ADVANCED SOIL MECHANICS .

REPORT ABOUT:

EFFECTIVE OF GRAIN SIZE AND SHAPE ON FILTER DESIGN

PREPARED BY

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Contents

LIST OF SYMBOLS

D = Particle diameter

Y = unit weight of matrials or

B = Base

Db = diameter of base matrial.

Df = diameter of filter matrial

F = The flow forces act in the flow direction.

Ɣw = is the unit weight of the water,

K = as defined by the permeability coefficient.

F = Filter (first stage)

D15F =   Particle diameter at 15%passing for a one-stage filter.

K = Hydraulic conductivity (soil permeability to water)

. i = Gradient, the ratio of head loss over the distance (length) that head loss occurs: (Δh/Δl)

D85 = The particle size diameter in millimeters of 85th percentile passing grain size

D85B = The particle size diameter in millimeters of 85th percentile passing grain size of the base soil

A = The percentage of soil passing the No. 200 sieve, fines content.

D15F = The particle size diameter in millimeters of 15th percentile passing grain size of the filter

D15B = The particle size diameter in millimeters of 15th percentile passing grain size of the base soil

Cu = Coefficient of uniformity, as determined from a grain size analysis, equal to the ratios D60/D10 ,where D60and D10are the particle diameters corresponding to 60 and 10% finer on the cumulative gradation curve, respectively

Cc = Standard symbol for coefficient of curvature, replaced in this manual with the symbol analysis, calculated from the relationship:

Cz = D302/(D60* D10)FEMA .

Where D60, D30, and D10are the particle diameters corresponding to 60, 30, and 10%finer on the cumulative gradation curve, respectively.

D60 = The particle size diameter in millimeters of the 60th percentile passing grain size

D10 = The particle size diameter in millimeters of the 10th percentile passing grain size

ABSTRACT

Many existing dams have filters which do not satisfy modem design Criteria, being too coarse by design or having segregated during construction. In the review of the safety of these structures, it is necessary to evaluate the likelihood of damages to the dam in the event of piping developing in the core of the dam, potentially leading to failure (breaching) of the dam[2]. The presence of water has a major influence on the design of soil structures as it reduces the effective stresses and hence shear resistance, and applies seepage forces in case of flow. This key topic is well known to every geotechnical engineer and the design principle for soil structure is to drain groundwater, infiltrated surface water or seepage water in a controlled manner from the soil. However, for soil structures whose purpose is to retain water, such as embankment dams impounding a reservoir, or dikes for flood protection along rivers and channels, both sealing and draining have to be ensured by the structures. With simple construction measures such as filter and drainage zones incorporated in earth structures composed of selected and treated materials, the stability and safety of these structures can be improved considerably. This paper discusses seepage control measures as well as the selection and design of appropriate filter materials [3].

1. Introduction

Between 1980 and 1985, the Soil Conservation Service (SCS), now known as the Natural Resources Conservation Service (NRCS), performed an extensive study to determine appropriate gradation criteria for sand filters to be used for filter/drainage zones in embankment dams. The study was performed at the NRCS Soil Mechanics Laboratory in Lincoln, Nebraska with the assistance of the late James L. Sherard, eminent earth dam consultant. The study included a large number of tests simulating cracks or other anomalies in dams with the potential for developing concentrated leaks under high water pressure. Filters with varying gradations were placed downstream of a simulated core material containing simulated cracks to determine the gradation necessary to prevent movement of base materials through the filter and to provide a self- healing condition. Self-healing is defined as the ability to seal cracks and stop the development of concentrated leaks and internal erosion. A large variety of materials were used to simulate the base soil of the dam upstream of the filter/drainage zone. Specific testing was performed to verily the properties of the filter that determine its ability to prevent the base or protected soil from passing through it for use in designing filter gradations. These properties included the ratio of particle size at 15 percent passing of the filter to the particle size at 85 percent passing of the base soil, uniformity of the filter gradation, and other factors influencing segregation, permeability, and grading of the filter.Filters have been recognized as a means of controlling the erosion problem due to seepage discharge through embankments, dam foundations and other hydraulic structures and to allow the passage of seepage water through these structures safely i.e. without the migration of base soil. For developing suitable criteria for designing a protective filter which meets the above requirements, there have been several attempts. Most of these attempts are based on or guided by the empirical relations evolved by Terzaghi (1961). Traditionally, the design criteria for soil filters are empirical based and are expressed in terms of certain ratios of the sizes of base soil particles and the filter particles, which vary over wide ranges in different cases (Betram, 1940; Sherman, 1953; USBR, 1987; Sherard, 1984; NRCS, 1994). The general objectives of these criteria were to ensure that the filter material prevent migration of the base soil particles and possesses adequate permeability for free flow of seepage water. Subsequently, several mechanistic models have been developed to predict particle migration and entrapment (Honjo and Veneziano, 1989; Aberg, 1993; Indraratna and Vafai 1997; Locke et al., 2001). In most of the cases, the treatment of the filtration phenomenon qualitatively and quantitatively has often been based on empiricism, not taking into account the real physics of , the phenomenon because of difficulty in describing the porous media. The literature reveals that the researchers have a strong feeling about the inherent discrepancies in all the existing criteria. [1] .

One of the primary functions of the filter downstream of the core is to prevent the development of piping through the dam in the event of a concentrated leak through the core. The good performance of dams with filters designed in accordance with modern design criteria have proven that these filters are capable of reliably sealing **concentrated** leaks (Sherard and Dunnigan, 1989; Peck 1990). However, many existing dams have filters that do not satisfy these criteria, teing too coarse by design or having segregated during construction. In the review of the safety of these structures, it is necessary to evaluate the likelihood of damages to the dam in the event of piping developing in the core of the dam, potentially leading to failure (breaching) of the dam. The main issues of concern in these circumstances are:

(i) If a concentrated leak forms through the core of the dam, will the filter prevent continuing erosion of the core material (i.e. will the leak be eventually sealed by the filter)

(ii) How much erosion of the core material is required for **the** filter to seal the leak and can this be tolerated? Since the 1920s there have been numerous experimental and theoretical studies into the development of filter criteria for the design of dams. Despite this, there is little guidance in the literature on the assessment of filters of existing dams, particularly for the situation where filters do not meet current criteria.

Modern design criteria are based on laboratory tests that simulate a crack in the core of a dam exiting into the downstream filter. One of the most widely used criteria are those recommended by Sherard and Dunnigan (1989). This criteria is based on the results of the No Erosion Filter (IF) test which allows no visible erosion of a Imm diameter hole through the base specimen.(2-A) ..The design of filters for embankment dams in Japan is based on the criteria used throughout the world (JANCOLD, 1971, MOC, 1985) including the following rule; Filters should not contain more than about 5% of fines passing a #200 (0.074mm) sieve, and the fines should be cohesionless. Recently in Japan, we have much trouble in meeting this regulation economically. However, systematic research on identification of filter cohesion has not been made yet. In such present condition, the applicability of the Sand Castle test (SC test) proposed by Vaughan (Vaughan, 1978, Vaughan and Soares, 1982) is examined as a testing method of identifying the non-cohesion of filter materials..[2] Soils are composed of single particles. The loads are transferred at the particle contacts with normal and shear forces1. The maximum shear force which can be transferred at the particle contact is proportional to the effective normal force at the contact, as defined by the total inter particle force and the pore water pressure, should the soil be saturated. The porewater pressures can correspond to the (a) hydrostatic head, should the soil skeleton be submerged, or (b) to an excess pressure which exceeds the hydrostatic head. Excess pressures develop for example (a) in loose deposits of low permeable granular soils, such as silts and fine sands, during an earthquake event (see e.g. Messerklinger et al., 2011a) or (b) by the application of an external load, e.g. during construction work, on compressible and low permeable soils such as clays and silts. Summarizing: The water of a submerged soil skeleton reduces the effective interparticle forces and hence the shear resistance of the soil. If the water in the soil skeleton is flowing with a velocity (v) at a hydraulic gradient (i), forces due to water flow are applied on the soil particles. These flow forces on the soil particles act in addition to the pore water pressures. The flow forces (F) act in the flow direction. Their magnitude is $F=i\cdot\gamma w\cdot A$ where γw is the unit weight of the water and A is the cross-sectional area (in flow direction) of the soil body the water is flowing through. This is the average force on a soil body due to water flow at a hydraulic gradient of i. However, the flow forces acting on a single particle vary significantly. The flow velocity of the water in the pore space depends on the pore diameter and increases approximately with the square of the pore diameter. If the pore diameter changes, the pore flow velocity will also change. However, in permeability tests only the overall soil permeability, as defined by the permeability coefficient (k), is determined. Summarizing: In case a hydraulic gradient is applied to the water in a submerged soil skeleton, the water will flow around the single particles, which applies flow forces in flow direction. These flow forces depend on the hydraulic gradient and are independent of the volume of water flowing through the soil.[3] Design of soil filters and drainage layers is a crucial element governing the stability and performance of subsurface infrastructure in geotechnical and geo environmental engineering. The motivation for earlier studies on filter design (Bertram 1940; Lund 1949; U.S. Bureau 1955) was primarily the protection of base soils from erosion and the stability of structures such as earth dams and retaining structures. Many studies during the recent decades were fueled by unending revelations of dam failures associated with inadequate filter design (Vaughan and Soares 1982; Von Thun 1985; Peck 1990; Vick 1996). Reddi and Bonala (1998) and ICOLD (1994) documented the state of the art in filter design. In general, current practice in filter design is largely based on a comparison of the particle sizes of the soil filter and the base soil. The existing literature documented the general validity of this approach (Sherard et al. 1984a,b; Honjo and Veneziano 1989; Indraratna and Vafai 1997) for the problems where stability of the base soils is of primary concern. However, when soil filters are also expected to serve as drainage layers such as in the case of a pavement drainage layer or a leachate collection system underneath a landfill, the permeability changes of the soils become important. Soil filters might be successful in preventing the erosion of base soils, but they might undergo significant reductions in permeability as a result of progressive fine particle entrapment [4].

