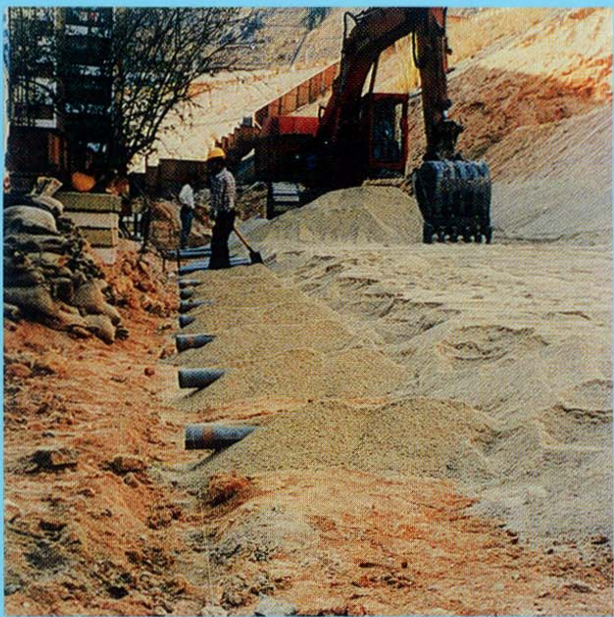
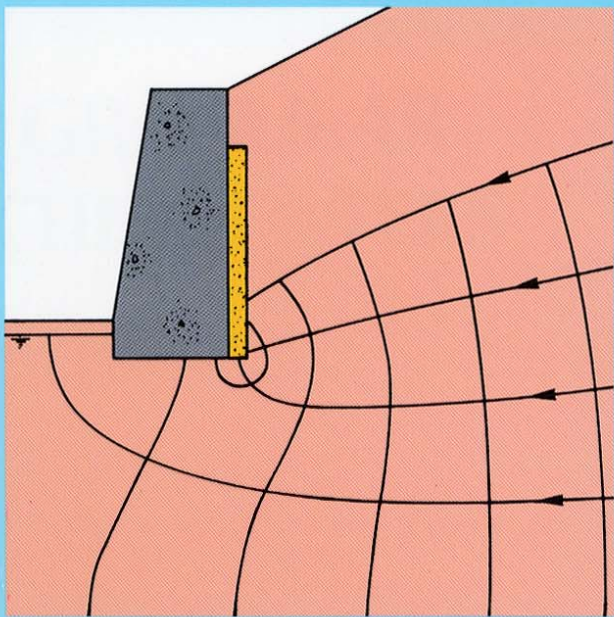
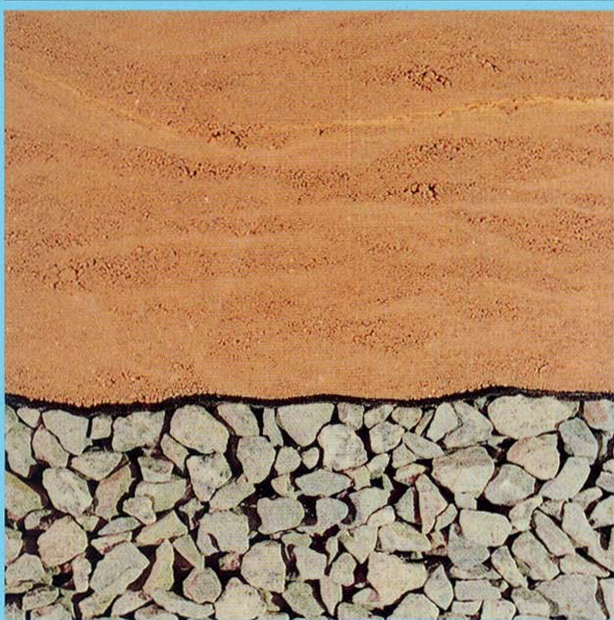
GEO PUBLICATION No. 1/93

REVIEW OF GRANULAR AND GEOTEXTILE FILTERS







GEOTECHNICAL ENGINEERING OFFICE
Civil Engineering Department
Hong Kong

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Civil Engineering Department
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Captions of Figures on the Front Cover :

Top Left	Granular Filter Blanket for Fill Slope Under Construction
Top Right	Steady-state Flow Net Corresponding to Groundwater Drawdown Due to Drainage Layer Behind a Retaining Wall
Bottom Left	Separation of Base Soil and Drainage Layer by Means of a Geotextile Filter
Bottom Right	Laboratory Filtration Tests on Geotextile Filters Used with Granitic Saprolites

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FOREWORD

This document presents a review of principles and practice related to the design of filters for use in drainage systems for earthworks in Hong Kong. Recommendations are made for design of filters, and guidance is given about their construction.

The document was prepared in the Geotechnical Engineering Office (GEO) under the direction of Messrs J.B. Massey and Y.C. Chan. It draws on the findings of two research projects under the GEO Research & Development Theme on Slope Stability and Drainage Measures. These projects involved reviews of granular filters and geotextile filters by Mr L.C. Mak and Dr P.L.R. Pang respectively. This document was edited initially by Mr S.H. Tse and Dr T.S.K. Lam and later by Mr S.H. Mak and Mr K.K.S. Ho, and it was reviewed by Dr P.L.R. Pang and Mr K.S. Yuen. In the course of preparing this publication, many individuals in the GEO have also provided input, and their contributions are gratefully acknowledged.

Practitioners are encouraged to provide any comments they may have on the contents of this publication to the Geotechnical Engineering Office.

A.W. Malone
Principal Government Geotechnical Engineer
December 1993

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PART I

INTRODUCTION

1. SCOPE

This document reviews the design and construction of granular and geotextile filters as applied to slopes and retaining walls in Hong Kong (Figures 1 and 2). Guidance on design and construction of filter layers is also provided. The use of filters in maritime works, the protection of clay cores in dams and in structures subject to vibratory loads or cyclic reversal in the direction of groundwater movements is not covered.

This document consists of four parts :

- Part I gives an introduction to the subject matter, an outline of the basic principles of filtration together with a summary of the engineering properties of Hong Kong soils relevant to filter application.

- Parts II and III deal with the design and construction aspects of granular filters and geotextile filters respectively. In Part II, a review of the characteristics affecting granular filter performance and recommendations on the design and construction of granular filters are given. In Part III, the characteristics of geotextiles, such as durability, filtration behaviour and basic properties are discussed. A review of the design and construction using geotextile filters is also included.

- Part IV gives the overall conclusions and recommendations of this study, together with a discussion on the choice of granular filters and geotextile filters.

In this document, design rules and guidance on construction for granular filters and geotextile filters are recommended. These recommendations supersede Section 4.6 of the Geotechnical Manual for Slopes (GCO, 1984).

2. FILTER APPLICATION AND PERFORMANCE CRITERIA

2.1 APPLICATION OF FILTERS IN HONG KONG

Filters have a wide range of applications in civil engineering. In Hong Kong, they are commonly incorporated in slope works and behind retaining walls as part of the subsurface drainage system. Their functions are to prevent internal erosion during movement of water from the base soil through the filter to the drainage outlet and to permit the unimpeded flow of water within the drainage system (Figures 1 and 2).

The two types of filters in common use are granular filters and geotextile filters. In Hong Kong granular filters generally consist of graded crushed rock products, whereas geotextile filters are permeable textile fabrics.

2.2 BASIC PRINCIPLES OF FILTRATION

The term "filtration" in civil engineering is used to describe the process of preventing the migration of particles of a base soil into or through a filter under the action of flowing water. The success of the filtration process relies on the establishment of a stable interface between the finer base soil and the filter. Some movements of the finer particles of the base soil into or through the filter may occur before a stable condition develops. Under such migration, the base soil which is directly in contact with the filter will become coarser whilst the layer of filter material in contact with the base soil may be partially clogged with the fine particles. A transition interface between the filter and the base soil is thus formed with the permeability increasing from that of the base soil to that of the filter across the interface. Once a stable interface is formed, there will be no further migration of fines unless the hydraulic gradients are substantially higher than those already experienced or where cyclic flow conditions occur (Wolski, 1987). A stable interface can only be formed provided the filter is not excessively coarse. The thickness of such migration must be small such that there is no undue loss of fine particles from the base soil. Also, the permeability of the soil/filter system must be sufficiently high to permit free flow of water and to prevent significant build-up of pore water pressure in the base soil which may jeopardize the stability of the engineering structure.

2.3 PERFORMANCE CRITERIA FOR FILTERS

The two principal performance criteria for filters are as follows:

(a) *Retention Criterion* - There must be no excessive loss of fine particles from the base soil during the service life of the engineering structure.

(b) *Permeability Criterion* - The permeability of the drainage system must reach a steady state value which is sufficiently high for water to flow freely, and which must not reduce with time.

The establishment of a stable filter based on the above two criteria is shown diagrammatically in Figure 3.

These two performance criteria are applicable for the design of both granular filters and geotextile filters. To ensure satisfactory long term performance, the filter material and its structure should remain largely unaltered throughout its service life. For granular filters, the main consideration relates to the stability of the filter grading. Loss of fines from the granular filter network under the movement of water will result in a change of the retention capacity and permeability of the filter. Segregation of particles prior to and during construction of the filter must be prevented. For geotextile filters, the synthetic fibres of the textile fabric form the filter network. The focus is therefore on assessing the potential for degradation of the textile fabrics and the risk of clogging under the movement of water.

3. PROPERTIES OF HONG KONG SOILS PERTINENT TO FILTERS

3.1 CHARACTERISTICS OF HONG KONG SOILS

The principal soil types encountered in most slope and retaining wall works in Hong Kong are colluvium, residual soils and saprolites derived from insitu weathering of granitic and volcanic rocks. Colluvium is typically a structureless, highly variable mixture of soil and rock fragments forming a mantle to or deposited at the lower part of natural slopes. Residual soils are materials in which the parent rock texture, fabric and structure have been destroyed in the process of weathering. Saprolites are soils in which the texture, fabric and structure of the parent rock are retained. The nature of residual soils and saprolites derived from weathering of granites and volcanic rocks in Hong Kong is described in Brand (1985a & b). Some of the typical properties, such as grading and permeability, are given by Lumb (1962, 1965 & 1975). The two important characteristics of Hong Kong soils which are relevant to filter design are described below :

(a) *Variability* - Hong Kong soils are inherently variable. A wide range of particle sizes can be present and this often gives rise to difficulties in the design of filters. This is particularly evident in the case of colluvium which usually is gap-graded or has a highly variable particle size distribution.

(b) *Soil Mass Structure* - The hydraulic characteristics of saprolites are largely controlled by the presence of discontinuities (e.g. relict joints) and the material fabric inherited from the parent rock. The mass permeability of these materials is often higher than that of a transported soil with a similar grading. Vaughan (1985) considered that this is partly due to the aggregation of clay minerals, which gives larger effective particle sizes and consequently larger hydraulic pore channels. Erosion pipes and fracture zones can also have an important influence on the hydraulic properties of saprolites and their spatial variability (Massey & Pang, 1989).

Some relict or secondary bonding may be present in saprolites and residual soils which is advantageous in filtration behaviour as particles are less likely to be eroded from the soil mass by the imposed hydraulic forces. It is reasonable to assume that conventional filter design methods based on remoulded soil properties are generally conservative in such cases. However, there may be some important exceptions. The completely decomposed andesite in the region of Tuen Mun is known to be susceptible to severe internal erosion, and warrants extreme caution.

3.2 GRADINGS OF SAPROLITES

Examples of grading curves of granitic saprolites and volcanic saprolites tested by the Geotechnical Engineering Office (GEO) are given in Figures 4 and 5. Samples of weathered granite samples were recovered from King's Park, Glenealy and Shouson Hill whereas samples of weathered volcanics were obtained from Po Shan Road and a borrow area to the north of Tai Po Industrial Estate. In the figures, the grading envelopes obtained by Lumb (1962 & 1965) in his earlier studies of the engineering properties of these two types of materials are also included. It is observed that with the exception of the weathered volcanic samples recovered from Po Shan Road, which exhibit a greater degree of decomposition, all the weathered granitic and volcanic samples tested conform reasonably well with Lumb's grading envelopes. As can be seen in the figures, the granitic and volcanic saprolites are widely-graded, covering particle sizes in the silt, sand and gravel ranges. It is not intended here to give a generalised grading envelope for Hong Kong saprolites, for the following reasons:

(a) The gradings of a saprolite are site-specific and can vary widely. The grading envelope determined will depend on the sampling locations and the number of samples tested.

(b) A generalised grading envelope may not be useful, because any envelope thus established is most likely to have such a wide range that no single filter material can satisfy all the design criteria.

It should be noted that the gradings of Hong Kong saprolites generally fall within the envelope of 'problem soils' under the filter criteria given by Heerten (1986) as shown in Figure 6. The particle size distribution curves are also largely within the grading envelope of soils which have experienced internal erosion in earth dams as reported by Sherald (1979) and shown in Figure 7. Therefore care should be exercised in designing suitable filters for saprolitic soils in Hong Kong.

PART II

GRANULAR FILTERS

4. CHARACTERISTICS OF GRANULAR FILTERS

4.1 GENERAL

The principal factors governing the performance and effectiveness of a granular filter are as follows :

(a) *Retention of Base Soil* - The filter pore network, which comprises a system of interconnected pores, should be capable of preventing a continuous loss of soil particles from the base soil into the filter.

(b) *Permeability of Base Soil and Filter* - The filter should be more permeable than the base soil and be able to accommodate the design flow without a significant build-up of water pressure.

(c) *Filter Grading* - The grading of the filter should be such as to prevent loss of its own finer particles during the passage of water through the filter layer.

(d) *Minimum Filter Thickness* - The filter should have a sufficient thickness to arrest particles migrating from the base soil such that a stable interface can be formed by self filtering.

Many researchers have investigated the above factors in an attempt to improve the understanding of the behaviour of granular filters. A review of the findings of these investigations is described in the following sections to provide a background to the criteria recommended for granular filter design in Hong Kong.

4.2 RETENTION OF BASE SOIL

4.2.1 Size and Network of Pores in Filters

The ability of a filter to retain base soil particles primarily depends on its pore size and the structure of the pore network. Early studies on filter pore network (e.g. Terzaghi, 1922) were generally based on a model of identical spherical particles. The relationship between the equivalent diameter of the pores (D_p) for such a model and the diameter of the equivalent spherical particles (D) are as follows :

$$D = 2.4\ D_p \text{ for a cubical packing} \qquad \text{(1)}$$

$$D = 5\ D_p \text{ for a hexagonal packing} \qquad \text{(2)}$$

This spherical particle model, although idealized, can provide an estimate of the apparent pore size of a filter composed of uniform particles. It forms the basis for the development of a number of formulae for granular filter design. Some researchers, including Silveira (1965), Wittmann (1979), Sherard et al (1984a) and Kenney et al (1985), have carried out further investigations on the pore size distribution of granular filters using either a theoretical or experimental approach.

Silveira (1965) developed a method, based on probability theory, of estimating the pore size distribution curve from the particle size distribution curve of soil assuming dense configuration of spherical particles. From the pore size distribution curve, using absorbing Markov chain process, Silveira estimated theoretically the thickness of filter layer necessary to catch washed-out particles of base soil. However, upon extension of the regular packing model to random packing, Silveira's method needed extensive computation, being still not sufficiently precise.

Wittmann (1979) developed a method for estimating the average pore area in a filter based on the assumption that the porous medium was represented by a sectional plane. The method becomes more complicated when extended to hetero-dispersive packing and treated statistically. Based on probability theory, Wittmann derived the theoretical filtration length (hence the filter thickness) from the average pore area distribution. Wittmann's concept is good for describing a porous medium, but in the present shape, it is limited in practical application.

Sherard et al (1984a) carried out a series of experiments to evaluate the pore size of sand and gravel filters and concluded that pore sizes can be related to the D_{15} size, where D_m is the size of sieve (in mm) that allows m% by weight of the material to pass through. Particles smaller than 0.10 D_{15} which were carried in water suspension could generally pass through and out of the pores of the filter. Thus, the filter effectively acted as a sieve with openings about 0.11 D_{15} in size.

Kenney et al (1985) carried out an extensive investigation into the filter pore network with particular reference to the size of the "constriction". They suggested that the filtration ability of a material was controlled by the size of the constriction, instead of the apparent pore size or pore area. A controlling constriction size (D^*_c) may then be defined as the size of the largest particle which can be transported through the filter by water flow. Using probability theory, they showed that the effects of filter thickness on filter performance can be explained by the size of the constriction of the pore channels. Based on above work, they proposed that for 'naturally-graded' soils, the controlling constriction size can be estimated by the following expressions :

$$D^*_c \leq 0.25\, D_5$$

$$\text{or} \qquad D^*_c \leq 0.20\, D_{15} \qquad \ldots\ldots\ldots (3)$$

It seems that D_{15} is a useful index for assessing the retention ability of a filter. However, the results of Kenney et al (1985) appear to be somewhat different from those obtained by Sherard et al (1984a). This apparent discrepancy may be attributed to differences in the hydrodynamic conditions applied in the tests.

4.2.2 Particle Size Distribution of Base Soil

For a satisfactory filter, the pores need to be sufficiently small to prevent continuous loss of the soil particles from the base soil into the filter. It is therefore necessary to define a parameter for representing the base soil particle size and to establish a correlation of this parameter with the filter pore size.

Terzaghi (1922) and Bertram (1940) identified the D_{85} of the base soil as a suitable parameter in their filter criteria. They considered that by preventing the coarse particles of size D_{85} of the base soil from entering the filter voids, an effective transition zone could be formed behind the filter and the remaining 85% of the finer particles retained. A filter criterion to prevent piping or internal erosion failure may therefore be established by ensuring that the equivalent pore size or pore constriction of the filter is smaller than the D_{85} of the base soil.

Lund (1949) and Soares (1980) carried out tests on soils using a series of sieves each acting as a single layer filter. The materials tested were relatively uniform sands (C_u = 1.5 in Lund's tests and C_u = 2.86 in Soares' tests, where C_u is the uniformity coefficient defined as D_{60}/D_{10}). It was observed that there was an abrupt increase in the loss of fines when the sieve openings were larger than the D_{85} size of the base soil. These results thus confirmed the usefulness of the D_{85} parameter in filter design against excessive loss of fines.

4.3 PERMEABILITY OF BASE SOIL AND FILTER

As a general rule, the filter should be sufficiently more permeable than the base soil it retains. This can generally be achieved using a material coarser than the base soil. In the case where a large quantity of water is expected to flow through the filter, it is essential to determine the permeability of both the filter material and the base soil reasonably accurately to ensure a reliable drainage design.

For the base soil, insitu permeability tests, such as falling head permeability tests and pumping tests, are preferred to laboratory tests for obtaining permeability values of the soil mass, particularly when the hydraulic characteristics are predominantly controlled by relict joints. Methods of insitu permeability tests are given in Geoguide 2 (GCO, 1987).

For filter material, insitu permeability tests would not normally be carried out. The permeability is usually estimated from empirical formulae based on the particle size distribution. A list of these formulae is given in Table 1 for easy reference. It should be noted that these formulae are empirical and would give only rough permeability values of the filter. In cases where the permeability of the filter needs to be known with more confidence, laboratory permeability tests would need to be carried out to simulate the actual field conditions.

Sherald et al (1984a) conducted laboratory permeability tests on four specimens each of sub-rounded alluvial particles and of angular particles of crushed limestones. They concluded that angular particles of crushed rock are as satisfactory as rounded alluvial particles for filters.

4.4 FILTER GRADING

4.4.1 Grading Stability Model

The internal stability of a granular mass relates to its ability to prevent the loss of fine particles when subject to external disturbing forces arising from seepage. A material is described as having a stable grading if the particles in the material do not migrate within itself. When particles are removed by the flow of water, the filter will become more coarse-grained and less effective as a filtering medium in preventing loss of particles from the base soil.

Grading stability depends on four factors :

(a) shape of grading curve,
(b) porosity or relative density,
(c) homogeneity of the material as placed, and
(d) severity of the disturbing hydrodynamic drag forces.

Filters comprising uniform-sized particles are intrinsically stable, irrespective of the filter density and seepage velocity. The potential for instability increases as the width of the grading curve and seepage velocity increase. Instability is likely to occur in soils having irregularly-shaped grading curves, such as a gap-graded soil, although experience shows that reasonably well-graded soils could also prove to be unstable (Scheurenberg, 1986).

Kenney & Lau (1985) put forward a physical model to explain grading stability. They suggested that all soils possess a primary fabric which supports loads and transfers stresses. Within the pores of this primary fabric, there are loose particles which do not transfer stresses but are free to move within the pore network. At locations where the constriction in the pore network of the primary fabric is larger than the size of the loose particles, these particles can be transported to the neighbouring pores. The loose particles can either move from pore to pore until they are discharged from the parent material or come to a halt if they encounter smaller constrictions. Once trapped, the loose particles will act as part of the filter pore network fabric, that is, the filter fabric is composed of those particles making up the primary fabric together with the loose particles trapped by smaller constrictions. Where a deficiency in the number of particles of a particular size range exists, such that the constrictions in the primary fabric cannot be blocked, these constrictions will remain open and will allow the continual washing out of the smaller particles. Based on this model, it was concluded that grading instability will most likely occur in soils which have a gently-inclined section in the lower part of their grading curves, i.e. a wide range of particle sizes.

4.4.2 Experimental Studies

The significance of the shape of grading curve on the internal stability of filter materials was first demonstrated by the test results presented by USCE (1953). Four mixtures of different proportions of 'concrete sand and gravel', with C_u ranging between 6 and 23, were subject to permeability tests under a hydraulic gradient of up to 16. Based on the change in permeabilities and the amounts of materials washed out, two mixtures having smaller percentages of sand (C_u = 23) were considered inherently unstable. No attempt was made, however, to account for the hydraulic gradient at which inherent instability occurred.

The influence of the shape of grading curve on the internal stability of filter materials was further studied by Kenney & Lau (1985). A series of permeability tests was conducted using materials with C_u ranging from 3 to 35 and particle sizes between 0.1 to 100 mm. To maximize the migration of particles through the filter, the samples were vibrated and the flow conditions were much more severe than those in actual practice. All the specimens were compacted to a relative density of at least 80%. By comparing the test results using normalised grading curves (termed "shape curves"), a boundary line can be defined to separate the 'stable' grading from the 'unstable' grading.

The findings reported by Kenney & Lau (1985) on filter grading stability are very conservative, as discussed by Milligan (1986) and Sherard & Dunningan (1986), since the tests were carried out under very severe conditions which are unlikely to be experienced in the field.

Recognizing that the problem of internal stability of filters was, to some extent, controversial and had not been fully solved, Wolski (1987) suggested that for preliminary analysis, the simple criterion of $C_u < 20$ may be used as a yardstick to define stable grading of filters. Under such a criterion, widely-graded filters, which are potentially liable to become unstable, would be excluded.

4.4.3 Segregation

Segregation of filter materials during construction can adversely affect the performance of a filter. It has been generally accepted that widely-graded or gap-graded materials are more susceptible to segregation (USCE, 1953; Sherard et al, 1984a).

The main cause of segregation in widely-graded or gap-graded materials is the presence of coarse gravel particles. These particles with little or no sand filling the voids frequently accumulate in pockets or streaks at the base soil-filter interface. The dimensions of these pockets increase rapidly with the size of the coarse particles in the filter. For a segregated filter to function satisfactorily, there must first be substantial migration of base soil into the filter to fill the open voids in the segregated zone. Such large migration is most undesirable and has an adverse affect on the long term performance of a filter.

4.5 MINIMUM FILTER THICKNESS

The theoretical minimum filter thickness is related to the filtration length of a filter which is defined as the maximum distance that fine particles from the base soil and the loose particles in the filter can travel within the filter mass. To prevent any loss of particles, the filter thickness should be greater than the filtration length. A number of theoretical methods, such as those given by Silveira (1965) and Wittmann (1979), are available for assessing the filtration length. These methods, which were based on the theoretical work described in Section 4.2 for estimating the equivalent pore size and pore size distribution, are generally too complicated for use in routine design. In Hong Kong, the average particle size of a granular filter is usually less than 2 mm and the minimum filter thickness required would theoretically be less than 100 mm.

Using Darcy's law, GEO (1993) gives a simple method for designing the thickness of the filter/drainage materials required based on the design seepage flow rate into the drainage system of a retaining wall or slope, the permeability of the drainage material and the hydraulic gradient of the flow within the drainage material. In assessing the rate of seepage flow into the drainage system, the permeability of the soil mass which includes the effects of relict joints should be used.

The minimum filter thickness is often governed by construction considerations rather than by the drainage capacity criterion. As discussed in Section 6.3, the practical minimum thickness would be at least 300 mm.

5. GRANULAR FILTER DESIGN

5.1 REVIEW OF GRANULAR FILTER DESIGN CRITERIA

5.1.1 Introduction

A number of design criteria for granular filters based on ratios of particle sizes have been proposed in the literature. The ratios selected include $D_{15}F/D_{85}S$, $D_{15}F/D_{15}S$, $D_{15}F/D_{50}S$ and $D_{50}F/D_{50}S$ where D_m is the size of the sieve (in mm) that allows m% by weight of the material (soil or filter) to pass through and F and S refer to the filter and base soil respectively. A summary of the filter design criteria reviewed is given in Table 2. It can be seen that these criteria are generally specified to satisfy two functional requirements and one performance requirement : internal stability, permeability and segregation. Based on the review, a number of observations are discussed below.

5.1.2 Observations

(1) *Relevance of $D_{15}F/D_{85}S$.* The use of $D_{15}F/D_{85}S$ as the principal filter design criterion is generally agreed in the literature. The lower limit of the $D_{15}F/D_{85}S$ ratio ranges from 4 to 10. The results of tests carried out by Lund (1949) and Sherald et al (1984a) indicated that the filter criterion, $D_{15}F/D_{85}S \leq 5$ is generally adequate with a factor of safety against excessive loss of fines of about 2. This criterion will ensure stability of the filter during the passage of water through it.

(2) *Relevance of $D_{15}F$, $D_{15}S$, $D_{50}F$, and $D_{50}S$.* Sherald et al (1984a) pointed out that in a sand or gravel filter, the sizes of the internal pore channels are governed by the finer particles, $D_{15}F$. As the average particle size of the sand or gravel filter, $D_{50}F$, is not a satisfactory measure of the minimum pore sizes, they considered that filter criteria using D_{50}, such as $D_{50}F/D_{50}S < 25$ (USBR, 1955) are not founded on a satisfactory theoretical or experimental base. The argument that the use of an appropriate $D_{50}F/D_{50}S$ ratio will prevent excessive segregation during construction is not well founded as filter segregation should be limited by restrictions on the range, and not the average, of particle sizes in the filter. They also considered that as the D_{15} size of the base soil has no significant influence on the properties of the filter, criteria for filter stability based on $D_{15}F/D_{15}S$, such as $D_{15}F/D_{15}S < 40$ (USBR, 1955), should not be used. However, as the relative permeability of the base soil and the filter will depend, to a certain extent, on the square of the $D_{15}F/D_{15}S$ ratio, it would be useful to set the lower limit of this ratio to at least 5 (i.e. a relative permeability of around 25) to ensure that the filter is permeable enough to allow unimpeded flow of water from the base soil.

(3) *Finest and Coarsest Fractions.* USBR (1974) suggested that the filter should not contain more than 5% of materials finer than 75 μm. For the maximum size of any filter, USBR (1974) recommended this be 75 mm. This recommendation was supported by Sherald et al (1984b).

