2. The need for a drain envelope

2.1 Functions of a drain envelope

A drain envelope is porous material placed around a perforated pipe drain to perform one or more of the following functions:

Filter function: to provide mechanical support or restraint of the soil, at the drain interface with the soil, to prevent or limit the movement of soil particles into the drainpipe where they may settle and eventually clog the pipe. Initially, there might be some fine and colloidal material passing through the envelope into the drain. After construction when the soil-envelope combination has stabilised, it is expected and acceptable that a limited flow of clay and other suspended particles will remain in suspension in the drained water and leave the drain. The filter function may be temporary, i.e. long enough to allow the disturbed soil to stabilise (organic envelopes have been used successfully for this purpose in the Netherlands).

Hydraulic function: to provide a porous medium of relatively high permeability around the pipe to reduce entrance resistance at or near the drain openings.

Mechanical function\(^1\): to provide passive mechanical support to the pipe in order to prevent excess deflection and damage to the pipe due to soil load.

Bedding function\(^1\): to provide a stable base to support the pipe in order to prevent vertical displacement due to soil load during and after construction.

Over the years a number of terms have been used to describe drain envelopes. Dieleman and Trafford (1976) used the terms envelope, filter, and surround, to distinguish between types of envelopes based on their principal function. The term envelope has also been used as a generic name for any artificial material placed on or around a drain to improve its functioning without specifying the reason for its use. A filter is an envelope used specifically to keep fines from the soil from entering the drain. A surround is material specif-

\(^1\) Can only be achieved with gravel and sand envelopes.
ically selected to provide a zone of high hydraulic conductivity around the drain, to minimise entrance losses and thus create an ideal hydraulic drain.

ILRI (Ritzema 1994) defined a drain filter as: "A layer or combination of layers of pervious materials, designed and installed to provide drainage, yet prevent the movement of soil particles in the flowing water." In the literature, drain envelopes are referred to under names and definitions that seem to be a mixture of descriptions of the materials used and the functions listed above. In this book, the different types of envelopes are classified according to the material from which they are made. An envelope appropriate for use under specified field conditions could perform one or more of the above functions. Granular envelope material, such as fine well-graded gravel or coarse sand, will perform all of the functions of an envelope. Synthetic envelopes may only perform the filter and hydraulic functions.

The main need for a drain envelope is to keep the pipe sediment free. This need only involves the filter function of the envelope. There are conditions where a drain will function more efficiently if an envelope is installed to improve the hydraulic function of the soil. A soil with a high clay content could be mechanically stable, but might have a low permeability. Since most of the potential energy moving water toward the drain is dissipated very close to the drain, the efficiency of drainage can be increased by placing some highly permeable envelope material around the drain to increase the effective diameter (hydraulic function). A larger effective drain diameter resulting from installation of a thick layer of highly permeable envelope material around the drain also decreases the exit gradient of water leaving the soil.

The mechanical function of a drain envelope is important when a flexible plastic pipe is used as a drain. From the mechanical function standpoint, the ideal drain envelope is a gravel envelope. The gravel fills the space between the pipe and the undisturbed soil of the sides of the trench with incompressible material that can enhance the full load-bearing strength of the pipe. It prevents flattening or deflection of the vertical pipe diameter that would reduce the hydraulic capacity of the pipe. A thick fibrous or geotextile drain envelope does not enhance the structural strength of a drainpipe.

When synthetic envelope material is used around a flexible plastic drainpipe (and also when no envelope is used on the same type of pipe) it is necessary to place the pipe in a groove, ploughed or cut into the undisturbed soil in the bottom of the trench, to provide structural support for the pipe. The groove can be a ninety-degree 'V' shape or it can be semicircular to conform to the outside diameter of the lower half of the pipe. Either bedding configuration results in a strong pipe support system, with a load-bearing capacity approximately equal to that of a pipe inside a gravel envelope.
The bedding function of a drain envelope is only accomplished by use of a gravel envelope. If the trench bottom is irregular, due to excavation by hand or by a backhoe type machine, gravel or sand is sometimes put into a trench and smoothed down by hand, so that the pipe will have a smooth uniform foundation (called bedding) that will not alter during backfilling. Installing special bedding material might also be necessary when unstable trench bottoms are encountered. Covering the base of the trench with gravel (envelope) material could give it sufficient weight to stabilise it. In some cases, a separate dewatering operation may be necessary to stabilise the trench bottom and sides so that the drainpipe and envelope can be properly installed and the trench backfilled without displacing or flattening the pipe.

2.2 Soils that require a drain envelope

When a new drainage project is being proposed, one of the first questions that arises is whether a drain envelope will be needed for any or part of the systems planned. Drain envelopes add an extra cost to a project, but if an envelope is necessary, drains installed without envelopes will fail.

Sedimentation and clogging of subsurface drains could result if:
1. the openings in the drain are too large and bridging of soil particles does not take place; or,
2. the soil itself is unstable under prevailing water flow gradients and the perforations/openings of the drain are not adequately protected by a drain envelope; and,
3. once the soil particles are in the drain, the grade of the drain or water velocity in the drain is not sufficient to flush the particles out of the drain.

The decision on the need for a drain envelope in a particular soil can be based on local experience or on empirical relations between measurable soil properties. Unless sandy, soils in humid areas, generally have a strong structural strength and drains can be installed in such soils without envelopes. Soils with a high clay and/or organic matter content also have higher structural strength. Simple correlation of soil structural strength with organic matter content or clay content have not been conclusive in determining whether drain envelopes will be needed for a particular soil, but this information, coupled with local experience can give dependable predictions.