2. Shape of Filter Design

Six aspects are considered to the design of state-of-the-art filter materials which includes; filter ability, internal stability, self healing, material segregation, drainage capacity, and material durability.

2.1 Filter ability

With the identification of effective stresses in soils by Terzaghi and his co-workers in the early thirties of the last century, (Terzaghi 1936) a new era in soil mechanical engineering was initiated. This was the time when the effects of water on soil were investigated in depth, and resulted in the development of the consolidation theory (Terzaghi & Fröhlich 1936). At the same time, Bertram (1940) proposed the criterion D15filter/d85base soil ≤ 6 for soil filters based on laboratory investigations. This filter criterion was later modified to D15coarse-side filter/d85fine-side base soil ≤ 4 and a drainage criterion of D15fine-side filter/d85coarse-side base soil ≥ 4 was added by Terzaghi and Peck (1948), (Fig.1).

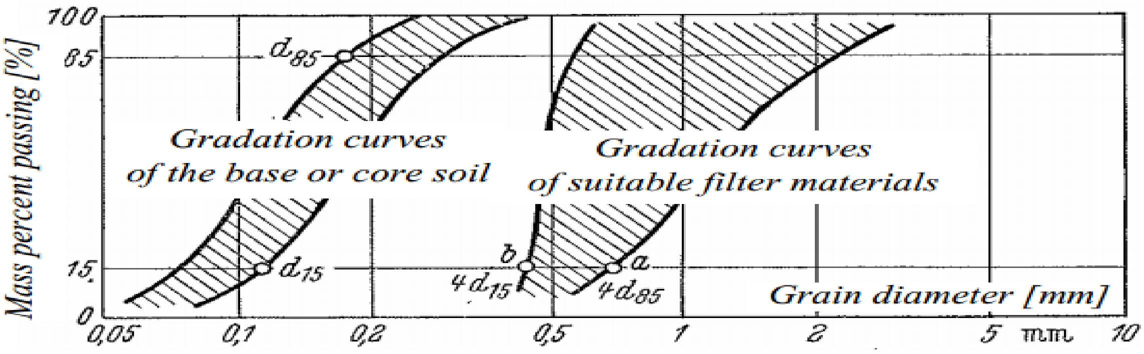


Figure 1: Filter and drainage criteria from Terzaghi & Peck (1948).

The filter design was reconsidered after incidents at and failures of major dam structures. E.g. after the Balderhead dam incident, where core material was eroded from an open fracture in the core zone into the filter material so causing sinkholes at the dam crest (Vaughan et al. 1970), Peter Vaughan and his coworkers searched for what they called the "perfect filter". The idea was to hold back the smallest grain of a core material even under severe conditions such as concentrated seepage flow at high hydraulic gradients through e.g. a crack in the core. The approach towards the criterion was not via the gradation curve, such as adopted before by Terzaghi and his co-workers, but by the permeability coefficient of the filter material. Vaughan believed that *"..effectiveness of a filter may be defined by its permeability with more generality than by its grading.*" (Vaughan & Soares 1982, p.17). They proposed a linear correlation between the permeability coefficient (k in m/s) and the filtered particle diameter of k = 6.1E-6 · δ1.42 (δ in µm, Note: The particle size of clays with flocculated structure is the floc-size.). At the same time, James Sherard was investigating the cracking and failure of embankment dams built in the United States (Casagrande 1950, Sherard et al. 1963, Bertram 1967). In 1973 he wrote (p. 272): *"... at present it is well known that cracks have developed in the impervious sections of many dams ...*". He identified that the cracking was mainly caused by differential settlement of homogenous clay dams or by hydraulic fracturing of the core material due to the water pressure after impounding of the reservoir. Numerous filter tests were performed (Sherard et al. 1984a), and based on the slot test data (Sherard at el 1984b) four soil categories with four individual filter criteria were identified:

1.) Sandy silts and clays (d85b: 0.1-0.5 mm): D15f/d85b ≤ 5

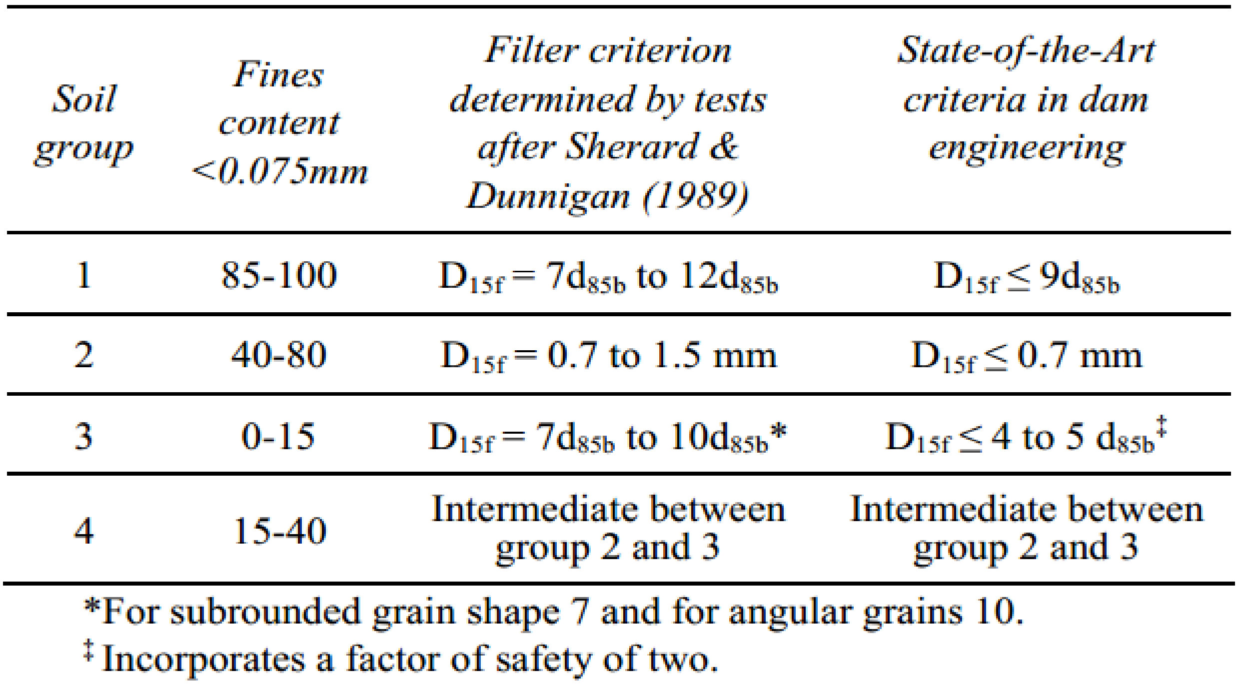
2.) Fine-grained clays (d85b: 0.03-0.1 mm): D15f ≤ 0.5 mm

3.) Fine-grained silts (d85b: 0.03-0.1 mm): D15f ≤ 0.3 mm

4.) Exceptionally fine soils (d85b < 0.02 mm): D15f ≤ 0.2 mm

With the non-erosion filter test the filter criteria were further developed and termed criteria for "critical filter" (Sherard & Dunnigan 1985, 1989) as distinct from the "perfect filter" discussed above. For the critical filters four categories were defined based on the fines content (<0.075 mm, sieve 200) of the base soil (or core material). The fines content was determined on a gradation curve with a maximum grain diameter of 4.75 mm (sieve 4). For base soils with a maximum grain size exceeding 4.75 mm, the gradation curve was regraded to ≤4.75 mm in order to determine whether the base soil falls into category 1, 2 or 4. Whether the base soil falls into category 3 was determined on the original, non-regraded curve. For each of the 4 categories a filter criterion was defined (Tab. 1).