(4) *Segregation of filters.* It is very difficult to prevent some segregation of filters during placement. The existing guideline of only limiting the C_u value of the filter to a

maximum value of 20 is not entirely satisfactory since particles larger than D_{60}, such as D_{90} size, commonly govern the magnitude of the problem. Although there are no widely-agreed quantitative criteria for determining the maximum acceptable broadness of filter grading to limit segregation, it would seem reasonable to bound the C_u of the filter to between, say, 4 and 20 to ensure an appropriate spread of the grading in the finer fraction, together with an upper bound of say 50 mm on the maximum particle size in the coarser fraction.

5.2 RECOMMENDED GRANULAR FILTER DESIGN CRITERIA

Based on the characteristics of granular filters described in Chapter 4 and the review of filter design criteria discussed in Section 5.1 above, it is concluded that filter design has to satisfy the following requirements :

(a) *Stability* - The pores in the filter must be small enough to prevent excessive migration of the base soil being drained. As discussed in Section 5.1.2(1), the common filter design rule of limiting the $D_{15}F/D_{85}S$ to 5 is appropriate. As an additional measure against failure, the filter should not be gap-graded to prevent the loss of fine particles from the filter itself.

(b) *Permeability* - The filter must be sufficiently more permeable than the material being drained. This requirement would be satisfied by limiting the $D_{15}F/D_{15}S$ ratio to at least 5 as discussed in Section 5.1.2(2). The presence of fine particles in significant quantities could also influence the permeability of the filter. Hence the amount of particles finer than 63 μm should not exceed 5% as discussed in Section 5.1.2(3); the particle size of 63 μm has been chosen to correspond to the BS sieve size nearest to 75 μm. The filter should also be cohesionless to prevent the formation of shrinkage cracks in the filter as a result of drying.

(c) *Segregation* - The filter should not become segregated or contaminated prior to, during, and after installation. As discussed in Section 5.1.2(4), it is very difficult to prevent segregation of the filters during placement. However, to minimize this problem, the filter should not have a broad grading and that the maximum size of the particles should be limited. It is recommended that the C_u value be restricted to between 4 and 20 with the maximum size of particles limited to 50 mm.

Based on the above requirements, six rules for granular filter design are recommended and summarized in Table 3.

5.3 OTHER DESIGN CONSIDERATIONS

In determining the particle size distribution of soils by mechanical means, a dispersing agent, such as sodium hexametaphosphate, is usually added (BSI, 1990). Research by GEO and its Consultants into the effects of dispersants on the particle size distribution of saprolites showed that there was a large increase in percentage of fine particles for soils treated with dispersants. The higher percentage of fines in samples treated by dispersing agents is a result of the breakdown of clay aggregation by the chemicals. However, in practice, these clay aggregates form the finer particles in the base soil and control its hydraulic stability. It would not therefore be appropriate to use dispersing agents in the determination of the grading of base soils for filter designs.

For the design of granular filters, the base soil particle size distribution should be determined by wet sieving using a method such as that given by BS 1377 (BSI, 1990) but without the use of dispersants. Dry sieving is not recommended because clay particles may adhere to the larger-sized particles, and the particle size distribution so obtained will not be representative of the material.

Other factors which may be applicable to granular filter design are covered in the notes in Table 3. With regard to Note (2) of Table 3, it is known that the coarse particles of widely-graded base soils, which are commonly found in Hong Kong, have little effect on the filtration process. Therefore, for those base soils containing a significant amount of both gravel and fines, the coarse part should be ignored, and a revised base soil grading curve consisting of the particles smaller than 5 mm only should be considered.

The minimum thickness of filter layers recommended in Note (3) of Table 3 is intended to ensure integrity and consistency in performance of filters appropriate to the chosen method of construction.

Note (4) of Table 3 draws attention to the point that Rule 5 should be applied to individual batches of the filter. The fact that an individual batch grading curve complies fully with the design limits of the filter grading envelope does not necessarily ensure that it satisfies Rule 5.

It should be noted that Rules 2, 4, 5 and 6 of Table 3 are concerned with the internal requirements of a filter. If these are satisfied, the material is a good filter, but it is also necessary to check that it is compatible with the particular base soil, in accordance with Rules 1 and 3.

Under Rule 3, the relative permeability of the base soil and filter has been assumed to be largely dependent on the $D_{15}F/D_{15}S$ ratio. However, for base soils whose mass permeability is predominantly governed by that of relict discontinuities, it would be necessary to check that the permeability of the filter designed in accordance with Table 3 is at least 25 times that of the soil mass.

Where a filter material is used in conjunction with a coarser free-draining material, such as a crushed rock fill, the grading of the coarser material should also satisfy the filter design criteria. To separate materials of widely different particle sizes, such as weathered volcanic and rockfill, two or more filter zones may be required.

Filter materials should be adequately compacted into place so as not to form a weaker zone which could affect the stability of the engineering structure.

Where perforated or slotted drainage pipes are provided within a filter material, the filter particles should be sufficiently large so as not to enter the perforations, slots or open joints in the pipes. The ends of the pipes should also be closed to prevent entry of the filter materials.

6. CONSTRUCTION CONSIDERATIONS

6.1 GENERAL

For the purpose of ensuring that a filter will serve its designed functions, the securing of the necessary filter materials, the method of construction and of control and monitoring should be properly planned during the early construction stages. Test runs of the filter production and placement equipment would be most desirable prior to commencement of the placement of the filter layer.

6.2 FILTER PRODUCTION

In Hong Kong, granular filter materials are generally derived from crushed rock products. These are usually supplied in bulk from quarries in accordance with the filter envelope specified by the designer. This would, in most cases, ensure a fairly consistent and well-mixed filter. The practice of mixing materials of different particle sizes on site to produce the filter is strongly discouraged.

6.3 CONSTRUCTION OF FILTER LAYERS

Filter layers constructed behind retaining walls and in slopes should be at least 300 mm thick. Construction of these layers should be carried out with care to prevent contamination by fines arising from the adjacent fill materials and to ensure that the filter is adequately compacted. Equipment used for compacting the filter materials should be properly cleaned first to avoid unnecessary contamination. It is also important to avoid excessive compactive effort as this could cause particle crushing and hence a reduction in permeability.

Horizontal filter blankets should be placed on a well compacted, clean and prepared surface. Traffic conveying filter materials to the site should be restricted to temporary access roads which are to be properly prepared prior to laying of filters in these areas. Placement of vertical and inclined filters should proceed almost concurrently with that of the general fill.

In placing and compacting the filter materials, care should be taken to avoid segregation.

6.4 SITE CONTROL AND MONITORING

Any defects in the filter system will be very difficult, if not impossible, to rectify. To ensure satisfactory long term performance of the filter system, adequate site control during construction is most important. The grading of the filter materials delivered should be checked regularly for compliance with the specification. Particle size distribution analyses should also be carried out on samples selected by the engineer after the filter material has been placed and compacted. Where persistent water seepage into the filter system is taking place, the effectiveness of the installed system should be monitored throughout the construction phase by measuring the discharge from the drainage outlet and the piezometric responses as a result of the construction. Post-construction monitoring should also be carried out, if necessary.

PART III

GEOTEXTILE FILTERS

7. TYPES OF GEOTEXTILES

7.1 GENERAL

Durable geotextiles are manufactured from synthetic polymer fibres. The most commonly-used polymer fibres, in decreasing order of use, are polypropylene, polyester, polyamide (nylon) and polyethylene. Geotextiles can be classified according to the manufacturing processes into five main groups : woven, nonwoven, knitted, stitch-bonded and combination geotextiles (Lawson & Curiskis, 1985). Geotextile filters are usually woven or nonwoven fabrics which have good dimensional stability. A combination of geotextiles is sometimes used to perform several functions. These are discussed below.

7.2 WOVEN GEOTEXTILES

Woven geotextiles are manufactured generally by interlacing two perpendicular sets of monofilaments, yarns or tapes. Two terms are used to describe the alignment of the principal directions of fabric construction: "warp" and "weft". The warp direction is parallel to the direction of manufacture of the geotextile while the weft is inserted perpendicular to the warp. Figure 8 illustrates the various types of interlacing that may be found in different woven geotextiles using a combination of the three weaves, viz., "plain", "twill" and "satin". Usually, the warp elements lie parallel to each other. The "leno" weaves are an exception, in which some of the warp elements are twisted partly around other warp elements, thus resulting in an open and yet stable fabric. Another form of woven construction which may be of interest is the "triaxial" fabric. However, the cost of weaving this type of fabric is high and only a limited width of the fabric is produced.

Woven geotextiles can be divided into five sub-groups, according to the use of monofilaments, yarns or tapes in their manufacture, as described below. Some of the indicative properties of the fabrics are given in Table 4.

(a) *Monofilament wovens* - These consist of monofilaments in both the warp and weft directions; the monofilaments are either circular or elliptical in cross-section.

(b) *Yarn wovens* - These consist of multifilament yarns, composed of continuous filaments twisted into a yarn structure, in both the warp and weft directions; a flattening of the yarn cross-section is generally observed at the interlacing points.

(c) *Tape wovens* - These consist of split-film tapes, composed of continuous lengths of single flat tapes produced by splitting an extruded thin sheet in both the warp and weft directions; the width of the tapes generally varies between 1.5 mm and 4 mm.

(d) *Fibrillated wovens* - These consist of fibrillated yarns in both the warp and weft directions. Fibrillated yarns are either approximately elliptical or rectangular in cross-section and are made from tapes by the fibrillation process (a process which breaks up the tapes into fibrous strands but in which the strands may still be interconnected to each other at various points along their lengths).

(e) *Combination wovens* - These are characterised by having one type of filament in the warp direction and another type in the weft direction.

The mechanical behaviour of woven geotextiles is generally anisotropic (i.e. dependent upon the direction of loading). Differences in the stress-strain behaviour in the warp and weft directions are often observed, due partly to the possible use of different warp and weft elements in the fabric, and partly to the differences in the warp and weft tensions arising from weaving and the subsequent processing.

7.3 NONWOVEN GEOTEXTILES

Nonwoven geotextiles are manufactured by first forming a loose "web" (i.e. a layer of short fibres or continuous filaments) arranged in an orientated or random pattern, and then subjecting this to some form of bonding, thus achieving a cohesive planar structure (Pfliegel, 1981).

In the manufacturing process, the method of web formation is important as it is primarily responsible for the spatial distribution and orientation of the fibres within the final geotextile product. Web formation is achieved by first opening and blending the fibrous elements (i.e. separating and mixing the fibres, including those of different polymer types and with different physical characteristics, if required), and then depositing them onto a moving belt or lattice. Several layers can be combined to achieve the desired geotextile unit weight and also the preferred pattern of fibre orientations within the formed web. The web is then subjected to the bonding operations. After bonding, some form of finishing treatment may be applied in order to enhance some of the geotextile's properties, e.g. "calendering" (i.e. compression between rollers) with heated and/or textured rollers to achieve particular surface characteristics. The general aim is to produce a dimensionally stable geotextile with a more or less uniform thickness.

Nonwoven geotextiles can be divided into three sub-groups depending upon the bonding method used, as described below. The essential features of the bonded structure of these geotextiles are illustrated in Figure 9 and some of their indicative properties are given in Table 4.

(a) *Needle-punched nonwovens* - In this method of bonding, thousands of barbed needles, set into a board and with the barbs pointing towards the needle tip, are punched through the formed web which is supported on a perforated plate. As a needle travels through the web thickness, it carries with it fibres which are caught on the barbs. The needle is then withdrawn, leaving the fibres physically entangled within the structure. This results in a flexible geotextile which, in application, can conform well to the surface irregularities in the adjacent soil.

(b) *Heat-bonded nonwovens* - This method of bonding is based on the principle that thermoplastic fibres are softened by the application of heat (e.g. through a high-temperature oven or calendering operation). While in the softened state, pressure may be applied (e.g. by rollers) to force the fibres to adhere together at their contact points. Two basic approaches are often used : the homofilament bonding and heterofilament bonding. For homofilament bonding, all the filaments are composed of the same polymer type although some filaments, called binder filaments, which have a different melting temperature, are used either throughout their length or along part of their length. The geotextile may be wholly composed of filaments only. For heterofilament bonding, some or all of the filaments are heterofils composed of two polymer types with different melting temperatures. In the case of a skin-core arrangement, the lower melting point polymer would form the skin. The application of heat and pressure is controlled in such a manner that only the skin is melted and fused, leaving the inner core relatively unaffected. Using this technique, selective strong bonds within the fibrous structure can be formed. The resultant geotextile is a relatively flat compact product with less flexibility but better abrasion resistance compared to the needle-punched nonwovens.

(c) *Resin-bonded nonwovens* - This is achieved by impregnating the fibrous web with a resin or glue. After curing and/or calendering, strong solid bonds are formed between the fibres, giving the geotextile dimensional stability. Resin-bonded nonwovens are less flexible but more resistant to abrasion than needle-punched nonwovens.

7.4 COMBINATION GEOTEXTILES

Combination geotextiles are those geotextiles which incorporate two of the above major fabric-forming processes in their construction. Examples include high strength fibres stitched onto a heat-bonded nonwoven base, a woven fabric with a heat-bonded backing, and a nonwoven mat needled-punched onto an open weave fabric.

8. DURABILITY OF GEOTEXTILES

8.1 GENERAL

The durability of a geotextile is a function of the resistance of its polymer fibres (and resins, if it is resin-bonded) to environmental attack. The polymer fibres have a relatively brief history (Giroud, 1986) compared with the traditional civil engineering materials. Therefore, the long-term durability of geotextiles to environmental attack, which includes chemical and biological attack, outdoor exposure and temperature effects, is of major concern in permanent engineering works.

Table 5 summarizes the information available on the chemical and thermal stability of the four basic polymer types commonly used in the manufacture of geotextiles, viz., polypropylene, polyester, polyamide and polyethylene. Apart from the basic polymer type, the resistance of a geotextile to environmental attack also depends on the endurance of the anti-oxidants, ultra-violet (UV) stabilizers, fillers and other additives that are used in the manufacturing process.

A brief review of the laboratory and field studies on the durability of geotextiles is given in Sections 8.2, 8.3 and 8.4. Detailed discussions of this subject can be found in specialist texts (e.g. Van Zanten, 1986) and in the papers contained in the 1988 Special Issue on Durability and Long Term Performance of Geotextiles (Ingold, 1988).

8.2 RESISTANCE TO CHEMICAL ATTACK

The first systematic investigation of the resistance of geotextiles to chemical attack was carried out at the United States Waterways Experiment Station (Calhoun, 1972). The investigation included laboratory tests on six woven and one nonwoven geotextiles, composed of propylene and vinylidene chloride. The fabrics were immersed in solutions of sodium and potassium hydroxide (pH 10) and hydrochloric acid (pH 3), jet fuel and toluene for six to twelve months. None of the fabrics tested lost more than 2% strength after immersion in a solution of pH 3 or pH 10, although some of them lost 10 to 14% strength after immersion in jet fuel or toluene. It was concluded that the fabrics evaluated had good resistance to oxidation and chemical attack.

Laboratory tests to estimate the resistance of a polypropylene fabric to solutions of sodium hydroxide (pH 12) and hydrochloric acid (pH 3) were carried out by the French Committee on Geotextiles in 1979 and 1980. The loss of tensile strength and elongation at ultimate tensile stress did not exceed 5% after one year's immersion at 20°C.

The resistance of three geotextiles (composed of polyester, polyamide and aramid) to chemical attack was investigated by Troost & den Hoedt (1984). The fabrics were immersed in solutions of pH 5 and pH 9 for periods of up to thirty months. In addition, immersion of geotextile samples in a range of organic solvents (including benzene, methanol and toluene) were carried out for periods of up to twelve months. None of the fabrics lost more than 10% strength.

Halse et al (1987a & b) subjected six geotextiles, viz. two polypropylene, one polyvinyl chloride and three polyester, to alkaline solutions of calcium and sodium hydroxide (pH 10 and 12). No reduction in strength was observed in the polypropylene and polyvinyl chloride fabrics after immersion of up to 120 days in these solutions. However, strength losses of up to 53% were observed in two of the polyester fabrics and micrographs from a scanning electron microscope revealed etching on the fibre surface of these materials. No measurable strength loss was found in the third polyester fabric. It was suggested that the type of polymer resin (including its molecular weight, molecular weight distribution, crystallinity, etc.) and the method of processing the fibres (including the orientation and draw ratio) could have a significant effect on the resistance of polyester fabrics to alkaline attack.

The above investigations have shown that the polymer fibres are generally resistant to chemical attack, except under extremely aggressive environments. In Hong Kong, investigations on the aggressiveness of soils and groundwater have indicated that the conditions are generally not very aggressive. Kennard et al (1982) and Lee & Ma (1982) carried out studies on the aggressiveness of weathered granites in Hong Kong, with regard to their use as fill in reinforced fill structures. The pH of the soils, which were taken from nine sites in each study, was found to lie between 5 and 9. The Environmental Protection Department (EPD) of Hong Kong has carried out groundwater quality monitoring on a number of wells in the New Territories, including wells close to industrial and agricultural areas where the surface stream waters are polluted by livestock waste and domestic sewage. A review of the unpublished EPD data showed that the pH of the well water fell between 5 and 8. A similar study on the chemical quality of well water in the New Territories was carried out by Lam (1983). The pH of the well water was found to range from 4.7 to 8.7.

8.3 RESISTANCE TO BIOLOGICAL ATTACK

A number of studies have shown that the synthetic polymers used in geotextiles are generally resistant to attack by micro-organisms (i.e. aerobic and anaerobic growth of bacteria, fungi or algae). A detailed review of the subject up to around 1975 can be found in Rankilor (1981). More recent investigations and important findings are described below.

Ionescu et al (1982) immersed 1 400 samples of six geotextiles (four polypropylene, one polyester and one composite) in eight types of media including various bacterial cultures and composites for five to seventeen months. None of the geotextiles showed any signs of bio-degradation and the mechanical properties and structures were found to be unchanged.

Troost & den Hoedt (1984) investigated the resistance of six woven geotextiles (two polypropylene, two polyester, one polyamide and one polyethylene) to eleven species of fungi found in soils. The fabrics were stored for three months in media with fungi cultivated under optimum conditions. There was no loss of strength for the polyester and polyamide geotextiles. However, the polyethylene and polypropylene fabrics were found to have lost 10% and 25% strength respectively.

Colin et al (1986) buried five nonwoven fabrics (polypropylene, polyethylene terephthalate (polyester) and mixed polypropylene/polyamide-coated polypropylene filaments) in soil over a seven-year period. The burial environment was moist, organically-rich soil maintained at 29°C and 85% to 90% relative humidity with a pH of 6.7. No significant reduction in burst strength of the fabrics was observed, although there was some delamination of the sheath from the core of the fabric made from the bi-component fibre.

Van Zanten (1986) reported tensile strength results for selected geotextiles (composed of polypropylene, polyethylene, polyester and polyamide) exposed for thirteen months in a mildew-feeding matrix (agar-agar) which had been treated with a mixture of mildew strains commonly found in soils. Strength losses were found for the polypropylene and polyethylene fabrics but not for the polyester and polyamide fabrics. Rodriguez (1985), however, reported that polyesters and polyamides may degrade in the presence of some micro-organisms.

It has been found that the molecular weight of a polymer, together with the molecular weight distribution, is a good indicator of resistance to bio-degradation. Totally synthetic polymers are found to be generally resistant to micro-organisms when the molecular weight exceeds about 5 000 grams (Rodriguez, 1985). In their review of microbial degradation, Cooke & Rebenfeld (1988) reported work which showed that high-density polyethylene (HDPE) with a molecular weight above 1 000 grams is inert to microbial degradation. It appears that very low molecular weight components in the fibre structure, and the presence of certain types of additives (e.g. plasticisers) applied during manufacture, can provide nutrients for micro-organisms. Whether the fibres will degrade or not (usually exhibited as a loss of strength and elongation rather than loss of hydraulic properties) appears to depend upon whether the enzymes generated by the organisms act as catalysts for molecular degradation processes. Further work is required to enable predictions to be made in this area.

In the various studies of microbial degradation noted above, there is a distinct lack of common terminology used in the description of the soils and in the characterization of the biological activities. This renders the synthesis of knowledge in this area extremely difficult. A pedological soil classification is given in Rankilor (1981). However, this is considered to be inappropriate for situations where the geotextile is buried at depth within engineering structures in which biological activity is likely to be less than near the ground surface. Also, the types of micro-organisms found in hot climates are likely to be significantly different from those in temperate climates.

8.4 RESISTANCE TO OUTDOOR EXPOSURE

Raumann (1982) reported outdoor exposure tests of a range of polyester and polypropylene geotextiles in the USA. The samples were exposed at various sites in Florida, Arizona and North Carolina for periods up to about thirty six weeks. All samples were found to lose strength under outdoor exposure. Some samples lost virtually all their strength within a period of sixteen to twenty four weeks of exposure. Raumann suggested that the actual performance of geotextiles under outdoor exposure depends on factors such as expected sun hours, energy of sunlight, atmospheric pollution and on other factors related to weather such as rainfall, wind, temperature and relative humidity. Van Wijk & Stoerzer (1986) pointed out that the effects of natural weathering on geotextiles would depend on geographical latitude as this determines the intensity of solar radiation.

Greenway et al (1986) summarised the results of outdoor exposure tests on six nonwoven geotextiles carried out by the GEO in 1981 to 1982. These fabrics were composed of polyester, polypropylene and polypropylene-polyethylene. The period of exposure was about two months. All the samples tested lost a certain amount of strength although no clear relationship between degradation behaviour and polymer type was established.

In 1989, the GEO carried out further investigation into the long term outdoor exposure performance of selected geotextiles that might be used as filters. The results of this investigation were reported by Brand & Pang (1991). Twelve nonwoven, one woven and one composite geotextiles, composed of polyester, polypropylene, polyethylene and polyamide, were tested for a period of up to nine months. It was found that all the fourteen types of geotextiles lost strength and elongation upon exposure under Hong Kong outdoor conditions (Figure 10). The loss of strength in the first month was found to be less than 16%, with some geotextiles performing better than others. The long term performance of the geotextiles varied widely, with some geotextiles losing virtually all their strength after six months exposure to direct sunlight and weather. The half life of the geotextiles was found to range from three months to over nine months. The effect of outdoor exposure is particularly important in Hong Kong where the solar radiation intensity and ambient temperature are high. The investigation concluded that it is important to give adequate protection to the geotextiles against attack by sunlight and weather prior to their installation.

8.5 TEMPERATURE EFFECTS

The Royal Observatory (RO) in Hong Kong regularly publishes data on meterological parameters (including soil temperatures) observed at the RO Headquarters in Tsim Sha Tsui and at King's Park. Both stations are located in areas of granitic soil. Figure 11 shows the seasonal variation of the monthly mean soil temperature at 0.2, 0.5 and 3 m depths in the ground at the RO Headquarters. These soil temperatures appear to follow the same cyclic pattern as the seasonal variations of daily global solar radiation and air temperatures. At a depth of 3 m, the seasonal variation of soil temperature is reduced and the monthly means all fall between 20°C and 30°C. For geotextile filter applications, where the tensile stresses imposed on the geotextiles are usually quite small, it is considered that the range of ground temperatures in Hong Kong will not lead to problems of tensile rupture or reduction in elongation to rupture. Also, these soil temperatures are unlikely to have a significant effect on the hydraulic properties and filter performance of geotextiles (see Table 5).

8.6 TESTS ON EXHUMED GEOTEXTILES

Although laboratory-accelerated tests give some indication of the resistance of a geotextile under severe environmental conditions, the durability of a geotextile under the combined effects of stresses and aggressive elements in the ground can only be assessed accurately by examination of samples exhumed after burial in soil for a number of years. A few studies of this kind have been carried out.

Van Zanten & Thabet (1982) removed polypropylene, polyethylene and polyamide fabrics that had been in service for over ten years in canal banks in the Netherlands and compared their physical properties with those of the original fabric. The loss of strength and the reduction in elongation to rupture were, respectively, 26% and 62% for the polypropylene, 11% and 24% for the polyethylene, and 23% and 0% for the polyamide. It is not clear whether these losses were due to environmental attack or physical damage during installation and in service.

A valuable study on durability was reported by Sotton et al (1982b). This was commissioned by the French Ministry of Industry and was carried out by members of the French Committee on Geotextiles. About 200 samples of geotextiles (composed of polypropylene, polyester and polyester/polyamide) were exhumed from over 30 sites in France. These had been buried in various types of soils for periods of up to twelve years. Examination and testing of all the samples were carried out, including measurement of thickness, tensile strength, permittivity and various fibre properties. Losses of tensile strength of up to 30% were measured, but these were explained as being due to site damage and, in a few cases, exposure to sunlight. No specific ageing of the geotextiles was identified. In particular, it was stated that there was no observable chemical change in the polymer fibres due to the surrounding soil and that visual examination of the retrieved samples did not reveal any attack from micro-organisms. Based on the results of this study, they were sufficiently optimistic to state that "in proper conditions of use, geotextiles .... seem to age as well as .... traditional building materials".

Leflaive (1988) presented results of three additional French studies on the durability of geotextiles, which were recovered after burial in natural soils for periods of up to 17 years. It was concluded that essentially no time-dependent chemical or biological change could be observed. However, further field and laboratory tests were considered necessary to obtain information over a longer time scale.

8.7 REVIEW OF OVERSEAS GUIDANCE ON GEOTEXTILE DURABILITY

Little guidance can be found in national codes and standards on the subject of geotextile durability, although some standard test methods exist for textile fabrics (see, e.g. BSI, 1972; BSI, 1974a & b; Studer, 1982; Van Zanten, 1986).

The USCE Civil Works Guide Specification for Plastic Filter Fabric (USCE, 1977) requires that plastic yarns used to manufacture engineering fabrics consist of long-chain synthetic polymers composing at least 85% by weight of polypropylene, ethylene, ester, amide or vinylidene chloride, and should contain stabilizers and/or inhibitors added to the base polymer, as necessary, to make the filaments resistant to deterioration from ultraviolet and heat exposure. The Canadian Ministry of Transportation and Communications (CMTC, 1981) has adopted similar general property specifications.

The French Geotextile Manual on the use of geotextiles in drainage and filtration systems (CFGG, 1989) does not give any specific limits on the properties of soil for which geotextiles should not be used. This is because the French Committee on Geotextiles and Geomembranes (CFGG), as a result of the French studies, believes that geotextiles from reputable manufacturers can be expected to last at least one 'generation' in civil engineering applications. It does, however, advise users to beware of potentially aggressive sites, e.g. sites close to factories or waste disposal facilities.

In the Oosterschelde project in The Netherlands, the durability requirements for the geotextiles used in a marine environment were established for a design life of 200 years (Wisse & Birkenfeld, 1982). Special polypropylene fabrics were developed and extensively investigated using oven-ageing, leaching and artificial weathering tests. It was estimated that the life of some of the special fabrics developed is of the order of 1 000 years. Clearly, not all geotextiles on the market are of this design quality, and very few projects to date have required such extensive development work. Nevertheless, the Oosterschelde project does indicate what can be achieved with co-operation between engineers and textile specialists.

8.8 DURABILITY OF GEOTEXTILES IN THE HONG KONG CONTEXT

Based on the review of information given in the above sections, the following recommendations on geotextile durability under Hong Kong conditions are formulated.

Where site conditions are non-aggressive, geotextile filters composed of resistant synthetic polymers are suitable as alternatives to granular filters in permanent works. Polypropylene, polyester, polyamide and polyethylene, each with a molecular weight which exceeds 5 000 grams, may be regarded as resistant synthetic polymers. Some general data on the chemical and thermal stability of synthetic polymer fibres are given in Table 5. In order to provide the geotextile fibres with resistance to deterioration caused by the effects of exposure to weather and burial, the base polymer of the fibres should contain suitable additives such as UV stabilizers and anti-oxidants. These additives provide the fibres with resistance to deterioration due to the effects of the weather and the burial environment. Laboratory and field studies to date have shown that the synthetic polymers used in geotextiles are generally resistant to deterioration by micro-organisms.