Soils in humid areas do not share the same relationship between texture and stability as do soils in arid areas. For soil conditions in the humid areas found in the Netherlands, Van Zeijts (1992) developed relationships between clay and silt contents of soils and the need for a drain envelope, as well as the appropriateness of envelope types (organic, synthetic, thin or voluminous) for certain
soil types (see Table 31). Properly designed gravel envelopes can be used for all soils. Geotextiles and fibrous envelopes have some limitations that are related to the mechanical and bedding functions. In the Netherlands drains can be installed without an envelope in soil with a clay content of more than 25%. In Egypt (DRI-staff, 1983 and Abdel-Dayem, 1985) it was found that clay and concrete drainpipes without envelopes remained sediment free in soils with a clay content of 30% or more, provided that construction of the loosely-connected concrete pipe segments had been satisfactorily carried out and no serious misalignment had occurred over the years. In clay soils with substantial amounts of the montmorillonite clay particles and consequently with potentially deep cracks, drains had sediment inside and it was postulated that sediment found inside the drains had been the result of surface erosion, and/or erosion of the cracks during irrigation. In India soils with clay < 30% and also soils with SAR > 8-13 and clay < 40% were found in need of drain envelopes (Rajad Project staff 1995). More information on the possible effect of SAR is given in Box 2. The philosophy of the US Bureau of Reclamation (USBR) is that in settings where normally drains are to be constructed there will always be soils that require an envelope if not for filtering, than for hydraulic capability or for bedding of the plastic pipe. Even extensive investigations might not reveal the exact location of where problem soils could be encountered along the drain line. Therefore, the USBR automatically uses a granular envelope appropriate to the soil conditions on virtually all pipe drains.

Arid region soils are generally less stable than humid area soils, so clay content alone is not a good indicator of soil strength and stability. A parameter called Hydraulic Failure Gradient (HFG) has been developed (see Section 5.3) to determine the resistance of soils to flowing water. The expected inflow to the drains and the area of openings in the drains can be used to calculate the exit gradient (related to the velocity of water in the soil, Section 5.1) of water entering the drain openings. If the exit gradient exceeds the HFG of the soil, an envelope is needed. The Plasticity Index and the Saturated Hydraulic Conductivity of the soil are used in an empirical equation to determine the HFG of a particular soil for comparison with the computed exit gradient. Placing a properly designed envelope around the drain to protect the drain openings will also reduce exit gradients providing additional protection. Increasing the drain diameter, increasing the area of perforations, or decreasing the drain spacing are other alternatives for decreasing exit gradients.

Drains installed in soils that are mechanically unstable when they are wet will need the additional protection of a drain envelope. Drainage contractors refer to these soils as problem soils. Unstable soils are non-cohesive or weakly cohesive soils such as fine sands and silts. Sodium-affected soils can also be unstable (Box 2). Coarse-textured soils that have a uniform fine particle size are especially troublesome. Soils containing a high clay percentage tend to be
more stable and many have sufficient inherent cohesion that they do not need envelopes. If excavated auger holes or trenches collapse shortly after they are opened below a water table, drains installed in that soil are most likely to require a drain envelope.

Various other physical factors related to installation conditions affect the decision on the need for drain envelopes in a particular soil. If the soil is dry or moist (not saturated) during installation an envelope might not be needed, whereas a soil that is wet (fully saturated) at the time of installation (and the installation depth is below the water table) would. Yet, dry soil clods can lose their structural strength upon wetting due to splitting caused by the escape of enclosed air. Dry soil can therefore also pose sedimentation problems when the escaping air causes dispersion.

Furthermore, the speed of the trencher has an effect on the type of drain envelope selected in situations where speed and immediate backfilling are essential to prevent uplift of the pipe laid. Installing a fabric envelope in a trench containing a slurry could result in instantaneous failure of the envelope if the fabric used is too fine (blocking of the envelope). For questionable soils and installation conditions, it might be necessary to make an initial decision based on the best information available, followed by a pilot installation to check procedures and performance of the drain and envelope and the installation procedure.

Stuyt (1992) concluded that the best method to determine whether an envelope is needed is to install test drains and monitor sedimentation over time.

Huinink (1992) and Van Zeijts (1992) in the Netherlands, and Samani and Willardson (1981) and the Soil Conservation Service (SCS 1991) in the USA have developed procedures for assessing the need for a drain envelope. However, all of the prediction methods are presented with limiting qualifiers such as the subjective statement of ripened or unripened soil (Table 31, see Glossary for definition), clay and silt combinations and the term instability, or the all-encompassing statement of ‘unstable soil’. A basic understanding of the flow of water towards the drain and the soil mechanics in action at the soil-envelope and envelope-drain interface is therefore essential for making proper judgements on the need for a drain envelope and the design requirements thereof. Whether or not a drain envelope is needed for a specific situation depends on both the hydraulic conditions and the stability of the soil near the drains. Early indicators for the need of a drain envelope are collapse of the auger hole during the pre-drainage soil investigation, and anticipated construction of the drains below the water table.

Some indirect methods of assessing the need for a drain envelope in a particular soil are presented in Section 2.6 (direct methods would be field-testing of drains). Specific soil tests and calculation of expected flow gradients are needed for further evaluation.
The Sodium Adsorption Ratio (SAR) of the soil water is a measure to judge whether soil is in danger of becoming alkaline when it comes into contact with certain water qualities. When the SAR > 13 and the Electrical Conductivity of irrigation water (EC$_w$) < 2 dS/m the soil may disperse (deflocculate), which will cause considerable reduction in permeability due to the movement of very fine particles into small pores. The adjusted SAR (SAR$_{adj}$) is used to assess the permeability hazard based on irrigation water quality (Hoffman et al. 1980). If the SAR of the soil water at drain depth is high the clay will be dispersed only once all the salt has been leached and the EC$_w$ is low.

Usually intrinsic soil permeability is defined in terms of saturated hydraulic conductivity of the soil along with physical properties of the flowing solution, such as its viscosity and density. These fail to describe the dependence of permeability on effective soil porosity (function of clay swelling properties) and the concentration and composition of the soil solution. Swelling of soil clay particles (Smectite/Montmorillonite) in a confined system decreases the size of large pores, while dispersion and movement of clay platelets further blocks the soil. Many researchers predicted changes in permeability as a function of salt concentration and ionic composition changes in swelling soils (Breder et al. 1982).