Table 1. Filter criteria.



Soil group	*Fines content <0.075mm*	*Filter criterion determined by tests after Sherard & Dunnigan (1989)*	*State-of-the-Art criteria in dam engineering*
1	85-100	$D_{15f} = 7d_{85b}$ to $12d_{85b}$	$D_{15f} \leq 9d_{85b}$
2	40-80	$D_{15f} = 0.7$ to 1.5 mm	$D_{15f} \leq 0.7$ mm
3	0-15	$D_{15f} = 7d_{85b}$ to $10d_{85b}$*	$D_{15f} \leq 4$ to $5\ d_{85b}$‡
4	15-40	Intermediate between group 2 and 3	Intermediate between group 2 and 3

*For subrounded grain shape 7 and for angular grains 10.

‡ Incorporates a factor of safety of two.

2.2 Internal stability

For filter materials to be internally stable means that within the soil skeleton the small particles do not move due to water flow forces. All soil particles should remain at their position even for water flow at high (>1) hydraulic gradients such as occur at a fracture in the sealing zone of an embankment. A good definition of internal stability is given e.g. by Kenney & Lau (1985): “Internal stability of granular material results from its ability to prevent loss of its own small particles due to disturbing forces such as seepage and vibration.”. Concerning the formation of sinkholes at the crest of zoned embankment dams, James Sherard (1979) studied the phenomenon and recommended use of a method proposed by Prof. Victor de Mello (1975) for the investigation of gap-graded soils, in order to assess the internal stability of filter materials. In this method, which is also called “retention ratio criterion”, the gradation curve of the filter material is divided into two curves at a selected grain diameter (dS), gradation curves for the portions finer and coarser than dS, respectively. For the two gradation curves the retention ratio (RR) is calculated from the Terzaghi filter criterion: RR = D15f/d85b. This is repeated for different values of dS. All grains are considered to be stable if they satisfy the criterion RR ≤ 7÷8 for subrounded grains or RR ≤ 9÷10 for angular grains. The grain diameters (dS) for which the retention ratio exceeds the given limits are potentially unstable and can be eroded by the water flow.

2.3 Self healing

Self-healing means that cracks which can form in the filter zone due to e.g. differential settlement, etc. do not stay open but close in case of water flow. Hence, the filter material must not have cohesion. This is assured by limiting the content of non-plastic (IP<5%) fines to less than 5% (the latest ICOLD Bulletin on CFRD’s, No. 141, allows 7% of fines). The sand-castle test (Vaughan & Soares 1982), confirms that the selected filter material meets the self-healing requirements. 2.4 Material segregation When the filter material segregates, meaning that the coarser particles separate from the finer particles, the filter zone can no longer fulfill its purpose of preventing fine particles moving from the core to the filter zone or within the filter zone, because the segregated coarse grained components do not form a filter to the adjacent materials. Hence, the segregation of filter materials has to be avoided. Whether a material segregates depends on the handling and placement methods and on the gradation of the material.

2.3 Drainage Capacity

The Terzaghi criterion D15f/d85b ≥ 4 still applies and Sherard recommends D15f ≥ 0.2 mm. Casagrande, A. 1950. Notes on the Design of Earth Dams. J. Boston Soc. Civil Eng. Oct. 1950, Vol. 37. DeMello, F. 1975. Some lessons from unsuspected, real and factitious problems in earth dam engineering in Brazil. 6th Regional Conf. on Soil Mech. & Found. Eng., South Africa (11).

2.6 Material durability

The durability of filter materials is typically investigated with standard tests such as the Los Angeles abrasion test (ASTM C535) or the wet and dry strength variation (typical limit ≤35%). However, for important dam structures a mineralogical and chemical investigation of the dam material is recommended. This can highlight if the material has inclusions of (i) swelling clay minerals or (ii) minerals which dissolve in water, e.g. gypsum or carbonate rocks. Latter materials cannot just dissolve but also re-cement at the particle contacts and create true cohesion. Materials with carbonate and sulphide content should be used with care for dam filter materials . [3]

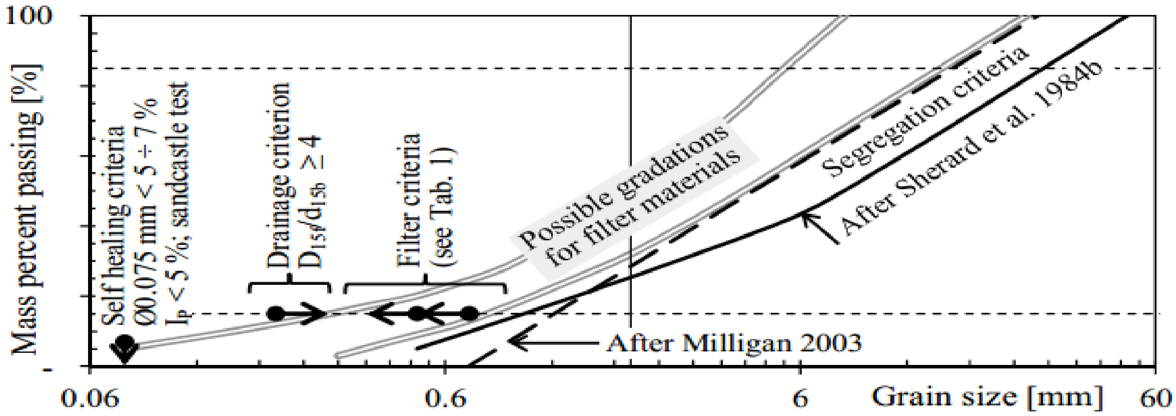


Figure 2: Summary of filter criteria.

3. Size of Filter Design

Filters used to control seepage must satisfy certain fundamental requirements. The pores must be small enough to prevent particles from being carried in from the adjacent soil. The permeability must simultaneously be high enough to ensure the free drainage of water entering the filter. The capacity of a filter should be such that it does not become fully saturated. In the case of an embankment dam, a filter placed downstream from the core should be capable of controlling and sealing any leak which develops through the core as a result of internal erosion. The filter must also remain stable under the abnormally high hydraulic gradient which is liable to develop adjacent to such a leak. Based on extensive laboratory tests by Sherard et al. (1984a, 1984b) and on design experience, it has been shown that filter performance can be related to the size D15 obtained from the particle size distribution curve of the filter material. Average pore size, which is largely governed by the smaller particles in the filter, is well represented by D15. A filter of uniform grading will trap all particles larger than around 0.11D15; particles smaller than this size will be carried through the filter in suspension in the seeping water. The characteristics of the adjacent soil, in respect of its retention by the filter, can be represented by the size D85 for that soil. The following criterion has been recommended for satisfactory filter performance:

$$\frac{(D_{15})_f}{(D_{85})_s} < 5$$

where (D15)f and (D85)s refer to the filter and the adjacent (upstream) soil, respectively. However, in the case of filters for fine soils the following limit is recommended for the filter material:

$$D_{15} \leq 0.5\,\text{mm}$$

Care must be taken to avoid segregation of the component particles of the filter during construction. To ensure that the permeability of the filter is high enough to allow free drainage, it is recommended that

$$\frac{(D_{15})_f}{(D_{15})_s} > 5$$

Graded filters comprising two (or more) layers with different gradings can also be used, the finer layer being on the upstream side..(B-1)

For example, consider the earth dam section shown in Figure 7.23. If rockfills were only used at the toe of the dam, the seepage water would wash the fine soil grains into the toe and undermine the structure. Hence,

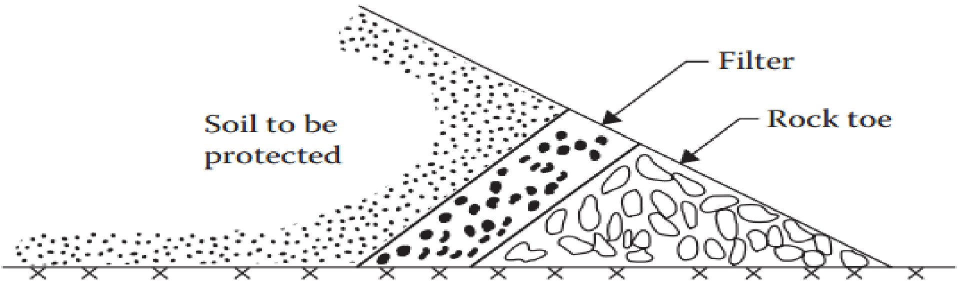


Figure 7.23 Use of filter at the toe of an earth dam.