It is considered that geotextiles can be used as filters in many areas of Hong Kong without a high risk of encountering durability problems. Nevertheless, site investigation for permanent works should assess the potential aggressiveness of the site with respect to geotextile materials. As a minimum, the pH of the natural soil, the groundwater, and the fill which will be placed close to the geotextile should be checked. Only geotextiles produced by established international manufacturers should be considered for use in permanent works. Where aggressive conditions (e.g. pH outside the range of 5 to 10) are found to exist, advice should be sought from the geotextile manufacturers and, if necessary, polymer scientists and industrial chemists working in the geotextile field. The manufacturer should be required to confirm the adequacy of the resistance of his products to the in-service soil environment, such as the observed pH and any potentially aggressive substances. Particular care should be taken where the site is in a potentially aggressive area, e.g. close to factories or waste disposal facilities.

It should be noted that geotextiles are not impenetrable to burrowing rodents, such as rats, and that plant roots may penetrate a geotextile. Although damage by these causes is not likely when the geotextile is buried at depth, such possibilities should be considered in the design when there is only a shallow soil cover.

During the construction phase of a project, exposure of geotextiles to some direct sunlight and other weather effects is unavoidable. The effect of exposure is particularly important in Hong Kong where the solar radiation intensity and ambient temperature are relatively high and exposure should therefore be minimized. The total period for which geotextile filter is exposed to sunlight or other sources of ultra-violet radiation during delivery, storage and installation should not exceed seven days.

It is recommended that geotextile rolls delivered to a site be maintained in roll form and covered (e.g. with opaque tubular sleeves) until they are to be installed. If no cover is provided, then the first two wraps of geotextile in the rolls should be discarded. Depending on the requirement on seam/joint strength, exposed roll edges should not be seamed/joined together if the roll has been exposed on site for any appreciable length of time.

Geotextiles should be covered up as soon as possible after installation. Provided this is carried out, there should be little deterioration in strength and elongation to rupture due to exposure effects.

The designer should assess the likely amount of time that a geotextile will be exposed on site before being covered. It may be necessary to specify that the method of working should minimize the period of exposure, especially when large areas of geotextiles are to be installed. If it is foreseen that a geotextile cannot be protected within seven days after laying, the specification should state that geotextile strength and elongation requirements shall be met prior to backfilling, and that allowance shall be made in the provision of geotextile under the contract for any adverse changes in properties due to exposure. Also provisions should be made for tensile testing of geotextile samples taken immediately prior to covering, so that the designer will have the option of checking that the geotextile installed meets the specified quality. Such tests should be carried out wherever there is doubt as to whether an unacceptable loss of strength may have resulted from outdoor exposure. The acceptance criterion should take into account the variability of the materials. For this purpose, the use of statistically-based characteristic values should be considered.

9. HYDRAULIC PROPERTIES OF GEOTEXTILES

9.1 GENERAL

The geotextile hydraulic properties which are relevant to filter design are the pore or opening size and the water permeability of the geotextile. Different methods have been developed for their measurements and these are discussed below.

9.2 GEOTEXTILE OPENING SIZE

The geotextile opening size, sometimes known as the apparent opening size (AOS), is a measure of its effective pore channel diameter. This governs the size of soil particles which can pass through the geotextile during the filtration process. Therefore, the AOS is principally related to the retention criterion : if the opening size is too large, continuous loss of fines of the base soil will occur under the action of flowing water. The AOS is also related to the permeability criterion in that both the AOS and the porosity of a geotextile govern its water permeability.

The different methods developed for the measurement of AOS, as summarized in Table 6, can produce very different results. For example, the opening size O_{90} (O_m being the size at which m% by weight of particles are retained on the geotextile) of a needle-punched geotextile tested by the GEO using dry sieving for the sand fractions, was twice the opening size given by the geotextile manufacturer, which was obtained by performing hydrodynamic sieving. A similar discrepancy for a heat-bonded geotextile was also found in the test, but in this case the method used by the manufacturer was also dry sieving. While the appropriate range and limitations of each test method are given in Table 6, there is clearly a need to establish further guidelines on the suitability of the test methods for different types of geotextiles. It appears that dry sieving is applicable to woven, knitted, stitch-bonded and thin nonwovens, while hydrodynamic sieving is more appropriate for thick needle-punched nonwovens. However, the latter test generally is considered to be superior in modelling the field hydraulic condition and has the advantage of being able to determine smaller geotextile opening sizes.

A valuable study was conducted by Faure et al (1986b) to investigate the suitability of five different test methods for determining geotextile opening sizes. A summary of their results is given in Table 7. The following can be observed from these results :

(a) The opening size, O_{95}, obtained by dry sieving using "ballotini" (spherical glass beads) (Method 1) was almost always larger than that obtained by using other methods. This is probably due to the roundness of the smooth glass beads.

(b) The opening size, O_{95}, obtained by dry or wet sieving using different size fractions of sand (Methods 2 and 3) was generally similar to that obtained by Method 1, although values up to 20% smaller were determined in a few cases.

(c) The opening size, D_w, obtained by wet sieving using a well-graded sand (Methods 4 and 5) was generally within 15% of that obtained by hydrodynamic sieving (Method 6). This was irrespective of the method of calculation adopted for D_w : for Method 4, D_w is based on the D_{95} of sand passing the geotextile, and for Method 5, D_w is based on a formula recommended by Heerten (1981).

(d) The opening size, O_f, obtained by hydrodynamic sieving using a well-graded sand (Method 6) was 15% to 50% smaller than that obtained by Method 1.

(e) The geotextile construction and thickness, as well as the test conditions, were found to have some influence on the measured opening sizes (even when obtained by the same method).

However, the effects of sample variability of individual geotextile type, which is inherent in the manufacturing process, have not been investigated. Such manufacturing variability and the reproducibility of results by different laboratories are worthy topics for further study.

9.3 GEOTEXTILE PERMEABILITY

The permeability of a geotextile to water movement is a function of its opening size and porosity.

Table 8 summarizes the test methods which are used for the measurement of geotextile water permeability. While each test method has its own limitations, the parameters, permeability (k_n), permittivity (ψ), volume water flow rate (VWFR), percent open area (POA), and porosity (n_g) have all been incorporated into different permeability criteria, see Table 9.

The structure of a geotextile can be modified during or after installation into the works, resulting in a reduction in its water permeability. A number of factors can cause this reduction, e.g. compression under load (Bucher et al, 1982; Gourc et al, 1982b; McGown et al, 1982) and contamination (Giroud et al, 1977; Heerten, 1982; Sotton et al, 1982a, Van Zanten & Thabet, 1982). These factors may need to be accounted for in designing geotextile filters.

10. LONG TERM FILTRATION BEHAVIOUR OF GEOTEXTILES

10.1 BRIEF SUMMARY OF PREVIOUS INVESTIGATIONS

A large number of investigations have been carried out on the long term filtration behaviour of geotextiles since the systematic investigation by Calhoun (1972). As a result, many filter design rules have been proposed (Calhoun, 1972; Ogink, 1975; McKeand, 1977; Schober & Teindl, 1979; Giroud, 1982; Tan et al, 1982; Lawson, 1984, 1986a & b, 1987; Rollin & Lombard, 1988). A summary of these design rules for geotextiles under unidirectional water flow is given in Table 9, together with the basis used in the formulation of the upper and lower limits for satisfying the retention and permeability criteria respectively. Some of the rules in Table 9 are based on laboratory studies, using different soil types and geotextiles. Others are arrived at theoretically or by deduction from existing design rules for granular filters. The rules proposed by Schober & Teindl (1979) and Giroud (1982) involved coefficients B and E for the upper limit. These coefficients are defined in Figures 12 and 13. A more detailed description of Giroud's (1982) retention criteria and Lawson's (1987) design criteria is given in Tables 10 and 11 respectively.

It should be noted that different geotextile parameters are adopted in the various design rules, and that different test methods are used to determine these geotextile parameters. In view of the variable results which can be obtained by the use of different test methods (see Sections 9.2 and 9.3 and Tables 6 and 8), it is not possible to assess the applicability of the various design rules for a particular set of soil conditions except in cases where the parameters are determined by methods appropriate to the original formulation. The main reason for the wide range of proposed filter design rules is the use of different test methods, test conditions and materials in their derivation, together with the absence of common criteria for judging the success or failure of filtration performance.

The soils used in previous laboratory investigations were mostly sands and silts of transported origin with small uniformity coefficients, C_u. To establish geotextile filter design rules appropriate to Hong Kong, the studies by Lawson (1982, 1984, 1986a & b, 1987), GEO (Greenway et al, 1986) and Resl (1988a & 1988b), all of which involved Hong Kong saprolites, are more relevant. The results of these studies are discussed in detail in the following three sections. A discussion of the potential problem of clogging due to chemical deposits and organic residues is given in Section 10.5.

10.2 LAWSON'S WORK ON COMPACTED SOILS DERIVED FROM HONG KONG SAPROLITES

10.2.1 Background

An extensive investigation into filter behaviour with compacted soils derived from Hong Kong saprolites has been undertaken by Lawson (1982, 1984, 1986a & b). Twenty filtration tests were carried out using completely decomposed granite (CDG) and completely decomposed volcanic (CDV) samples in conjunction with four heat-bonded nonwovens, two wovens and a geogrid. The grading curves of the two soils tested are shown in Figure 14. The opening size and water permeability of the geotextile filters were chosen to cover a wide range. Permeameters, 150 mm diameter, identical to those described by Rycroft & Dennis-Jones (1982), were used in the tests. A hydraulic gradient of 10 was employed in most tests, and the test duration ranged from 25 to 700 days.

Stable filtration behaviour was observed in all the tests using geotextiles, but uncontrolled loss of fines leading to failure occurred in the four geogrid tests. The failure of the geogrid to act as a filter was attributed to its relatively large opening size of 7 mm, which is of the same order as the pore sizes in typical coarse drainage aggregates.

Based primarily on the CDG filtration test results, Lawson established geotextile filter design rules specifically for Hong Kong soils (Table 11). This set of rules, published by Lawson (1987), was evolved from the criteria established in his earlier papers (Lawson, 1982, 1984, 1986a & b).

Based on his laboratory test findings, Lawson further showed that the retention criteria of Calhoun (1972) and McKeand (1977) are satisfactory, those of Schober & Teindl (1979) and Giroud (1982) underestimate the actual limit for excessive loss of fines and those of Ogink (1975) and Tan et al (1982) overestimate this limit (and hence are unsafe for remoulded CDG). It should be noted that the retention criteria of Ogink (for nonwovens) and Tan et al allow the geotextile opening size to be greater than the largest particle of the base soil if the base soil is uniform. Stability under these conditions must depend on arching of the particles of the base soil over the openings of the geotextile instead of just the reversed graded filter formed in most situations. Lawson's results show that it is not prudent to allow for arching in filter design for remoulded CDG. It is worth mentioning that the permeability limit cannot be assessed accurately from Lawson's tests as there were no failures due to inadequate permeability.

Since the water permeability of a geotextile is a function of its porosity as well as its opening size, Lawson (1982) introduced the minimum volume water flow rate (VWFR) requirement, which differentiates between 'filtering' and 'non-filtering' geotextiles of a given opening size (Table 11). This requirement is based on the fact that two geotextiles with the same opening sizes can have markedly different water permeabilities as opposed to granular filters where the same particle sizes yield almost identical permeabilities. In addition, Lawson recommended that in all cases O_{90} should be greater than D_{15} to avoid clogging in the long term.

10.2.2 Discussion on Lawson's Work and Design Criteria

The following points concerning Lawson's work should be noted:

(a) The O_{90} size of the geotextiles tested was determined by performing dry sieving using "ballotini".

(b) The tests were performed using thin wovens and heat-bonded nonwovens. No thick needle-punched geotextiles were selected for testing as Lawson (1984) considered that their use was relatively uncommon in filter applications in Hong Kong. The GEO survey on the use of geotextiles in

Hong Kong showed that significant amounts of needle-punched geotextiles have been used as filters and separators in recent years. Therefore, the applicability of Lawson's design rules to thick needle-punched nonwovens needs to be assessed.

(c) The minimum VWFR versus O_{90} relationship (Table 11) was based on field observations and experimental results. Some data for filters, as well as for non-filters, were first given by Lawson (1982), in which the delineation derived was based on field results in sandy and silty sandy soils. The delineation was subsequently revised (Lawson, 1986b & 1987) to take account of data from laboratory permeameter tests on remoulded soils. It should however be noted that details such as soil type, grading and permeability, geotextile type, and normal stress on the geotextile in each case, were not available.

(d) The permeability limit $O_{90} \geq D_{15}$ was established based on the concept of equivalent pore diameters for granular filters, i.e. $O_{90} \approx 0.2D_{15}F_f > D_{15}S_c$ (see Rule 3 in Table 3). There is also a proviso that the geotextile must be more permeable than the base soil, which Lawson (1984) considered to be almost always the case for nonwovens and highly permeable wovens. However, it should be noted that the use of dispersants in a grading test can reduce D_{15} significantly although it may have little effect on the D_{85} size of the soil. This may lead to an unsafe filter design of inadequate water permeability for cohesive soils with clay minerals which do not exist in a dispersed form.

(e) The upper limit for excessive loss of fines, i.e. $O_{90} < D_{85}$, was established based on the condition where constant system permeability occurred and the fines migrated through the geotextile finally reduced to zero. It took no account of the amount of soil actually migrating through the geotextile during the initial stabilization phase. This upper limit is similar to that proposed by Calhoun (1972). Due to the widely-graded nature of saprolites, a considerable amount of fines can migrate through the geotextile initially and equilibrium conditions can still be attained (which may not necessarily be the case for other soil types). To cater for the possibility of this quantity of soil clogging the pores of the drainage material, it is advisable for designers to choose a suitable grading and thickness of the drainage material behind the geotextile filter so that there are sufficiently large pores in the drainage zone for this quantity of soil to be flushed out with the water flow. Alternatively, the upper limit should be reduced to minimize the amount of fines passing the geotextile.

10.3 THE GEO'S WORK ON COMPACTED SOILS DERIVED FROM HONG KONG SAPROLITES

10.3.1 Background

In 1981, an investigation into the filtration behaviour of six nonwoven geotextiles (three heat-bonded and three needle-punched fabrics) using 300 mm diameter permeameters with compacted CDG and CDV was carried out by the GEO. This work was summarized by Greenway et al (1986).

In these tests, each permeameter was 600 mm high and could accommodate a 260 mm high soil specimen in the upper half (Figure 15). The CDG and CDV samples were recovered from King's Park and a borrow area to the north of Tai Po Industrial Estate respectively. Their grading envelopes are shown in Figures 4 and 5.

In the tests, the geotextile was placed against the soil after it had been compacted to 90% and 95% of the British Standard Maximum Dry Density, for CDV and CDG respectively, into the top part of the permeameter. Seven small piezometers, tapped into the soil specimen, were located from 2.5 mm to 250 mm above the geotextile. The permeameter was then temporarily inverted and a uniform 20 mm crushed aggregate was poured onto the geotextile and tamped. Two additional piezometers were installed within the aggregate layer at 25 mm and 225 mm from the geotextile. Finally, the permeameter was re-inverted and then saturated in an upward direction. In all the filtration tests, a constant water head was applied to the top of the soil specimen, which created an overall hydraulic gradient of approximately 7 through the soil.

The geotextiles tested with the CDG comprised three heat-bonded and three needle-punched fabrics, with thicknesses varying from 0.3 to 1.2 mm and 1.2 to 3.3 mm respectively. Apparent opening sizes were found to range between 0.1 and 0.3 mm when determined by dry sieving using a sub-rounded river sand. This corresponds to an O_{90}/D_{85} ratio of between 0.04 and 0.11. Soil particles which piped through the geotextiles were not collected. However, no continuous piping was observed in any of the tests during the 80 to 230 day testing period.

Seven tests were carried out on CDG with six types of nonwoven geotextiles. One test was carried out on CDV with a heat-bonded geotextile. Flow rates and the piezometric heads from the piezometers installed at various levels were recorded for each test throughout the testing period. The results allowed a detailed evaluation of the permeability and the hydraulic gradient of the drainage system.

10.3.2 Discussion of Test Results

The piezometric measurements showed that generally there was negligible head loss through the geotextiles, and hence no impedance of water flow, throughout the testing period.

One exception to this was a heat-bonded geotextile (O_{90}/D_{85} = 0.05) which was subjected to an alternative compaction technique whereby the base soil was compacted directly onto the geotextile. The water permeability of the geotextile was found to have been reduced by roughly one-and-a-half orders of magnitude. A 0.5 m water head was observed to have built up immediately above the geotextile. This was probably due to fine soil particles being forced into the geotextile, blocking its openings during heavy compaction. Despite this build-up of water pressure, the system (and soil) permeability still reached an equilibrium value of about 10^{-7} m/s.

Scott (1980) remarked that the water permeability of a geotextile may have little influence on the overall hydraulic performance of a drainage system when the flow path through the base soil is sufficiently long compared with the thickness of the geotextile and the adjacent filter zone. He used a simplified method of calculation to show that, even for the short flow path through the soil in laboratory filtration tests, considerable reduction in the water permeability of the geotextile due to clogging can usually be tolerated without giving rise to an unacceptable reduction in system permeability.

The hydraulic gradients measured in the tests revealed that at equilibrium a relatively more permeable (i.e. low gradient) zone developed in the base soil near the geotextile. The thickness of the permeable zone could be as thick as 160 mm depending on the geotextile used. This would seem to indicate that different quantities of the fine soil particles had migrated towards or through the geotextiles during the tests.

The system permeability at equilibrium for the tests in CDG was found to be of about 5×10^{-8} to 9×10^{-8} m/s and for the test in CDV of about 1×10^{-8} m/s. The system permeability measured in each test was always found to be close to or higher than the original permeability of the compacted base soil.

As no excessive loss of fines occurred in any of the tests, this work cannot be used to assess the upper limit. All the geotextiles used satisfied Lawson's minimum VWFR and O_{90} size requirements except that the heat-bonded fabric used in the test with the alternative compaction technique was only marginally acceptable.

10.4 RESL'S WORK ON UNDISTURBED HONG KONG SAPROLITES

10.4.1 Background

A series of long term tests (up to 147 days) were carried out by a manufacturer (Resl, 1988a & b) on 'undisturbed' saprolitic soil samples with needle-punched spun-bonded geotextiles. It is the first systematic investigation of geotextile filtration behaviour performed using 'undisturbed' saprolitic soils.

Samples of three completely decomposed granites (CDG) were provided by the GEO. Those from King's Park and Ho Man Tin were 90 mm blocks trimmed from large 'undisturbed' block samples while the Shouson Hill samples were retrieved by driving 98 mm diameter stainless steel tubes into the soil. Because of the small size of the test specimens, no relict joints or soil pipes were present, and the water flow in the filtration tests occurred entirely through the fabric of the CDG. The grading curves of the three samples were very similar, as shown in Figure 16.

The four needle-punched geotextiles tested were 1.1 to 2 mm thick and had opening size, D_w, (obtained by wet sieving using the Franzius Institute Hannover method, see Van Zanten, 1986) of between 0.11 and 0.13 mm. The VWFR of the geotextiles was much higher than the minimum requirement of Lawson shown in Table 11, even at a compressive stress of 200 kPa. The D_w/D_{85} ratio of all the soil/filter systems tested was about 0.03. The O_{90} size of two of the geotextiles was tested by the GEO and this was about twice the value of D_w supplied by the manufacturer (i.e. O_{90}/D_{85} of about 0.06). However, this did not significantly affect the conclusions of the investigation.

The filtration test set-ups, selected geotextile properties and the test results are shown in Figures 17 and 18. The permeabilities of the geotextiles were much higher than those of the soil samples. All the tests were carried out on 'undisturbed' soil except for test no. 4, where the soil was remoulded. In all the tests, the system permeability stabilised with time, with negligible (unmeasurable) quantities of soil passing the geotextiles.

10.4.2 Discussion of Test Results

For tests nos. 1 and 2, geotextiles of different thicknesses and D_w were used. However, the equilibrium system permeability was about 10^{-5} m/s in both cases. Tests nos. 3 and 4 were performed with the same geotextile except that the soil was remoulded in the latter but with similar dry density. Again, the equilibrium system permeability was about 10^{-5} m/s in both tests. For tests nos. 5 and 6, the same geotextile was used but the soil sample in test no. 5 was much denser. The system permeability in test no. 6 was found to be higher than that of test no. 5. It should be noted that tests nos. 1 to 4 and test no. 6 yielded more or less the same equilibrium system permeability. This is not surprising because the geotextiles were very permeable and the water flow was likely to be governed by the soil samples, which were all relatively loose and had roughly equal permeabilities.

Cessation of the water supply in the tests (akin to the effects of seasonal fluctuations in groundwater flow) was found to result in an enhanced permeability initially, which then returned to the equilibrium value later. This increase in permeability was attributed to the shrinkage of the soil sample during this closure period, which resulted in gaps between the soil sample and the side wall of the permeameter. After the second closure, the increase was much reduced and collapse of the loose sample in test no. 6 was observed. It should be noted that the system permeabilities in all the tests are of the same order as the field permeabilities of typical Hong Kong CDG and are significantly higher than those observed in the tests carried out by the GEO on compacted granitic soil.

10.5 CLOGGING DUE TO CHEMICAL DEPOSITS AND ORGANIC RESIDUES

While the subject of soil clogging which can result in permeability failure has been discussed in the previous sections, the problem of clogging due to chemical deposits or organic residues warrants separate discussion.

Rollin & Lombard (1988) discussed the mechanism of salt (e.g. carbonate and sulphate) precipitation on geotextiles which can occur as a result of a prolonged dry period. Tests carried out by Halse et al (1987a) showed that precipitation caused by passing alkaline solutions through geotextiles significantly decreased the flow rate. This was due to the formation of a relatively impermeable layer of salt particles above the geotextile which clog the geotextile structure. The precipitation was formed as a result of reaction between the alkaline solution and the atmospheric CO_2.

Van Zanten (1986) indicated that clogging of a geotextile may occur due to the deposition of iron compounds carried in groundwater. He also reported that, in The Netherlands, water jetting at periodic intervals has been used for flushing out materials deposited on geotextiles used for lining pipe drains. However, this method should be applied with care, as high pressure water jets can destroy the stable soil filter zone adjacent to the geotextile and consequently result in excessive loss of soil particles.

The clogging of geotextile fabrics by precipitation of iron compounds resulting from biological activity was reported by Scheurenberg (1982). Iron clogging, a phenomenon well known in wells and drains, is caused by the biological (bacterial) oxidation of iron which results in the precipitation of non-water-soluble ferric oxides on the geotextile fabrics. This subject was studied by Van Zanten & Thabet (1982). Puig et al (1986) suggested a methodology for assessing the risk of iron clogging. The pH, iron content and organic matter content, together with the degree of aeration of the soil are considered to be important parameters in the assessment of such risks. A low pH (< 5), a high iron content and organic matter content, together with high oxygen content in the soil will indicate a favourable environment for the precipitation of ferric oxides. Based on the experience in applications in agricultural drainage, Van Zanten (1986) suggested that the organic matter content of the soil should not be more than 0.5% to avoid the possibility of iron clogging.

Problems can also arise in situations where the geotextile is buried in a drainage system which favours bacteria, fungi or algae growth (Koerner et al, 1988; Rollin & Lombard, 1988). Some biological clogging was observed in the tests carried out by Ionescu et al (1982), but it was found that this was a rather slow phenomenon : macroscopic and microscopic examinations revealed no significant change in geotextile filtration and drainage properties. Van Zanten (1986) reported on investigations carried out in the Netherlands, which indicate that the drying out of a geotextile (and the soil adjacent to it) can result in re-opening of geotextile pores which have been clogged with humus and iron deposits. Periodic drying was considered to be beneficial in ensuring the continuous satisfactory performance of the geotextile. Koerner et al (1988) suggested that post-construction flushing of geotextiles with a biocide may be a possible solution to problems caused by biological activities.

Up to the present, the above-mentioned phenomena have not been studied in sufficient detail to establish guidance on critical clogging levels for chemical deposits or organic residues. In view of the infrequent occurrence of documented failures resulting from clogging due to chemical deposits or organic residues, it would be inappropriate to exclude the use of geotextiles on these grounds alone. However, where the proposed construction poses a high risk to life (as defined in Table 5.2 of GCO, 1984), it would be prudent to carry out a detailed investigation of the site conditions, in particular in areas adjacent to factories and waste disposal facilities, to assess the likely risks of such forms of clogging. This should include an examination of the long term performance of drainage systems in the vicinity of the site. It should be noted in passing that problems of clogging due to chemical deposits and organic residues are not confined to geotextile filters. The above comments are also applicable to granular filters.

11. REVIEW OF GEOTEXTILE FILTER DESIGN CRITERIA

11.1 GENERAL

A number of generalised geotextile filter criteria have been established by various international bodies. Tables 12 to 14 give the criteria recommended by:

(a) the Working Group No. 14 of the German Society for Soil Mechanics and Foundation Engineering (GSSMFE) (Heerten, 1986),

(b) the United States Federal Highway Administration (FHWA) (Christopher & Holtz, 1988), and

(c) the French Geotextile Manual (CFGG, 1989).

These three criteria, together with Lawson's criteria (Lawson, 1987) given in Table 11, have been developed from respective local experience. The background of these four criteria and their appropriateness to Hong Kong soil conditions are reviewed in the following sections.

11.2 LAWSON'S CRITERIA

Lawson's criteria (Table 11) are based on his work on compacted soils derived from Hong Kong saprolites. The comments given in Section 10.2.2 should be noted. These design criteria appear to be the best which are currently available for Hong Kong saprolites. They are most appropriate for cases where these soils are used as compacted fill, and where the geotextiles are thin wovens or nonwovens (e.g. heat-bonded geotextiles). Caution should be exercised when applying these rules to undisturbed saprolites, or to existing fill of saprolitic origin where the field permeabilities are higher than those obtained in Lawson's tests. There are at present insufficient scientific data to support the application of these criteria for thick needle-punched nonwovens.

It is also worth noting that Lawson's minimum VWFR (permeability) criterion given in Table 11 is very roughly equivalent to specifying a minimum geotextile permittivity of between 0.1 and 0.7 s^{-1} or a minimum geotextile water permeability of between 1 and 7 x 10^{-4} m/s.

11.3 GSSMFE CRITERIA

The retention criteria given by the GSSMFE (Table 12) are based on D_w, which is generally smaller than the opening size, O_{90}, obtained by dry sieving. As discussed in Section 3.2, Hong Kong saprolites generally fall within the envelope of 'problem soils'. The relevant retention criterion $D_w < 5\sqrt{C_u}D_{50}$ and $< D_{90}$ under the 'problem soils' category is generally less stringent than the criterion $O_{90} \leq D_{85}$ of Lawson. The permeability criterion $k_n \geq 50k$, which relates geotextile water permeability, k_n, to soil permeability, k, is more stringent than the FHWA criteria for critical/severe applications (see Table 13). It should be noted that the German criteria are largely based on coastal engineering and shore protection experience and hence may not be appropriate for geotextile filter applications covered in this publication.

