3. Material selection and design of envelope

Steps 1 - 3 of Figure 1 have now been completed and it has been determined that an envelope is needed. Before proceeding to the actual design of the envelope as far as its required functions are concerned (filtering, hydraulic, mechanical, bedding), step 4 should be performed comprising a number of considerations:

- the selection of the material as function of availability (cost being a main factor);
- whether or not the envelope should act as filter or any of the other functions or a combination thereof;
- the conditions that the envelope material will be exposed to during transport and placement;
- the environment in which the envelope will function; and
- whether a thick (voluminous) or thin envelope should be used.

In the following sections of Chapter 3 a description is given of the steps that will lead to a successful selection of an appropriate envelope material and detailed design once the envelope material is selected. The key elements of the complete design process are given in:

1. Figure 1 Steps in drain envelope design.
2. Figure 7 Flow chart to determine the need for an envelope.
3. Figure 8 Flow chart for selection of voluminous or thin envelopes.
4. Section 3.3 Granular Envelopes.
5. Section 3.4 Organic Envelopes (Table 5 and 6).
6. Section 3.5 Synthetic Envelopes.

Additional information may be found at the following locations elsewhere in the book:

7. Box 10 Summary of desirable properties of synthetic materials for drain envelopes.
8. Figure 9 Typical open area of water entry per unit length of pipe for different envelope materials.
9. Figure 58 Compressibility of geotextiles as function of load.

One may also wish to consult the following:

10. Table 34 Overview of existing design criteria for the use of sand and gravel around drainpipes.
11. Table 35 Existing filter criteria for geotextiles.
12. Table 27 Relationships between different pore sizes for non-woven geotextiles.
13. Figure 74 Unified Soil Classification Chart.
3.1 Selection of type of material for the envelope

Based on the material used the following types of envelopes can be distinguished:

- Granular envelopes. Gravel or sand/gravel combinations.
- Organic envelopes. A wide range of organic materials have been used in the past, such as peat, top soil, sod, building paper, hay, straw, corn cobs, cloth, burlap, leather, wood chips, etc. More recently, wire coir or coconut fibre, have primarily been used. Coconut fibre combined with synthetic fibres are used too. In Europe, Pre-wrapped Loose Material (PLM) are commonly used.
- Fabric envelopes. In recent years, wide ranges of (synthetic) fabric material have been used as drain envelopes (besides limited use of natural fabrics like jute and cotton). These are the above-mentioned PLM envelopes with synthetic fibres only, thin knitted materials (also known as socks, or available as sheet material), and a variety of non-woven materials, mostly thin to thick needle punched.

3.1.1 Environmental conditions

To select the type of envelope material a set of general conditions should be checked first:
1. the availability of materials, and hence the likely cost;
2. the expected function: hydraulic, filter, mechanical, bedding;
3. loading on the pipe and envelope;
4. handling characteristics during transport and transportation;
5. danger of biochemical fouling (iron ochre);
6. ripening process of the soil;
7. organic matter and pH of the soil;
8. calcium carbonate content (of soil and granular envelope) and pH of the water; and
9. the climatic conditions.

ad.1. First of all a list of the available materials must be obtained, including the source, and the distance from the source to the construction site. Most regions in which drainage projects are executed will have ready access to some form of granular material, which may or may not be suitable for a drain envelope. Even where granular material is readily available, transportation and handling costs can easily result in higher total envelope costs than when imported synthetic materials are used (see Chapter 4). Recent experience has shown that in most cases synthetic materials are cheaper than gravel and sand.

ad.2. To effectively improve the hydraulic function, a voluminous envelope is
generally necessary. The Hydraulic Failure Gradient (HFG) determination and estimation of the gradient at the pipe-envelope and the envelope-soil interface (Figure 8) can assist with the determination of the required thickness. Several example calculations are given in Section 5.3.2, while the steps are shown as a flow chart in Figure 8. Based on the perforations and their arrangement along the pipe circumference, it may be necessary to create flow along the pipe (in case of perforations alternately in parallel corrugations, Figure 15). Longitudinal flow is readily achieved in granular filters, but with synthetic envelope materials due attention should be paid to the flow characteristics in the plane of the material (Sections 5.1 and 5.6.8). The relative openness of a particular envelope material is shown in Figure 9. To accommodate the filter function, thin synthetic filter fabrics might be considered in addition to the traditionally used gravel filters. To avoid possible clogging and loss of permeability of these thin materials special criteria is given in Section 3.5. For the mechanical function only granular material will suffice. For bedding any gravel material will generally be acceptable.

ad.3. Loading conditions are to be considered for several reasons: (1) gravel might be selected to hold the pipe down immediately following construction when uplifting water forces are expected; (2) gravel could be selected to enhance the strength of the pipe-envelope combination when excessive loads are expected (for instance in unstable soils where soil wedges of collapsing trench walls may damage the pipe); and (3) where loading plays a role with the compressibility of the potential synthetic/organic envelope material (Section 5.6.6). The required thickness as determined with the HFG method should be achieved under compressed conditions. Actual loads in the field (Box 8) may range from 15 kPa to 40 kPa when a drainpipe is at a depth of between 0.75 m and 2.0 m (Figure 58, p 197). Standard testing of voluminous materials is done at 2 kPa (equivalent to the pressure of a wet, saturated, soil at an approximate depth of 0.1 m).