For the safety of the structure, a filter should be placed between the fine soil and the rock toe (Figure 7.23). For the proper selection of the filter material, two conditions should be kept in mind:

1. The size of the voids in the filter material should be small enough to hold the larger particles of the protected material in place.

2. The filter material should have a high permeability to prevent build up of large seepage forces and hydrostatic pressures.

Based on the experimental investigation of protective filters, Terzaghi and Peck (1948) provided the following criteria to satisfy the above conditions:

$$\frac{D_{15(F)}}{D_{85(B)}} \leq 4-5 \quad \text{(to satisfy condition 1)}$$

$$\frac{D_{15(F)}}{D_{15(B)}} \geq 4-5 \quad \text{(to satisfy condition 2)}$$

where

D15(F) is the diameter through which 15% of filter material will pass

D15(B) is the diameter through which 15% of soil to be protected will pass

D85(B) is the diameter through which 85% of soil to be protected will pass

To determine the grain-size distribution of soils used as filters is shown in Figure 7.24.

Consider the soil

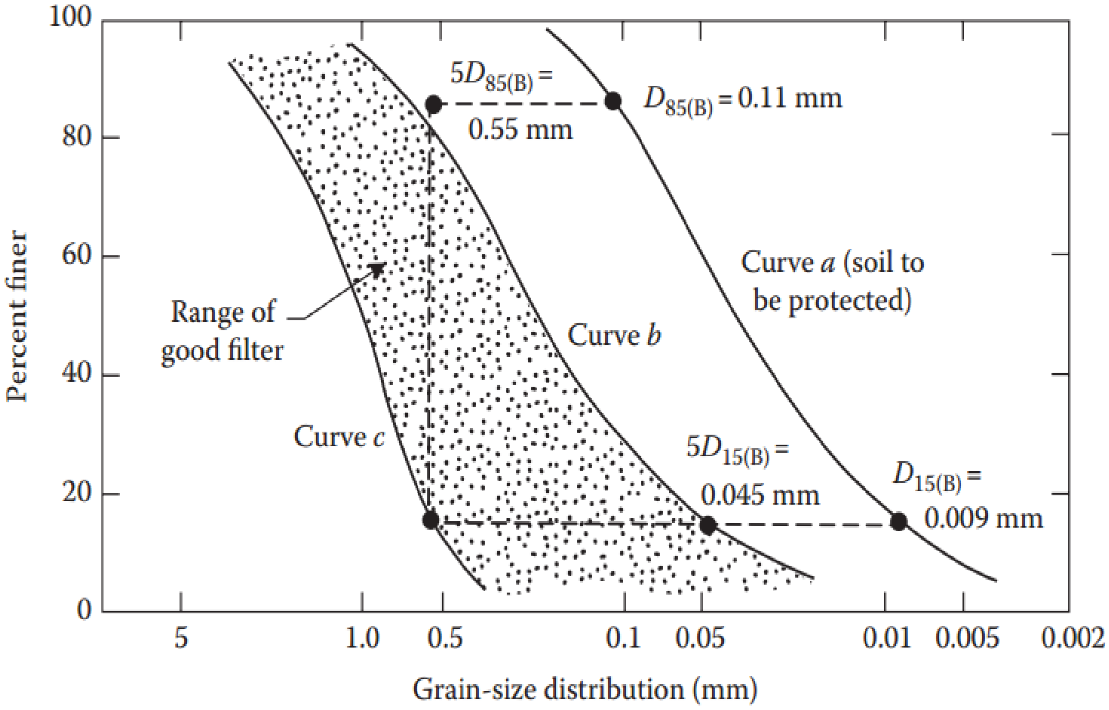


Figure 7.24 Determination of grain-size distribution of soil filters using Equations 7.94 and 7.95.

Let the grain-size distribution of this soil be given by curve a in Figure 7.24. We can now determine 5D85(B) and 5D15(B) and plot them as shown in Figure 7.24. The acceptable grain-size distribution of the filter material will have to lie in the shaded zone. Based on laboratory experimental results, several other filter design criteria have been suggested in the past. These are summarized in Table 7.2. [5].

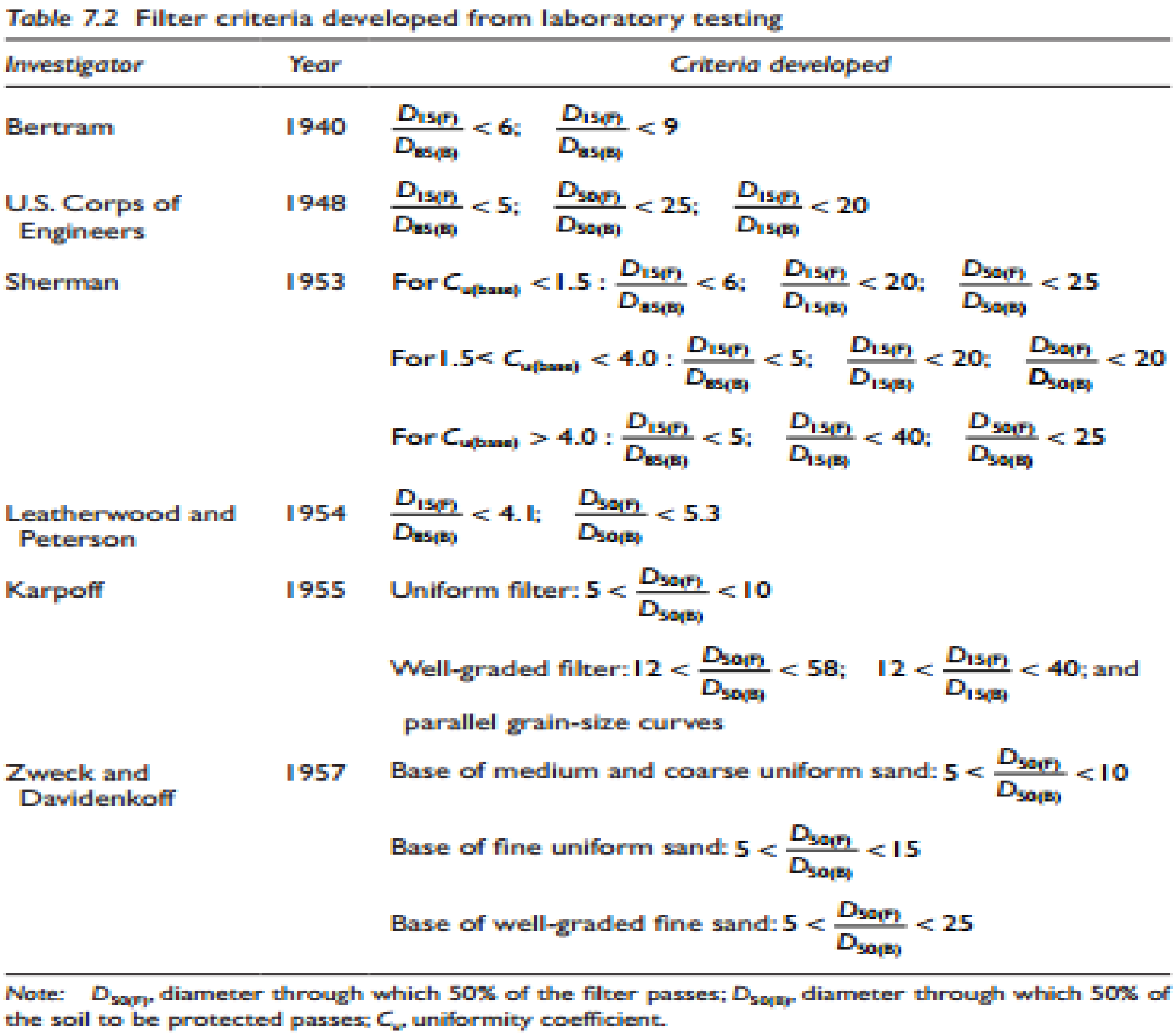
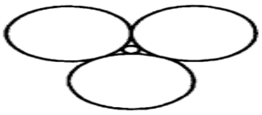