11.4 FHWA CRITERIA

With regard to the FHWA retention criteria (Table 13), Hong Kong granitic soils generally have less than 50% passing 74 μm and an uniformity coefficient, C_u of much larger than 8. Therefore, the relevant retention criterion is $O_{95} \leq D_{85}$, which is approximately the same as Lawson's retention criterion $O_{90} \leq D_{85}$ provided that the opening size is determined using the same method. The criterion for C_u values of between 2 and 8, which permits an O_{95}/D_{85} ratio of greater than unity, appears to rely on arching of soil particles across the geotextile openings. Hong Kong decomposed volcanics generally have more than 50% passing 74 μm. For nonwovens, the relevant retention criterion is thus $O_{95} \leq 1.8\ D_{85}$, which appears to be based on Ogink's work conducted at the Delft Hydraulics Laboratory and is presently adopted in Dutch practice. While this may be satisfactory in an upward flow situation with low hydraulic gradients, i.e. where the downward body forces of the soil particles (self weight) counteracts the upward seepage forces, the permitted arching implied in this criterion is not proven with local soils for downward flow conditions.

The FHWA recommends that the geotextile should be specified with the maximum possible opening size (Note 4 in Table 13). This is essentially an economic strategy because geotextiles with large opening sizes generally contain less fibres and are therefore cheaper, especially in the case of nonwovens (Lawson, 1984). It should be noted that this approach is extremely undesirable for relatively uniform soils, as a small error in the design may result in all the particles of the base soil being smaller than the geotextile opening size, which could lead to uncontrolled excessive loss of fines. For saprolitic soils, the same error may give rise to substantial quantities of soil particles passing through the geotextile.

The general FHWA approach to the permeability criteria is to specify a geotextile permeability higher than the soil permeability, and to check separately against clogging (caused by fine particles trapped in the geotextile which clog up the pores) or blinding (caused by the formation of an impermeable cake upstream of the geotextile which retards flow). For less critical/non-severe applications, Calhoun's (1972) empirical rule of a minimum open area of 4% is specified for wovens and a minimum porosity of 30% is specified for nonwovens. In addition, the openings of the geotextile may also be specified to be sufficiently large such that selected portions of the fines in the soil can pass. The criterion, $O_{95} \geq 3D_{15}$, which is based on grouting principles, indicates that soil particles will migrate through the geotextile if they are at least three times smaller than the pores. The criterion $O_{15} \geq 3D_{15}$ specifies an even greater pore size and is to cover the uncertainty about the number of O_{95} size pores in the geotextile so as to ensure that the smaller pores are not clogged or blinded (Christopher & Holtz, 1988). Both criteria appear to be conservative when compared with Lawson's criterion $O_{90} \geq D_{15}$.

Some comments should also be made on the FHWA gradient ratio criterion, which originates from the work of Calhoun (1972) (see also Haliburton & Wood, 1982). This is used to check against clogging in the case of critical/severe applications. The gradient ratio test is essentially a constant head permeameter test incorporating a geotextile which supports a remoulded soil specimen 100 mm high. The piezometric head is measured at various depths in the soil specimen and the gradient ratio is defined as:

$$\frac{\text{hydraulic gradient over geotextile and first 25 mm of soil adjacent to it}}{\text{hydraulic gradient over next 50 mm of soil (i.e. 25-75 mm above geotextile)}}$$

measured at the end of a 24-hour test period. This test suffers from a few shortcomings. The results of permeameter filtration tests carried out by the GEO on Hong Kong soils (Greenway et al, 1986) show that the locations at which the hydraulic gradients are measured in the gradient ratio test are not necessarily the most appropriate for characterising filtration behaviour. The 'permeable zone' adjacent to the geotextile was found to be up to 150 mm thick. Also, the 24-hour test period may be too short. The 'stabilization time' in a filtration test varies widely depending on the soil type. It is typically a few hours for sands, up to 200 hours for silts (Koerner & Ko, 1982), and over 1 000 hours for well-graded silty sands (Koerner et al, 1988). It is also a function of the geotextile's hydraulic properties (Rollin & Lombard, 1988). For saprolitic soils, GEO's test results revealed that the stabilization time was about 80 days in compacted materials, while Lawson (1984) recorded over 140 days in loosely-placed remoulded soil. Undisturbed saprolites appear to need less time to reach an equilibrium system permeability (see Figures 17 and 18). It is worth noting the difficulty in assuring reproducibility of results between different laboratories as there are no standardised procedures given for the gradient ratio test documented in the specification by USCE (1977).

In summary, adoption of the gradient ratio test and criterion would seem to be of dubious value for Hong Kong saprolites. A modified gradient ratio (MGR), defined by Scott (1980) as the ratio of the hydraulic gradient in the filter zone (including the geotextile) to the hydraulic gradient in the unaffected soil, may be a more appropriate parameter. An MGR < 1 indicates that the filter zone is more permeable than the original soil and that the geotextile is an acceptable filter; an MGR > 1 indicates that a clogged geotextile is hindering the flow (Greenway et al, 1986). However, more piezometers will be required to obtain the profile of the hydraulic gradient in the soil specimen in the MGR test as compared with the gradient ratio test.

11.5 FRENCH GEOTEXTILE MANUAL CRITERIA

Of all the criteria mentioned in Section 11.1, the French Geotextile Manual filter criteria (Table 14) appear to be the most general in that they cover most of the important parameters. The French criteria are largely based on experience with needle-punched geotextiles, the opening sizes of which can reduce significantly on compression.

The retention criteria of the French Geotextile Manual, which are related to soil grading, soil density, hydraulic gradient and the geotextile function, are based on the filtration diameter, O_f, as determined from hydrodynamic sieving. The relevant criterion for the Hong Kong soils tested by Lawson (i.e. well-graded continuous loose soil, with hydraulic gradient of between 5 and 20 and filtration function only) is $O_f \leq 0.64\ D_{85}$. Results of tests on needle-punched geotextiles by dry sieving using different size fractions of "ballotini" (Table 7) indicate that, on average, $O_f = 0.64\ O_{95}$. Substituting this into the above French criterion gives a relationship which is approximately the same as the criterion $O_{90} \leq D_{85}$ given by Lawson. It is coincidental that the French retention criteria, based on experience with needle-punched geotextiles, are similar to Lawson's criteria, which are derived from tests using thin wovens and heat-bonded nonwovens.

In the French retention criteria, a lower limit of $O_f \geq 50\ \mu m$ ($\approx O_{90} \geq 78\ \mu m$) is specified for 'fine' soils. This is similar to Lawson's limit for non-dispersive fine-grained soils given in Table 11. The French limit, which incidentally will only apply to the very fine decomposed volcanics, appears to allow for the presence of cohesion in fine soils, which permits 'vault network formation' (i.e. formation of soil arches above the geotextile openings). The criterion $O_f \geq 4D_{15}$ ($\approx O_{90} \geq 6D_{15}$) in Table 14 is to account for the possibility of mobile coarse soil particles blocking the openings of a geotextile. This will only occur in 'problem soils', the fines of which can easily go into suspension, or as a result of poor installation (Rollin & Lombard, 1988). However, this criterion is considered unnecessarily conservative for Hong Kong saprolites.

The permeability criteria of the French Geotextile Manual relate geotextile permittivity (ψ) to soil permeability (k). Allowance is made for contamination of the geotextile during installation and in service, and for compression of the geotextile under load (see Section 9.3), both of which can reduce the permittivity of the geotextile. A factor $A_1 = 100$ is specified to allow for contamination of the geotextile. The factor $A_2 = 3$ (which is to allow for compression of the geotextile under load), although generally applicable to needle-punched nonwovens, is likely to be conservative for thin wovens and heat-bonded nonwovens, the permeabilities of which are less sensitive to compression. It should be noted that in the case of undisturbed soils (e.g. insitu CDG) with a permeability of around 10^{-5} m/s, the French permeability criterion for 'high risk structures', i.e. $\psi \geq 10^5\ k = 1\ s^{-1}$, is more conservative than Lawson's minimum VWFR requirement (see Section 11.2). The French criterion for 'other structures', i.e. $\psi \geq 0.1\ s^{-1}$, appears to give broadly the same requirement for water permeability as Lawson's.

12. GEOTEXTILE FILTER DESIGN FOR HONG KONG SAPROLITES

12.1 GEOTEXTILE FILTER DESIGN CRITERIA

Based on the review in Chapter 11, the geotextile filter criteria given by both Lawson (1987) and the French Geotextile Manual (CFGG, 1989), as summarised in Tables 11 and 14 respectively, are considered appropriate for Hong Kong soils including saprolites provided that the following important conditions are met in the proposed engineering works:

(a) The flow through the geotextile filter is unidirectional.

(b) The hydraulic gradients close to the filter are moderate to low.

(c) The effective normal stresses acting on the geotextile are static (i.e. little or no dynamic stress is exerted on the geotextile).

The above conditions are usually satisfied in the application of geotextile filters in slopes and retaining walls, as illustrated in Figures 1 and 2. Until more experience is gained, Lawson's criteria (Table 11) should be used for 'thin' wovens and heat-bonded nonwovens and the French Geotextile Manual criteria (Table 14) for 'thick' needle-punched nonwovens. It should be noted that reversing flows, cyclic loads and vibrations, which are often experienced in geotextile applications in shore protection, marine and railway works, can give rise to more onerous conditions for the filter. These loadings are not covered by the filter criteria given in Tables 11 and 14.

12.2 OTHER DESIGN CONSIDERATIONS

In the design, consideration should be given to the following factors:

(a) Soils derived from insitu weathering of rocks in Hong Kong can be highly variable within a small area. An adequate number of grading tests should be carried out to obtain parameters which are representative of the soils on site, or the soils intended to be used as fill materials in the proposed construction. It is recommended that grading tests should be carried out without dispersants, similar to granular filters (Section 5.3). For a widely-graded base soil having $D_{90} > 2$ mm and $D_{10} < 0.06$ mm, the percentage of particles greater than 5 mm should be ignored and the finer fraction of the grading curve should be used for filter design. This is because the coarse particles in such soils are known to have little effect on the filtration process.

(b) The D_{85} size for use in the retention criterion should be selected conservatively to allow for soil variability.

Consideration should be given to the likely quantity of soil particles which will pass through the geotextile filter and the possible effect on the drainage system. The use of the maximum possible geotextile opening size is not recommended.

(c) While the permeability of compacted fill of saprolitic soil origin is generally low ($< 10^{-6}$ m/s) and will not be a major consideration in geotextile filter design, the permeability of undisturbed saprolites and some existing fills can be much higher. It is recommended that insitu permeability tests should be carried out on the latter materials, at least for designs involving construction which poses a high risk to life (as defined in Table 5.2 of GCO, 1984). However, it should be noted that permeability tests give, at best, only a rough indication of the true soil permeability and again some allowance should be made for soil variability in the design.

(d) Where there is evidence that concentrated water flows exist in an undisturbed soil mass, e.g. in soil pipes and shear zones, the use of geotextile filters as primary protection may not be adequate. Other drainage measures, such as a piped drainage system, should be incorporated to cope with the anticipated water flow and to support any loose material which may result from subsurface erosion.

(e) Plant roots extending through the backfill into the base soil may damage or adversely affect the performance of the geotextile filter. It would be necessary to avoid planting trees in areas where the soil cover above the filter is small.

(f) Different test methods exist for the determination of geotextile hydraulic properties and may give rise to different values. Tables 6 and 8 summarise the test methods for determining the opening size and water permeability of geotextiles respectively. The limitations of the various test methods should be noted. It is recommended that geotextile properties relevant to the filter criteria used in the design should be determined using appropriate tests. In particular, where dry sieving is used to obtain geotextile opening sizes, the tests should be performed using "ballotini" in order to obtain conservative results. If the water permeability (e.g. permittivity and VWFR) of the geotextile has been determined without the application of a compressive stress in the test, some allowance for the effect of the compressive stress under working conditions should be made in the check against the permeability criteria of either the French Geotextile Manual or Lawson. The factor A_2 = 3 given in the French Geotextile Manual will generally be adequate for slopes and retaining walls illustrated in Figures 1 and 2. For thin wovens and heat-bonded nonwovens, the effect of compression is not as prominent as for 'thick' needle-punched nonwovens and a smaller factor may be applied.

(g) While there is little published information on the effects of sample variability on the hydraulic properties of geotextiles (Ruddock, 1977), some allowance should be made for this in the design. Ideally, statistically-based characteristic values should be used. However, where there are insufficient test data to determine characteristic values, it is tentatively proposed that a partial 'material' factor of about 1.5 should be applied to the opening size of a geotextile. In the permeability criteria given by the French Geotextile Manual, a global safety factor, A_5 = 3, is applied to obtain the required permittivity value. This factor is considered to be adequate to cover for variations in geotextile permittivity due to sample variability inherited from the manufacturing process. A similar factor should also be applied where Lawson's minimum VWFR criterion is used.

Where the risk to life is high (as defined in Table 5.2 of GCO, 1984) and the geotextile filter is required to perform in situations where the groundwater is continually being removed, or where the control of pore water pressures is crucial to the stability of the proposed works (as opposed to situations where flow occurs only in severe rainstorms), consideration should be given to performing filtration tests as part of the design. The tests described by Greenway et al (1986) or Scott (1980) are suitable and they should be carried out using the soils on site or the proposed fill materials, as appropriate.

As contamination or damage of a geotextile during installation and in service cannot be properly modelled in filtration tests, the water permeability of the geotextile selected for performance testing should be higher than that required by the design. It should have a value such that the geotextile to be used in the works can be shown to have an adequate factor of safety against the permeability criterion, after allowing for factors such as contamination, compressive stress and sample variability in the filtration test results. The maximum hydraulic gradient anticipated in the field should be applied in the tests. In cases where filtration tests are required, allowance should be made in the project programme for the relatively long time it may take to carry out such tests.

Particular attention should be given when the soil is found to be gap-graded or dispersive. 'Suffosion' (i.e. the continuous migration of fines through the coarse soil matrix), which is likely to occur for gap-graded soils, may result in blinding/clogging of the geotextile filter under unfavourable hydraulic conditions. The use of grading curves derived from the fine portion of the base soil for design against excessive loss of fines is recommended (CFGG, 1989). Further discussion of the process of suffosion can be found in Sherard (1979), ICOLD (1986) and John (1987). Guidance on identification of dispersive soils is given by Sherard et al (1976a & b) and Sherard & Decker (1977). Little is known about the filtration behaviour of such soils when used with geotextile filters. Lawson (1987) specifies that the O_{90} size should not be less than 0.03 mm for dispersive soils (Table 11). It is recommended that long-term filtration tests be performed for designs involving gap-graded or dispersive soils. Fortunately, these soils do not appear to be common in Hong Kong.

Where the proposed construction poses a high risk to life, it is recommended that a detailed investigation of the site conditions should also be carried out to assess the likely risk of clogging due to chemical deposits and organic residues. This should include an examination of the performance of drainage systems in the vicinity of the site. Particular care should be taken where the site is adjacent to factories or waste disposal facilities, or where a high level of soil biological activity is anticipated, e.g. as indicated by a high organic matter content in the soil.

12.3 GEOTEXTILES AS POSSIBLE PLANES OF WEAKNESS

Geotextiles buried in soil can act as planes of weakness because of the effect of a reduced shear strength at the soil/geotextile interface. Data given by Degoutte & Mathieu (1986) and Myles (1982) show that the coefficient of friction between sandy soils and geotextiles may be as low as (2/3) tan ϕ', where ϕ' is the angle of shearing resistance of the soil. The results of undrained direct shear tests on several cohesive soils given by Christie (1982) showed that the effect of the geotextile is to destroy pore water suction at low normal stresses, thus giving interface strengths much lower than the undrained shear strength of the soil. Fourie & Fabian (1987) considered that low interface strengths between clays and geotextiles can also be due to the low transmittivity of the geotextile.

Where appropriate, the effect of a reduced shear strength at soil/geotextile interfaces should be considered in slope stability analyses and earth pressure calculations. In cases where the interface strength is likely to be a critical controlling factor in a design, direct shear tests should be carried out to determine the interface shear strength. Alternatively, this weakness may be removed in the design by incorporating a number of slope benches on which the geotextile is to be placed.

13. CONSTRUCTION CONSIDERATIONS

13.1 MECHANICAL PROPERTY REQUIREMENTS AND INSTALLATION METHODS

To ensure that the geotextile filter can perform satisfactorily in service, it must have adequate mechanical properties, and the installation must be carried out in such a manner that the fabric is not damaged or excessively strained during construction. The level of supervision to be provided during installation of a geotextile filter should be appropriate to the risk category of the proposed works (see Table 5.2 of GCO, 1984). Manufacturers' certificates and relevant literature, as well as test certificates, should be required in contracts where geotextiles are used as permanent filters. The contractor should be required to provide details of the proposed geotextile, including its constituent polymers and additives, type of construction, the relevant hydraulic and mechanical properties, and the date and place of manufacture. Quality control tests on geotextile samples should be specified and carried out for works that belong to the high risk category. Guidance on mechanical property requirements, test requirements, and installation methods can be found in Christopher & Holtz (1988), Lawson (1987) and in the French Geotextile Manual (CFGG, 1989). Excessive exposure of the geotextile to sunlight should be avoided (see Section 8.8)

Prior to laying a geotextile filter, protrusions (e.g. sharp corners of rock) or depressions in the ground should be smoothed out, and erosion gullies formed on a slope surface as a result of heavy rainfall should be filled or trimmed back. Installation of the filter should be carried out in a manner that avoids excessive loads being imposed. Machines or vehicles should not be operated on a geotextile which is not covered by adequate fill or drainage material.

Drainage materials placed adjacent to the geotextile filter should preferably not contain particles larger than 63 mm. If aggregates of a relatively uniform size are used, the maximum size of the particles should be limited to 20 mm in order to minimize the 'span' of the geotextile across the particles. The maximum particle size requirement for drainage materials can be relaxed for designs in low and negligible risk to life situations (GCO, 1984) where the geotextile can be replaced easily (e.g. shallow trench drains), but large stones should never be dropped on a geotextile from any height.

The simplest method of providing continuity for a geotextile filter is by overlapping the geotextile strips. In order to prevent direct contact between the soil and drainage material on either side of the geotextile, it is important to ensure that the overlapping strips are not displaced during construction and that they do not separate as a result of long term ground movements. In slope and retaining wall applications in Hong Kong, an overlap of 0.3 m is usually sufficient, although for an irregular ground surface or poor subgrade a larger overlap may be required. An alternative method of providing a continuous geotextile filter is by sewing, in which case an overlap of about 0.1 m is required. Also, there should be intimate contact between the geotextile and the base soil, without which localized concentrated flow and erosion may occur. The casting of no-fines concrete against a geotextile filter should not be permitted, as the cement paste may block the pores of the geotextile completely.

When installing a geotextile on a slope, the fabric should be unrolled in the cross or down slope directions, either in one piece or in strips. Adjoining strips should either be stitched together or overlapped by a minimum of 300 mm. Stones may be used to hold the geotextile in place along the slope. Steel pins are also useful to anchor the fabric at the top of the slope. Sewn seams should have adequate mechanical properties, i.e. as close as possible to those of the parent geotextile material.

Geotextile filters should have sufficiently high wettability to become easily saturated in service. Wettability is a measure of the ease of water penetration through the geotextile under an extremely low water head of a few millimetres. A simple test of wettability is to pour a glass of water over a sample of the geotextile to check if the water penetrates readily. In some cases, hydrophilic agents may have to be sprayed on the geotextile to ensure good wettability.

13.2 QUALITY CONTROL PROCEDURES DURING CONSTRUCTION

Manufacturers' certificates provided for geotextiles used as permanent filters should include information on the date and place of manufacture, constituent polymers and additives, geotextile construction, and the results of relevant tests of the hydraulic and mechanical properties. The information should be checked with specifications for non-compliance.

For slopes and retaining walls belonging to the high risk category, compliance tests on geotextile samples selected by the engineer should be carried out during construction. In particular, the mass per unit area, tensile properties (tensile strength and elongation at failure) and hydraulic properties (opening size and water permeability) of selected samples should be determined and checked against the requirements of the specification.

13.3 MONITORING OF GEOTEXTILE FILTER PERFORMANCE

Monitoring of the performance of drainage works does not need to be carried out on a routine basis simply because the works contain a geotextile. However, such monitoring should only be considered where the conditions mentioned in Section 12.1 are not fully met. The monitoring requirements should be specified to a standard appropriate to the risk category of the proposed construction. Piezometric monitoring should generally cover a minimum of at least one wet season. Where considered necessary, this period should be extended to include a severe rainstorm for which the design can be more fully tested. Where possible, the flow of groundwater through a geotextile filter should be channelled through an inspection pit, in order that the quantity and nature of the outflow may be assessed.

PART IV

CONCLUSIONS AND RECOMMENDATIONS

14. CONCLUSIONS AND RECOMMENDATIONS

14.1 GRANULAR FILTERS

There are many phenomena associated with the filtration process, such as particle transport, permeability and self-filtration. These phenomena are related to the characteristics of the pore channels of the materials concerned, the size of the pore constrictions and the particle size distributions.

The effectiveness of a granular medium as a filter to protect a granular base soil depends on the following factors:

(a) *The characteristics of particles forming the filter and the base soils* : these include grain size, particle size distribution, range of gradation, porosity (or degree of compaction) and, to a much less extent, grain shape.

(b) *The hydraulic conditions and properties of the pore fluid* : frequent reversal in flow direction or high hydraulic gradient may encourage the migration of fines.

(c) *The filter thickness* : the characteristics of filter pore networks will be significantly affected if the thickness of the filter layer is less than a certain value. Generally, this is not a problem in practice because the requirements for construction or drainage capacity usually call for a sufficiently large filter thickness.

(d) *The method of filter placement* : this has a direct bearing on the minimum filter thickness and the degree of filter segregation. Proper compaction of filter material is also essential because porosity has a marked influence on the size of particles that can move through the filter.

Based on a review of the design criteria developed overseas and taking into account the characteristics of Hong Kong soils, the design criteria for granular filters as summarised in Table 3 are recommended. These rules are to satisfy both functional and performance requirements, i.e. stability, permeability and segregation. In the stability requirement, the particle size ratio of $D_{15}F/D_{85}S$ is used, whereas the particle size ratio of $D_{15}F/D_{15}S$ is adopted in the permeability criterion. The grading curves of the filter need not be of a similar shape to the base soil, but they must not be gap-graded. It is established that for a widely-graded base soil, particles coarser than 5 mm should be neglected when applying the design criteria. To minimise separation of coarse and fine particles within the filter, the uniformity coefficient of the filter material should be limited to 20 and the maximum particle size to 50 mm.

It should be noted that grading curves of Hong Kong saprolites determined with the use of dispersing agents may differ significantly from those obtained without dispersing agents. For filter design, it is considered appropriate to determine particle size distribution without the use of dispersing agents to better simulate field conditions.

14.2 GEOTEXTILE FILTERS

In general, geotextiles composed of resistant synthetic polymers are a suitable alternative to granular filters in permanent works where site conditions are non-aggressive. It is envisaged that the use of geotextile filters can be permitted in many areas of Hong Kong without a high risk of encountering durability problems. Nevertheless, site investigations for permanent works should assess the potential aggressiveness of the site with respect to geotextile materials.

Geotextile filter criteria for static loading, moderate to low hydraulic gradients and unidirectional water flow conditions are well established. The criteria of both the French Geotextile Manual (CFGG, 1989) and Lawson (1987) can be applied to Hong Kong soils. The design should take account of the characteristics of the soils encountered, in particular their variability and permeability as well as the variability inherent in the geotextile. Geotextile properties relevant to the filter criteria to be used in design should be determined using appropriate tests. Where the risk to life is high and the filter is required to perform in a situation where groundwater is continually being removed, or where the control of pore water pressures is crucial to stability, consideration should be given to performing filtration tests as part of the design. Performance monitoring requirements should be specified to a standard appropriate to the risk category of the proposed engineering works.

To ensure that the geotextile filter will perform satisfactorily in service, it must have adequate mechanical properties and the installation must be carried out in such a manner that the fabric is not damaged or excessively strained during construction. Particular consideration should be given to the possibility of the geotextile acting as a plane of weakness in the works. The level of supervision to be provided during installation of a geotextile filter should be appropriate to the risk category of the proposed works. Excessive exposure of geotextiles to sunlight and weather should be avoided. Manufacturers' certificates should be required in contracts where the geotextiles are used as permanent filters, and compliance tests on selected geotextile samples should be carried out during construction for works belonging to the high risk to life category.

14.3 CHOICE OF FILTERS : GRANULAR FILTERS VERSUS GEOTEXTILE FILTERS

In the past, fabric filters have been used only in permanent drainage works in low and negligible risk to life situations in Hong Kong. The two exceptions to this are when the fabric is required to function for rare storm events or when the performance of the fabric can be monitored for a period of at least five years and can be removed and replaced if it ceases to function properly (GCO, 1984). As a result of improved understanding of the long term durability and performance of geotextiles as filters, there is now an increasing use of geotextiles in permanent applications and in works belonging to high risk to life category. A wide range of geotextiles suited for different applications is available, and designers now generally can choose between using granular filters or geotextile filters in the works.

In choosing the type of filter appropriate for the works, it is necessary to consider the ground conditions, the material properties, the cost and availability of materials, construction constraints, the nature of work and the risk to life category.

There are advantages in using granular materials as filters in that aggregates are durable, and their long term durability is guaranteed even in hostile and aggressive site conditions. However, there are disadvantages in that aggregates may segregate during handling and placement, and the resulting grading may deviate from that assumed in the design. There has been a concern over the long term durability of geotextile fabrics, but it is considered that if the recommendations given in Section 8.8 are followed, the risk of geotextiles having durability problems should be minimal.

In general, geotextiles composed of resistant synthetic polymers can be used as an alternative to aggregates in permanent works where site conditions are non-aggressive. For sites where aggressive conditions prevail, advice from geotextile manufacturers and material scientists and chemists should be sought to confirm the adequacy of the resistance of the products to the in service soil environment. Geotextile fabrics have more consistent and well defined properties than aggregates, and they can be made to meet strict specifications. However, quality control tests would need to be carried out for works that belong to the high risk to life category.

In terms of cost and availability of material, aggregates are generally more expensive than geotextiles to purchase, transport and place. There can also be an additional cost involved in exporting soils from the site, which could otherwise be used for backfilling (i.e. where the aggregates have taken up the space). Different sizes of aggregates are required in drainage work. There is a danger that the appropriate sizes are not available, or they may have to be produced specifically for the job.

Use of appropriate types of materials as filter and drainage layers also depends on site constraints and configuration requirements of the works. Where the insitu ground surface is irregular, granular filters may be preferable to geotextiles because the aggregates can easily fill the voids at the filter/base soil interface.

In summary, there is no absolute answer as to which type of filter material is more suitable. In deciding on the type of filter material to be used, the designer should consider carefully the range of factors discussed above.

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Table 1 - Expressions for Estimating the Permeability of Granular Soils

Reference	Expression	Remarks
Hazen (1892)	$k = CD_{10}^2$	C ranges from 0.0041 to 0.0146 and usually taken as 0.01. Loudon (1952) found that this expression may lead to an error of a factor of 2 either way.
Terzaghi (1922)	$k = C\left[\frac{n-0.13}{\sqrt[3]{1-n}}\right]^2 D_{10}^2$	C varies from 8 for rounded sands to 4.6 for angular sands.
Kozeny (1927)	$k = \frac{g}{C\mu S^2}\frac{n^3}{(1-n)^2}$ $S = f\sum_{i=0}^{n} x_i S_i$ and $S_i = \frac{60}{\sqrt{d_x d_y}}$	C is an empirical constant and equal to 5 for spherical particles.
Rose (1950)	$k = \frac{gD^2}{10\mu}\frac{1}{f(n)}$ $f(n) = 1.115(1-n)\frac{[(1-n)^2+0.018]}{n^{1.5}}$	At n = 40%, f(n) = 1.
Kenney et al (1984)	$k = CD_5^2$	C ranges from 0.005 to 0.01. k was found to be practically independent of the shape of gradation. For correlation of k with D_{15}, C ranges from 0.002 to 0.008.
Sherard et al (1984a)	$k = CD_{15}^2$	C ranges from 0.002 to 0.006 with an average of 0.0035. These are similar to the recommendations of Kenney et al (1984).