A typical example of sodium-induced deflocculation given by McNeal and Coleman (1966) showed that saturated hydraulic conductivity decreased as the salt concentration decreases or as the Exchangeable Sodium Percentage (ESP) of the soil increases. The effect is normally greatest in soils with high clay contents and/or high contents of swelling clay minerals, although exceptions in Hawaiian soils have been documented. McNeal and Coleman presented a figure which showed the saturated hydraulic conductivity (K$_s$) related to salt concentration and SAR (the latter as curve parameters) for Pachappa sandy loam and Waukena clay loam. The K$_s$ of the Pachappa sandy loam with a SAR of 40 did not begin to decrease until EC$_w$ (Electrical Conductivity of the [irrigation] water) dropped below 6 dS/m, while for the Waukena Clay Loam K$_s$ started dropping when the EC$_w$ dropped below 17 dS/m. Since the finer soil would be the least stable, relating the EC$_w$ and SAR of the Waukena Clay Loam would present a conservative approach for assessing the potential of reduction in K$_s$ because of dispersion:

\[
EC_b = -2.3 + 0.5 \times \text{SAR} \quad \text{Eq. 1}
\]

where,

\(EC_b\) is the dispersion or deflocculation boundary of the electrical conductivity of soil water in dS/m

At the boundary value or at lower EC$_w$ values soil particles become detached and the soil tends towards dispersion for the given SAR value. If the EC$_w$ of the soil water is high enough there is no danger of deflocculation which would clog the envelope or drain. To assess the danger, evaluation of the SAR and ground water quality at drain depth would seem appropriate.

The SAR and ESP relationship can be obtained by (Jurinak and Suarez 1990):

\[
\text{SAR} = \frac{\text{ESP}}{k'_s \times (100 - \text{ESP})} \quad \text{Eq. 2}
\]

where,

\(k'_s\) is the modified Gapon selectivity coefficient in (mmol/l)$^{-1/2}$, typical values 0.016 - 0.008; a value of 0.015 is widely used for Illite clays.

Ayers and Westcot (1976, 1985) and Hoffman et al. 1980 give additional guidelines to judge potential dispersion/permeability problems based on EC$_w$ and the SAR$_{adj}$. 

| Box 2 | Use of SAR, EC and ESP to assess likelihood of dispersion. |
2.3 Soils that do not require a filtering drain envelope

Where an envelope is not needed to satisfy the filtering function to keep fine sediments out of the pipe, there might still be certain hydraulic or installation conditions that necessitate the use of envelopes. Here, specific criteria pertaining to the hydraulic, mechanical, or the bedding function apply. The soils that do not require a filtering envelope are:

- heavy clay soils (heavy clay soils can be defined as having a clay percentage > 60% and hydraulic conductivity < 0.1 m/d);
- clay soils with the percentage clay exceeding 25 - 30% in humid climates;
- soils with a Plasticity Index (PI) greater than 15;
- soils with a Coefficient of Uniformity ($C_u$) > 12; and
- coarse soils with 90% of the particle sizes larger than the maximum drainpipe perforation width.  

2.4 Soil characteristics to determine envelope need, and for design and functionality

To determine the need for a drain envelope, to design it properly, and to anticipate any problems after its installation a number of soil properties need to be known. These will be described briefly. A section follows this on how to deal with the potentially large amount of soil data available, making it manageable for design purposes.

The standard reference in the text to particle size of base or soil material and granular envelope material respectively will be $d_{xx}$ and $D_{xx}$. The lower case $d$ refers to the base or soil material at drain depth, whether used with granular, organic or synthetic material, while the capital D denotes the size of the granular envelope material. The number following each letter (xx) is the percentage of the sample, by dry weight (cumulative percentage passing) that is finer than the $d$ or $D$ in mm as determined by a sieving test (Section 5.5.1).

There are two traditional methods to display the soil data: the soil texture triangle, which serves to give a unified name to a particular soil; and the semi-logarithmic plot, or particle size distribution curve (PSD curve). Examples of these graphs can be found throughout the book.

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2 This criterion is rather conservative. More precise and more flexible bridging criteria are described in Section 3.3.4 & 5.2.
2.4.1 Required soil investigation

The following data need to be collected:

1. Soil samples from drain depth in sufficient number and with sufficient material to perform the following tests:
   a) sieve analysis (Section 5.5.1). The analysis is needed to assess the particle diameter at certain cumulative percentages of material passing for use in the design formulas (Section 3);
   b) Plasticity Index (PI) determination (Section 5.5.2), as an indicator of soil stability and to determine the Hydraulic Failure Gradient (HFG) without the need for direct laboratory determination;
   c) the soil texture analysis using the hydrometer method (sand, silt and clay percentages, Section 5.5.5). The clay percentage provides the first indication for the need for an envelope, and the finer particle ranges are important in granular envelope design;
   d) chemical analysis to determine the susceptibility of soils to disperse (deflocculate): EC<sub>e</sub>, EC<sub>w</sub>, SAR, etc.;
   e) iron ochre, calcium carbonate, sulphur and manganese content in the soil (Section 5.5.5).

2. Saturated hydraulic conductivity (K<sub>s</sub>) at drain depth. If the hole from which the soil samples were taken for the sieve analysis etc. remains open until the next day, the same hole can be used for the auger hole method for the determination of the Saturated Hydraulic Conductivity. Instability of the auger hole is a first indication of potential construction problems and the need for an envelope. The auger hole method is one of the standard pre-drainage investigation tests. Not only is it used for the drain envelope design but also for drain spacing determination. In unstable soil, a screen will need to be used in order to perform the auger hole method of hydraulic conductivity determination (Oosterbaan and Nijland 1994);

3. Depth of the impermeable layer. This information is needed to determine the gradients to be expected at the drain and to compare these with the HFG, and is part of the standard pre-drainage investigation. The accuracy of the depth of the impermeable layer is less critical than the determination of the hydraulic conductivity (Box 5).

