Chapter 3

Envelope materials

Porous material placed around a subsurface drain, to protect the drain from sedimentation and improve its hydraulic performance, should be referred to as a drain envelope. It is worthwhile to distinguish between the definition and function of an envelope and that of a filter.

During the early development of design criteria for drain envelopes, existing filter criteria were often used as a basis for research. Hence, the word 'filter' is often mistakenly used in reference to drain envelopes. A filter is by definition 'a porous substance through which a gas or liquid is passed to separate out matter in suspension' (Merriam-Webster, 1993). Filtration also is defined as 'the restraining of soil or other particles subjected to hydraulic forces while allowing the passage of fluids' (ISO 10318, 1990). Hence, a *filter*, used as a drain envelope, would eventually become clogged because particulate matter would be deposited on or in it, reducing its permeability.

Envelopes have the task to improve the permeability around the pipe, and act as permeable constraints to impede entry of damaging quantities of soil particles and soil aggregates into drainpipes. Yet the majority of small particles of soil material and organic matter, suspended in water moving toward a drain, will actually pass through a properly selected and installed drain envelope without causing clogging. The relatively coarse envelope material placed around the drain should stabilize the soil mechanically and hydraulically, but should not act as a filter.

In addition to the functions described above, drain envelopes can improve the bedding conditions. This bedding function is primarily associated with gravel envelopes in unstable soils. Gravel provides a mechanical improvement in the drain-envelope-soil system, serving as bedding and side support for large diameter plastic pipes (Framji *et al.*, 1987).

Envelope materials used to protect subsurface drains have included almost all permeable porous materials that are economically available in large quantities. Based on the composition of the substances used, they can be divided into three general categories: mineral, organic, and synthetic envelopes.

MATERIALS

Granular mineral envelopes

Mineral envelopes mainly consist of coarse sand, fine gravel and crushed stone, which are placed under and around the drainpipe during installation. If well designed and installed, mineral granular envelopes are quite reliable because they are voluminous and can store comparatively large quantities of soil material without noticeable malfunctioning. As such, they have provided satisfactory long-term service under most circumstances. Traditionally, pit run naturally graded coarse sand or fine gravel containing a minimum of fines is the most common and widely used drain envelope material. Such material can be as permanent as the soil itself. Properly designed graded gravel envelopes fulfil all the mechanical and hydraulic functions of a drain envelope and are the ideal envelope from a physical standpoint.

Graded gravel should be a homogeneous, well-graded mixture of clean sand and gravel free from silt, clay, and organic matter, which could adversely affect its permeability. The use of limestone particles must be avoided, because a high percentage of lime in gravel envelopes is a source of incrustation. In addition, the gradation of a gravel envelope should be made in accordance to prescribed parameters (Section *Specifications for gravel envelopes*).

The use of gravel as drain envelope has become a bit controversial. One of the conclusions of a symposium held in Wageningen, The Netherlands in 1986 was the following: ‘Gravel remains for the time being the most reliable filter material. In view of the cost of gravel the development of design criteria for synthetic materials merits the highest priority’ (Vos, 1987). However, at a conference, held in Lahore, Pakistan in 1990 which was devoted specifically to the design and application of envelopes, it was concluded that engineers who were not familiar with synthetic envelopes, were reluctant to recommend their use (Vlotman, 1990). Considering the current tendency, it may be assumed that synthetic envelopes will gradually replace the application of gravel as envelope material in future drainage projects.

Organic envelopes

Organic materials, many of which are by-products of agricultural production, have successfully been applied as drain envelopes. They are voluminous, so they can be used in cases where both particle retention and hydraulic function are important. Organic materials may be applied directly on the drainpipe in the trench as loose blinding material, or may be prewrapped around the drainpipe as Prewrapped Loose Materials (PLMs). An intermediate type of application has been in strip-form, applied on top of the drainpipe. This type of application is now obsolete.