Legend :

k	Coefficient of permeability of soil (in m/sec for the above expressions)
C	Empirical constant used in permeability expressions
D_m	The size of sieve (in mm) that allows m% by weight of the soil to pass through
n	Soil porosity
g	Acceleration due to gravity (= 9.81 m/sec^2)
S	Surface area per unit volume of particles (in cm^2/cm^3 for the expression by Kozeny, 1927)
f	Angularity factor (= 1.1, 1.25, 1.4 for rounded sand, sand of medium angularity and angular sand respectively)
S_i	Specific surface of material (in cm^2/cm^3) lying between sieve sizes d_x and d_y
x_i	Percentage of total mass of soil retained between sieve sizes d_x and d_y
d_x, d_y	Size of sieve (in mm for the expression by Kozeny, 1927)
D	Diameter of equivalent spherical particle ($\approx$ 60/S, in mm for the expression by Rose, 1950)
μ	Viscosity of water in poise (μ = 0.0131 poise at 10°C)

Notes :

(1) Based on the experimental work of Loudon (1952), the expression given by Kozeny (1927) is the best when compared those given by Hazen (1892), Terzaghi (1922) & Rose (1950).

(2) The range of k values estimated by Kenney et al (1984) and Sherard et al (1984a) are fairly similar and would be very useful for a rough estimate of k.

(3) Other theoretical expressions for estimating permeability of granular soils are also available such as that proposed by Silveira & Peixoto (1975). However, these expressions are too complicated for routine use.

Table 2 - Published Design Rules for Granular Filters (Sheet 1 of 4)

Reference	Uniformity Coefficient, C_u		Filter Criteria				Remarks
	Base Soil	Filter	$D_{15}F/D_{85}S$	$D_{15}F/D_{15}S$	$D_{15}F/D_{50}S$	$D_{50}F/D_{50}S$	
Terzaghi (1922)	None	None	< 4	> 4	None	None	Criteria based on experience
Bertram (1940)	1.2	1.2	< 6.5	< 9	None	None	Hydraulic gradient 8 to 20
Newton & Hurley (1940)	3.08 - 4.77	Uniform	None	< 32	< 15	None	Failed specimens had $D_{15}F/D_{85}S$ ratio less than 4
USCE (1941)	Uniform	2.3 - 8	< 5	None	None	None	Hydraulic gradient 2
Lund (1949)	1.05 - 7.0	Uniform	None	None	None	None	Hydraulic gradient 10; Lund opined that the Terzaghi (1922) criteria had a safety factor of 2
USCE (1953)	1.2 - 6.1	2 - 23	< 5	< 20	< 25	None	Hydraulic gradient 1 to 26
Leatherwood & Peterson (1954)	1.3 - 2.9	1.2 - 1.3	< 4.1	None	None	< 5.3	Criteria based on maximum head loss at interface

Legend :

D_mF The size of sieve (in mm) that allows m% by weight of the filter material to pass through
D_mS The size of sieve (in mm) that allows m% by weight of the base soil material to pass through
C_u Uniformity coefficient ($= D_{60}/D_{10}$)

Table 2 - Published Design Rules for Granular Filters (Sheet 2 of 4)

Reference	Uniformity Coefficient, C_u		Filter Criteria				Remarks	
	Base Soil	Filter	$D_{15}F/D_{85}S$	$D_{15}F/D_{15}S$	$D_{15}F/D_{50}S$	$D_{50}F/D_{50}S$		
USBR (1955)	1.4 - 7.0	1.2 - 1.4	None	None	None	5 to 10	Uniform Filters	Additional requirements : (1) $D_{100}F$ < 75 mm. (2) Gradings of base soil & filters of similar shape (3) Base soil for particles finer than 4.76 mm only
	7 - 25	5 - 30	None	12 to 40	None	12 to 58	Graded Filters	
	None	None	None	6 to 18	None	9 to 30	Crushed Materials	
Kolbuszewski (1957)	1.15	1.05 - 1.08	< 10	None	None	None	All filters tested were stable; max. $D_{15}F/D_{85}S$ was 12.5	

Legend :

D_mF	The size of the sieve (in mm) that allows m% by weight of the filter material to pass through
D_mS	The size of the sieve (in mm) that allows m% by weight of the filter material to pass through
C_u	Uniformity coefficient (= D_{60}/D_{10})

Table 2 - Published Design Rules for Granular Filters (Sheet 3 of 4)

Reference	Uniformity Coefficient, C_u		Filter Criteria				Remarks	
	Base Soil	Filter	$D_{15}F/D_{85}S$	$D_{15}F/D_{15}S$	$D_{15}F/D_{50}S$	$D_{50}F/D_{50}S$		
Zweck & Davidenkoff (1957)	1.2	1.2	None	None	None	5 to 10	Medium sand	Maximum hydraulic gradient of 2.2
						5 to 15	Fine Sand	
						5 to 25	Graded Sand	
Thanikachalam & Sakthivadivel (1974a; 1974b)	None	None	None	None	None	None	The authors proposed the following criteria : $\frac{D_{60}F}{D_{10}S} = 0.941\frac{D_{10}F}{D_{10}S} - 5.65$ $\log(\frac{D_{10}F}{D_{10}S} - 3) = \frac{1.55}{\log(1000D_{10}S-1)}$	

Legend :

D_mF The size of the sieve (in mm) that allows m% by weight of the filter material to pass through
D_mS The size of the sieve (in mm) that allows m% by weight of the filter material to pass through
C_u Uniformity coefficient (= D_{60}/D_{10})

Table 2 - Published Design Rules for Granular Filters (Sheet 4 of 4)

Reference	Uniformity Coefficient, C_u		Filter Criteria				Remarks
	Base Soil	Filter	$D_{15}F/D_{85}S$	$D_{15}F/D_{15}S$	$D_{15}F/D_{50}S$	$D_{50}F/D_{50}S$	
Lafleur (1984)	6.9 - 9.5	1.8 - 23	< 9	None	None	None	Coarse particles (>4.76 mm) omitted in calculating $D_{85}S$
Sherard et al (1984a)	Uniform	1.1 - 4.4	< 5	None	None	None	No significant amount of fine particles (< 75 μm) in filter
	Well-graded	1.1 - 4.4	< 9	None	None	None	Filter & base soil gradings need not be of similar shape
Kenney et al (1985)	3 - 14.3	1.2 - 12	None	None	< 5	None	In addition, $D_5F/D_{50}S < 4$
Honjo & Veneziano (1989)	None	None	None	None	None	None	Proposed design rule : $\frac{D_{15}F}{D_{85}S} \leq 5.5 - 0.5\frac{D_{95}F}{D_{75}S}$ (for $\frac{D_{95}F}{D_{75}S} \leq 7$)

Legend :

D_mF The size of the sieve (in mm) that allows m% by weight of the filter material to pass through
D_mS The size of the sieve (in mm) that allows m% by weight of the filter material to pass through
C_u Uniformity coefficient (= D_{60}/D_{10})

Table 3 - Design Criteria for Granular Filters

Rule Number	Filter Design Rule[1]	Requirement
1	$D_{15}F_c < 5 \times D_{85}S_f$	Stability (i.e. the pores in the filter must be small enough to prevent infiltration of the material being drained)
2	Should not be gap-graded (i.e. having two or more distinct sections of the grading curve separated by sub-horizontal portions)	
3	$D_{15}F_f > 5 \times D_{15}S_c$	Permeability (i.e. the filter must be much more permeable than the material being drained)
4	Not more than 5% to pass 63μm sieve and that fraction to be cohesionless	
5	Uniformity Coefficient $4 < \dfrac{D_{60}F}{D_{10}F} < 20$	Segregation (i.e. the filter must not become segregated or contaminated prior to, during, and after installation)
6	Maximum size of particles should not be greater than 50 mm	

Notes :

(1) In this Table, $D_{15}F$ is the size of sieve (in mm) that allows 15% by weight of the filter material to pass through. Similarly, $D_{85}S$ is the size of sieve (in mm) that allows 85% by weight of the base soil to pass through. The subscript c denotes the coarse side of the envelope, and subscript f denotes the fine side.

(2) For a widely graded base soil, with original $D_{90}S > 2$ mm and $D_{10}S < 0.06$ mm, the above criteria should be applied to the 'revised' base soil grading curve consisting of the particles smaller than 5 mm only.

(3) The thickness of a filter should not be less than 300 mm for a hand-placed layer, or 450 mm for a machine-placed layer.

(4) Rule 5 should be used to check individual filter grading curves rather than to design the limits of the grading envelope.

(5) The determination of the particle size distributions of the base soil and the filter should be carried out without using dispersants.

Table 4 - Range of Values for Some Representative Properties of Selected Geotextiles Used as Filters

Geotextile Construction	Tensile Strength (kN/m)	Maximum Elongation (%)	Apparent Opening Size@ (mm)	Volume Water Flow Rate * ($l/m^2/s$)	Unit Weight (g/m^3)
WOVENS					
Monofilament	20-80	5-35	0.07-2.5	25-2000	150-300
Yarn#	40-800	5-30	0.2-0.9	20-80	250-1300
Tape	8-90	15-20	0.05-0.1	5-15	100-250
NONWOVENS					
Needle-punched	7-90	50-80	0.02-0.15	25-200	150-2000
Heat-bonded	3-25	20-60	0.01-0.35	25-150	70-350
Resin-bonded	4-30	30-50	0.01-0.35	20-100	130-800

Legend :

* Normal to the plane of the geotextile with 100 mm constant head (see Table 8 for methods of measurement)

\# Fibrillated tapes are included in this category

@ For methods of measurement of Apparent Opening Size, see Table 6

Note : This table is based on Lawson (1982).

Table 5 - Some General Data on Chemical and Thermal Stability of Synthetic Polymer Fibres Commonly Used in the Manufacture of Geotextiles

Polymer Type	Resistant to		Stable between (°C)	Remarks
	Acid Conditions	Alkali Conditions		
Polypropylene	pH ≥ 2	All	-15 to 120	Attacked at elevated temperatures by hydrogen peroxide, sulphuric acid and nitric acids. Weakened by certain solvents, e.g. diesel fuel. Insignificant change in strength between 20°C and 35°C.
Polyester	pH ≥ 3	pH ≤ 10	-20 to 220	Degrades by hydrolysis under strongly alkaline conditions. Therefore, concrete must not be cast directly against it. Insignificant change in strength between 20°C and 35°C.
Polyamide (nylon 6.6)	pH ≥ 3	pH ≤ 12	-20 to 230	Degrades by hydrolysis under strongly acidic conditions. Reduces in strength by up to 30% when immersed in water or used in a saturated environment. Insignificant change in strength between 20°C and 35°C.
Polyethylene	pH ≥ 2	All	-20 to 80	Same as polypropylene, except strength at 35°C is lower than that at 20°C by about 25%.

Note : Data based on Cooke & Rebenfeld (1988), Lawson & Curiskis (1985) and Van Zanten (1986).

Table 6 - Different Methods for the Measurement of Geotextile Opening Size

Method and Brief Description	Measure of Geotextile Apparent Opening Size (AOS)	Remarks
Visual Means (Calhoun, 1972) : Direct measurement made from a magnified image of the geotextile projected on a screen with the use of a light source	O_{95}, also known as Effective Opening Size (EOS)	Only applicable to geotextiles with fairly uniform and well defined openings, e.g. woven monofilaments. Appropriate for opening sizes down to about 100 microns. Not suitable for nonwovens.
Dry Sieving (also known as Reverse Sieving): Measurement of the opening size distribution made by sieving particles of known size range through the geotextile using vibratory sieving equipment.		Applicable to a wide range of woven and nonwoven geotextiles but limited by the smallest size particle fraction that can be sieved. Not a problem for wovens as O_{90} is generally greater than 100 microns. Extrapolation normally used for nonwovens with $O_{90} < 75$ microns; not normally used for $O_{90} < 50$ microns. Results are sensitive to test apparatus (e.g. sample holder) and test conditions, such as characteristics of vibration (frequency and direction), temperature and humidity. Reproducibility of results between laboratories not proven (Fayoux et al, 1984).
(a) Dry sieving using sand fractions (Ogink, 1975 ; Schober & Teindl, 1979)	O_{90} is taken as the size at which 90% by weight of particles are retained on the geotextile.	Use of particles finer than 60 microns not recommended as interparticle forces can affect results (Lawson, 1984).
(b) Dry sieving using "ballotini" (spherical glass beads) (McKeand, 1977, Ruddock, 1977, USCE, 1977)	O_{90}, as above, or O_{95} (EOS) taken as the sieve size at which 5% by weight of particles passes the geotextile (USCE, 1977).	Minimum size of commercially available ballotini is about 70 microns (Lawson, 1984). Anti-static device required to neutralize build-up of static electricity. Ballotini may break as a result of repeated use and their sizes have to be checked regularly.
Wet Sieving (Heerten, 1981, 1982) : Sand sample sieved through geotextile using modified vibratory sieving equipment with water spraying at regular intervals.	D_W calculated using specified relationship (see Van Zanten, 1986).	Limited number of sieves used, resulting in large gaps in values of D_W. Different quantity of sand used for testing nonwovens and wovens, making it difficult to compare results (John, 1987; Van Zanten, 1986).
Hydrodynamic Sieving (Fayous, 1977, CFGG, 1984) : Sand sample supported by the geotextile is repeatedly immersed in water at a specified frequency for a period of about 24 hours, then the grading of the soil passing the geotextile is determined.	O_f, also known as the filtration diameter, is taken as the D_{95} of the soil that has passed the geotextile.	Considered to model field conditions better than dry sieving : reproducibility of results between laboratories reportedly satisfactory (Fayoux et al, 1984). Alternating water flow encourages the formation of a natural filter above the geotextile. O_f found to be smaller than opening sizes obtained by dry sieving or wet sieving (Faure et al, 1986b). Appropriate for opening sizes O_f down to 30 microns. Time consuming to perform.
Suction Method (Andrei et al, 1982, Dennis & Davies, 1984, Paute & Chene, 1977) : Pore size distribution of the geotextile estimated using a capillarity model which relates the volume of water retained in the pores of the geotextile and the suction applied to it.	Pore size distribution.	Only applicable when sufficient suction can be applied to the geotextile to obtain a meaningful result. Normally applied to geotextiles with pore sizes less than 70 microns.
Image Analyser Technique (Masounave et al, 1980) : Geotextile is impregnated with transparent resin and a cut and polished cross-section scanned optically using automatic equipment. Porosity and pore size distribution are deduced using probabilistic theory in terms of the observed fibre surface density.	Pore size distribution and porosity.	Only applicable to 'thick' needle-punched nonwovens. Appropriate for pore sizes from 20 to 200 microns. Empirical relationship exists between fibre density and permeability for needle-punched fabrics thicker than 15 mm (Masounave et al, 1980), which enables porosity and pore size distribution to be derived from permeability measurements without direct observation of fibre density.

Table 7 - Results of Comparison of Different Test Methods for Determining Geotextile Opening Size

Geotextile	Construction	$O_{95}^{(1)}$	$O_{95}^{(2)}$	$O_{95}^{(3)}$	$D_W^{(4)}$	$D_W^{(5)}$	$O_f^{(6)}$
tFy25	W, MF	87	72	67	70	69	62
tPt48	W, MF	195	187	187	125	143	120
tPt54	W, MF	395	390	385	280	324	320
SC150	W, ST	140	138	140	103	111	100
TP270	NW, M	85	82	74	72	67	72
BD280	NW, N	180	168	163	100	113	113
BD550	NW, N	86	77	105	80	89	72
TS500	NW, N	190	170	-	-	120(7)	115
TS600	NW, N	185	165	-	-	110(7)	95
TS700	NW, N	136	138	108	93	90	83

Legend :

W	Woven	NW	Nonwoven
MF	Monofilament	M	Heat-bonded (melted)
ST	Strip	N	Needle-punched

Notes on Methods :

(1) By dry sieving using different size fractions of "ballotini" (spherical glass beads).

(2) By dry sieving using different size fractions of sand.

(3) By wet sieving using different size fractions of sand.

(4) By wet sieving using well-graded sand (based on D_{95} of passing geotextile, where D_{95} is the 95% size of the sand).

(5) By wet sieving using well-graded sand (Heerten, 1981).

(6) By hydrodynamic sieving using well-graded sand.

(7) Values furnished by the manufacture.

Notes : (1) This table is based on Faure et al (1986b)
(2) Opening sizes are in microns.

Table 8 - Different Methods for the Measurement of Geotextile Water Permeability (Sheet 1 of 2)

Method	Measure of Water Permeability	Interpretation	Remarks
Test involves direct measurement of open areas in a geotextile from a projected screen image by means of a planimeter (Calhoun, 1972).	Percent Open Area, POA (%)	Calhoun (1972) proposed the use of a minimum POA for specifying the requirement of water permeability of woven geotextiles. $POA = \dfrac{\text{Total of individual open areas}}{\text{Total projected area of geotextile specimen}}$	Only applicable to wovens.
Test using constant or falling head permeameter (e.g. the Franzius Institute Hannover (FIH) method, see Van Zanten (1986)) or modified Rowe Cell (McGown et al, 1982). Multiple layers may be used to induce laminar flows in geotextiles.	Normal Permeability, k_n (m/s)	Ogink (1975) proposed the use of a modified Darcy's law to describe water flow through geotextiles : $\left(\dfrac{\delta Q}{\delta t}\right)^{\alpha} = k_n A \dfrac{\delta h}{\delta x}$ where $\dfrac{\delta Q}{\delta t}$ is rate of flow of water through geotextile A is surface area through which flow occurs $\dfrac{\delta h}{\delta x}$ is hydraulic gradient through geotextile k_n is coefficient of permeability of geotextile α is a coefficient which depends on the type of flow (for laminar flow $\alpha = 1$, for semi-turbulent flow $1 < \alpha < 2$, and for turbulent flow $\alpha = 2$)	Modified Darcy's law accurately describes the range of flow behaviour of geotextiles. Interpretation based on nominal thickness of geotextile, as actual thickness is not measured in test. For thick nonwovens, $\alpha \approx 1$. For thin nonwovens, knitted, stitch-bonded and most woven geotextiles, $1 < \alpha < 2$. For very open wovens, $\alpha \approx 2$ & k_n can be directly related to soil permeability, k, where $\alpha = 1$, but not for other values of α. Test complex to perform if flow is not laminar. Use of multiple layers makes interpretation difficult.

Table 8 - Different Methods for the Measurement of Geotextile Water Permeability (Sheet 2 of 2)

Method	Measure of Water Permeability	Interpretation	Remarks
Test on uncompressed specimens using a constant or falling head permittivity apparatus (ASTM, 1987; CFGG, 1984).	Permittivity, $\psi = \frac{k_n}{T_g}$ (s^{-1}) where T_g is the thickness of geotextile	Giroud & Perfetti (1977) introduced the concept based on regrouping of the terms in Darcy's law : $\frac{\delta Q}{\delta t} = k_n A \frac{\delta h}{\delta x} = \frac{k_n}{\delta x} A \delta h = \psi A \delta h$ i.e. $\psi = \frac{k_n}{\delta x}$ and $\delta x = T_g$	Only applicable where Darcy's law applies. CFGG (1984) places an upper limit on velocity of flow for which Darcy's law is taken to apply (based on work by Gourc et al, 1982a). ASTM (1987) requires applicability of Darcy's law to be checked.
Test using a volume water flow rate apparatus with 100 mm constant water head (Lawson, 1982). Compressive stress may be applied across the geotextile during the test.	Volume Water Flow Rate, VWFR $(l/m^2/s)$	Lawson (1982) proposed the use of a minimum VWFR criterion to differentiate between geotextiles that act as filters and those that are non-filters. $\text{VMFR} = \frac{\delta Q}{\delta t}/A$ at 100 mm constant water head $= 100\psi$ where Darcy's Law applies. Units of $\delta Q/\delta t$, A and ψ are in m^3/s, m^2 and s^{-1} respectively.	Test simple to perform and results are independent of applicability of Darcy's law. Often Darcy's law does not apply and VWFR is not the same as 100ψ. Cannot be directly related to k unless flow is laminar.
Image analyser technique (Masounave et al, 1980).	Porosity of geotextile, $n_g(\%)$	$n_g = \frac{\text{Volume of voids}}{\text{Total volume of geotextile specimen}}$	Only applicable to thick nonwovens.

Table 9 - Variety of Filter Design Criteria for Geotextiles Under Unidirectional Water Flow

Reference	Upper Limit (Retention Criteria)	Lower Limit (Permeability Criteria)	Remarks
Calhoun (1972)	$0_{95} \le D_{85}$	POA $\ge$ 4%	Upper limit : Tests on six woven monofilaments, one needle-punched and one heat-bonded nonwoven, loose sands and silt sands. Lower limit : No tests done.
Ogink (1975)	$0_{90} \le D_{90}$ (wovens) $0_{90} \le 1.8D_{90}$ (nonwovens)	$k_n > k$	Upper limit : Tests on wovens and nonwovens, sandy soils. Lower limit : Based on semi-turbulent water flow through geotextile.
McKeand (1977)	$0_{50} \le D_{85}$	$k_n > 5k$	Upper limit : Tests on heat-bonded nonwovens, sandy silts and silty sands. Lower limit : Applied by deduction.
Schober & Teindl (1979)	$0_{90} \le BD_{50}$	$k_n > k$	Upper limit : Tests on one woven and four nonwovens (two needle-punched, one heat-bonded and one resin-bonded), sand and corundum fractions with uniformity coefficient up to five. B depends on uniformity coefficient of soil and geotextile construction (see Figure 12). Lower limit : Applied by deduction.
Giroud (1982)	$0_{95} \le ED_{50}$	$k_n > 0.1k$	Based on theoretical analysis. E depends on relative density and uniformity coefficient of soil (see Table 10 and Figure 13).
Tan et al (1982)	$0_{95} \le 2D_{85}$	None	Upper limit : Tests on fine sands to clayey silts. Details of types of geotextiles used were not given. Lower limit : None given.
Lawson (1984, 1986a & b, 1987)	$0_{90} \le D_{85}$ (granular soils) $0.08mm \le 0_{90} \le 0.12mm$ (non-cohesive and non-dispersive cohesive soils) $0.03mm \le 0_{90} \le D_{85}$ (dispersive cohesive soils)	$0_{90} \ge D_{15}$ and minimum VWFR using $0_{90} = D_{15}$	Tests on two wovens, four heat-bonded nonwovens and one geogrid with Hong Kong saprolitic soils (silty sand) with very high uniformity coefficients. The design rules are described in more details in Table 11.
Rollin & Lombard (1988)	$0_f < 1.5D_{85}$ (uniform soils) $1.5D_{85} < 0_f < 3D_{85}$ (well-graded soils)	None	Tests on six wovens, seven needle-punched and one heat-bonded nonwovens, uniform silts and fine sands (Faure et al, 1986a).

Legend :

k_n	Coefficient of permeability normal to the plane of a geotextile (Table 8)	k	Coefficient of permeability of soil
VWFR	Volume water flow rate of a geotextile (Table 8)	0_f	Filtration Diameter (Table 6)
D_m	The size of sieve (in mm) that allows m% by weight of the soil to pass through	0_m	Opening size of a geotextile measured by testing the particle size at which m% by weight of particles are retained on the geotextile upon dry sieving using "ballotini" (spherical glass beads)
POA	percentage open area of a geotextile (Table 8)		

Table 10 - Giroud's Retention Criteria for Geotextile Filters

Soil Description	Relative Density	Linear Uniformity Coefficient of Soil, C_u'	
		$1 < C_u' < 3$	$C_u' > 3$
Loose Soil	< 35%	$0_{95} < C_u' D_{50}$	$0_{95} < \frac{9}{C_u'} D_{50}$
Medium Dense Soil	35 - 65%	$0_{95} < 1.5\ C_u' D_{50}$	$0_{95} < \frac{13.5}{C_u'} D_{50}$
Dense Soil	> 65%	$0_{95} < 2\ C_u' D_{50}$	$0_{95} < \frac{18}{C_u'} D_{50}$

Legend :

0_{90} Opening size of a geotextile measured by testing the particle size at which 90% by weight of particles are retained on the geotextile upon dry sieving using "ballotini" (spherical glass beads)

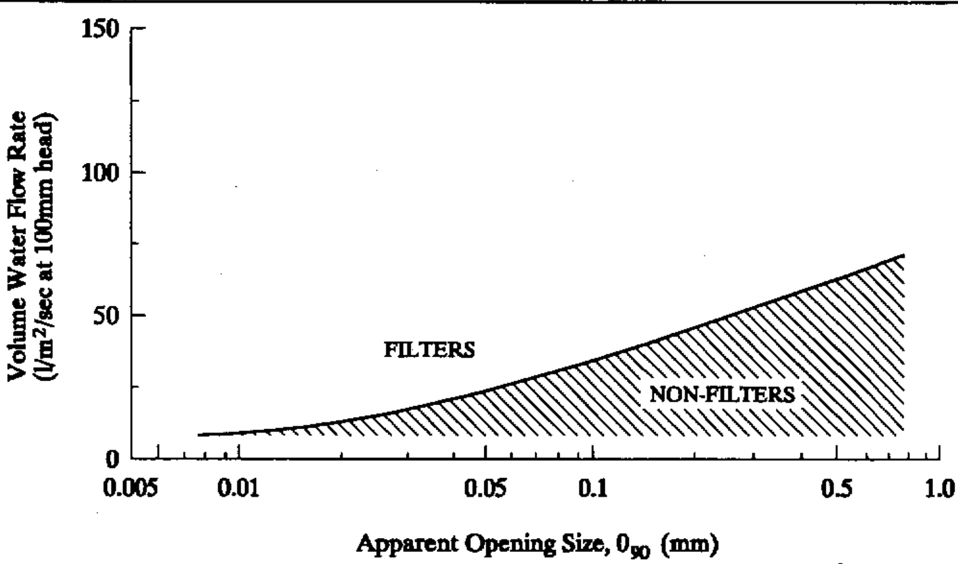
D_m The size of sieve (in mm) that allows m% by weight of the soil to pass through

C_u' Linear uniformity coefficient, see definition in Figure 13

Note : This table is based on Giroud (1982).

Table 11 - Geotextile Filter Criteria by Lawson

Retention Criteria	Permeability Criteria
For predominantly granular soils with D_{85} > 0.10 mm, e.g. residual soils which are granular in nature and alluvial sandy soils, and for PFA : $O_{90} \leq D_{85}$	$O_{90} \geq D_{15}$ and minimum VWFR requirement using $O_{90} = D_{15}$ (see diagram below)
For predominantly fine-grained soils with D_{85} < 0.10 mm, use appropriate criterion below :	
(a) For non-cohesive soils, e.g. silts of alluvial or other origin, and for non-dispersive cohesive soils, 0.08 mm $\leq O_{90} \leq$ 0.12 mm	VWFR $\geq$ 35 $l/m^2/s$
(b) For dispersive cohesive soils, 0.03 mm $\leq O_{90} \leq D_{85}$	VWFR $\geq$ 35 $l/m^2/s$



Legend :

O_{90} Opening size of a geotextile measured by testing the particle size at which 90% by weight of particles are retained on geotextile upon dry sieving using "ballotini" (spherical glass beads)

D_m The size of sieve (in mm) that allows m% by weight of the soil to pass through

VWFR Volume water flow rate of a geotextile, defined as volume of water passing/unit area/unit time/100 mm water head, see Table 8

Notes :

(1) Criteria which are based on Lawson (1987) should be used for 'thin' wovens and heat-bonded nonwovens.
(2) Consideration should be given to soil and geotextile variability and the effect of geotextile compression on VWFR in design.
(3) The determination of the particle size distribution of the base soil should be carried out without using dispersants.