The amount of soil collected using an auger 8 - 10 cm in diameter over a 30 cm length will usually be sufficient to perform all the necessary mechanical and chemical analyses. The density of the measurements depends on the particular needs, but for soil investigation purposes a density of one measurement per 10 - 25 ha (grids of 300 x 300 m or 500 x 500 m) is commonly used. Gallichand et al. (1992) found that for preliminary surveys a grid of 900 x 900 m would provide adequate information on hydraulic conductivity, while optimum results were obtained with grids that had distances between 400 - 600 m.
Certain assessments (e.g. the critical gradient) might require the void ratio and the specific gravity of the soil, in which case undisturbed samples need to be taken. The void ratio (porosity) is not used in standard drain envelope design, except to compare the Hydraulic Failure Gradient, but is more commonly used to determine water-holding capacity. Data from pre-project investigations or indicator values from laboratory tests (Sections 5.5 and 5.6) with typical soils can be used.

2.4.2 Base soil bandwidths

Several sources (see Figure 2 and 3) have displayed bandwidths of problematic soils (or soils in which drains are known to need envelopes). Some of these bandwidths seem to define a narrow range of soils that always need envelopes. However, close perusal shows this to be far from true and that the narrowness was more a function of how the graphs were presented rather than a true well-defined band. There is, therefore, a need for a methodology to define the best representative bandwidth for a soil. Classical design procedures give ranges of soils covering more than is necessary for agricultural conditions. Some examples from the literature follow in the next paragraphs.

SCS (1994) presented four classifications of soils (Table 1) each with a slightly different granular filter design. SCS filter design includes soils with clay percentages of over 25 – 30 %, which do not need a drain envelope for agricultural applications. Detailed design of synthetic envelopes with Egyptian Delta soils showed a range of soils that is too large is not practical (Vlotman and Omara, 1996), and it was found that several classes are needed to limit the required number of standard synthetic envelopes (Table 2). Regardless of the standardisation effort, it is desirable to design geotextile envelopes for the coarser soils individually. In the Netherlands, the choice of envelope material classes (prewrapped loose material PLM) went from three to two, with one being rather dominant in use (75% of the cases based on typical soils).

Soils in the Netherlands that were in need of drain envelopes were represented in a rather narrow band (Figure 2C), while in Canada and Germany the bandwidth of problematic soils was rather wide (Figure 3C). The US never produced a bandwidth recommendation, but guidelines by the USBR (1993, Table 34, p. 270), the SCS (1994), and the chart using the Plasticity Index (PI) of the Unified Soil Classification system (Figure 74, p. 250) clearly divide the full range of soils into certain classifications, each of which requiring a slightly different design (for general purpose filters).
Figure 2  Particle Size Distribution (PSD) curves for soils in need of drain envelopes USA, UK, Egypt, the Netherlands (NL).
A  USA soils, Cache Valley, Utah, USA (Willardson and Ahmed 1988).
B  UK (Davies et al. 1978), Egypt (Abdel Hadi 1996).
Figure 3  Soils in need of drain envelopes Pakistan, Canada, Germany.
A  Pakistan soils requiring envelope.
B  Canadian problems soil range (Irwin and Hore 1979, Cavelaars et al. 1994).
C  German problem soil range (FGSV 535, 1994).
Table 1  Soil classification for filter design by the Soil Conservation Service (SCS 1994).

<table>
<thead>
<tr>
<th>% finer than 0.074 mm after regrading*, where applicable</th>
<th>Base soil descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 85</td>
<td>Fine silt and clay</td>
</tr>
<tr>
<td>40 – 85</td>
<td>Sand, silt, clay, and silty and clayey sand</td>
</tr>
<tr>
<td>15 – 39</td>
<td>Silty and clayey sand and gravel</td>
</tr>
<tr>
<td>&lt; 15</td>
<td>Sand and gravel</td>
</tr>
</tbody>
</table>

* Regrading: using d < 4.76 mm sieve results only.

Table 2  Ranges of selected d90 values for use with Egyptian soils. (after Vlotman and Omara 1996).

<table>
<thead>
<tr>
<th>d90 in μm</th>
<th>Base soil description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 60</td>
<td>fine soils &gt; 30% clay: no need for envelope</td>
</tr>
<tr>
<td>60 – 200</td>
<td>Soil range 1; standard synthetic envelope no.1 with O90 = 200 – 600 μm</td>
</tr>
<tr>
<td>200 – 500</td>
<td>Soil range 2; standard synthetic envelope no.2 with O90 = 500 – 1250 μm</td>
</tr>
<tr>
<td>500 – 3000</td>
<td>soil range 3: broad range individual design necessary</td>
</tr>
<tr>
<td>&gt; 3000</td>
<td>gravel soils; no envelope needed</td>
</tr>
</tbody>
</table>

The smallest sieve size most commonly used (standard sieve no. 200, 0.074 mm) is often used as the classification criterion (SCS 1994, Wilson-Fahmy et al. 1996).

Wilson Fahmy et al. (1996) use three basic soil types to judge geotextile filter performance and filter criteria (Table 3).

Table 3  Example of soil classification used to group assessment of geotextiles. (Wilson-Fahmy et al. 1996).

<table>
<thead>
<tr>
<th>% finer than 0.074 mm</th>
<th>Base soil description</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 50</td>
<td>fine grained</td>
</tr>
<tr>
<td>13 – 49</td>
<td>mixed soils</td>
</tr>
<tr>
<td>≤ 12</td>
<td>Granular</td>
</tr>
</tbody>
</table>

USBR (1993) employs a distinctly different method that is similar to traditional divisions into silt, and sand ranges; the range within which the d60 falls is used for the classification: 0.02 – 0.05, 0.05 – 0.1, 0.1 – 0.25, and 0.25 – 1.0 mm.