ad.4. Proper handling of envelopes during transport and placement is critical for both granular and non-granular fabric envelopes. For granular envelopes, guidelines to prevent segregation are necessary, while for synthetic envelopes strength criteria are important (puncture strength, tensile strength, etc.). Gaps in overlaps or seams can be prevented when stitching is done properly and the strength of the seam is adequate (see Sections 4.2 - 4.4 and 5.6.4 - 5.6.7).

ad.5. Thin synthetic envelopes should not be used in areas where problems with ochre can be expected. In the Netherlands, pipes with perforation widths ranging from 1.4 to 2 mm are recommended in such situations⁴.

⁴
Box 8  Determining load on drainpipe and envelope.

The load on the drain and hence the envelope may be calculated from (ASAE 1997, Luthin et al. 1968, Manson 1957):

\[ W_c = C_d \rho_s g B_c B_d \]  

Eq. 9

where,

- \( W_c \) the pipe load in N/m
- \( C_d \) the load coefficient, dimensionless. Typical values as a function of the ratio \( H/B_d \) are:
  - damp top soil and dry wet sand: \( A = 1.3 \) \( B = 0.94 \)
  - saturated top soil: \( A = 1.08 \) \( B = 0.98 \)
  - damp yellow clay: \( A = 0.95 \) \( B = 0.99 \)
  - saturated yellow clay: \( A = 0.83 \) \( B = 0.99 \)
- \( \rho_s \) the bulk density of saturated soil in kg/m\(^3\). Typically \( \pm 2000 \) kg/m\(^3\)
- \( g \) gravity acceleration in m/s\(^2\) (9.81 m/s\(^2\))
- \( B_c \) the pipe width in m
- \( B_d \) the trench width in m

Box 9 gives additional information for dealing with situations where iron ochre is a problem;

ad.6. Soils that are have recently been reclaimed and have not yet ripened (oxidised) have a low hydraulic conductivity (\( K_s \leq 0.1 \) m/d). Therefore, voluminous envelopes (thickness > 2 mm without load) are recommended. Since this might be a temporary situation until the soil has ripened as a result of oxidation and biological activity, and since hydraulic conductivity could increase 100-fold in 1 to 1.5 years, voluminous organic materials are suitable, provided that soils do not become unstable after ripening;

ad.7. Deterioration of organic envelope material is enhanced when there is much organic matter (humus) in the soil, which will stimulate biological activity and affect the lifetime of an organic envelope. This could be particularly true in areas with peat soils. Oxidised remains readily clog thin envelopes - as was experienced in the Netherlands - so larger pipe perforations are recommended\(^6\). Organic matter in clay soils with high pH will deteriorate faster and therefore organic envelopes will not last long.

ad.8. Soils rich in calcium cause more rapid deterioration of organic matter, hence organic envelopes are less suitable. A quick test can be performed by applying a few drops of a 10% HCl solution; if no visible or audible

\(^5\) Manson used \( B_d^2 \) in Eq. 3 rather than \( B_c B_d \).

\(^6\) Class B of NEN 7036, which prescribes perforation size between 1.4 - 2 mm width: Dutch standard on corrugated PVC drainpipes.
reaction takes place the soil is low in calcium. The calcium of the soil in combination with a pH < 5.8 may cause limestone deposits to affect the functioning of fine filters. However, solubility of gypsum (a different form of calcium in the soil) is not a function of pH, and will not cause additional movement of calcium in the soil (Section 5.5.5);

ad.9. Organic envelopes last longer in temperate than in tropical climates. Synthetic envelope material (PVC more than PE) exposed for extended periods of time to sunlight, deteriorates. However, hot weather and an abundance of sunlight should not preclude the use of certain synthetics; protective measures during storage are necessary.

Box 9 Dealing with iron ochre during design, operation and maintenance of pipe drains.

When the possibility of iron ochre problems has been identified the following options to prevent and/or reduce the impact are available to the designer:
1. Include easy pipeline flushing features in the design.
2. Do not use thin woven synthetics, or fibre glass or similar materials with small openings.
3. Use drainpipes with maximum allowable perforation size (i.e. 1.4 - 2 mm in the Netherlands, Type B pipe).
4. Apply materials containing copper in or around the drain as copper is bactericidal, but it is not an environmentally sound solution and therefore not recommended.
5. Apply tannic acid to the envelope material (see Section 4.5). This is however a temporary solution with also possible negative environmental side effects, and is not recommended.
6. Construct the drains deep so they are submerged most of the time. Although in theory this should prevent oxidation, in practice it was found to work only partially in the Netherlands (Scholten 1989), the USA and Canada (McKyes et al. 1992). See Section 5.5.5 for details.