Table 12 - Geotextile Filter Criteria Given by the Working Group 14 of GSSMFE

Retention Criteria	Permeability Criterion
For soils of grain size range A, i.e. soils with ≥ 40% passing 0.06 mm, $D_W < 10D_{50}$, but for 'problem soils' within envelope shown in Figure 6, $D_W < 10D_{50}$ and $< D_{90}$ and for soils with 'stable cohesion', $D_W < 2D_{90}$ For soils of grain size range B, i.e. soils with < 15% passing 0.06m. $D_W < 5\sqrt{C_u}D_{50}$ and $< 2D_{90}$ but for 'problem soils' within envelope shown in Figure 6, $D_W < \sqrt{C_u}D_{50}$ and $< D_{90}$ For soils of grain size range C, i.e. mixed grained soils, use criterion for soils of range B.	$k_n \geq 50\ k$

Legend :

D_W	Opening size of geotextile obtained by wet sieving using modified vibratory sieving equipment and a well-graded sand (see Table 6)
D_m	The size of sieve (in mm) that allows m% by weight of the soil to pass through
C_u	Uniformity coefficient of soil (= D_{60}/D_{10})
k	Coefficient of permeability of soil
k_n	Coefficient of permeability normal to the plane of a geotextile

Note : The criterion of $D_W < 2\ D_{90}$ should only be applied if the cohesive properties of the base soil are absolutely preserved even under load.

Table 13 - Geotextile Filter Criteria Given by FHWA

Retention Criteria	Permeability Criteria
For soils with $\leq$ 50% passing US No. 200 sieve (74 μm), $O_{95} \leq BD_{85}$ where $B = 1$ for $C_u \leq 2$ or > 8 $B = 0.5C_u$ for $2 < C_u \leq 4$ $B = \frac{8}{C_u}$ for $4 < C_u \leq 8$ For soils with > 50% passing US No. 200 sieve, $O_{95} \leq D_{85}$ for wovens $\leq 1.8\ D_{85}$ for nonwovens and AOS of fabric $\geq$ size of No. 50 sieve (0.297mm)	For critical/severe applications[1], $k_n \geq 10k$ and the designer should perform filtration tests[2] to check against clogging. Suggested performance criterion for filtration tests : Gradient ratio[3] ≤ 3 Alternatively, use approved list of specification. For less critical/non-severe application[4], $k_n \geq k$ In potential clogging situations[5], the following qualifiers should be met : Percent Open Area $\geq$ 4% for wovens Porosity $\geq$ 30% for nonwovens and additional qualifiers : $O_{95} \geq 3D_{15}$ (optional) $O_{15} \geq 3D_{15}$ (optional)

Legend :

- O_m Opening size of a geotextile measured by testing the particle size at which m% by weight of particles are retained on the geotextile upon dry sieving using "ballotini" (spherical glass beads)
- D_m The size of sieve (in mm) that allows m% by weight of the soil to pass through
- AOS Apparent opening size of a geotextile (see Table 6)
- k Coefficient of permeability of soil
- k_n Coefficient of permeability normal to the plane of a geotextile
- C_u Uniformity coefficient of soil ($= D_{60}/D_{10}$)

Notes :

(1) Critical applications are those which pose a high risk to life or high economic risk (GCO, 1984). Examples of severe applications are those involving gap-graded soils, high hydraulic gradients and reversing flow.

(2) Filtration tests may be carried out before specification to prequalify the geotextile, or after selection and before the tender closes.

(3) Gradient ratio is defined as :

$$\frac{\text{hydraulic gradient over geotextile and first 25 mm of soil adjacent to it}}{\text{hydraulic gradient over the next 50 mm of soil (i.e. 25 to 75 mm above the geotextile)}}$$

(4) Geotextile should be specified with maximum opening size possible from retention criteria.

(5) Examples are those involving gap-graded soils and silts.

Table 14 - Geotextile Filter Criteria Given in the French Geotextile Manual

Retention Criteria	Permeability Criteria
$O_f < C_g \times D_{85}$ where $C_g = C_1 \times C_2 \times C_3 \times C_4$ C_1 = 1.0 for well graded continuous soil 0.8 for uniform soil ($C_u < 4$) C_2 = 1.25 for dense[2] and confined soil 0.8 for loose[2] or unconfined soil C_3 = 1.0 for hydraulic gradient, $i < 5$ 0.8 for $5 < i < 20$ 0.6 for $20 < i < 40$ or alternating flow C_4 = 1.0 for filtration function only 0.3 for filtration and drainage functions For 'fine' soils, i.e. soils with a $C_g \times D_{85}$ value less than 0.05 mm, O_f can be taken as 0.05 mm. For 'problem soils', i.e. soils containing fines which can go easily into suspension (e.g. sand with low clay content), $4D_{15} < O_f < C_g \times D_{85}$ For gap-graded soils, use grading curves of fine fraction for design.	$\psi > A_g \times k$ where $A_g = A_1 \times A_2 \times A_3 \times A_4 \times A_5$ For high risk structures, e.g. earth dams, A_1 = 100 to allow for contamination during installation and in-service A_2 = 3 to allow for compression of geotextile under load A_3 = 10 to allow for i up to 10 A_4 = 10 for allowable headloss $\delta h = 0.1$ m A_5 = 3 is a global safety factor $\therefore \psi > 10^5 k$ For other structures, e.g. slopes, embankments and drainage trenches, $\psi > 10^4 k$ For clean sands with fewer than 12% < 0.08 mm, $\psi > 10^3 k$

Legend :

O_f	Opening size (also known as filtration diameter) of a geotextile (see Table 6)	k	Coefficient of permeability of soil
D_m	The size of sieve (in mm) that allows m% by weight of the soil to pass through	k_n	Coefficient of permeability normal to the plane of a geotextile
C_u	Uniformity coefficient of soil (= D_{60}/D_{10})	ψ	Permittivity of a geotextile (= k_n/T_g (s^{-1}), where T_g is thickness of the geotextile)
MDD	Maximum dry density of compacted soil		

Notes :

(1) Criteria which are based on the French Geotextile Manual (CFGG, 1989) should be used for 'thick' needle-punched nonwovens.
(2) 'Dense' soil : degree of compaction ≥ 95% MDD or relative density ≥ 65%.
'Loose' soil : degree of compaction < 95% MDD or relative density < 65%.
(3) For potentially dispersive soils, long-term filtration tests are recommended.
(4) As note (3) of Table 11.

FIGURES

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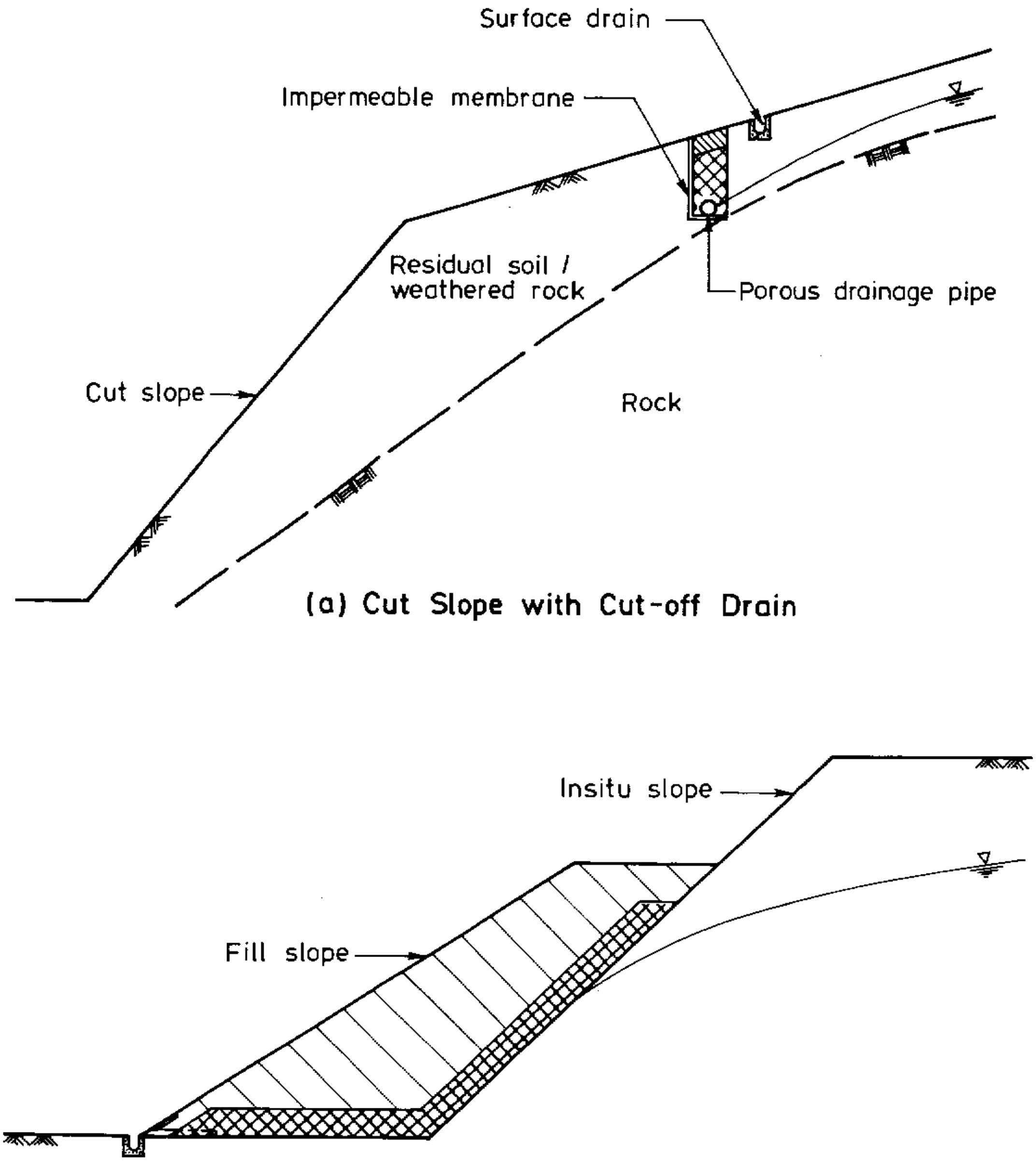
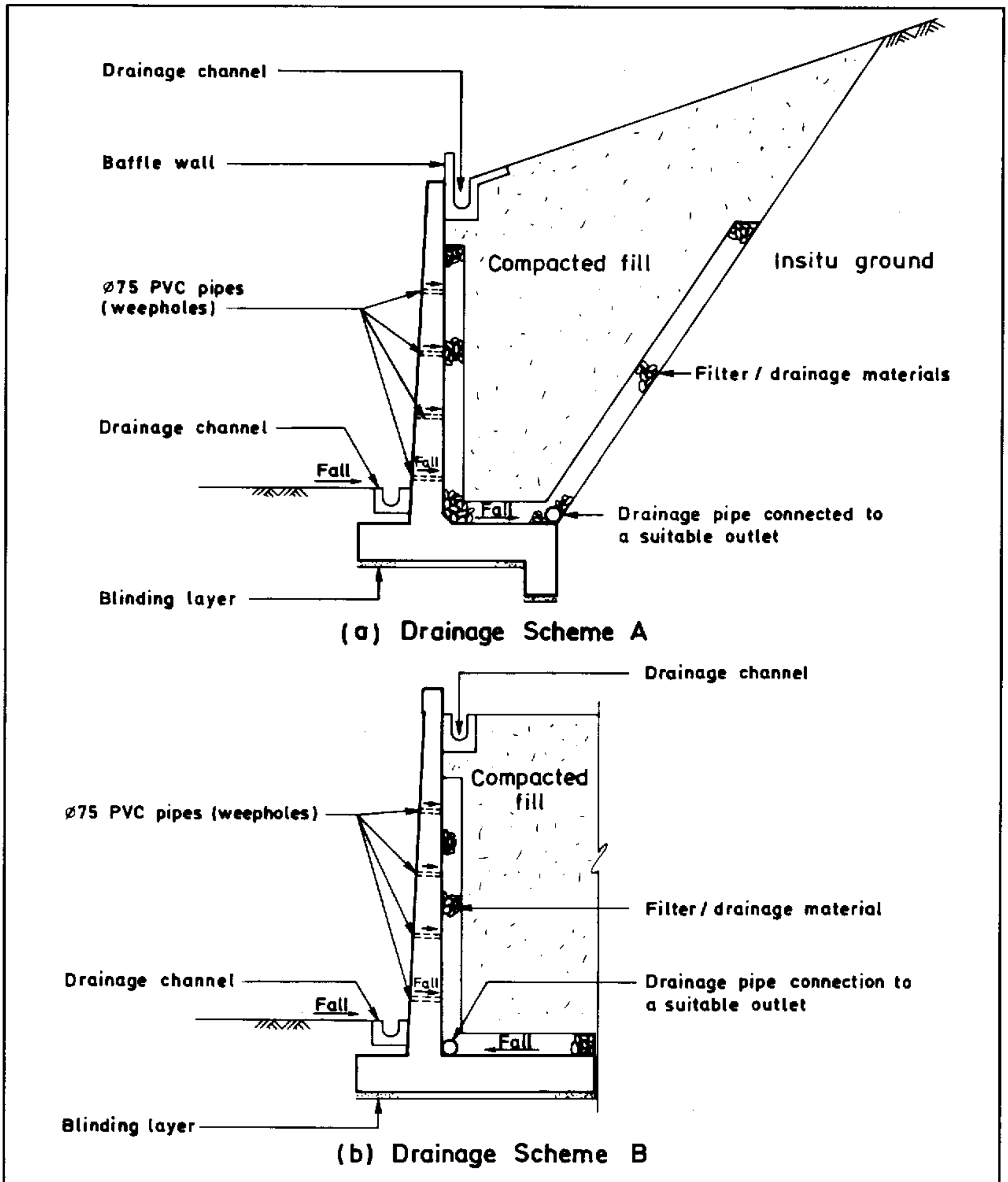


Legend :

Water table
Low permeability compacted backfill
Granular or geotextile filter/drainage layers

Figure 1 - Examples of Use of Filters and Drainage Layers in Slopes

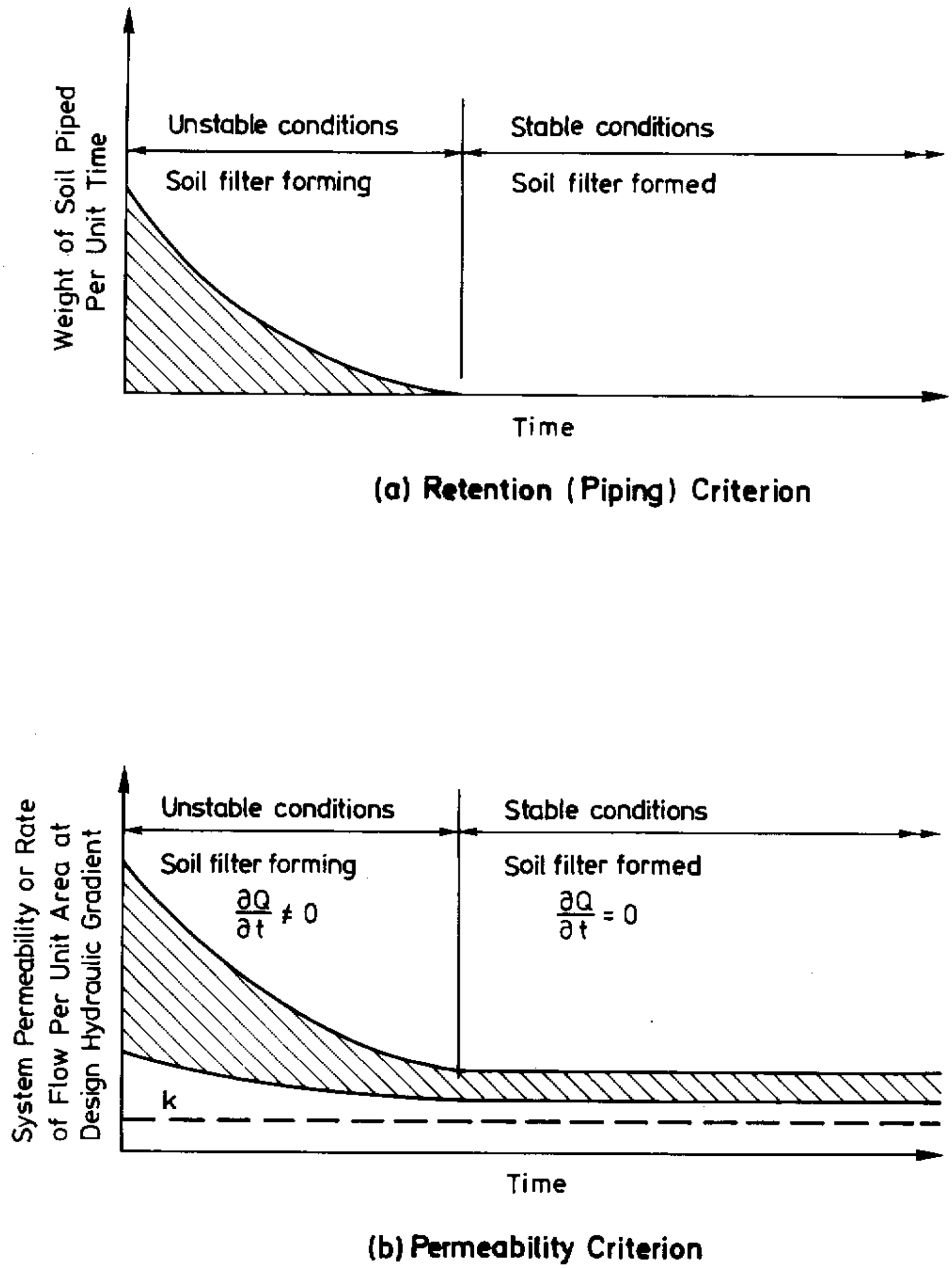


Notes :

(1) Drainage scheme A is preferred. The extent of the inclined drain is dependent on the design groundwater level behind the retaining wall. To intercept infiltration, the inclined drain should be installed to a level of at least two-thirds of the height of the wall.

(2) The filter/drainage layers may be omitted if a free-draining granular backfill is used. However, a drainage pipe should be provided to discharge water safely.

Figure 2 - Examples of Use of Filters and Drainage Layers in Retaining Walls

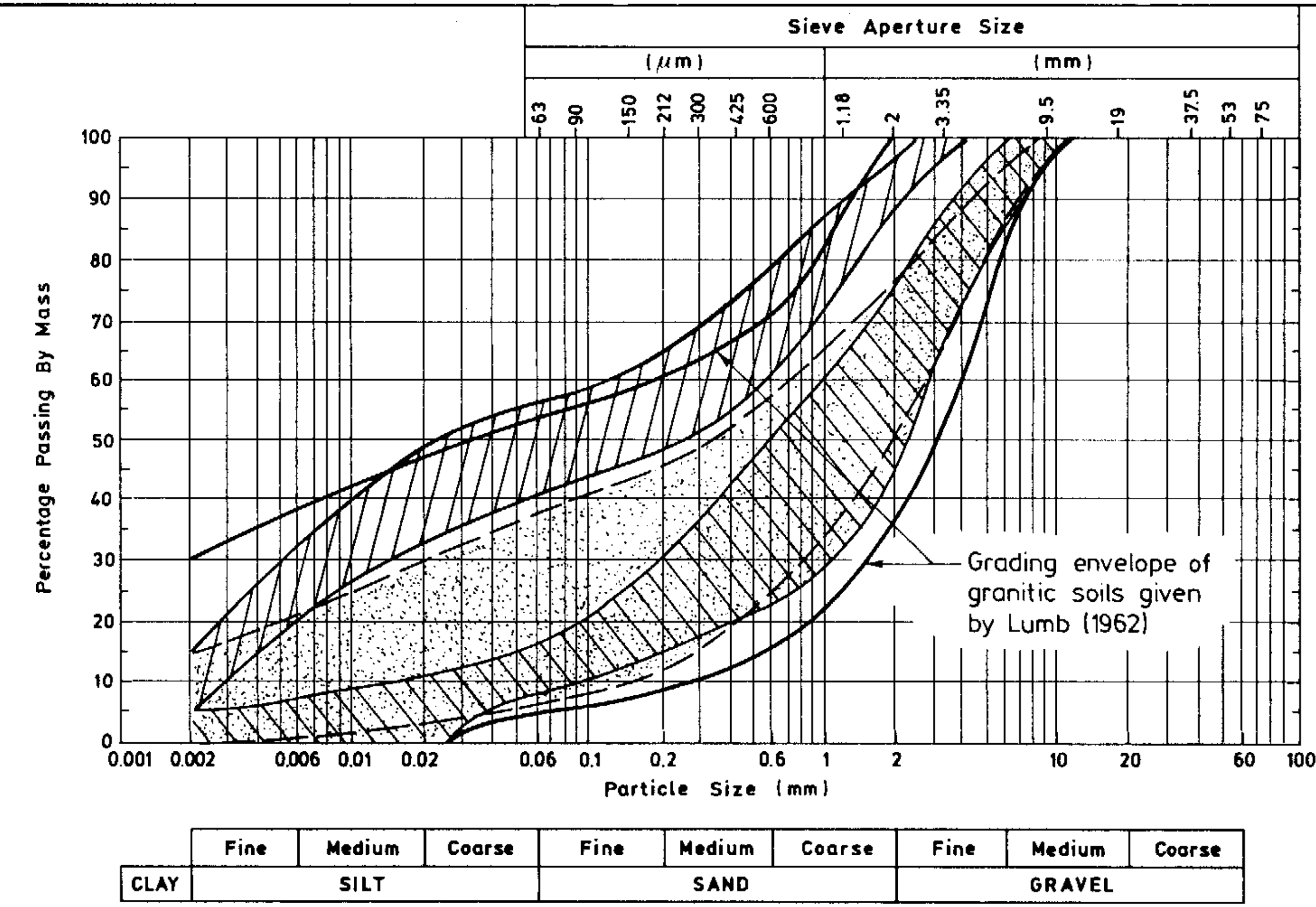


Legend :

k	Coefficient of permeability	$\frac{\partial Q}{\partial t}$	Rate of flow

Note : Figure based on Lawson (1987).

Figure 3 - Performance Criteria for Granular and Geotextile Filters



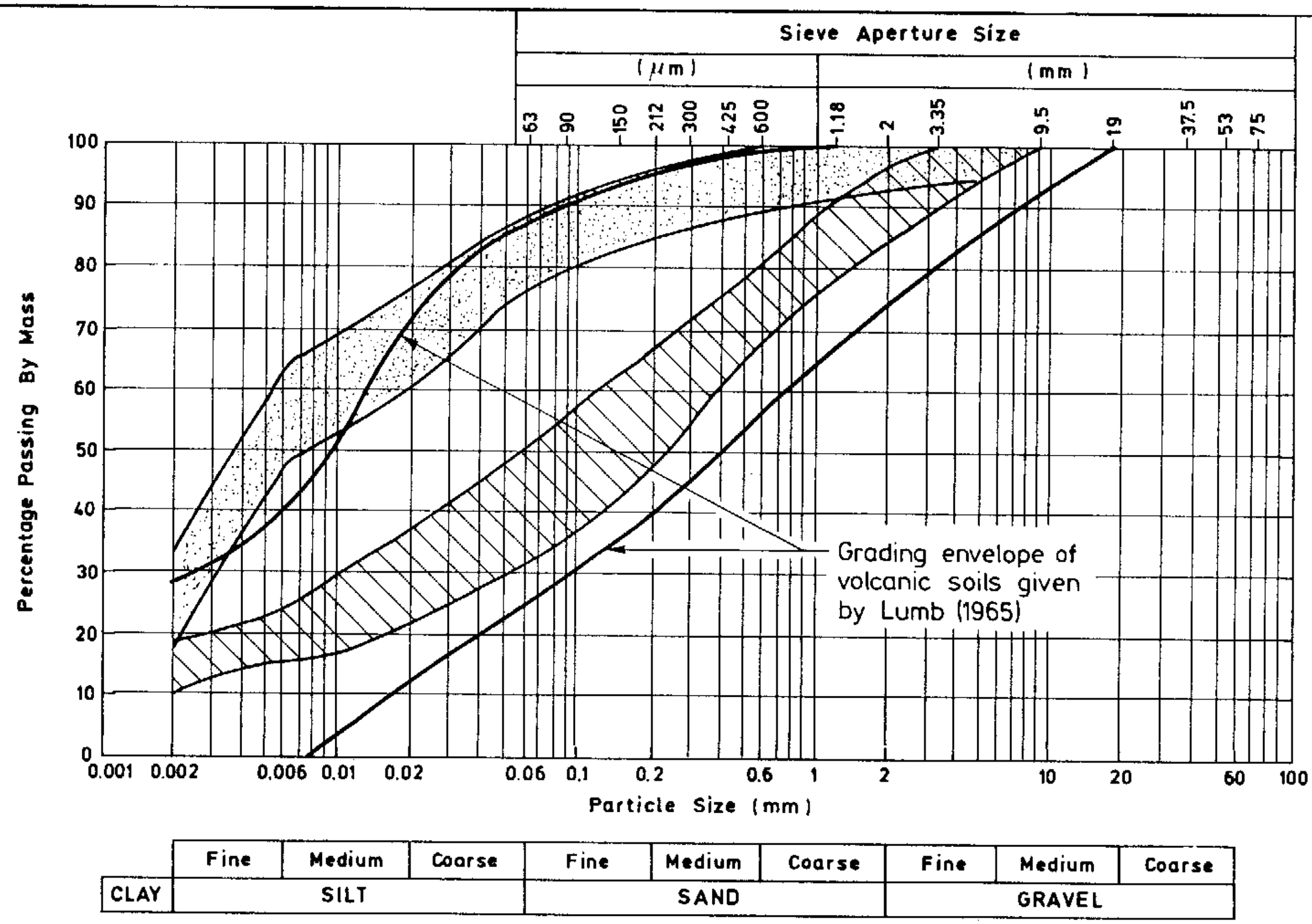
Legend for Grading Envelope :

Shouson Hill granite (Grade V)

King's Park granite (Grade V)

Gleneally granite (Grade IV/V)