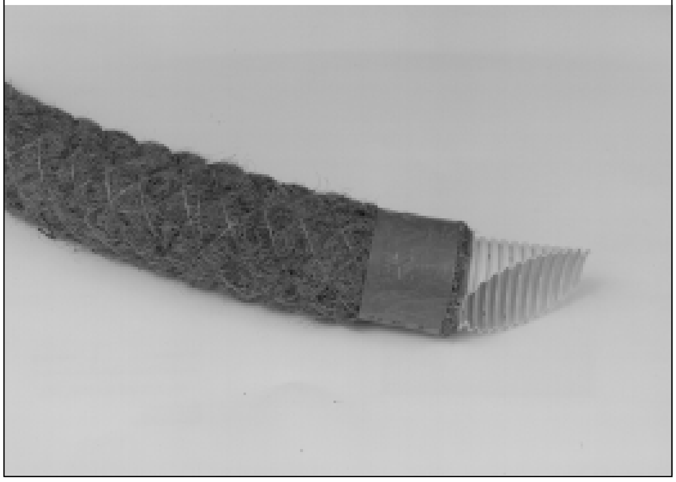
Organic envelope materials include chaff, cereal straw, flax straw, rice straw, cedar leaf, bamboo, corncobs, wood chips, reeds, heather bushes, chopped flax, flax stems, grass sod, peat litter and coconut fibre (Juusela, 1958; Framji *et al.*, 1987).

In northwestern Europe (Belgium, Germany, and The Netherlands), the most common organic envelopes were made from peat litter, flax straw and coconut fibres. The use of fibrous peat litter as a cover layer of drain tiles has been common practice for decades until the end of the 1950s. It was found that the hydraulic conductivity of the peat litter would often decrease drastically due to swelling of the envelope under permanently wet conditions due to e.g. subirrigation (Rozendaal and Scholten, 1980).

During the subsequent period, flax straw has been used. It was applied originally as a cover strip and later as prewrapped envelope. The coarseness of the flax envelope did however not always guarantee the particle retention function. On a much smaller scale, other organic envelopes have been applied. These materials were not always available in the required quantities and their handling was often laborious. The use of straw was not successful because it usually decomposed into a low-permeability layer around the pipe.

At the end of the 1960s, coconut fibre (Figure 16) was introduced (Jarman and Jayasundera, 1975). Being relatively cheap, it soon dominated the market because high quality peat litter became scarce and expensive (Meijer, 1973) and because the flax industry declined. Moreover, the finer coconut fibre was considered a more appropriate envelope material than the coarser-

FIGURE 16
Coconut fibre PLM envelope



structured flax straw. Very soon it was discovered that coconut fibres were often subject to microbiological decay (Meijer and Knops, 1977; Antheunisse, 1979, 1980, 1981). The envelopes were usually fully decomposed after two to five years, particularly if the pH of the soil exceeded the value 6. More than a decade later, many farmers complained about mineral clogging of their drains. A research project was set up to investigate the problem of mineral clogging. More than 1000 excavations were made and they confirmed that the mineral clogging problems, although partly due to the large effective pore size of the coconut fibre envelope, mainly resulted from the decomposition of the organic substances (Blom, 1987).

In the mid-1980s, various attempts were made to retard or stop the decomposition of organic envelope materials. In Germany and in France a so-called ‘Super-Cocos’ envelope was introduced. Its fibres were impregnated with copper sulphate ($CuSO_4$), to kill the bacteria that cause the decomposition (Antheunisse, 1983, 1984). In addition, some envelopes contained tiny copper wires. ‘Super-Cocos’ envelopes had limited success because decomposition was postponed for a few years only. In addition, environmental legislation made installation of ‘Super-Cocos’ illegal in most countries, because the chemical agent leached out rapidly. Coconut fibre envelopes are still being applied in northwest Europe due to their comparatively low price, but their use is declining in favour of synthetic materials.

Organic envelopes have never been popular in countries located in arid climates because the comparatively high soil temperature activates microbiological activity and consequently accelerates their decay. In the irrigated lands of the arid tropics, organic envelope materials usually fail (Van der Molen and Van Someren, 1987). The successful application of organic envelopes in the Scandinavian countries, where mainly fibrous peat and wood chips were used, was due to the reduced microbiological activity at lower soil temperatures.