From the foregoing it is clear that there is neither a unified approach to classify soils for drain envelope design, nor one for filter envelope design. Based on sieving techniques, some criteria stipulate the range of particle sizes that fall within or outside certain percentages of the soil, while others stipulate actual particle sizes regardless of the percentage of the soil it represents.
To make a first assessment of envelope need it is important to know the percentage of clay particles (particle sizes smaller than 0.002 mm). In addition, as clearly shown in Section 3.3, it is necessary to determine the finer boundary of the base soil bandwidth for filtration purposes and the coarser boundary for use with the permeability/hydraulic criteria (granular envelopes only). The boundaries at the percentages most commonly used to describe certain Particle Size Distribution (PSD curve) characteristics must be determined on some rational basis. In other words the finest curve found is not necessarily the one to be used for the fine boundary. A frequency analysis of the occurrence of the $d_5$, $d_{10}$, $d_{15}$, $d_{60}$, $d_{85}$ and $d_{90}$ sizes is recommended for the coarse boundary. Then, depending on the shape of the frequency distribution one can use quartile percentages, standard deviation sizes, and the like (Section 5.5.1) to determine the actual boundary for use in the design.

Based on pre-drainage investigation results, it is expected that the data for one or more representative base soil bandwidths are available for the area where subsurface drains are to be constructed. Broad bandwidths (with coarse/fine boundary ratios > 10, such as in Figure 2A and C, and Figure 3C) will not result in satisfactory drain envelopes that will meet the opposing requirements of filtering and high permeability (See also Box 3). Hence, one should check whether bandwidths representative for sub-areas from topographical point of view or sub-areas with similar soil types can be produced. Bandwidths with coarse/fine boundary ratios of 3 - 6 (Figure 2B and Figure 3A and B) will result in appropriate granular envelope bandwidths. Bandwidth could be based on the 25% and 75% quartiles of the full set of base soil samples or other reasoning.

Figure 4 gives the final result of an example of bandwidth determination using the 25 and 75 % quartile methodology. Soil samples were collected from different depths, based on a grid of 150 x 150 m, in anticipation of construc-

---

**Box 3  Soil boundaries and re-grading.**

*Base soils at drain depth should be represented by a bandwidth on the Particle Size Distribution (PSD) curve. The finer boundary of the band represents the PSD curve that needs to be retained for filtering purposes, providing that the percentage clay is less than 25 - 30%. The coarser boundary represents the soil PSD line that should be used in assessing the desirable hydraulic properties of the envelope.*

*Regrading of the soil sample, which is removing large particle sizes to better reflect the true hydraulic properties of the soil under investigation, as suggested by SCS 1994 and Sherard et al. 1984a, is generally recommended when a substantial amount of the sample has particles larger than 4.75 mm. Most examples of agricultural soils used in this book have $d_{100} < 4.75$ mm and hence regrading is generally not needed for agricultural soils. Regrading is adjusting the amounts retained on each sieve by excluding the combined weight of the particle sizes greater than 4.75 mm, which means the weight retained of particles on sieve no.4 of the Standard US Sieve set (Table 15, p 164) and higher.*

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tion drain depths ranging between 1.2 and 1.9 m. Four different depth ranges were statistically analysed. Soils at depths of 100 – 125 cm were heavy textured with a bandwidth ratio (25%/75%) ranging between 1.7 and 3.4 m. Soils deeper down were lighter textured with bandwidth ratios of around 1.5. Figure 4 shows little difference between the bandwidths at the various depths. It is the reason for the decision to recommend that the final bandwidth for designing the drain envelopes should encompass all possible soils based on the quartile analyses. The fine boundary of the soils at a depth of 100 - 125 cm at $d_{90}$, $d_{85}$, ...$d_{15}$ (the 25% quartile values) and the coarse boundary of the soils of the 175 - 200 range (the 75% quartile values) were used to set a smooth, fine, and coarse boundary of the final bandwidth. This final bandwidth is the one used for the design of the drain envelope. The bandwidth ratios of the final boundaries in Figure 4 range between 2.3 at $d_{100}$ and 4.3 at $d_{60}$.

2.5 Determination of drainage discharge, drain depth and drain spacing.

The drainage coefficient, drain depth and drain spacing must be determined prior to using certain drain envelope need determination methodologies. In theory, once these have been determined and the system designed, one can estimate the maximum discharge that would cause the highest gradients at the soil-envelope interface. While details of these design items go way beyond the scope of this book, some general and helpful descriptions can be found in Figure 5 and Box 4.

The drainage coefficient is the result of a comprehensive water balance determination. It can be defined as the amount of water that will recharge to the
**Box 4  Components of a water balance.**

**Net Recharge** is the amount of water that causes the water table to rise or drop. It is the result of all factors affecting the water table behaviour, including the effect of existing drainage systems and subsurface in- and outflow of the area of interest.

**Drainable Surplus** is the amount of water that must be removed from an area within a certain period to avoid an unacceptable rise in the levels of groundwater or surface water. Vertical or horizontal subsurface drainage systems or surface drainage systems might remove this surplus.

**Drainage Coefficient** is the discharge of a particular (subsurface) drainage system, expressed as a depth of water that must be removed within a certain time. It is usually the **Design Discharge**. Its magnitude will depend on the **Dewatering Criterion**, which is the period in which the drainable surplus needs to be removed (typically 7 days in humid climates, and 3 - 5 days in semi-arid regions).

**Drainage Discharge** is the actual volume of water removed by a drainage system expressed as a rate. This may be higher or lower than the **Drainage Coefficient**. Drainage discharge can be used to determine design drainage coefficients and drainable surplus.