Figure 4 - Grading Envelope of Selected Granitic Saprolites

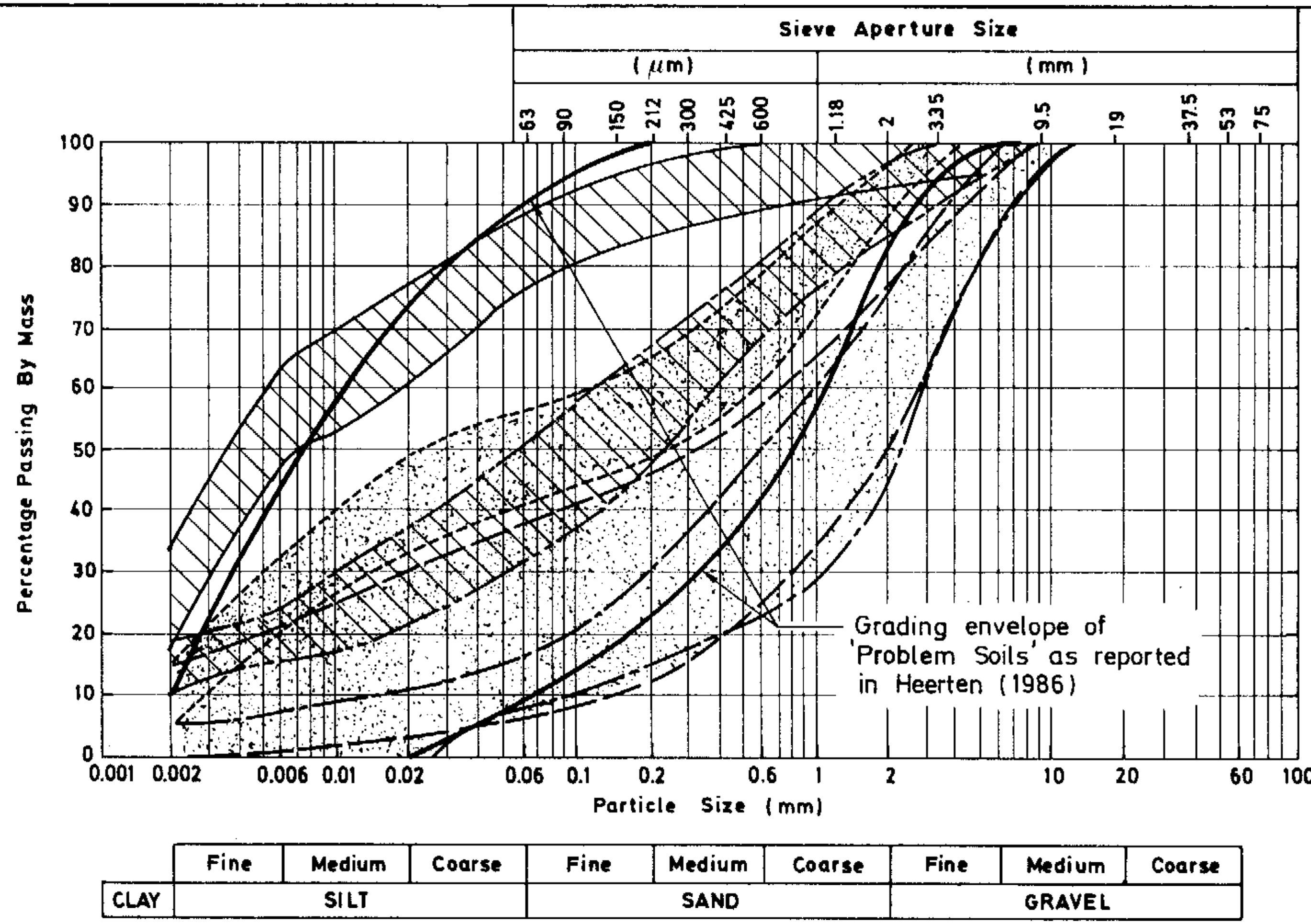


Legend for Grading Envelope :

Po Shan Road slipped material (Grade V) (Government of Hong Kong, 1972)

Volcanic from a borrow area to the north of Tai Po Industrial Estate (Grade IV)

Figure 5 - Grading Envelope of Selected Volcanic Saprolites



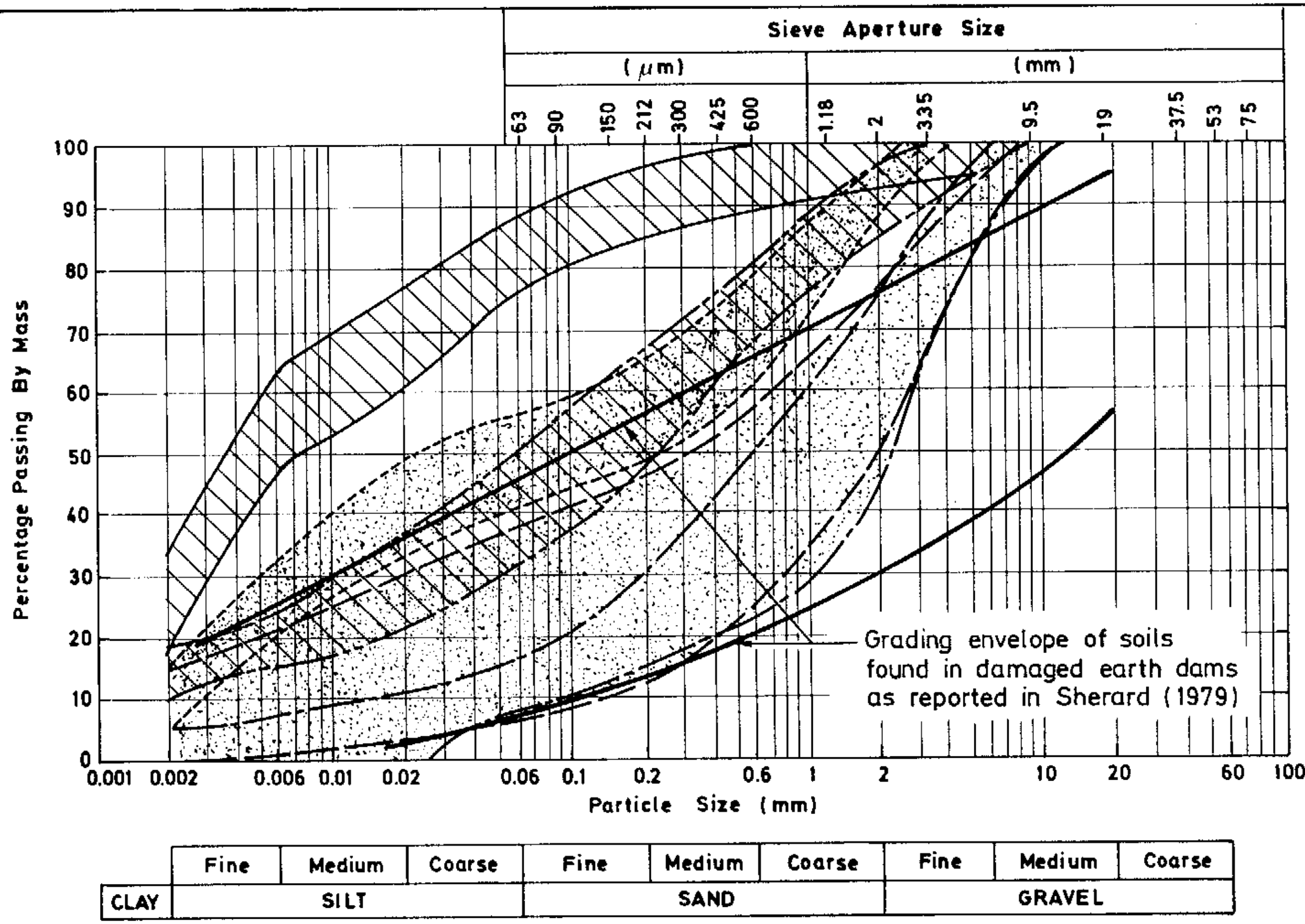
Legend :

Grading envelope of some Hong Kong granitic saprolites

Grading envelope of some Hong Kong volcanic saprolites

Note : Figure based on Heerten (1986) with local data included.

Figure 6 - Grading Envelope of 'Problem Soils' Identified in the Swiss Standard for Filter Materials



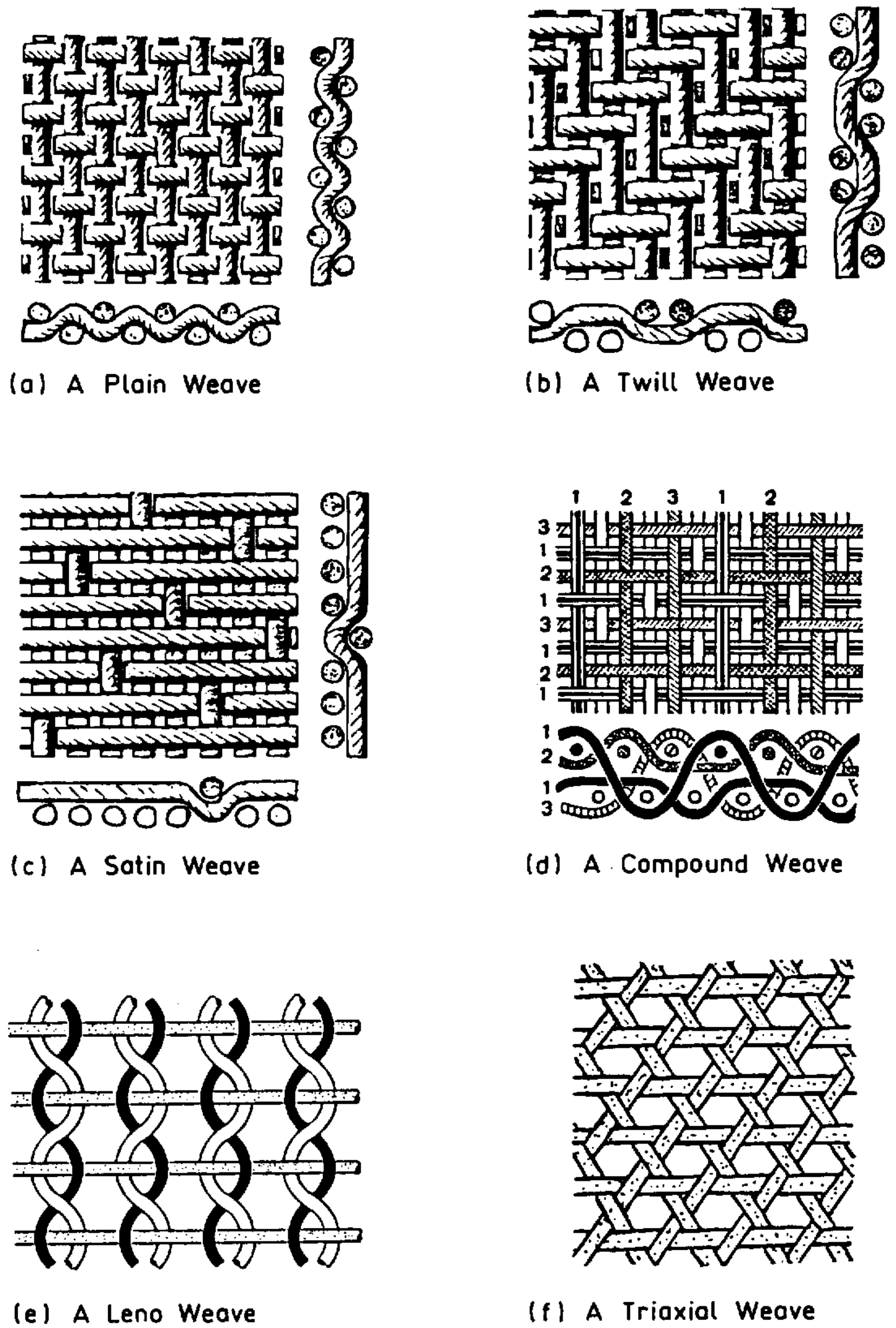
Legend :

Grading envelope of some Hong Komg granitic saprolites

Grading envelope of some Hong Kong volcanic saprolites

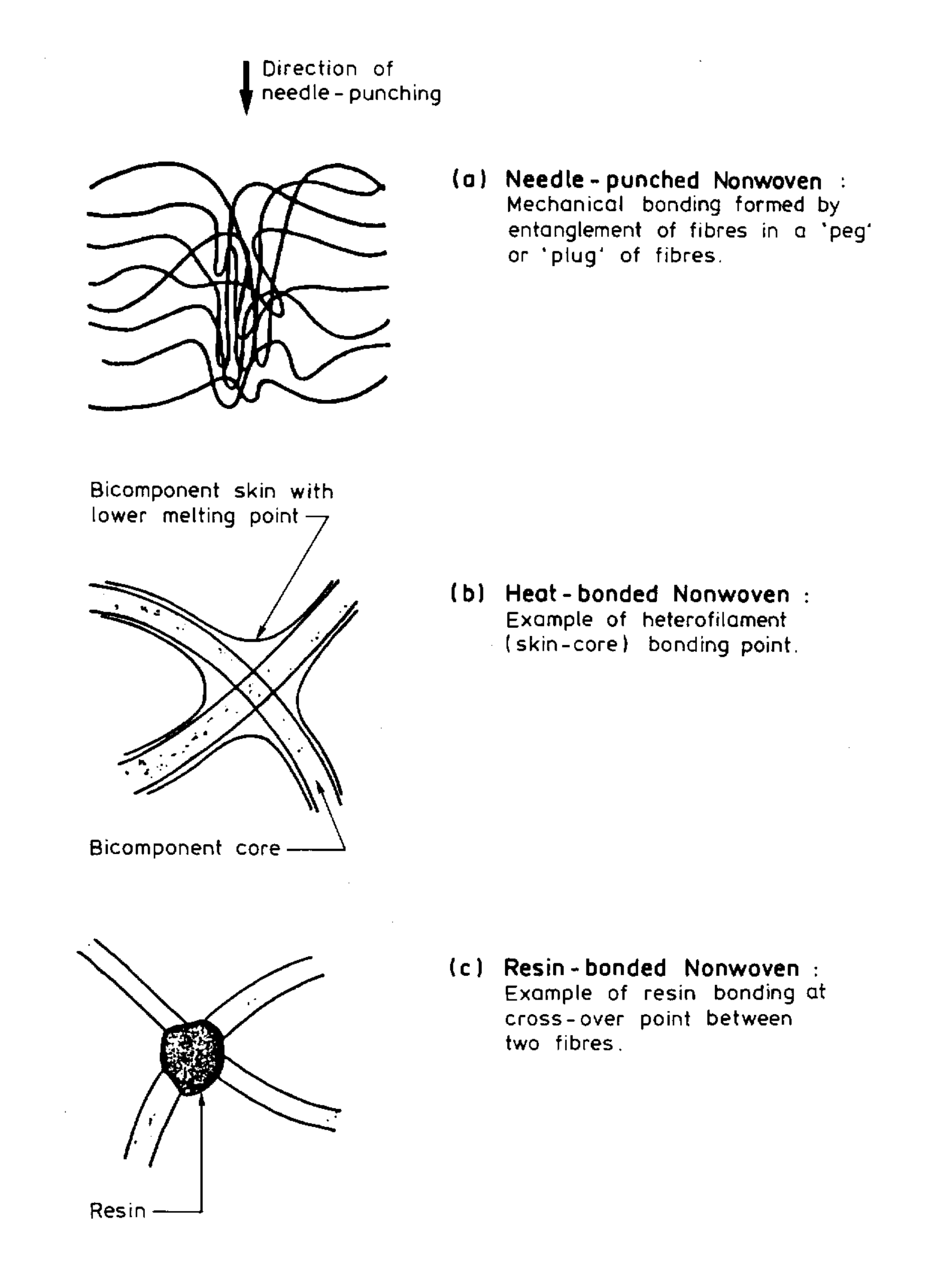
Note : Figure based on Sherard (1979) with local data included.

Figure 7 - Grading Envelope of Coarse Widely-graded Soils Found in Damaged Earth Dams



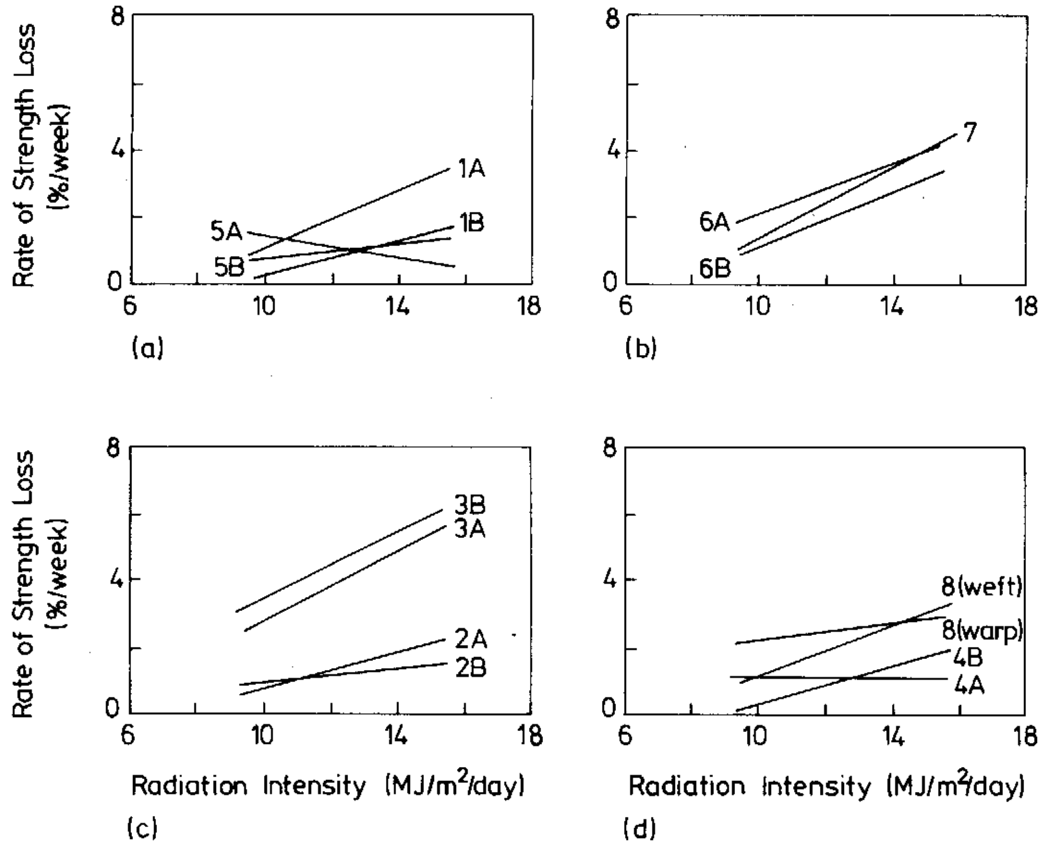
Note : Figure taken from Lawson & Curiskis (1985).

Figure 8 - Schematic Diagrams of Some Woven Fabric Construction



Note : Figure based on Lawson & Curiskis (1985).

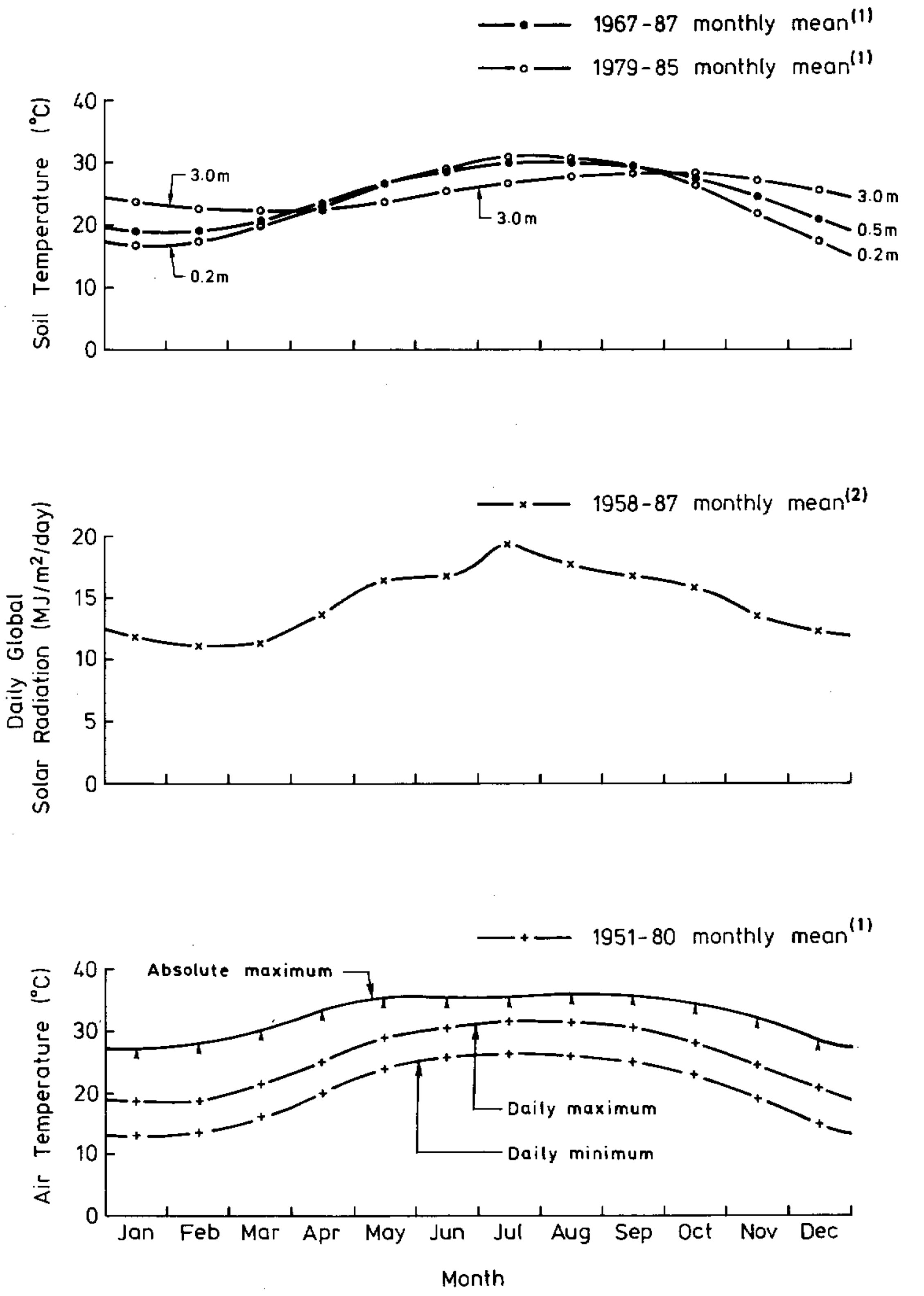
Figure 9 - Schematic Diagrams of Bonding in Various Nonwoven Fabric Construction



Geotextile Code	Trade Name	Trade Code
1A 1B	Bidim	U14 U24
2A 2B	Polyfelt	TS500 TS600
3A 3B	Tafnel	U26 U40
4A 4B	Terram	700/UV 1500/UV
5A 5B	Trevira	T150 T200
6A 6B	Typar	3407 3607-3
7	Lotrak	200
8	Stabilenka	150/45

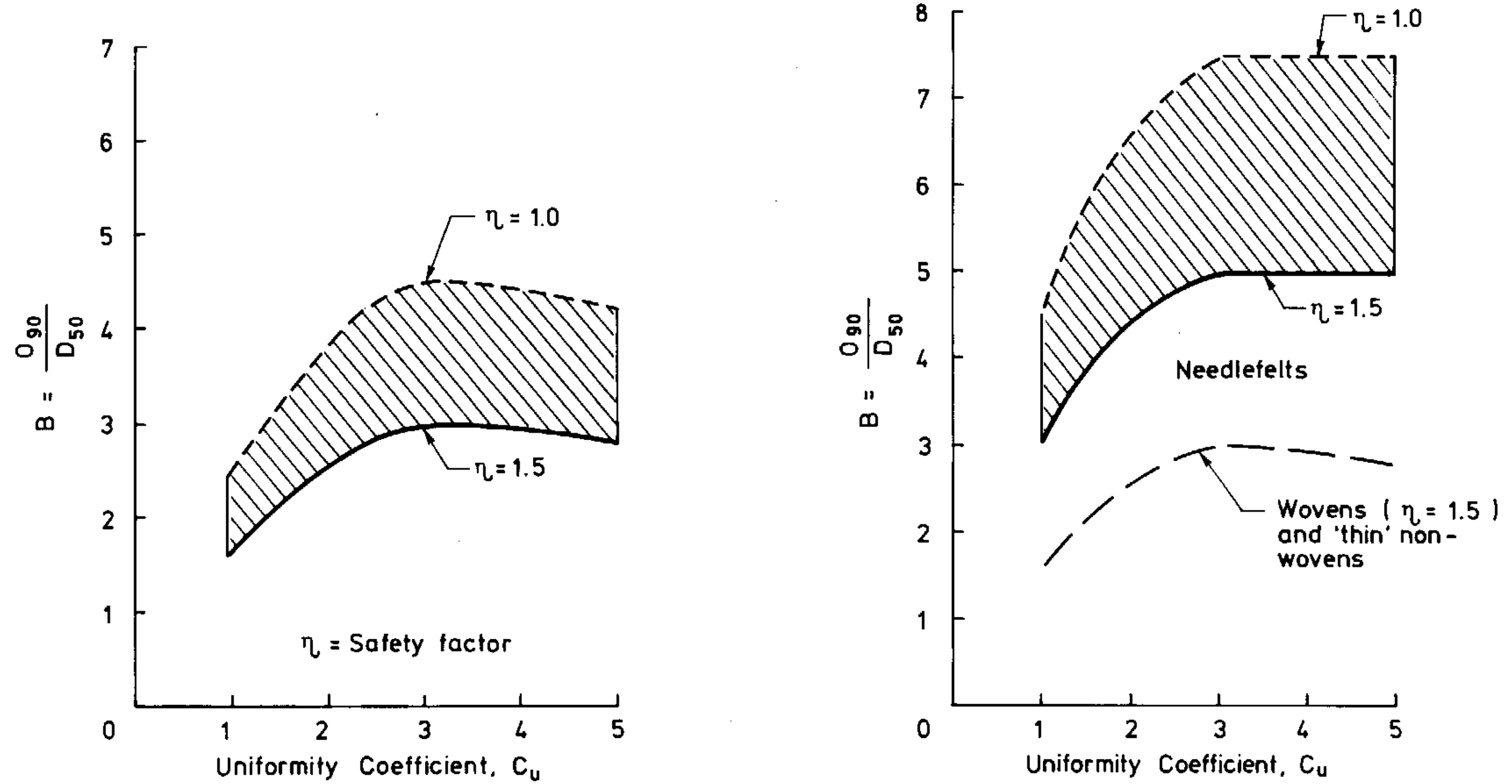
Note : This figure is based on Brand & Pang (1991). For properties of geotextiles, reference should be made to the paper.

Figure 10 - Effect of Polymer Type and Geotextile Construction on Rate of Strength Loss: (a) Needle-Punched Polyester; (b) Heat-Bonded and Wovens—Polypropylenes; (c) Needle-Punched Polypropylenes; (d) Heat-Bonded and Wovens—Other Polymers



Notes : (1) Source station : Royal Observatory headquarters.
(2) Source station : King's Park.