The service life and suitability of organic materials as envelopes for subsurface drains cannot be predicted with certainty. Eventually, the majority of organic envelopes will decompose, without any serious impact on the structural stability of the surrounding soil. Hence, these materials should be applied only in soils that become mechanically stable within a few years after installation of the drainage system (Van Zeijts, 1992). In addition, organic envelopes may affect chemical reactions in the abutting soil. This process may result in biochemical clogging of the drain. If iron ochre clogging of drains is likely, reluctance with the application of organic envelopes is justified. Even organic matter that is accidentally mixed with trench backfill material may severely enhance the risk of ochre clogging of the drain (Chapter 5).

The rapid decay of coconut fibre envelopes has stimulated the search for affordable, synthetic alternatives. The fact that synthetic envelopes can be more easily manufactured according to specific design criteria than organic ones has played a significant role in this development.

Synthetic envelopes

Prewrapped loose materials

A synthetic PLM is a permeable structure consisting of loose, randomly oriented yarns, fibres, filaments, grains, granules or beads, surrounding a corrugated drainpipe, and retained in place by appropriate netting and/or twines. Synthetic PLM envelopes are usually wrapped around the corrugated plastic drainpipes by specialized companies and occasionally in pipe manufacturing plants. The finished product must be sufficiently strong to resist handling and installation without damage.

Synthetic PLMs include various polymeric materials. Fibres may be made of polyamide (PA), polyester (PETP[1]), polyethylene (PE), and polypropylene (PP). Loose polystyrene (PS) beads can be wrapped around drains as PLMs in perforated foil or in string netting (‘geogrids’ or ‘geonets’). The beads are subject to compression from soil loads that may reduce envelope permeability (Willardson *et al*., 1980). In various European countries where the drain depth ranges from 0.9 to 1.2 m, the effect of the soil load is however relatively small. PLM envelopes made from PP (waste) fibres are increasingly used in northwest Europe and in arid areas where they replace expensive gravel.

FIGURE 17
PLM envelope made from polypropylene waste fibres (PP-300)

Information on some envelope materials, which are shown in Figures 17-20, is given below. Figures concerning the market shares of various envelope materials (‘turnover’) are given for The Netherlands, in 1997, for illustrative purpose only. The data are based upon the *installed lengths* of wrapped drainpipes.

PLM envelopes made from polypropylene waste fibres (PP-300) (Figure 17) are installed almost exclusively in Belgium for private drainage projects (turnover: 6 percent).

FIGURE 18
PP-450 envelope

PP-450 envelope (Figure 18) is a PLM envelope, manufactured from bulk continuous filaments. These filaments are waste when producing woven PP fibre carpets. In The Netherlands, it is by far the most popular envelope material (turnover: 65 percent).

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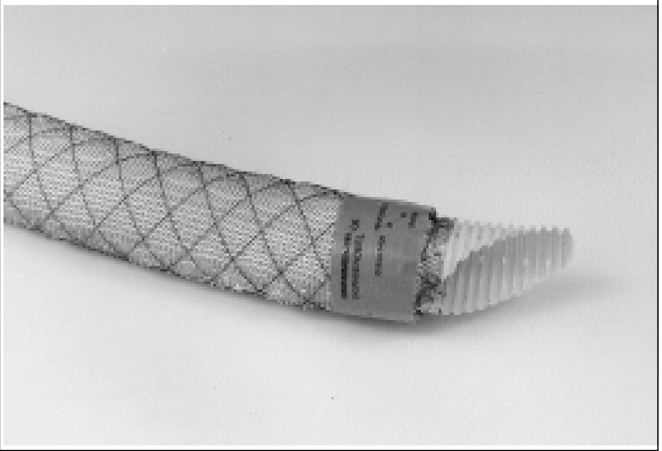
[1] ‘PETP’ is an acronym for polyethylene terephtalate.

PP-700 envelope is a PLM material, made from new PP fibres (Figure 19). Wrapping of pipes with this envelope is comparatively laborious, hence the high price (turnover: 4 percent). It is mainly used for larger pipe diameters (exceeding 160 mm).

FIGURE 19
PP-700 envelope

Due to the declining availability of PP waste fibres at competitive prices, waste PA fibres are used occasionally. Contrary to PP fibres, PA fibres absorb water as a result of which the coils may substantially increase in weight. In addition, it is more difficult to process PA fibres to homogeneous prewrapped envelopes because of problems with static electricity.