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**Figure 5** Schema of water balance components in unconfined aquifer.

ground water in a certain period, or the amount of water that will drain from the rootzone over that period. All factors such as evaporation directly from the soil, evapotranspiration from the vegetation, rainfall, irrigation, subsurface inflow into the area of interest, and pumping from existing systems should be
taken into consideration. Some typical values of design drainage coefficients ($q_d$) are:

- **Humid climates**: 7 - 14 mm/d  
- **Moderate climates**: 4 - 7 mm/d  
- **Irrigated areas with some rainfall**: 2 - 4 mm/d  
- **Arid irrigated areas**: 1 - 2 mm/d

The second parameter that requires judgement before drain spacing can be determined is the water table depth between two drains. Some typical values to consider are:

- **Shallow rooting crops, humid climate**: 0.5 m with drains at 0.7 - 1 m depth  
- **Grain crops, humid climate**: 0.7 m with drains at approx. 1 m depth  
- **Food crops irrigated areas, no salinity danger**: 0.9 m with drains at 1.2 - 1.5 m depth  
- **Arid irrigated areas, with salinity danger**: 0.9 - 1.5 m with drains at 1.2 - 3 m depth

As may be clear from the above listing, these guidelines are very, very, broad, and one should really check local experience before deciding on a combination of midway water table depth and drain depth. Main considerations to decide on depth are:

- typical crop root depth;
- number of days in which a certain water table depths is to be reached (dewatering criterion) after a recharge event (rain or irrigation);
- potential of secondary salinisation (salinisation due to evaporation or root extraction of water from the soil) which is primarily a function of irrigation water quality, soil type, water table depth, evapotranspiration and land use; and
- availability of construction equipment.

The depth of the impermeable layer is another parameter to be considered, or rather one that needs to be known, before applying drain spacing equations. Although no approximate value can be given, in most drain spacing formulas, if beyond a certain depth the actual depth is larger, it will have a negligible effect on the spacing calculation. The depth of the permeable layer is used to calculate the equivalent depth for use in the Hooghoudt equation. The equivalent depth takes into account the radial flow resistance near drains in deep homogeneous soils, and becomes approximately constant when the depth to the impermeable layer is approximately one quarter of the drain spacing ($D = \pm \frac{1}{4} S$) or greater.
To decide on the appropriate hydraulic conductivity to be used in the drain spacing equation, a map with contour lines of the hydraulic conductivity (K) should be prepared and areas with distinctly different values should be marked appropriately. If the area to be drained is fairly homogeneous the maps are not needed. Hydraulic conductivity should be divided into classes and for each of these classes the corresponding Plasticity Indices (PI), as well as the percentage clay are to be grouped and the average, standard deviation as well as the maximum and minimum values determined. The geometric mean of the measured K-values gives the best representation of the hydraulic conductivity for further drainage design (Van der Sluys and Dierickx 1986, Oosterbaan and Nijland 1994). The PI and % clay values are needed later when the various envelope need criteria are applied (Section 2.6).

If hydraulic conductivity values are not known they may be estimated from particle sizes (see Section 5.4). In that case it is necessary to have a map which indicates the areas represented by a certain particle size (the size of the particle for which 10 or 15 percent of the sample soil particles are smaller, d10 or d15).

The relative importance of the above-mentioned parameters in drainage design is given in Box 5. When the spacing and depth have been selected, the subsurface drain discharge is determined from the design drainage coefficient (q_d), the drain length and the drain spacing, resulting in the design discharge (Q_d, Figure 6) for determination of pipe size. This discharge is used for determination of drain diameter after one or more safety factors have been applied (Cavelaars et al. 1994). The design discharge, however, is not the discharge we are interested in for the purpose of envelope need determination.

Field observations of drain discharges (either collector drains or lateral drains) will show large variations above and below the design discharge (q_d or Q_d). Lower discharges of the collector drain, for instance, can occur if not all of the area is draining into the collector, simultaneously. The same will happen on a smaller scale with laterals in irrigated areas, if not all of the lateral catchment is irrigated at the same time. Higher discharges can temporarily occur if the water table rises above the design water table depth, or if the drain spacing deviates (smaller) from the design. These higher discharges (Figure 6) are of interest to drain envelope design: they will expose the envelope to higher than normal design gradients.

The simplest way to determine the maximum expected discharge is to use the same drain spacing equation as was used for the design, but this time solve the equation for the discharge using the design drain depth and spacing, and assume that the midway water table depth is at the surface! This will be referred to as the possible maximum discharge (Q_dmax). Another way of deter-
Figure 6  Possible discharges from subsurface drains.
A  Typical design situation.
B  Over-pressure in the drainpipe, maximum gradient at the pipe is one.
C  Maximum gradient under free flow conditions in the pipe.
The spatial and temporal variability of soil properties and climatic conditions introduce a considerable amount of uncertainty in subsurface drainage design. Much work is necessary to incorporate the uncertainty of design parameters into the stochastic and deterministic analysis of drainage systems.

Wu and Chieng (1990) carried out a detailed sensitivity analysis of homogeneous and two-layered soils: sensitivity being the rate of change of the selected parameter with respect to the change in drain spacing. They concluded that in both steady and transient drainage design, the drain spacing is very sensitive to: 1. the midpoint water table height; 2. hydraulic conductivity; and, 3. the drainage coefficient. Drain spacing is not highly sensitive to the depth of the impermeable layer below drains and the drain radius.

In transient state design, the initial water table height and the water table drawdown over a given period are the most sensitive parameters in the drain spacing determination. The sensitivity analysis was executed using the following range of parameters: $q = 0.001 - 0.02 \text{ m/d}$, $K = 0.1 - 6.0 \text{ m/d}$, $D$ or $d_0$ (depth to permeable layer) = $0 - 10.0 \text{ m}$ and $h$ (the midway water table height) = $0.1 - 1.2 \text{ m}$.

Box 6  Standard drainage design books.