Figure 11 - Soil Temperatures and Meteorological Data Published by the Royal Observatory

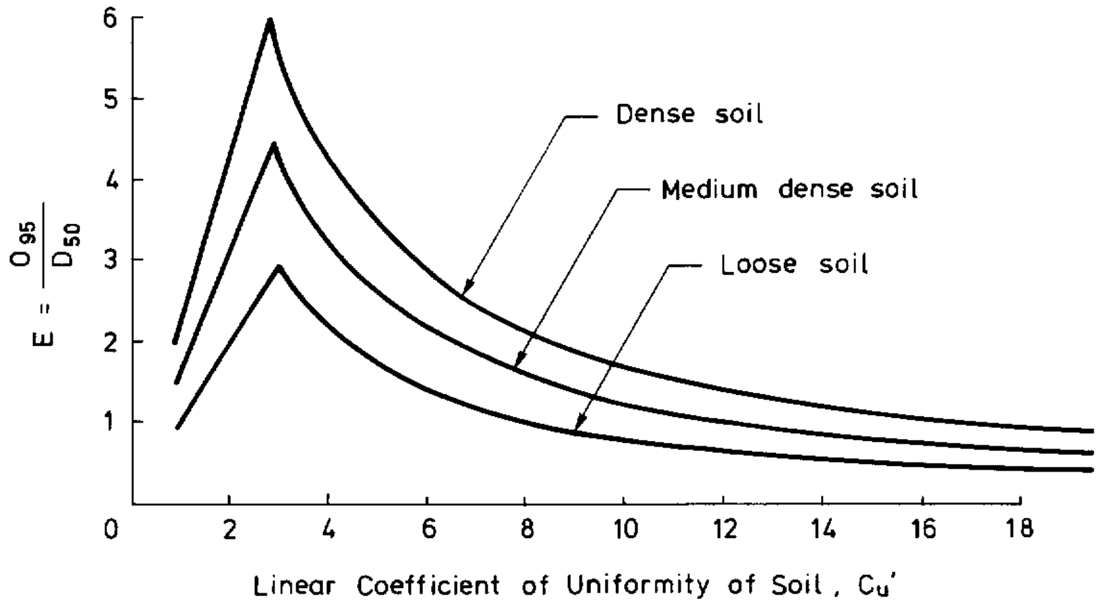


(a) Filter Criterion for Wovens and 'Thin' Nonwovens (Thickness Smaller than 1mm) with Steady Laminar Flow

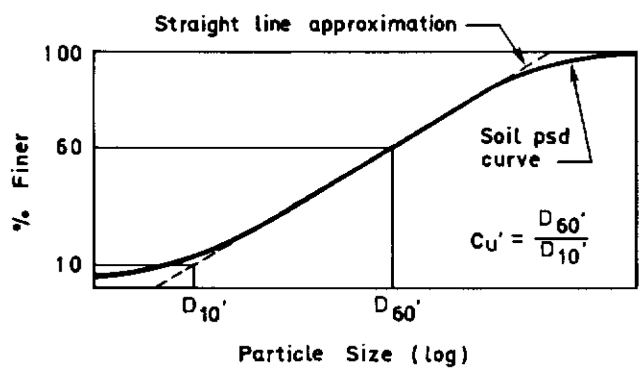
(b) Filter Criterion for Needlefelts (Thickness Greater than 2mm) with Steady Laminar Flow

Note : Figure based on Schober & Teindl (1979). For retention criterion, see Table 10.

Figure 12 - Values of Coefficient B in Schober & Teindl's Retention Criterion

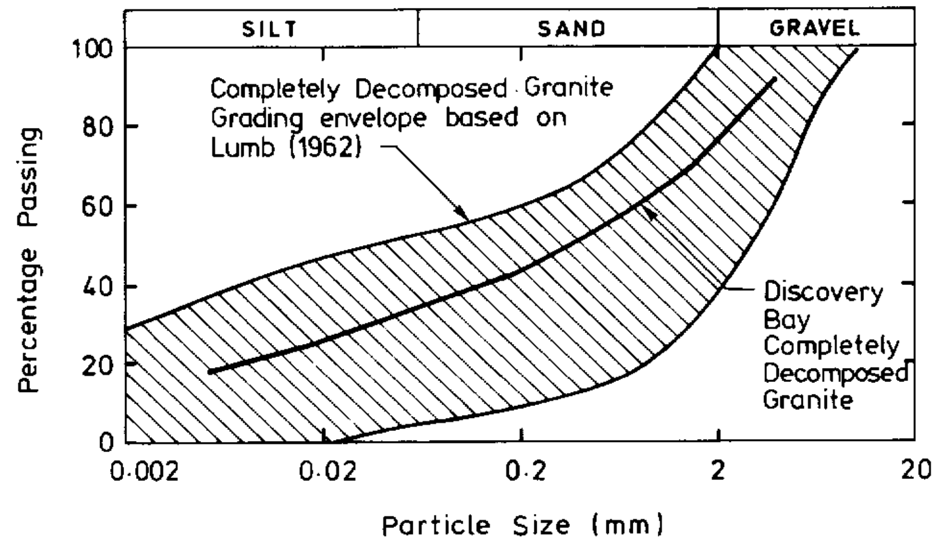


Definition of Linear Coefficient of Uniformity :

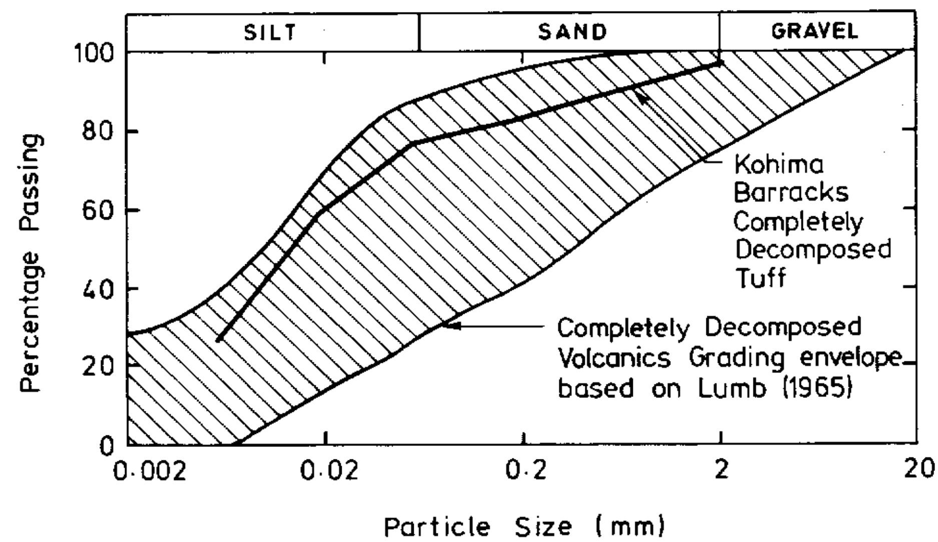


Note : Figure based on Giroud's (1982). For retention criterion, see Table 10.

Figure 13 - Values of Coefficient E in Giroud's Retention Criterion



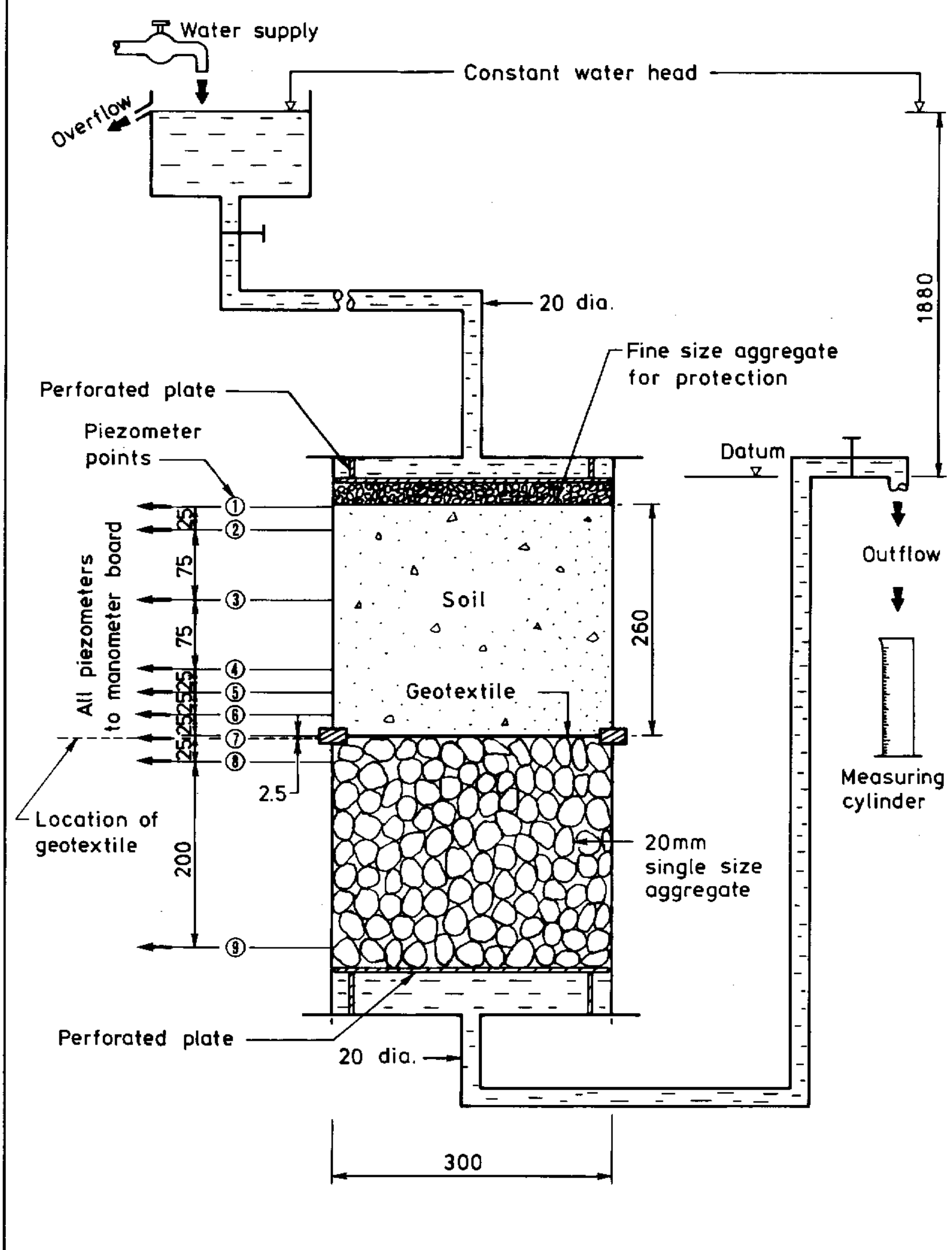
(a) Completely Decomposed Granite from Discovery Bay



(b) Completely Decomposed Tuff from Kohima Barracks

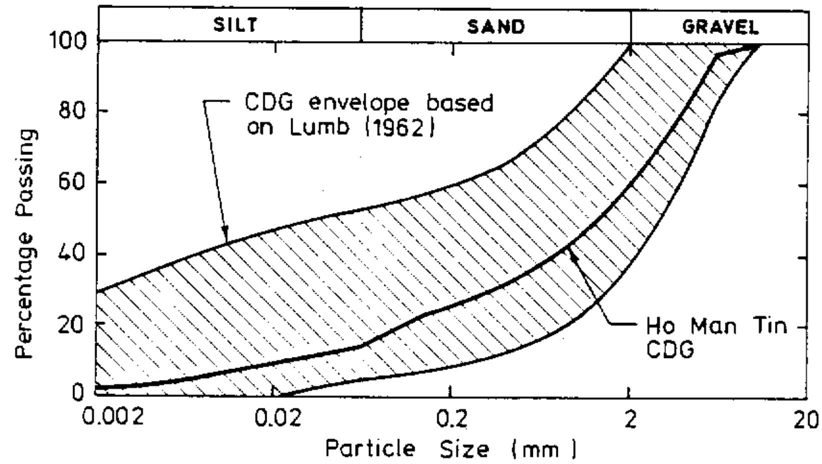
Note : Figure taken from Lawson (1986b).

Figure 14 - Grading Curves of Hong Kong Granitic and Volcanic Saprolites Tested by Lawson

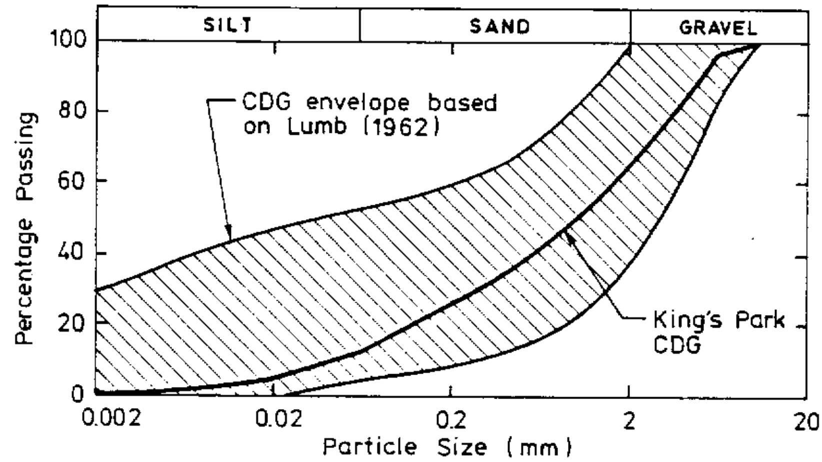


Note : All dimensions are in millimetres.

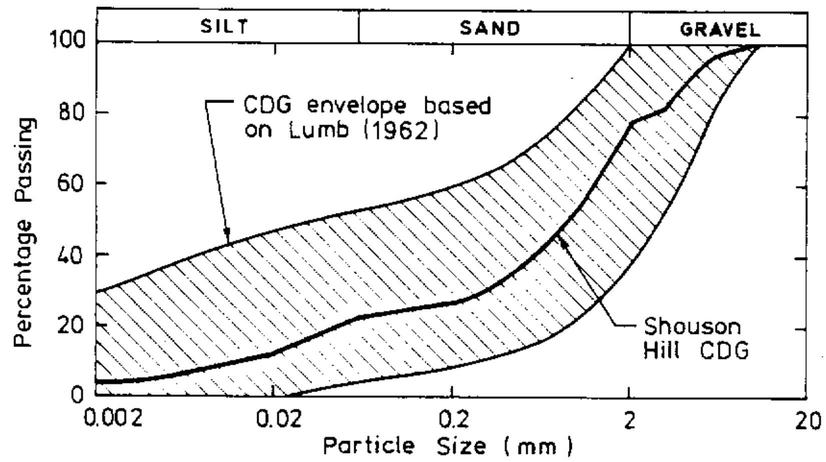
Figure 15 - Schematic Layout of Permeameter for the GEO's Filtration Tests



(a) Completely Decomposed Granite (CDG) from Ho Man Tin



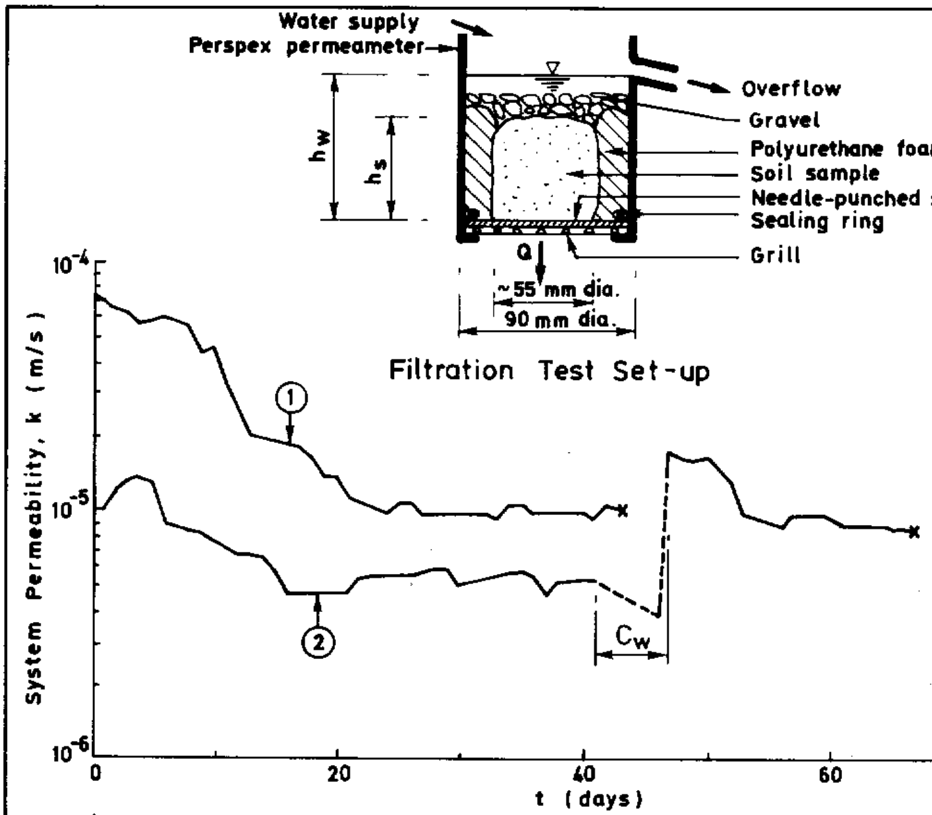
(b) Completely Decomposed Granite (CDG) from King's Park



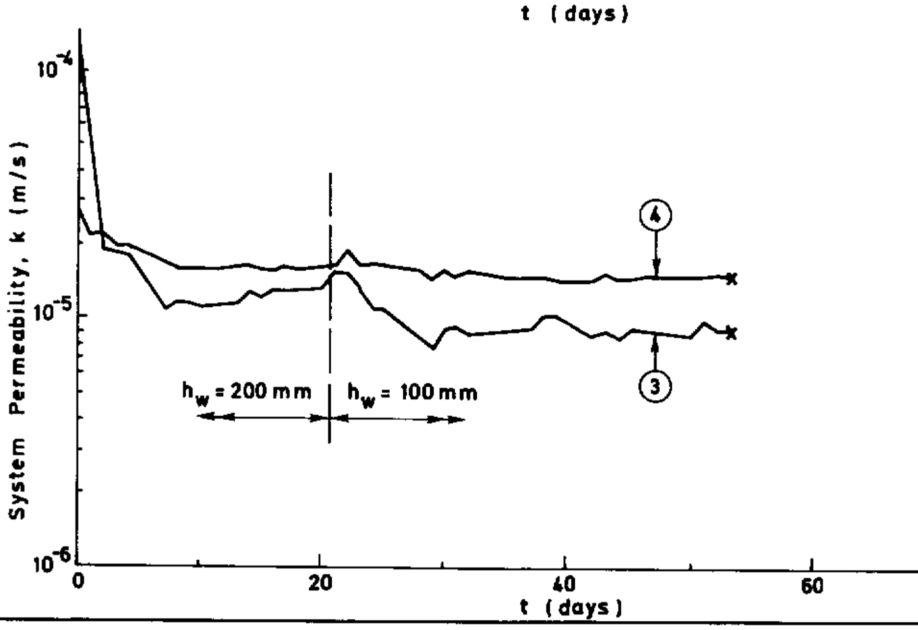
(c) Completely Decomposed Granite (CDG) from Shouson Hill

Note : Grading curves of the granitic saprolites are based on Resl (1988a & b).

Figure 16 - Grading Curves of Hong Kong Granitic Saprolites Tested by a Manufacturer



King's Park CDG		
Test no.	1	2
γ_d (kN/m^3)	14.3	14.1
h_w (mm)	100	100
h_s (mm)	65	60
i	1.54	1.67
T_g (mm)	1.1	2.0
D_w (mm)	0.13	0.11



Ho Man Tin CDG		
Test no.	3	4
γ_d (kN/m^3)	12.9	12.5
h_w (mm)	200 / 100	200 / 100
h_s (mm)	65	65
i	3.08 / 1.54	3.08 / 1.54
T_g (mm)	1.5	1.5
D_w (mm)	0.12	0.12

Legend :

1 Test no. C_w Closure of water supply i Hydraulic gradient = $\frac{h_w}{h_s}$

T_g Thickness of geotextile at 2kPa D_w Geotextile opening size (see Table 6)

Notes :

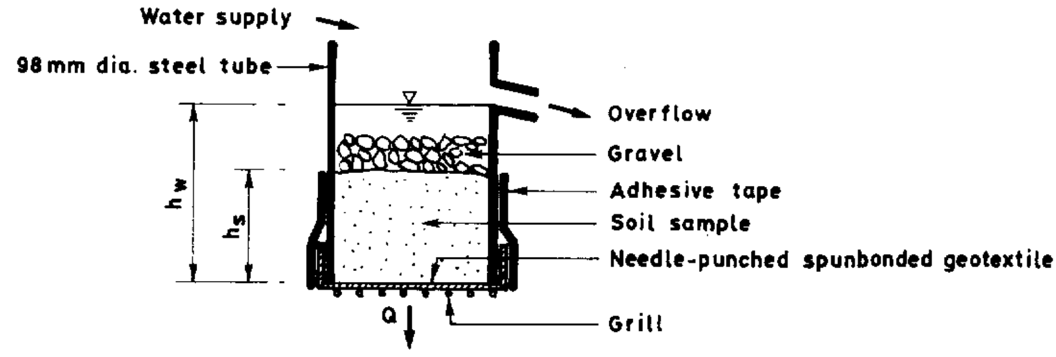
(1) Samples 1 to 3 are 'undisturbed' block samples and sample 4 is remoulded. Grading curves of the two granites are shown in Figure 16(a) and (b).

(2) Samples were soaked for a minimum of 48 hours before testing.

(3) $D_w/D_{85} \approx 0.03$ for all tests.

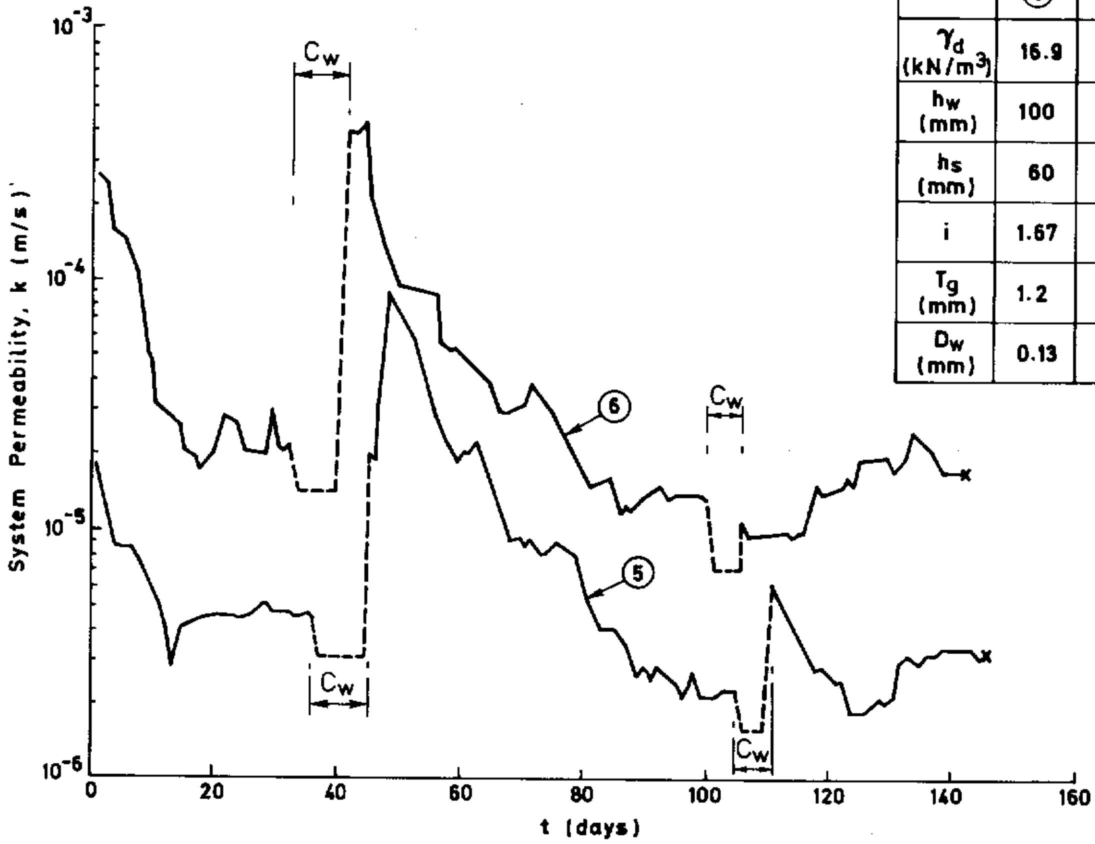
(4) Figure based on Resl (1988a).

Figure 17 - Filtration Test Results on Granitic Saprolites from King's Park and Ho Man Tin



Filtration Test Set-up

Shouson Hill CDG		
Test no.	5	6
γ_d (kN/m³)	16.9	13.5
h_w (mm)	100	100
h_s (mm)	60	60
i	1.67	1.67
T_g (mm)	1.2	1.2
D_w (mm)	0.13	0.13



Legend :

5 Test no. C_w Closure of water supply i Hydraulic gradient $= \frac{h_w}{h_s}$

Notes : (1) Samples 5 to 6 are driven tube samples. Grading curve is shown in Figure 16(c).
(2) Samples were soaked for a minimum of 48 hours before testing.
(3) $D_w/D_{85} \approx 0.036$ for both tests.
(4) Figure based on Resl (1988a).

Figure 18 - Filtration Test Results on a Granitic Saprolites from Shouson Hill

GLOSSARY OF SYMBOLS

GLOSSARY OF SYMBOLS

A	surface area of geotextile through which water flow occurs
A_g	a coefficient for calculating the required permittivity ψ of a geotextile (see Table 14)
A_1, A_2, etc.	parameters for calculating the coefficient A_g (see Table 14)
AOS	apparent opening size of a geotextile (see Table 6)
B	coefficient in retention criteria proposed by Schober & Teindl (1979) and FWHA (see Tables 9 and 13)
C	dimensionless parameter used in permeability expressions (see Table 1)
C_g	a coefficient for calculating the maximum filtration diameter O_f of a geotextile (see Table 14)
C_u	uniformity coefficient of soil ($= D_{60}/D_{10}$)
C_u'	linear uniformity coefficient (see Figure 13)
C_1, C_2, etc.	parameters for calculating the coefficient C_g (see Table 14)
D	diameter of equivalent spherical particle
D_m	the size of sieve (in mm) that allows m% by weight of the material (soil or filter) to pass through
D_mF_c, D_mF_f	the size of sieve (in mm) that allows m% by weight of the filter material to pass through with subscripts c and f denoting the coarse and fine side of the grading envelope respectively
D_mS_c, D_mS_f	the size of sieve (in mm) that allows m% by weight of the base soil material to pass through with subscripts c and f denoting the coarse and fine side of the grading envelope respectively
D_c*	controlling constriction size of the pore network of a filter, i.e. size of the largest particle which can be transported through the filter by water flow
D_p	equivalent diameter of the pores of a filter material
D_w	opening size of geotextile obtained by wet sieving using modified vibratory sieving equipment and a well-graded sand (see Table 6)
d_x, d_y	size of sieve (see Table 1)

EOS	effective opening size of geotextile (see Table 6)
f	angularity factor (see Table 1)
f(n)	a coefficient, expressed in terms of soil porosity, for calculating permeability (see Table 1)
g	acceleration due to gravity (= 9.81 m/s^2)
h_w	net hydrostatic head (see Figures 17 and 18)
h_s	thickness of soil specimen (see Figures 17 and 18)
i	hydraulic gradient
k	coefficient of permeability of soil
k_n	coefficient of permeability normal to the plane of a geotextile
MDD	maximum dry density of compacted soil
MGR	modified gradient ratio (see Section 11.4)
n	soil porosity
n_g	porosity of a geotextile (see Table 8)
O_f	filtration diameter of geotextile (see Table 6)
O_m	opening size of a geotextile measured by testing the particle size at which m% by weight of particles are retained on the geotextile upon dry sieving using "ballotini" (spherical glass beads)
POA	percentage open area of a geotextile (see Table 8)
Q	water flow through geotextile
S	surface area per unit volume of particles
S_i	specific surface of material lying between sieve sizes d_x and d_y (see Table 1)
T_g	thickness of geotextile
t	time in filtration test
VWFR	volume water flow rate of a geotextile (see Table 8)
x_i	percentage of total mass of soil retained between sieve sizes d_x and d_y (see Table 1)

α	a coefficient in the modified Darcy's law to describe water flow through geotextile (see Table 8)
ψ	permittivity of a geotextile (see Table 8)
δh	differential hydraulic head across geotextile
$\frac{\delta h}{\delta x}$	hydraulic gradient through geotextile
$\frac{\delta Q}{\delta t}$	rate of flow of water through geotextile
γ_d	dry density of soil
μ	viscosity of water (= 0.0131 poise at 10°C)
η	safety factor (see Figure 12)
ϕ'	angle of shearing resistance of soil in terms of effective stress