Finally, with drains in situ, aeration of the soil by deep ploughing or by constructing mole drains has been tried but met with limited success, so considered only a temporary solution. The idea was to stimulate oxidation and deposit iron in the soil before it reaches the drain.

3.1.2 Required envelope thickness

Once the nine factors above have been considered, an idea might have been formed about which type of envelope is desirable. Now the material thickness should be considered. The required thickness of the envelope could play a role in the selection of the type of material (synthetic thin or voluminous, or granular natural material).

To create the most favourable hydraulic condition at the soil-envelope interface, namely, the lowest possible gradient that is lower than the HFG, further consideration of the exit gradient at the soil-envelope interface is helpful (Figure 8, Steps 13 – 17):

Apart from iron ochre problems, bio-chemical problems can also relate to sulphur and magnesium reducing bacteria and their corresponding deposits (see Section 4.5).
1. Assume that it was already determined that $i_x > HFG$ (steps 1-12, Figure 7, implying an envelope is needed) and that selecting the next larger pipe size is not economical (should be checked again after the following calculations have been made). Even when a thin envelope is applied the $i_x$ will already be reduced simply because of the larger open area (Figure 9). Calculate the new exit gradient at the soil-envelope interface ($i_{env}$), using (Figure 8, steps 13–15):

- the appropriate envelope porosity or percent open area (POA) obtained from published data or test results (Sections 5.1.4, 5.6.8 and 5.6.9);
- the possible maximum discharge (as determined in Section 2.6); and
- the drain spacing and the soil permeability coefficient ($K_s$ or $K_c$ when calculated from particle size distribution).

Assume the validity of the Darcy equation for the situation at the soil-envelope interface (Sections 5.1.3 and 5.1.4). Darcy's equation is valid for laminar flow conditions. When flow is turbulent or in transition between laminar and turbulent, head losses will be higher and likewise the exit gradient for the same discharge.

At this stage whether or not a thick envelope will be necessary will not be known, so assume a thin woven synthetic envelope, which is less favourable than some of the other materials of 1 mm thickness as shown in Figure 9. Calculate $A_{pe}$ (step 14, Figure 8).

2. If $i_{env} < HFG$ then a thin envelope may be considered.

3. If $i_{env} > HFG$ then a voluminous envelope needs to be considered, and the required thickness can be determined (steps 15-16, Figure 8). The HFG is the maximum allowable exit gradient and the minimum radius required can be calculated to achieve this (Figure 8, item 17). Rather than using the POA for this calculation, the porosity ($\varepsilon$) of either the non-woven synthetic or the granular envelope needs to be considered (Sections 5.1.4, 5.6.8). Determine the minimum envelope thickness from the difference between the minimum radius and the outside radius of the drainpipe.

4. These are the options available:

   If the minimum thickness required is between 1 and 5 mm a voluminous synthetic envelope is the likely choice. This is the actual envelope thickness at drain depth and at the appropriate soil loading pressures. Depending on the synthetic material selected, use one of the compression ratios in Figure 58 (p 197) to determine the required thickness at 2 kPa. If no filtering function is required selecting a larger diameter pipe would reduce the exit gradient.

   If the minimum thickness is larger than 5 mm, then the costs of the synthetic material could be very high and the point at which a granular envelope becomes cheaper (see Chapter 4) can be determined. A granular enve-
Assume a thin (woven) synthetic envelope ($T_g \leq 1$ mm)

Calculate the exit gradient into the envelope at the interface with the soil:

$$A_{pe} = 2\pi(r_0 + T_g)a_e \text{ POA}$$

where $R_u$ is ratio wetted perimeter (0.5), $a_e = 0.6a$ = the area of corrugation exposed to water flow, POA is percent open area of woven fabric. POA=ε for non-woven fabrics, PLM and granular material.

$$i_{env} = \frac{q_{\text{max}}}{(K_s \epsilon A_{pe})}$$

Consider a voluminous envelope: $i_{env} \leq HFG$

Determine the required radius $r_{env}$ such that $i_{env} \leq HFG$

$$r_{env} = \frac{q_{\text{min}}}{(2\pi R_u a_e \epsilon K_s HFG)}, \text{ where } \epsilon = \text{ porosity voluminous envelope}$$

$T_g \geq 5 \text{ mm}$

Consider a voluminous synthetic envelope; on woven or Prewrapped Loose Material (PLM), see Section 3.5.3 for design details. If no need for filtering function consider larger diameter pipe.

Consider a voluminous envelope, synthetic material will become too expensive beyond a certain thickness, then consider granular envelope which for construction reasons will have $T_d > 75$ mm. If no need for filtering function consider larger diameter pipe.

**Figure 8** Flow chart for selection of voluminous or thin envelopes.
lope will always have a minimum thickness of 75 mm for construction reasons, regardless of what the calculation shows. For a thickness between 5 and 75 mm a larger pipe diameter might be considered as an economical alternative if sedimentation in the drainpipe is not a problem.

We now know which envelope is preferred and whether or not a filter function is one of the requirements. The next sections will give details of finalising the design, such that the retention, hydraulic and miscellaneous criteria are met.