FAO. Irrigation and Drainage Papers numbers:
   9, 1972. Drainage Materials
   15, 1973. Drainage Machinery
   28, 1976. Drainage Testing
   38, 1979. Drainage Design Factors
   55, 1996. Control of Water Pollution from Agriculture


mining a possible maximum discharge is by calculating the full flow capacity of the drain using the Manning equation\(^3\). The disadvantage with this method is that it does not include the potential restricting effect of flow towards the drain in soils with low hydraulic conductivity.

The design of the drainage system, including the layout, hydraulic capacities and the drain envelope, is an iterative procedure. For instance, to determine the need for the drain envelope decisions on spacing, depth and equivalent depth need to be made (for details see references in Box 6). During the drain spacing determination a pipe diameter is assumed, but the actual one may not be known until the pipe diameter has been determined based on design discharge. Drain discharge depends on spacing and the drainage coefficient. Therefore, educated guesses are made during the first calculations, but these need to be checked when finalising of the overall design.

2.6 Determining the need for an envelope

With the assumption that the various soil tests and other parameters such as tentative drain spacing, drain diameters, and depth to barrier are available, the process of determining the need for a drain envelope can begin as described in this section (steps 1, 2 and 3 in Figure 1). Some general considerations of the various components of this process are given, followed by more detailed explanations (Figure 7).

The first indicator of the need for a drain envelope is the percentage of clay in the soil. From experience in the Netherlands, Egypt and India, a clay percentage higher than 40% would most likely indicate that there is no need for a filtering drain envelope (Figure 7). The safe clay content was actually found to be closer to 17.5% in the Netherlands (Section 6.1.3) but safety factors resulted in a recommendation of clay > 25% at drain depth\(^4\).

A recent report (Rajad Project staff 1995) indicated that unfavourable combinations of the SAR in the soil with certain electrical conductivity values of irrigation water could lead to dispersion of clay particles at drain depth. This was found in soils with clay percentages of up to 40% and hence this factor was built into the flowchart for drain envelope need (Figure 7).

\(^3\) USBR has measured flows up to 1.2 times the maximum, computed by the Manning equation, when there was a head of water above the pipe.

\(^4\) Table 31 (p 256) mentions that an envelope is recommended if soil layers above drain depth have less than 25% clay.
Perform particle-size analysis of the base soil (PSD curve, histograms)
Determine percentages of sand, silt, and clay
Determine characteristic values of the PSD curve: d90, d60, d15, d10, d5, and Coefficient of Uniformity (CU) as needed
Determine Plasticity Index (PI)
Determine SAR of the soil-moisture extract

Dispersion of clay aggregates may occur causing enhanced pipe sedimentation: an envelope may be desirable. Local experience should be taken into account. Proceed with HFG method and design.

6 Determine saturated hydraulic conductivity (Ks) or calculate from d15 (Kc)
7 Estimate the Hydraulic Failure Gradient (HFG) of the soil from:
   \[ HFG = e^{0.332K + 1.07 \ln PI} \]
   K can either be Ks or Kc
8 From design obtain drain depth and spacing
9 From pipe specifications determine perforation area per unit length (Ap)
10 As function of Ks and water table at land surface, determine possible max inflow per unit length of drain from the drain spacing equation (q_{lmax})
11 Assume water enters only through lower half of drain pipe: Ap_{pu} = \frac{1}{2} Ap
12 Use Darcy’s Law to calculate the exit gradient (ix) at the pipe perforations assuming no envelope: ix = q_{lmax}/(Ks Ap_{pu})

\[ ix > HFG \]

An envelope will be required, for further selection see Figure 8

Consider a voluminous envelope to reduce entrance resistance. Ke_{env} and envelope thickness are primary design criteria (Figure 8)

Figure 7 Flow chart to determine the need for an envelope.
Closely related to the clay percentage indicator is the use of the Plasticity Index (PI) method (Dieleman and Trafford, 1976), this in itself is an indicator of soil stability. It was found that when the PI > 12 a filter for the purpose of retaining fine particles was not necessary. The same source reports the use of the Coefficient of Uniformity \( \left( C_u \right) \) also as a possible indicator; when \( C_u > 15 \) there is no need for a filtering envelope. This last indicator cannot be used in many cases, as most agricultural soils do not have such high \( C_u \) values. Nevertheless, it is a parameter that is readily available when particle size distribution analysis has been performed, and hence it can be considered in the overall assessment.

When the representative saturated hydraulic conductivity of the soils is between 0.02 m/d and 4.5 m/d, the Hydraulic Failure Gradient (HFG) method is useful for determining the envelope need as well as the selection of the type of drain envelope. At present the HFG method has really only been proven for Utah and Michigan soils (Figure 43), although research in Egypt is underway to test the applicability to Nile Delta soils. The uniformity coefficients of Utah soils are generally higher than most other soils that have been tested for drain envelopes or in which envelopes have been applied (Figure 43, p 148, Figure 79 and 80, p 259, 262). Since the HFG method may be the only one that is globally applicable it is recommended for use as one of the guidelines to determine the need for envelopes. HFG is compared with the expected exit gradient \( i_x \) at the pipe-soil and the envelope-soil interfaces: a smaller HFG of the soil indicates that an envelope is needed.

The HFG method is applied as follows:

1. Determine the possible maximum discharge \( Q_{d_{\text{max}}} \) as function of the hydraulic conductivity of the soil \( K_s \), the midpoint water table height above drain level \( H_{\text{max}} \) taken at the land surface (so not the design water table depth but rather the maximum head above the drain, which in many cases means equal to drain depth, that will cause the maximum gradient, \( i_{\text{max}} \) shown in Figure 6), and the drain spacing \( S \) from the Hooghoudt equation (with equivalent depth) or other drain spacing equation, e.g.:

\[
Q_{d_{\text{max}}} = q_{d_{\text{max}}} * S * L = \frac{8K_1d_e(h + d_{\text{wtd}}) + 4K_2(h + d_{\text{wtd}})^2}{S^2} * S * L \quad \text{Eq. 3}
\]

where,

- \( Q_{d_{\text{max}}} \) is the maximum possible discharge under free flow conditions in the drainpipe (m³/d);
- \( q_{d_{\text{max}}} \) the maximum possible discharge per unit area (m/d);
- \( S \) drain spacing (m);
- \( L \) drain length (m);
2. Calculate the exit gradient either at the soil-pipe interface (no envelope) or the soil-envelope interface, using appropriate opening size and permeability coefficients, assuming the validity of the Darcy equation for the situation (Sections 5.1.3 and 5.1.4). For example, the discharge per unit length is:

\[ q_{lmax} = q_{dmax} \times S = \frac{Q_{dmax}}{L} \]  \hspace{1cm} \text{Eq. 4}

where,
\[ q_{lmax} \text{ in } m^3d^{-1}m^{-1} = m^2/d, \text{ and} \]
\[ i_x = \frac{q_{lmax}}{K_2A_{pu}} \]  \hspace{1cm} \text{Eq. 5}

where,
\[ K_2 \text{ may be taken as } K_s \text{ at drain depth; and} \]
\[ A_{pu} \text{ actual area of inflow into the drainpipe (m}^2/m, \text{ section 5.1.4).} \]

3. Calculate the HFG using Eq. 34 (Section 5.3). The HFG formula should only be used if \( 0.02 < K_s < 4.5 \text{ m/d} \). If \( K_s \text{ is outside this range, use the other criteria (such as percent clay, PI, C_u and local field experience to determine the envelope need.} \)

4. Compare the HFG and \( i_x \). If \( i_x > \text{HFG} \) then an envelope will be needed.

Note, even if a filtering envelope is not needed (Figure 7), it is still advisable to calculate the exit gradient and compare it with the HFG. If the exit gradients are high, this indicates high entrance resistance, which is not desirable (see Section 5.1). Here, HFG is not used as a measure of stability (actually \( K_s \) is probably smaller than the 0.02 m/d) but merely as a boundary to limit exit gradient and the dependent entrance head loss. Close perusal of the calculation of the exit gradient will show that the exit gradient is independent of \( K_s \) in the methodology outlined above. This is because \( K_s \) is used to determine the
maximum drain discharge, and subsequently the same value is used again in
the Darcy equation; eliminating the $K_s$ in the final determination of the exit
gradient. For reasons of clarity the $K_s$ has been left in the methodology, since
it is needed to determine HFG. Rather than using the HFG as the limit for
acceptable gradients, the ratio of entrance head loss to the midway head loss
has been suggested as a possible indicator. However, as this indicator is so
dependent on site (spacing, drain depth) and location (country preferences),
we suggest not using it.

Box 7 Method to determine equivalent depth.

The equivalent depth can be calculated from the following formulas (Ritzema 1994):

$$d_e = \frac{\pi S}{8}$$

$$S = \frac{\ln}{\pi r_o} + F(x)$$

where,

$$x = \frac{2\pi D}{S}$$

and

$$F(x) = \sum_{n=1}^{\infty} \ln \coth(nx)$$

where,

- $r_o$, the equivalent radius of the drain trench in m, $r_o = \frac{u}{\pi}$
- $u$, wetted perimeter in m, for pipes in trenches: $b + 2r$
- $b$, width of the trench in m.

The above solutions are based on a series solution of the Hooghoudt equation. Traditionally,
tables were used before calculators included the $\coth(x)$ function. The method assumes drains
running half-full and no entrance resistance and water entrance area equal to the wetted
perimeter.

From the above it would appear that there are five indicator methods for
assessing the need for a drain envelope: the clay and SAR method; the clay
percentage method; the PI method; the $C_u$ method; and the HFG method. In
Figure 7 these methods have been aligned sequentially, so that once a method
has been used it should not be necessary to backtrack. This, however, needs
verification as the methods have never before been presented together (Table 4). In particular, the clay and SAR method and the position of the PI and $C_u$ methods at the end of the line might raise questions.

Table 4  Limitations of methods to assess envelope need.

<table>
<thead>
<tr>
<th>Method</th>
<th>Limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay and SAR method</td>
<td>Reported since 1995 (Rajad Project staff 1995) but not much field data</td>
</tr>
<tr>
<td></td>
<td>available in the literature. SAR value &gt; 8-12 may occur with clay % &gt;</td>
</tr>
<tr>
<td></td>
<td>40% or clay % &lt; 25%. Nothing is reported on these ranges. Also electrical</td>
</tr>
<tr>
<td></td>
<td>conductivity of the soil played a role, but is not further specified.</td>
</tr>
<tr>
<td>Clay method</td>
<td>Few hard data available and results reported from the Netherlands and</td>
</tr>
<tr>
<td></td>
<td>Egypt are partially based on personal (albeit long-term) experience of</td>
</tr>
<tr>
<td></td>
<td>authors referenced in articles. No data sets since early to mid-1980s</td>
</tr>
<tr>
<td></td>
<td>presented in the literature that show unambiguous boundary values. In</td>
</tr>
<tr>
<td></td>
<td>arid climates soils are less stable than in humid climates and clay</td>
</tr>
<tr>
<td></td>
<td>content alone may not be enough as indicator of soil stability $\rightarrow$</td>
</tr>
<tr>
<td></td>
<td>HFG method and inclusion of SAR in the judgements.</td>
</tr>
<tr>
<td>PI method</td>
<td>No limitation reported, little actual field data available in the literature. Since 1957 (Sherard 1957) and 1976 (Dieleman and Trafford, FAO 28).</td>
</tr>
<tr>
<td>$C_u$ method</td>
<td>Few agricultural soils seem to have $C_u$ values greater than 15. $C_u$ values are generally not reported in the literature in this context; little data presented since 1976 (FAO 28).</td>
</tr>
<tr>
<td>HFG method</td>
<td>Only tested in Utah and Michigan (USA) with 0.02 &lt; $K_s$ &lt; 4.5 m/d.</td>
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</tbody>
</table>