FIGURE 20
PS-1000 envelope



PS-1000 is a PLM envelope material that is manufactured from compressible PS beads in netting (Figure 20) and almost exclusively installed in agricultural areas where flower bulbs are grown (turnover: 7 percent). In these areas, the groundwater contains a relatively high amount of suspended particles, and PS-1000 has proven a very reliable envelope. In this application, the higher price of PS-1000 is a good investment; no farmer can afford to have drainage systems fail.

Synthetic materials deteriorate when exposed to solar (UV) radiation. Experiments with PLM envelopes, made of PP fibres in a temperate climate have indicated that deterioration can be hazardous within three years (Dierickx, 1998b). The speed of the deterioration will be double in semi-arid and arid regions where the average annual radiation is twice that in temperate regions. However, once installed, synthetic PLM envelopes, manufactured from suitable raw material (e.g. recycled PP fibres) are not subject to decomposition. These materials are therefore reliable and affordable substitutes for conventional gravel and organic envelopes.

Prewrapping with loose materials is limited to diameters of 200 mm or smaller. Once prewrapped around drains, PLM envelopes have functional properties that are similar to those of geotextiles.

Geotextile envelopes

According to prEN[2] 30318 (1998), a geotextile is defined as ‘a planar, permeable, polymeric (synthetic or natural) textile material, which may be woven, non-woven or knitted, used in contact with soils and/or other materials in civil engineering for geotechnical applications’. This definition includes application in agriculture since civil engineering incorporates drainage engineering in many countries.

Woven geotextiles are manufactured by interlacing, usually at right angles, two or more sets of yarns, fibres, filaments, tapes, or other elements. Non-woven geotextiles are sheets, webs, or batts, consisting of directionally or randomly oriented fibres, filaments, or other elements. These elements are bonded by mechanical, thermal and/or chemical means. Knitted geotextiles are manufactured by interlooping one or more yarns, fibres, filaments, or other elements.

The fibres, used for production of geotextiles are made from the same raw materials as those used for PLMs, namely: polyamide (PA), polyester (PETP), polyethylene (PE), and polypropylene (PP). The fibres of geotextiles may be monofilaments, multifilaments or tapes; the latter either flat, fibrillated or twisted. The combination of raw materials, fibre configuration and weaving, bonding or knitting techniques results in many types of geotextiles which differ widely in appearance, physical, mechanical and hydraulic properties.

In principle, geotextiles may be used as envelope material for drainpipes because they possess two important properties that are required for a drain envelope, namely water permeability and soil particle retention. Moreover, they facilitate the water acceptance of drainpipes, and they convey water in their plane, alongside the pipe wall. Woven geotextiles, however, are seldom used for the manufacturing of drain envelopes. The only justification for this fact must be their comparatively high price, because their specifications are indeed favourable.

In some European countries where organic and synthetic PLMs are used, there is persistent reluctance to use geotextiles as drain envelope because it is argued that their fine texture may enhance mineral and ochre clogging. Yet in countries with a geotextile industry like France, Canada and the United States, geotextile envelopes are applied successfully at a large scale. Laboratory experiments, field trials and practical experiences do not give clear evidence of the clogging risk of properly selected and properly installed fine textured geotextiles. There are, however, circumstances where fine textured geotextiles should preferably not be used (see Chapter 5).

FIGURE 21
Typar envelope

An example of a geotextile envelope is *Typar* which is the brand name of a non-woven fabric, made of continuous filaments of 100 percent polypropylene without any extraneous binders (Figure 21).

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[2] prEN is a draft European standard (EN) that is not yet finalized.

Wrapping of drains with geotextiles can be done for any diameter. Geotextile strips can be tied around the corrugated drain, or pulled over it after the edges have been sewn together.

Geotextiles that are exposed to solar natural weathering are also vulnerable to degradation. Rankilor (1992) recommends that exposure of geotextiles to natural weathering may not last longer than two months in temperate regions and only one week in arid and semi-arid regions. Geotextiles, manufactured from organic raw material such as jute will decay in a similar fashion as organic PLMs do, while synthetic geotextiles, like synthetic PLMs, do not.