Table 7.2 Filter criteria developed from laboratory testing

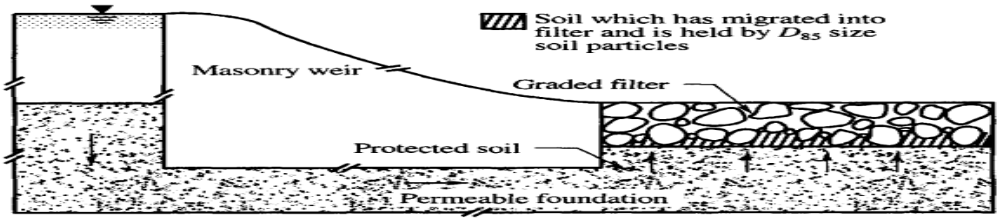
Investigator	*Year*	*Criteria developed*
Bertram	1940	$\frac{D_{15(F)}}{D_{85(B)}} < 6$; $\frac{D_{15(F)}}{D_{85(B)}} < 9$
U.S. Corps of Engineers	1948	$\frac{D_{15(F)}}{D_{85(B)}} < 5$; $\frac{D_{50(F)}}{D_{50(B)}} < 25$; $\frac{D_{15(F)}}{D_{15(B)}} < 20$
Sherman	1953	For $C_{u(base)} < 1.5$: $\frac{D_{15(F)}}{D_{85(B)}} < 6$; $\frac{D_{15(F)}}{D_{15(B)}} < 20$; $\frac{D_{50(F)}}{D_{50(B)}} < 25$
		For $1.5 < C_{u(base)} < 4.0$: $\frac{D_{15(F)}}{D_{85(B)}} < 5$; $\frac{D_{15(F)}}{D_{15(B)}} < 20$; $\frac{D_{50(F)}}{D_{50(B)}} < 20$
		For $C_{u(base)} > 4.0$: $\frac{D_{15(F)}}{D_{85(B)}} < 5$; $\frac{D_{15(F)}}{D_{15(B)}} < 40$; $\frac{D_{50(F)}}{D_{50(B)}} < 25$
Leatherwood and Peterson	1954	$\frac{D_{15(F)}}{D_{85(B)}} < 4.1$; $\frac{D_{50(F)}}{D_{50(B)}} < 5.3$
Karpoff	1955	Uniform filter: $5 < \frac{D_{50(F)}}{D_{50(B)}} < 10$
		Well-graded filter: $12 < \frac{D_{50(F)}}{D_{50(B)}} < 58$; $12 < \frac{D_{15(F)}}{D_{15(B)}} < 40$; and parallel grain-size curves
Zweck and Davidenkoff	1957	Base of medium and coarse uniform sand: $5 < \frac{D_{50(F)}}{D_{50(B)}} < 10$
		Base of fine uniform sand: $5 < \frac{D_{50(F)}}{D_{50(B)}} < 15$
		Base of well-graded fine sand: $5 < \frac{D_{50(F)}}{D_{50(B)}} < 25$

Note: $D_{50(F)}$, diameter through which 50% of the filter passes; $D_{50(B)}$, diameter through which 50% of the soil to be protected passes; C_u, uniformity coefficient.

Filter drains are required on the downstream sides of hydraulic structures and around drainage pipes. A properly graded filter prevents the erosion of soil in contact with it due to seepage forces. To prevent the movement of erodible soils into or through filters, the pore spaces between the filter particles should be small enough to hold some of the protected materials in place. Taylor (1948) shows that if three perfect spheres have diameters greater than 6.5 times the diameter of a small sphere, the small spheres can move through the larger as shown in Fig. 4.25(a). Soils and aggregates are always composed of ranges of particle sizes, and if pore spaces in filters are small enough to hold the 85 per cent size (D85) of the protected soil in place, the finer particles will also be held in place as exhibited schematically in Fig.4.25(b). The requirements of a filter to keep the protected soil particles from invading the filter significantly are based on particle size [6].



(a) Size of smallest spherical particle which just fits the space between larger spheres



(b) Condition of the boundary between protected soil and the filter material

Figure 4.25 Requirements of a filter

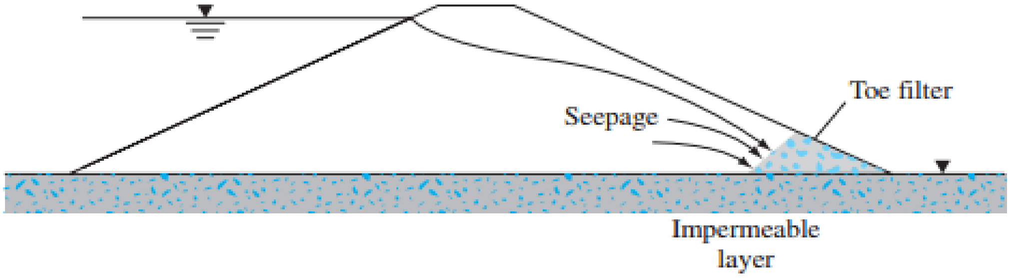


Figure 8.15 Steady-state seepage in an earth dam with a toe filter

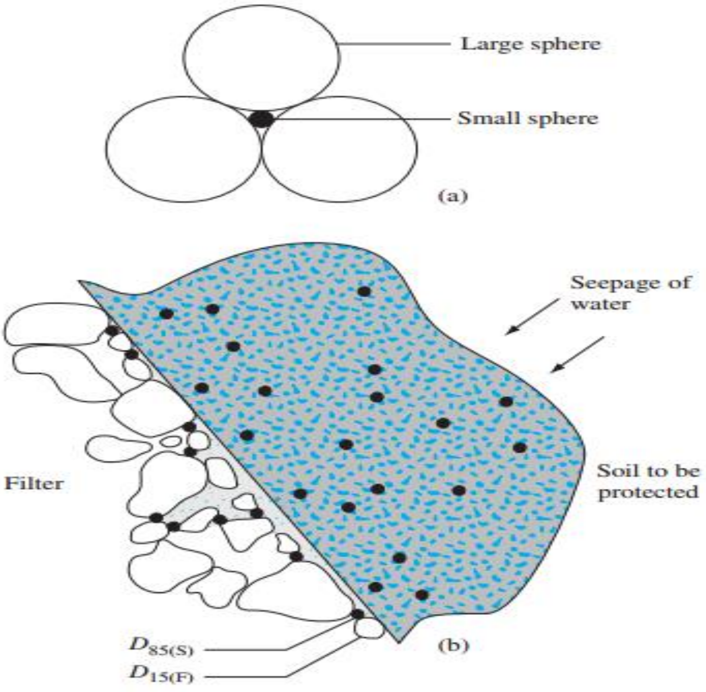


Figure 8.16 (a) Large spheres with diameters of 6.5 times the diameter of the small sphere; (b) boundary between a filter and the soil to be protected

The U.S. Navy (1971) requires the following conditions for the design of filters.

Condition 1: For avoiding the movement of the particles of the protected soil:

$$\frac{D_{15(F)}}{D_{85(S)}} < 5$$

$$\frac{D_{50(F)}}{D_{50(S)}} < 25$$

$$\frac{D_{15(F)}}{D_{15(S)}} < 20$$

If the uniformity coefficient Cu of the protected soil is less than 1.5,
D 15(F)/D85(S) may be increased to 6. Also, if Cu of the protected soil is
greater than 4, D15(F)/D15(S) may be increased to 40.

Condition 2: For avoiding buildup of large seepage force in the filter:

$$\frac{D_{15(F)}}{D_{15(S)}} > 4$$

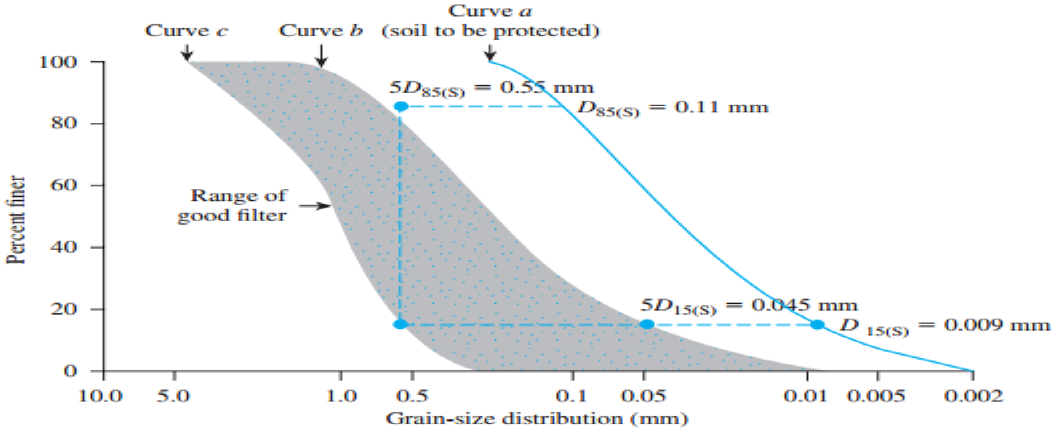


Figure 8.17 Determination of grain-size distribution of filter using Eqs. (8.41) and (8.42)

Condition 3: The filter material should not have grain sizes greater than 76.2 mm (3 in.). (This is to avoid segregation of particles in the filter.)