![Graph of entrance area vs. pipe diameter](image)

**Figure 9** Typical open area of water entry per unit length of pipe for different envelope materials.

### 3.2 Method of a drain envelope design

There are two approaches for designing drain envelopes. One can either use laboratory indicator tests or use generalised criteria derived from laboratory and field observations. The difference is that laboratory indicator tests are performed for each material and situation considered, while generalised criteria give guidance without further laboratory tests. Both are briefly described in the next two sections.

#### 3.2.1 Laboratory indicator tests

Indicator tests are performed in the laboratory and aim at simulating field conditions. Laboratory simulations and results are not often directly transferable to field conditions (Section 5.7). There are four primary tests that can be done:
1. Permittivity tests. These tests determine the hydraulic properties of the envelope material to be used. For granular material, the constant head and the falling head methods (Section 5.5.4) are the most common. No distinction is made between vertical and horizontal hydraulic conductivity as this is not relevant to disturbed soil, sand, and gravel analysis in the laboratory. For geotextile permittivity (hydraulic conductivity including material thickness) distinction is made in cross-plane permeability, with and without load, and in-plane permeability (also called transmissivity). The measurements determine water conveyance capabilities. When performed under standard conditions results can be compared with set values (see Sections 5.6.10 - 12);

2. The Gradient Ratio test (GR, Section 5.7.2). This test aims at measuring the clogging potential of the proposed material proposed and there are several standards available. The duration of the test is approximately 500 hrs. Standard guidelines for testing do not recommend indicator values. The GR test compares hydraulic gradient in the soil with a geotextile to that of the soil alone. An indicator often quoted is that GR_{GR} should be < 3 for a geotextile to be acceptable, provided testing conditions are exactly as specified. Serious doubts have been raised about the applicability, reproducibility, and best testing procedure (Shi et al. 1994, Li et al. 1994 and Section 5.7.2);

3. The Long-Term Flow test (LTF) also investigates clogging potential, but specifically the gradual clogging over time, which can be a problem with some non-woven synthetics. The test could last up to 2000 hrs. No indicator values or specific indicator parameters have been reported and judgement is based on interpretation of graphs that show permeameter results over time. Tests of a shorter duration are under development (Section 5.7.1);

4. The Hydraulic Conductivity Ratio test (HCR) uses permeability ratios to assess the clogging potential (Section 5.7.3). The test has not been used for agricultural drainage conditions, hence the reported boundary value of HCR = 0.2 should be applied with caution. High values of HCR suggest soil loss through the fabric, low values indicate clogging of the envelope material, and intermediate values suggest soil-to-geotextile equilibrium.

From the brief descriptions above, and from the details given in Section 5.7, it might be apparent that laboratory indicator tests are far from straightforward solutions to questions about desirable soil-envelope combinations. For a number of years various researchers have been using permeameters for testing soil-drain envelope combinations (Dierickx and Yüncüoglu 1982, Stuyt 1992, Lennoz-Gratin 1987, 1992, Vlotman et al. 1990, DRI staff 1992, Koerner 1994, Li et al. 1994). These tests often combine the various aspects tested in the four indicator tests described above. Based on permeameter testing for research purposes an upward-flow permeameter is recommended as an indi-
indicator test for drain envelopes (Sections 5.7.4 and 5). However, as indicator tests are time-consuming they are only recommended when criteria - described in the following sections - do not result in satisfactory drain envelopes, or when anticipated field conditions are distinctly different from those on which the criteria were based.

3.2.2 Generalised design criteria

The second approach to designing drain envelopes is the use of generalised design criteria based on previous experience and as reported in the literature. Proposed criteria for design of filters for a variety of hydraulic structures, including in some cases agricultural drains are given in Chapter 6. All of the criteria rely heavily on the assessment of the base soil PSD curve.

Few of the generalised criteria were specifically derived for selection of agricultural drain envelopes. In particular, the retention and/or filter criteria are primarily based on those derived for other civil engineering applications of filters, such as bed and side slope protection, dams and hydraulic structures, silt fences, road drainage and vertical drainage. Nevertheless, the experience gained from those applications is readily adaptable for use with agricultural drains (Box 10 and 11). The main differences between filter or retention criteria between agricultural drain envelopes and other civil engineering applications are:

1. Hydraulic and retention criteria both need to be satisfied at the same time, while with other civil engineering works, one or the other may be dominant.
2. In civil engineering applications multiple step filters are common, but are not practical for agricultural drains.
3. For civil engineering applications the criteria need to cover the full range of possible soils, from heavy clays to coarse gravel. For agricultural applications heavy clays and coarse material generally do not need filters, hence criteria that cover these soil ranges are not needed;
4. Civil engineering applications of filters are normally constructed in building pits that are kept temporarily well drained, which allows for optimal construction conditions. This is usually not the case in agricultural drain construction.
5. For civil engineering applications, the soils that need to be protected can often be represented by a single PSD curve, or by a very narrow bandwidth. For agricultural conditions this bandwidth is usually much broader.