SPECIFICATIONS FOR DRAIN ENVELOPES

In 1922, Terzaghi developed 'filter' criteria to control seepage under a dam. These criteria have since been tested for applicability for envelopes around subsurface drains. Terzaghi recommended that the 'filter' material be many times more pervious than the soil base material but that it not be so coarse that the base material would move into the 'filter'. Terzaghi's development has served as a basis for much work done since that time on gravel envelope design. For drain envelopes, his design criteria have been tested and modified, but his original concepts have been generally accepted.

Van Someren (FAO, 1972) reported on the research into and the guidelines for selection and application of drainage materials (pipes and envelopes) in various countries. In Belgium and The Netherlands, efforts were made to develop special design criteria for prewrapped loose materials (PLMs). Conventional design criteria were largely determined by analogue models in laboratories, supported by theoretical considerations, and verified by field trials. Monitoring the flow of water and soil particles near prewrapped drainpipes in the field was not an easy task without disturbing the system. In addition, the data, emerging from field experimentation are inevitably blurred because it is site specific. Results achieved at some places are not necessarily replicable at other locations.

Knops *et al*. (1979) published the first set of comprehensive guidelines for the selection of the then used prewrapped envelopes for use in Dutch soils. Subsequently, a series of research projects and concurrent practical evaluations, carried out by various companies and institutions, have produced design and application criteria for drain envelopes made of PLMs in The Netherlands (Huinink, 1992; Stuyt, 1992a; Van Zeijts, 1992). Many field surveys have been made into the possible factors that affect pipe sedimentation.

Drain envelopes should meet specifications but visual evaluation of materials is also important. Even if the best materials have been used and all specifications are met, a drainage system will not operate properly if envelopes exhibit some shortcomings due to careless wrapping, handling or installation.

Specifications for gravel envelopes

Specifications for gravel envelopes are discussed extensively in numerous publications. This section contains all the major issues. Sound design criteria for traditional granular envelopes (gravel and coarse sand) are available and have been applied successfully in practice (Terzaghi and Peck, 1961; Vlotman *et al*., in press; Stuyt and Willardson, 1999).

The US Army Corps of Engineers and the US Bureau of Reclamation have made extensive studies of gravel envelopes. The result is a set of specifications for graded gravel envelopes, which have been successfully used by the Soil Conservation Service (SCS, 1973), the US Bureau of Reclamation (USBR, 1993) as well as outside the United States.

The gradation curve of a proposed gravel envelope should be matched to the soil to be drained, as well as to the pipe perforations (Willardson, 1979). In addition, gravel should be internally stable to avoid internal envelope erosion. The general procedure for designing a gravel envelope for a given soil is as follows:

1. make a mechanical particle size analysis of both the soil and the proposed gravel envelope;
2. compare the two particle size distribution curves; and
3. decide, by some design criterion, whether the proposed gravel envelope material is suitable.

The involved design criteria consist of rules that prescribe how to derive the particle size distribution, required for a suitable gravel envelope, from particle size distribution data of the soil, in order to guarantee satisfactory service of the envelope.

Terzaghi's criteria

The first criteria, proposed by Terzaghi (US Army Corps of Engineers, 1941) for what he termed a 'filter', are:

- The particle diameter of the 15 percent size of the filter material (D_{15})[3] should be at least four times as large as the diameter of the 15 percent size of the soil material (d_{15}):

  $$D_{15} \geq 4\, d_{15}$$

  This requirement would make the filter material roughly more than ten times as permeable as the soil.

- The 15 percent size of the filter material (D_{15}) should not be more than four times as large as the 85 percent size of the soil material (d_{85}):

  $$D_{15} \leq 4\, d_{85}$$

  This requirement would prevent the fine soil particles from washing through the filter material.

Bertram (1940), Karpoff (1955), and Juusela (1958) suggested similar or modified 'filter' design criteria for use with subsurface drains.

Criteria of the US Soil Conservation Service

The SCS (1971) has combined the results of the research on gravel envelopes into a specification for evaluating pit run and artificially graded granular materials for use as drain envelope materials. These specifications are superseded by more recently published specifications (SCS, 1988), which distinguished between 'filter' and 'envelope'. The recommendation for naturally graded materials or a mixture of medium and coarse sand with fine and medium gravel for use as envelope is:

- $D_{100} \leq 38$ mm.
- $D_{30} \geq 250$ µm.
- $D_5 \geq 75$ µm.