Condition 4: To avoid internal movement of fines in the filter, it should have no more than 5% passing a No. 200 sieve.

Condition 5: When perforated pipes are used for collecting seepage water, filters also are used around the pipes to protect the fine-grained soil from being washed into the pipes. To avoid the movement of the filter material into the drain-pipe perforations, the following additional conditions should be met:[7]

$$\frac{D_{85(F)}}{\text{slot width}} > 1.2 \text{ to } 1.4$$

$$\frac{D_{85(F)}}{\text{hole diameter}} > 1.0 \text{ to } 1.2$$

4. Filters for Sands

The research by Sherard was performed first on sand materials to establish the basic properties of sand and gravel filters (Sherard et al. 1989). Base sand soils consisting of uniform gradations (nearly all one size particles) of fine to very fine sand were placed over filters and water was run through the system to try and wash the sand particles into the filter. The gradation of the filter was made coarser and coarser until the sand particles began to wash into the filter. The point where sand began to wash into the filter was established for a range of sizes of base sands. The conclusion of the research was that so long as the D15 of the filter was less than about nine times the d85 of the base sand, a successful condition resulted. The ratio of D 15/d85 = 9 that defined a successful filter was consistent over a wide range of base soil sand gradations from very fine to coarse sands. As shown in Figure 1, the base sands studied had d85 values between about 0.1 millimeter (mm) and 2 mm. Terzaghi had proposed designing filters with the D 15 equal to or less than five times the d85 of the base soil. The researcher‘s recommendation was to regard Terzaghi‘s criteria as being valid because they incorporated a safety factor of about 2 .[8]

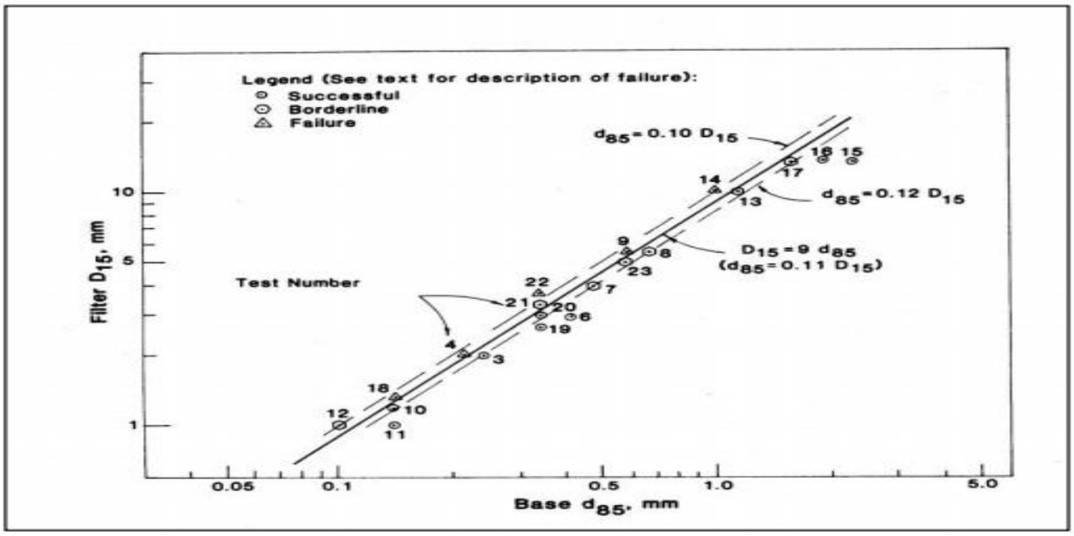


Figure L-10-1.—Relationship between D_{15} and d_{85} in initial SCS filter tests on sands and gravels.

5. Filters for Silts and Clays

The Sherard research (Sherard 1984b) then moved to silt and clay base soils. Laboratory experiments to investigate filters for silts and clays were begun after the research on sands and gravel base soils was completed. The base soils ranged from nearly cohesionless silts to tough, highly plastic clays and included some highly dispersive sodium clays from dams that had failed by piping. The filters used were subrounded to rounded, alluvial sands, and sand gravel mixtures. The filters were carefully fabricated by combining known weights of carefully sieved materials, using sieve sizes which ensured that the D15 size was reliably known. A total of 25 different filters were used with D15 ranging from 0.3 to 9.5 mm. In the experiments to determine the limits of filter compatibility for a variety of silt and clay base soils, the following experimental setup was initially used. A specimen of the base soil, a silt or clay, that was from 30 to 60 mm thick (about 1.2 to 2.4 in.) was compacted at about standard Proctor optimum water content on top of the filter being evaluated [8].

6. Uniformly Graded Versus Broadly Graded Materials

Grain size distribution of any given soil will affect that soil‘s permeability. Generally, a uniformly graded soil will have a greater permeability than a broadly graded soil when they have the same D10 size. This is because void space between sand particles in the uniformly graded sand is replaced by gravel particles in the broadly graded mixture as shown in Figure 6-5. The left side of the figure illustrates spheres of two sizes representing a uniformly graded soil (example: coarse sand). On the right side of the figure, three larger spheres overlay original figure and are shown in red. They represent the inclusion of gravel-size particles, making the soil broadly graded. The figure illustrates that the larger particles now replace previously available seepage space through voids, and that lost space has been highlighted in blue. Note that the figure has not been corrected for the larger particle‘s edge to edge contact with the surrounding particles. Theelimination of void space in the broadly graded soil results in a lower permeability (Pabst 2007).

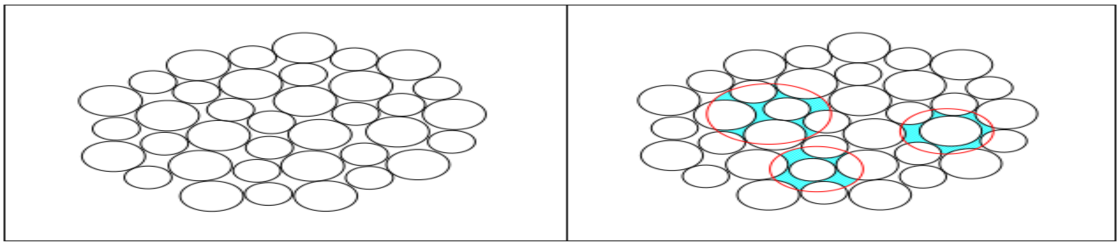


Figure 6-5. The illustration on the left shows idealized spheres of two sizes and resulting void space between the spheres. For the illustration on the right, three larger spheres (red) are overlain on the original illustration. This demonstrates how the larger spheres will replace once available void space, highlighted in blue.

7. Maintain Filter One Lift Ahead Of Core

The sequence of construction for this method is shown in Figure 7-2. This method has the advantage of inherently aiding in prevention of

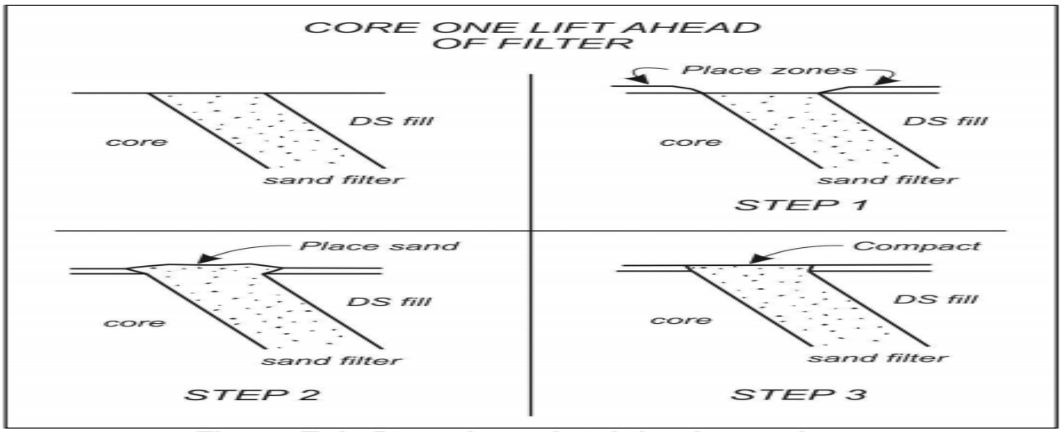


Figure 7-1. Steps in maintaining impervious core one lift ahead of a chimney.