Of the recent publications containing design criteria for sand and gravel filters such as SCS 1994, ASCE 1994, and USBR 1993, and for geotextile filters such as in Koerner 1994 and Santvoort 1994, only ASCE 1994 and Santvoort
1994 present criteria specifically intended for horizontal subsurface drains. Perusal of the criteria, however, clearly shows reliance on earlier criteria presented for other civil engineering applications, with minor adjustments for use under agricultural conditions (Box 10). USBR 1993 recognises that most drains are constructed in the wet but recommends construction of the drains in the dry, if possible, whenever accurate placement of the drains can be determined before high water table problems develop. The SCS 1994 publication shows an example that requires a multiple step filtering envelope.

Box 10 Comparing and contrasting.

When studying the literature on drain envelope design eventually one will be struck by the observation that in granular drain envelope design particle sizes of the base soil are related to particle sizes of the envelope, while in fabric design the particle size of the base soil is compared with the opening size of the fabric. The majority of fine particles need to be retained in place by the drain-envelope combination. The opening sizes in the envelope therefore need to be smaller than the smallest particle not likely to remain suspended in flowing water. If the opening size is larger than the soil particle, then the soil particles need to bridge across openings. It was found that in many cases the particles would bridge. Hence bridging plays an important role in envelope hydraulic resistance and stability.

As there is no direct means of measuring the pore size in granular filters a relationship has been determined between representative particle sizes of the granular envelope material and the expected characteristic pore size (See Sections 5.2 and 5.4 for more details). The basic principle is that the smaller particles of the granular filter are an indication of the characteristic diameter of the pores: they may be considered as being equivalent to an $O_{95} - O_{95}$ size of the pores. As with the soils and the granular envelopes the figures 85 or 95 refer to the percentage of pore sizes that have smaller openings than the $O_{95}$ or the $O_{95}$.

Therefore, when Terzaghi presented his original filter criterion in which he refers to the $D_{15}$ of the filter, he actually was referring to a characteristic pore size of the filter in the range $O_{95} - O_{95}$. Because bridging by smaller particles over the opening is likely, the actual pore size (opening) is allowed to be larger by ratios that vary from 4 - 7. For example: if $D_{15}$ represents the $O_{95}$ of the granular filter then Terzaghi's original criterion would read $O_{95} < 4d_{95}$ instead of $D_{15} < 4d_{95}$. The reason why $D_{15}$ and $d_{95}$ are used is not given. It might imply that if soil particle sizes were normally distributed, sizes that are one standard deviation from the mean both smaller and larger are the $d_{16}$ and $d_{64}$ sizes respectively (see Figure 53, p98). The bridging ratio is determined based on theory and practice (Sections 5.2 and 6.2.1).

Drainage of agricultural lands is proposed because water tables are high for prolonged times. Construction pumping to install drains with envelopes under dry conditions is likely to be costly and time-consuming. The arrival of trenching and trenchless techniques, where excavation, pipe laying and envelope placement are done in one procedure, allows successful construction of drains below the water table. This puts extra demands on the type of envelope used, and creates conditions that are hard to simulate in the laboratory. The generalised indicator criteria presented in the sections below are based on those presented in the literature (Box 14), and on recent specific experi-
Box 11 Which comes first, the envelope particle size or the base soil particle size?

The particle size of the granular envelope (or the opening size in case of organic and synthetic materials) is the dependent variable in relationships with base soils. Hence they should either be on the left side of the equation (equal sign or greater than sign), or in the numerator of a ratio. For instance:

$$D_{15} < 4d_{85} \quad \text{or} \quad \frac{D_{15}}{d_{85}} < 4$$

The above formulation is recommended. Occasionally it was observed (in the literature) that inconsistent use of this notation led to specifying that the soil had to be smaller or greater than the envelope opening size. So, although $d_{85} > 0.25D_{15}$ is mathematically equivalent to the expression given above, $d_{85}$ is generally not a function of the envelope material.

ences primarily in Pakistan, where adverse conditions in unstable soils put high demands on the retention properties of granular envelopes.

3.3 Granular envelopes

Design of a granular (sand-gravel) filter for use as a drain envelope is different from design of granular filters for hydraulic structures in that a drain envelope needs to satisfy both the demand for the filtering function and the demand for high permeability, simultaneously. This is not always easy and often designers will give preference to one or the other. For instance, one of the criteria will be relaxed to accommodate gradations as close as possible to those found in nature. This is quite acceptable if one carefully considers the consequences of such action. Crushing and mixing (or blending of materials from different sources) is acceptable provided some additional criteria are considered. Also, with crushed material, the perfect blend might be out of reach due to economic constraints.

Another consideration in proposing the best set of criteria for agricultural drain envelopes is the need for a one-step granular filter which can be placed with trenchers at the same time as the pipe: here, two- or three-step filters are not practical (Section 6.2.1). Trenchless techniques are generally not suitable for granular envelope construction. Two- and three-step filters are common with highway drainage, construction drainage and with bed and slope protection of hydraulic structures (dams, etc.); when a trencher is not used.