Additional criteria are suggested to prevent excessive fineness of an envelope material, designed to be used for finer textured soils (SCS, 1988):

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[3] The particle diameter D_x of the x percent size by weight of the filter material is defined as the diameter sieve where x percent passes. This also holds for the soil parameter d_x.

- $D_{15} < 7\ d_{85}$ but $D_{15} \geq 0.6$ mm.
- $D_{15} > 4\ d_{15}$.

Criteria of the US Bureau of Reclamation

For rigid, unperforated pipes, the US Bureau of Reclamation treats the joint opening, the length of the pipe section, and the hydraulic conductivity of the envelope material as a unified system. Their Drainage Manual (USBR, 1978, 1993) contains graphs which consider all these factors. Table 1, taken from this manual, gives recommended envelope gradations for soils with different 60 percent passing sizes.

TABLE 1
Gradation relationships between soil and diameters of graded granular envelope material (after USBR, 1978, 1993)

Soil, 60% passing (diameter of particles, mm)	Gradation limitations for envelope (diameter of particles, mm)											
	Lower limits, percentage passing						Upper limits, percentage passing					
	100	60	30	10	5	0	100	60	30	10	5	0
0.02-0.05	9.52	2.0	0.81	0.33	0.3	0.074	38.1	10.0	8.7	2.5	-	0.59
0.05-0.10	9.52	3.0	1.07	0.38	0.3	0.074	38.1	12.0	10.4	3.0	-	0.59
0.10-0.25	9.52	4.0	1.30	0.40	0.3	0.074	38.1	15.0	13.1	3.8	-	0.59
0.25-1.00	9.52	5.0	1.45	0.42	0.3	0.074	38.1	20.0	17.3	5.0	-	0.59

For some fine-textured and salty problem soils in Pakistan, the USBR criteria produced gravel envelopes that were obviously too coarse, allowing excessive amounts of fine soil materials to enter the drains (Vlotman *et al.*, 1990).

Other criteria

Since the design of gravel packs for wells is similar to the design of envelopes for subsurface drains, the criteria developed by Kruse (1962) for gravel packs may also be used for gravel envelopes. These criteria are based on the ratio of the 50 percent size of the pack (envelope) material to the 50 percent size of the aquifer (soil) and on the uniformity of the textural composition (see Chapter 6, Section *Physical properties of the soil*) of both the aquifer and the gravel. Kruse (1962) observed that sand movement was reduced by decreasing the uniformity of the gravel (i.e. increasing its uniformity coefficient) at all gravel-aquifer ratios and therefore distinguished between uniform soil and gravel pack up to a uniformity coefficient of 1.78 and non-uniform soil and gravel pack for larger values. The proposed maximum permissible gravel/aquifer particle size ratios for the various combinations of textural composition of both the aquifer and the gravel pack, to prevent excessive movement of aquifer material, are given in Table 2.

TABLE 2
Largest permissible gravel/aquifer size ratios
(after Kruse, 1962)

Textural composition of aquifer	Textural composition of gravel pack	Gravel/aquifer particle size ratio (D_{50}/d_{50})
Uniform (unstable)	Uniform (unstable)	9.5
Uniform (unstable)	Non-uniform (stable)	13.5
Non-uniform (stable)	Uniform (unstable)	13.5
Non-uniform (stable)	Non-uniform (stable)	17.5

Besides the 50 percent ratio of filter to aquifer material, Pillsbury (1967) also used the standard deviation resulting from the difference between the 95 percent and 50 percent sizes of the grading curve of the gravel envelope divided by 1.645, as a criterion for its effectiveness. Pillsbury (1967) presented a graph of the 50 percent size ratio envelope-aquifer vs. this standard deviation which was divided in two zones. Envelopes that fall below the limit line were judged unsatisfactory. Based on observations of some drain envelopes that had failed in the Imperial Valley of California, Pillsbury recommended an envelope-aquifer ratio of less than 24. He concluded that concrete sand, satisfying the appropriate American Society for Testing and Materials (ASTM) standard with a 50 percent size less than 1 mm and a standard deviation greater than 1.0 would be a satisfactory envelope material under most conditions.