Contamination and in maintaining vertical continuity and full width of the filter/ drain. This is especially true if the embankment surface is maintained so that the filter/drain is the high point of the cross section, resulting in runoff and potential contaminants flowing away from the filter/drain zone. A disadvantage of this method is that compaction may be more difficult because the sand has a tendency to spread at its outer edges when compacted. Spreading also may result in a greater quantity of filter/ drain material being used in order to construct the required width. This could result in a significant increase in cost as the filter/drain is often the most expensive material in the embankment. However, experience has shown that these disadvantages may be significantly overcome by blading up a windrow of loose material at the edge(s) of the filter/drain as shown in Figures 7-2 and 7-3. The windrow should be of sufficient width to effectively contain the filter/drain material, thereby minimizing spreading during compaction. Although this method may result in using additional drain material due to a small ―Christmas tree‖ effect, the extra cost is a small price to pay for ensuring that the drain width and gradation are constructed as designed. This method is especially applicable to filters/ drains having a relatively narrow width. (R-2)

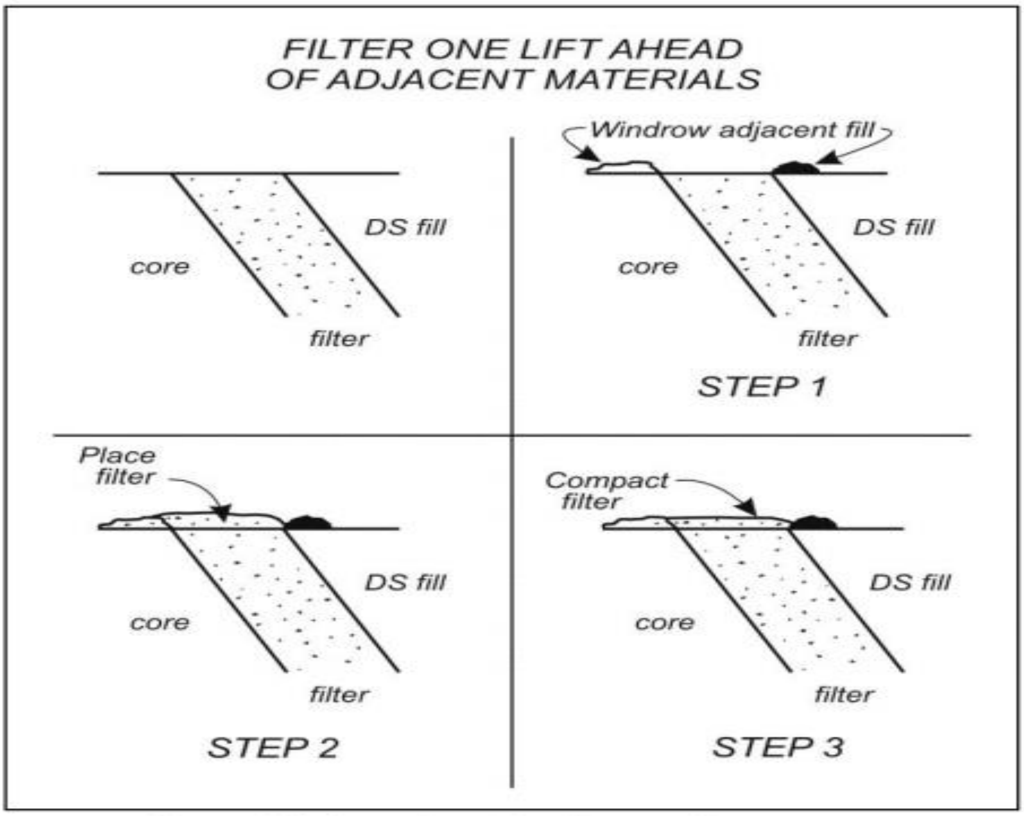


Figure 7-2. Steps in maintaining a chimney one lift ahead of impervious core.

Figure 7-3. Windrowing impervious material adjacent to a filter/drain.

8. Trenching

The trenching method is shown in Figures 7-4, 7-5, and 7-6 and is utilized when the filter/drain is constructed within a basically homogeneous impervious core. In this method, the impervious core is built completely over the filter/drain for a thickness of 3 to 5 ft. Using a trenching machine or other suitable excavation equipment, the core is then excavated down to the top of the previously completed filter/drain and the trench backfilled with compacted filter/drain material. The trenching method facilitates compaction since the material is confined on three sides, provides for closer control of quantities, and is conducive to obtaining excellent contacts between the filter/drain and adjoining impervious core. Disadvantages include the fact that trenching is time consuming, expensive, and

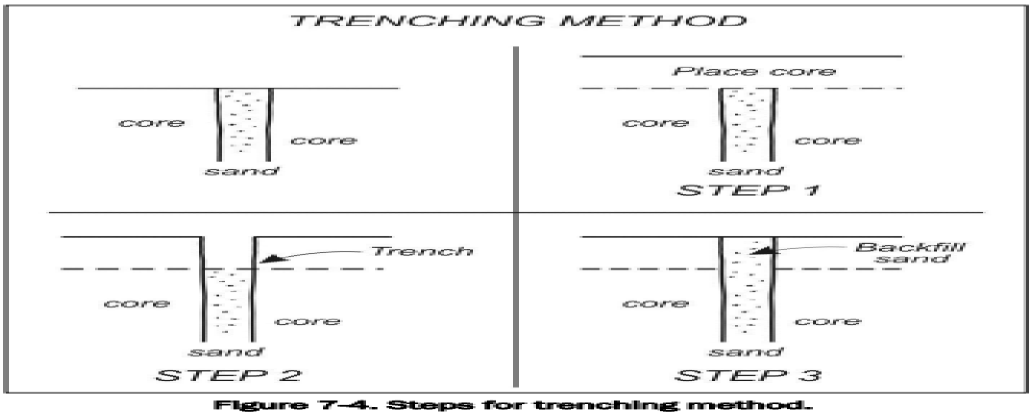


Figure 7-4. Steps for trenching method.

Figure 7-5. Trenching method – excavating trench.

Figure 7-6. Trenching method – backfilling trench.

inspection intensive (to ensure the tie-in between the existing filter/drain material and the newly placed material is not contaminated). In addition, this method can be used only for construction of narrow, vertical filter/ drains in embankments composed of central and downstream homogeneous material that will stand vertically without caving when trenched [8].

9. Flow Conditions Acting on Filters

The two flow conditions that typically act on filters are:

1. Flow perpendicular or approximately perpendicular to the interface:
   - At the downstream contact between the core and fine filter in an earth, earthrock or rockfill dam
   - At the upstream contact between the core and fine filter in an earth, earth-rock or rockfill dam, locations subject to a fluctuating reservoir (flow from core to filter during reservoir drawdown)
   - At the contacts between the fine filter and coarse filter (drain) in downstream chimney, blanket and finger drains

- At the contact between foundation soils and the bottom filter layer in a downstream blanket filter/drain or finger drain system
- At the contact between earthfill and the top filter layer in a downstream blanket filter/drain or finger drain system
- At the contacts between sand-gravel layers and silt-clay layers within alluvial foundations near the upstream and downstream toes of embankment dams, locations where seepage flows are perpendicular or nearly perpendicular to the slope of the layers

2. Flow parallel or approximately parallel to the interface:

- At the contacts between bedding filters and base material, and between bedding filter and riprap or revetment on the upstream slopes of embankment dams
- At the contact between gravel-cobble slope protection and base material on the downstream slopes of embankment dams
- At the contacts between sand-gravel layers and silt-clay layers within alluvial foundations below embankment dams, locations where seepage flows are parallel or nearly parallel to the slope of the layers
- At the contacts between coarse filters and fine filters within high flow capacity filter/drain blankets on downstream foundations . [9]