The most challenging part of a granular drain envelope design is meeting the conflicting criteria at the $D_{15}$ particle size range. The prescriptions of $D_{15}$ are primarily based on the $d_{85( fine)}$ and $d_{15c( coarse)}$ sizes of the base soil bandwidth. Depending on the base soil bandwidth, one might find that hydraulic criteria
based on the coarse boundary prescribes a size very close to the maximum size resulting from the filter criteria. The result is a very narrow impractical bandwidth at the 15% passing level. At the same time one may also find that bridging criteria (relating perforation width or diameter to a characteristic particle size) result in \(D_{15}\) sizes that are close to or larger than the maximum allowable size following from the filter criterion. The only way to resolve this is by using common sense, and by carefully weighing up the consequences of relaxing one or several of the criteria.

During the initial project stages, when base soil is analysed and materials for use as drain envelope are selected, it is important that all sieves indicated in a particular set are used for envelope selection rather than just 7 or 9 sieves deemed necessary to produce a semi-logarithmic gradation curve (21-sieve analysis in case of the US Standard Sieve Set, Table 15). The 21-sieve analysis will identify missing particle sizes, or ranges of particle sizes. These missing particles could be the result of sedimentation conditions in the past or the type of crushing machinery used. In Pakistan, a common indicator test, such as a 7-sieve analysis, was proved not sufficient to assess the cause of failure of gravel envelopes that occurred. Problems were overcome by: (1) assessing the potential envelope material with the full set of sieves (21 sieve analysis); (2) reducing the largest particle size allowed; and (3) relaxing the criterion for the amount of fines allowed in the envelope material. All these measures served the purpose of reducing the excessively high hydraulic conductivities of the original (failing) envelope material.

Once a suitable envelope has been designed using all 21 sieves, then during construction, for quality control, one can resort to using seven to nine sieves. It is assumed that at that moment a working granular envelope has been selected, and sieve analysis is then purely to check for segregation that may or may not have occurred during transport.

Segregation during transport and storage on-site should be prevented. To prevent segregation it is more important that certain ranges of particle sizes be present in the proposed material than individual particle sizes. Disallowing large particles (> 19 - 38 mm) will help in preventing segregation. Various researchers showed that the particle size gradation curves of the envelope material do not need to be parallel to the base material particle size gradation curve, as long as the individual Particle Size Distribution curve stays within the selected bandwidth of the envelope material. Boundaries of the bandwidth are controlled by prescription of the Coefficient of Uniformity \((C_u)\) for the boundary curves.

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8 Note that SCS (1994) prescribes a maximum \(D_{90}\) as function of \(D_{10}\) which ranges from 20 - 60 mm (Table 34).
Agricultural drainage conditions can be rather severe for short periods as is shown in Section 5.1. In particular, when the subsurface drainage system is a pumped system, high gradients can exist for short periods. Cyclic and reverse flow conditions will be more common in the future when there is greater demand for more flexible operation and management of subsurface drainage systems to save water and to lessen the impact of (poor) drainage water quality on the downstream environment.

When the drainage system is used for sub-irrigation, the envelope will be exposed to reverse flow conditions\(^9\) which may destroy the arching (bridging) that might have occurred at the soil envelope interface. The natural filter that might have built up will be destroyed and fine particles are likely to collect at the envelope-base material interface. When flow into the drain starts again these particles will move back and with a proper filter envelope new arches and new natural filter will build up again. If a filter fails it will do so almost immediately after construction. Clogging over time is a far more gradual process that may take many years and is not common with granular envelopes.

Based on the foregoing and the conclusions presented in Sections 5.7.5 and 6.2 a mixture of guidelines and criteria are thought best for the design of gravel envelopes. This resulted in establishing control points on the Particle Size Distribution (PSD) curve through which the coarse and fine boundaries of a granular envelope bandwidth can be drawn. Gradation curve guides and bandwidth guides determine the recommended shape of the gradation band. The guides are intended to create a realistic gradation bandwidth, which can be implemented in practice. The guides are not criteria.

### 3.3.1 Control points for the coarse boundary of the envelope material bandwidth

The subscripts c and f denote coarse and fine boundary, respectively. Examples of the application of the control points are shown in Figure 11 and Figure 12.

1. \(D_{15c} < 7*d_{85f}\) 

   Control point 1: the filter criterion \(d_{85}\) is that of the fine boundary of the base soil. Filters with a ratio greater than 9 always failed according to Sherard et al. (1984b). Retention criteria that specify that \(D_{15c}\) should be greater than or equal to (not less than) 0.6, 0.3 or 0.2 mm were mostly based on the fact that samples tested

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\(^9\) also a form of cyclic flow, a term which is more commonly used to describe conditions under wave actions.
2. $D_{60c} = 5 \times D_{15c}$

Control point 2, the gradation curve guide. Based on SCS (1994) guideline that $D_{10} = D_{15}/1.2$ and that $C_u = 6$.  