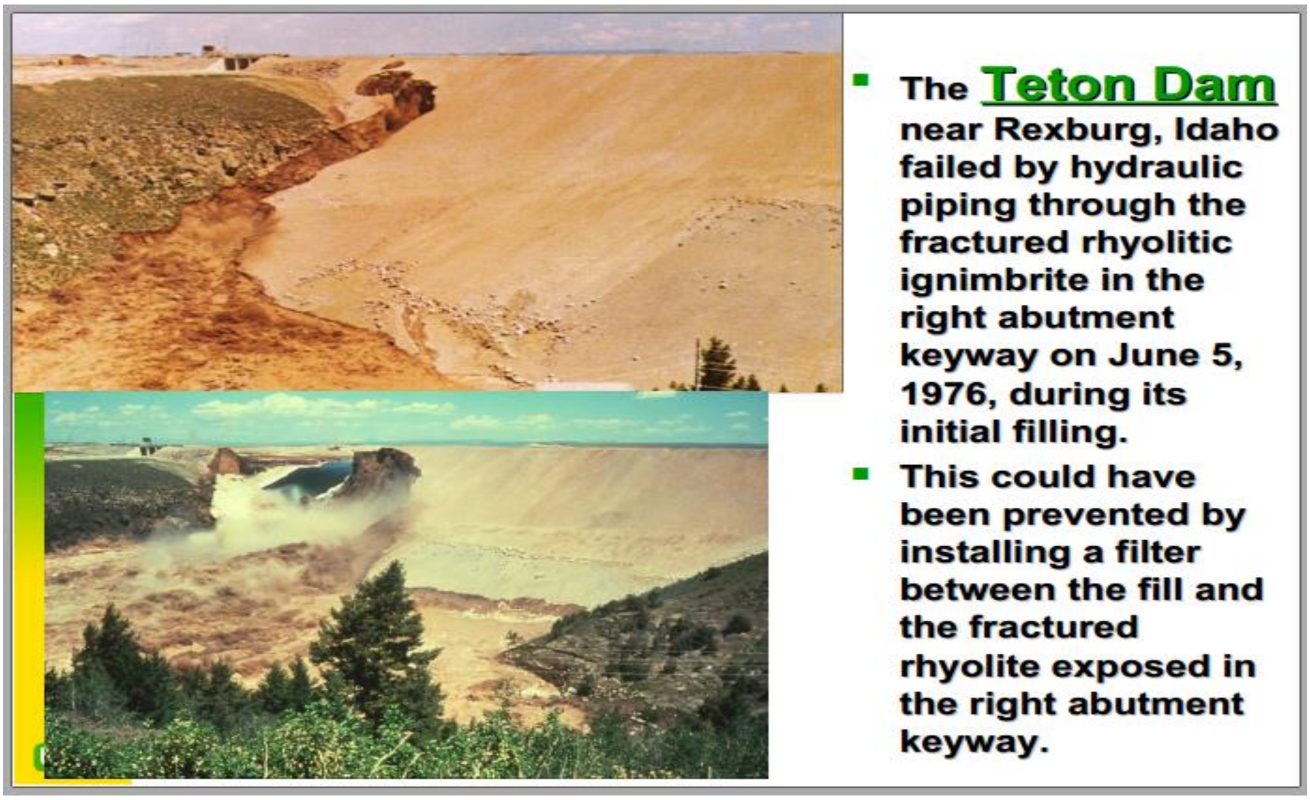
Placement of earthen clay core, up and downstream filters, and rockfill shells at Fena Dam on Guam by Navy Seabees in 1951. Upstream is to the right.

Piping occurred in the abutment, not within the embankment

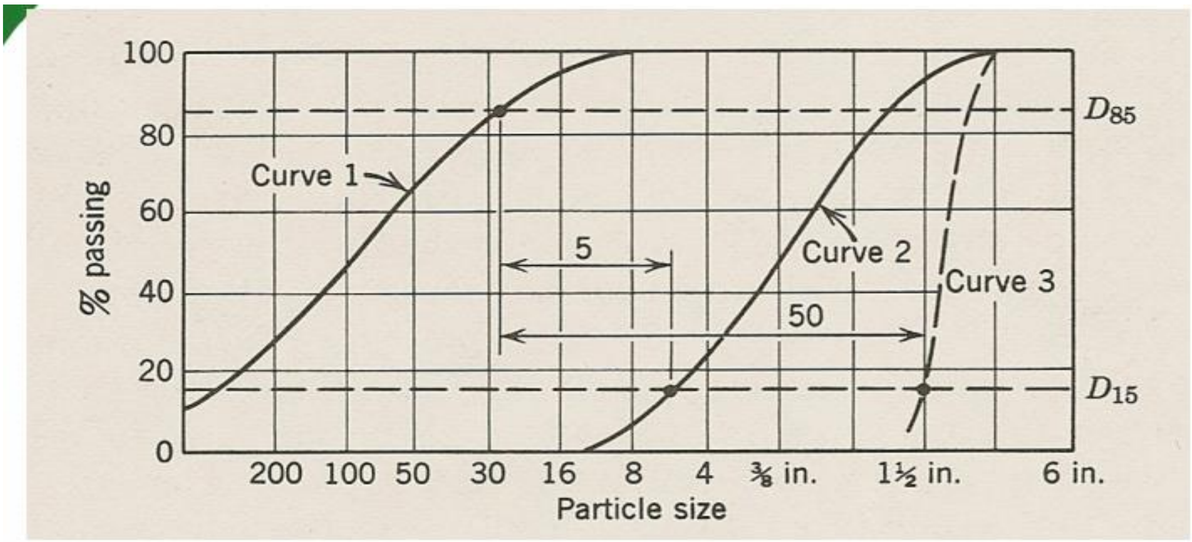
Piping occurred along a branch of the Newport-Inglewood fault, shown below

Water streaming from the reservoir's abutment, shortly before breach of the embankment

- The **Baldwin Hills Reservoir** in Los Angeles failed in Dec. 1963 by hydraulic piping through the rock abutment, along an active fault that had shifted about 1.5 feet over the previous decade



- The **Teton Dam** near Rexburg, Idaho failed by hydraulic piping through the fractured rhyolitic ignimbrite in the right abutment keyway on June 5, 1976, during its initial filling.
- This could have been prevented by installing a filter between the fill and the fractured rhyolite exposed in the right abutment keyway.



Segregated filter materials are very common if the material is excavated from a river or stream bed. Segregated materials can also cause problems. The D15 of the unsegregated filter aggregate (Curve 2) should be no more than 5D85 of the soil (Curve 1), but the D15 of segregated pockets of coarse filter material (curve 3) is actually 50D85 of the soil! This problem occurs more often than most engineers realize, and leads to poor pavement performance.

10. CONCLUSIONS

Water has a major influence on the stability and erosion resistance of natural and man-made soil structures. Draining the water out of the soil structure improves its stability. However, draining of the soil has to be done in a controlled manner without erosion. This is achieved with filter materials placed in or on the soil structures. Filter materials have to have certain properties which are described by filter criteria, significant development of which took place during recent decades. Now a days, these filter criteria are composed of six different parts and for each of these criteria are defined which have been discussed in this paper in detail. Despite of all the efforts in filter design a significant number of failures still occurs due to erosion. Embankment dam failures are given e.g. in the ICOLD Bulletin “Internal Erosion of Existing Dams and their Foundation”. About 4 of 10’000 large dams fail per year and 2 of these failures are caused by internal erosion. Overall about one embankment dam in 180 fail during its life time. A recent example is the failure at the Prudencia hydro-power plant in Panama, where a homogenous dam made of residual soils failed at the contact to a concrete gravity structure. Neither in the dam body or at the dam toe, nor at the contact to the rigid concrete wall, was any filter material placed. This supported the failure mechanism which was triggered in the first place by leakage in the geo-membrane sealing (Messerklinger, 2013). Although the design of filter materials and their application to soil structures is tought in undergraduate classes and is well known to geotechnical engineers, the lack of the design and placement of filter materials still causes numerous failures. Hence, further efforts on the selection of appropriate filter materials and their incorporation in soil structures are essential.[3]…Permeability reductions of more than an order of magnitude were noticed after about 300–600 pore volumes, for nominal concentrations (0.5–1.0 g/L) of polystyrene and kaolinite particles (which represent a range of migrating particle sizes) in the pore stream. The particles were smaller than the majority of the soil pores.An increase in particle concentration led to a faster reduction in permeability. In spite of their small and uniform sizes, kaolinite particles in the pore fluid caused permeability reductions comparable to those of polystyrene spheres, which are relatively large. This was concluded to be the effect of flocculation, resulting in 5% (by number) of particles in the size range of 4–55 microns.[4]

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