3. $D_{100c} < 9.5$ mm

Control point 3, the segregation criterion. Particles larger than 9.5 mm (Sieve no. 3 of the Standard US sieve set) seemed to cause segregation and handling problems (flowability of granular material in trencher boxes, see Section 4.3). Boundaries as suggested by SCS 1994 are not deemed applicable for the typical agricultural soils. The 9.5 mm accommodates the boundary for crushed material suggested by Rehman (1995).

3.3.2 Control points for the fine boundary of the envelope material bandwidth

4a. $D_{15f} > 4 \times d_{15c}$

Control point 4a, hydraulic criterion$^{10}$, $d_{15c}$ is that of the coarse boundary of the base soil. Assuming that $D_{15}$ and $d_{15}$ are the primary characteristic particle sizes that control the hydraulic conductivity (pore space, see Section 5.4), this criteria assures that the $D_{15}$ is larger than the $d_{15}$ of the coarse boundary of the base soil bandwidth, such that the hydraulic conductivity of the envelope may be expected to be one magnitude bigger than that of the coarsest base soil. This criterion, however does not work well for soils with particles $d_{15c} > 0.09$ mm (such as the Dutch, Canadian and UK soils in Figure 2 and 3). Prescribing a $D_{15f}$ based on a practical bandwidth ratio (such as step 5 below) will provide a more realistic value, but the result will be a lower hydraulic conductivity of the envelope.

4b. $D_{15f} = D_{15c}/5$

Control point 4b, bandwidth guide. Control point 1 (filter criterion) and control point 4a (hydraulic criterion) could possibly have conflicting results. Hence, control point 4b gives a control point based on the filter criterion. This control point is similar to control point 2 combining the control of the bandwidth and $C_u \leq 6$. If control point $4b > 4a$ use $4b$. If $4b < 4a$ the decision on what

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$^{10}$ when $D_{15} < \text{factor} \times d_{15}$ are mentioned it is a filter criterion else it is a hydraulic criterion!
to do will depend on the degree by which 4b is smaller than 4a. Use 4a if the bandwidth ratio remains within practical limits (i.e. check readily available material to see if they match the narrow bandwidth) and as long as $C_u > 2$. If $C_u < 2$ the material will be too uniformly graded preventing natural filter build-up under the adverse construction conditions often encountered at drain depth. Here, use 4b or something acceptable between 4b and 4a. This will result in a lower than desirable hydraulic conductivity, but may not be a problem if the perforation area of pipes selected is the maximum that will give the lowest possible entrance resistance. In the end it will be the engineer who decides on the final shape of the boundary of the gravel bandwidth. Examples of both situations are given later in the book.

Control point 5, hydraulic criterion. This was originally intended to prevent a hydraulic conductivity that would be too low, but will also control the amount of fine sediment passing into the pipe of the envelope immediately after construction. The $D_{5f}$ is not likely to bridge the perforation of the pipe. It is likely that this criterion conflicts if control points 4a and 4b are smaller than control point 5. This criterion can then be relaxed somewhat for very fine base soils when the final minimum $D_{15f}$ is less than 0.074 mm (resulting from control point 4a, b or c) and when removing fines of the envelope material is too expensive. Control point 4c stems from the first bridging criterion mentioned in Section 3.3.5.

Control point 6, bandwidth guide. The bandwidth of the specified envelope gradation should not exceed the ratio of 5 below the 60% passing level.

Control point 7, retention (bridging) criterion. This control point generally means $D_{85} > 2$ mm, and there is no difficulty satisfying this. Only for very fine soils (soils in Egypt, Figure 2) when $d_{85} < 0.074$ mm will this criterion result in too much restriction above the 60% passing level (for further considerations see below).

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5. $D_{5f} > 0.074$ mm

6. $D_{60f} = D_{60c}/5$

7. $D_{85} > D_{\text{opening}}$

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11 Most US manufacturers provide pipes up to 250 mm in diameter with 5 mm round holes and pipes > 250 mm with 10 mm round holes. The larger hole size is to meet the 1 sq. inch per foot open area criteria (see Box 15). It does compound envelope design (generally only for non-agricultural drains when these larger drain diameters are more common).
The foregoing steps and control points should result in an envelope bandwidth with a high likelihood of success, provided that the material has been checked for missing particle sizes. The material of the envelope bandwidth will have a higher hydraulic conductivity ($K_{env}$) than that of the base soil, but by how much is not quantified. It is more important to select the highest possible unit perforation area of the pipe, or the unit open area of the envelope to reduce entrance resistance (Figure 9). As far as the pipe is concerned, the prime concern when recommending a higher unit perforation area will be to maintain the pipe strength. We are unable to confirm that the commonly quoted 1-2% open area of the pipe is based on hydraulic or pipe strength considerations. Perhaps it is a mixture of both.

### 3.3.3 Miscellaneous criteria

1. All openings should be covered by at least 75 mm (3") of granular filter material (construction criterion).
2. The envelope material should not contain deleterious materials, such as plant materials or soil.

### 3.3.4 Additional requirements for the use of crushed material

The use of crushed rock for granular envelope material has been acceptable in most cases, except when it failed to function as a filter with subsurface drains in Pakistan. Therefore, crushed materials are acceptable provided the following provisions are adhered to:

1. There should be no particles that are (disproportional) larger in one direction by a factor 2 of the shortest dimension. This is a long time requirement in specifications originating from USBR and the Corp of Engineers criteria. Its merit lies in that it prevents segregation and large pore spaces. Missing particle sizes in the crushed rock envelope material was one of the factors that caused envelope failure in Pakistan).
2. A statistically satisfying number of samples should be analysed from the crushing plant with the full set of US standard sieves (21-sieve analysis) to see whether any particle ranges might be missing. The missing particle ranges are not apparent as gap-graded material in standard semi-log PSD curves; histograms representing the results of sieving of the individual sieves should be produced (Figure 50).
3. The hydraulic conductivity of the crushed rock should be assessed in the laboratory using permeameters, and should remain below 300 m/d to be acceptable.
3.3.5 Optional bridging criteria

Lacking among the present criteria are direct bridging criteria. The main problem with bridging criteria is the decision about which representative particle size of the soil (d\text{xx}) or envelope (D\text{xx}) to use: d\text{10}, d\text{15}, d\text{50}, or d\text{85}. SCS (1994) uses D\text{85} for non-critical situations (where surging or gradient reversal is not anticipated) and D\text{15} for critical situations. For agricultural conditions, where reversal of flow can occur, it is advisable to follow critical guidelines. The diameter of the circular perforations or the maximum width of slotted perforations is given by D\text{opening}. Bridging criteria should only be considered for the pipe-envelope or pipe-soil interface, or else use the retention criteria. Based on review of various bridging criteria (Section 5.2) the following control points for the fine boundary of the envelope bandwidth have been selected by us:

1. D\text{15} > 0.25*D\text{opening}  Control point 4c, retention (bridging) criterion. The ratio will vary (see two items below and Table 11, p 145) depending on the selected representative particle size of the envelope material (D\text{15}, D\text{50} or D\text{90}). Based on perusal of Section 5.2 a factor of 0.25 is recommended when using D\text{15}. However, although this presents a seemingly generous allowance, it will probably be found to be in conflict with control point 4a or 4b, because generally it will mean D\text{15} > 0.5 mm (in case max. opening width is 2 mm). When unstable soils are encountered and filtering is critical using a granular envelope, select pipes with maximum width of the opening to be less than 2 mm (see Box 15, p 141).

2. D\text{50} > 0.5*D\text{opening}  Additional check/control point, retention (bridging) criterion, based on personal judgement on considering the description in Section 5.2. Except for very fine soils (d\text{85} < 0.074 mm), this criterion will result in a control point right in the middle of the envelope bandwidth resulting from the first six control points.

3. D\text{90} > 1.5*D\text{opening}  Additional check/control point, retention (bridging) criterion, based on the material presented in Section 5.2. It might be noted that the greater the characteristic particle size selected, the less likely the bridging will be a function of that particular particle size. Rather, most of the particle sizes will be smaller; hopefully they bridge. The only reason to include this questionable checkpoint is for comparison with the design criteria of synthetics, described in Section 3.5.3. Note however that control point 7 above is similar but allows finer envelope material to be used.
3.3.6 Final remarks on granular envelope design and examples

Gap-graded soils are not common in agricultural soils. Gap-grading is mainly a phenomenon in poorly graded gravel envelopes and only found in examples of US guidelines or as constructed laboratory soils (Figure 52, p 168, Figure 80, p 262). It never refers to the curves as a PSD curve based on an actual soil/gravel sample.

There are a number of acceptable standard aggregate gradations used for concrete and bituminous mixtures that can serve just as well for agricultural drainage envelopes. They are the fine aggregate gradations prescribed by the America Society for Testing of Materials in ASTM C33-93 and ASTM D-1073 (Figure 10). They may be readily available in countries where these standards are used. Care must be taken to assure there are no particle size gaps.

![Figure 10 Standard aggregate gradations of ASTM appropriate for use as drain envelopes.](image)

Example of granular envelope design with typical problem soils in Pakistan.

The soil bandwidth displayed in Figure 11 is synthesised for the various bandwidths shown in Figure 86 (p 299) and is therefore somewhat wider than would normally be encountered. It is perhaps wider than desirable, but as shown the control points result in an envelope range without too much conflict between the criteria. For the final curve control point 7 is somewhat relaxed and smaller particles are allowed. There is no major conflict with control points 4a and 4b.
Example of granular envelope design with UK problem soil.

The UK base soil band (Figure 12) gives rise to the typical conflict between control points 4a and 4b. The hydraulic criterion (control point 4a) results in a point very close to that of control point 1, the retention criteria. As it is more important to retain the fines, the hydraulic criterion is relaxed, i.e., smaller particles are allowed. Control point 4 is the final selection of 4a, b or c. Control point 4, which coincides with the $d_{15c}$ serves as a guide, together with control point 5. A curve is drawn that seems natural in shape, resulting in a final control point number 4 for the fine boundary somewhere in between 4a and 4b.