Sherard *et al.* (1984a, b) developed filter criteria for protection of hydraulic structures. While not intended for application in subsurface drainage, the principles may equally well be applied for the design of gravel envelopes. The authors established that if a filter did not fail with the initial flow of water, it was probably permanently safe. Well-graded materials were more successful than uniform materials.

Sherard *et al.* (1984b) reported on tests with fine textured soils and concluded the following with respect to filter and base soil sizes:

- Sandy silts and clays (d_{85} of 0.1 - 0.5 mm) $D_{15}/d_{85} \leq 5$ is safe.
- Fine-grained clays (d_{85} of 0.03 - 0.1 mm) $D_{15} < 0.5$ mm is safe.
- Fine-grained silts of low cohesion (d_{85} of 0.03 - 0.1 mm) $D_{15} < 0.3$ mm is safe.
- Exceptionally fine soils ($d_{85} < 0.02$ mm) $D_{15} < 0.2$ mm or smaller is safe.

Sands and gravely sands containing fine sand fractions and having a D_{15} of 0.5 mm or less would be a suitable filter for even the finest clays. For clays with some sand content ($d_{85} > 1.0$ mm), a filter with a $D_{15} = 0.5$ mm would satisfy the $D_{15}/d_{85} \leq 5$ criterion. For finer clays, the $D_{15}/d_{85} \leq 5$ is not satisfied, but the finer soils tend to be structurally stable and are not likely to fail. Finally, Sherard et al. (1984b) found that well-graded gravely sand was an excellent filter for very uniform silt or fine uniform sand, and that it was not necessary that the grading curve of the envelope be roughly the same shape as the grading curve of the soil. Gravel envelopes that have a D_{15} of 0.3 mm and a $D_{15}/d_{85} \leq 5$ with less than 5 percent of the material finer than 0.074 mm will be satisfactory as envelope materials for most problem soils.

Dieleman and Trafford (FAO, 1976) reviewed criteria for selection of gravel envelope materials and included some comments regarding envelope selection for problematic soils. Dierickx (1992b) presented a summary of gravel envelope criteria from the United States and the United Kingdom. This summary clearly indicates that the criteria from various sources do not match, even if one takes into account the difference between ‘filter’ (mechanical) function and ‘envelope’ (hydraulic) function. This fact has prompted new research projects that have yielded new findings, i.e. improvements of existing criteria, which may be used to improve the design gravel envelopes (Vlotman *et al.*, 1997). Another finding of interest was that rounded and angular particles gave equivalent results (Vlotman *et al.*, 1992b).

Specifications for prewrapped envelopes

Prewrapped envelopes may be organic PLM, synthetic PLM and geotextile. Their physical properties such as thickness and mass per unit of surface area are important to check the uniformity of the envelopes, and their conformity with the required design standards. Characteristic opening size, hydraulic conductivity and water repellence determine the hydraulic properties of prewrapped envelopes. When using loose granular materials, particle size distribution parameters may be used as well. Depending on what kind of drain pipes is used and how envelope materials are wrapped around drainpipes, some mechanical properties of envelopes such as compressibility, abrasion damage, tensile strength and static puncture resistance may be part of the specifications.

In The Netherlands, recommendations for the design and application of PLMs have been developed on the basis of concurrent research projects, theoretical studies, mathematical modelling, empirical studies in experimental fields, analogue modelling in laboratories and practical experience covering a 30-year period (1960-1990) (Stuyt, 1992a).

Thickness

The *thickness* of prewrapped envelopes serves as a reference for uniformity and conformity. In addition, envelope thickness is found a factor of importance in theoretical analyses as it influences the soil retention capacity, the entrance resistance of drainpipes and the exit gradient at the soil-envelope interface.

The main task of an envelope is soil particle retention. In this respect, design criteria for envelope thickness are irrelevant. Thicker envelopes, however, may have higher porosities, which explain their popularity when chemical clogging is anticipated. Therefore, in the envelope selection procedure, envelope thickness is an important parameter, and often significant in terms of safety.

The thickness of an envelope should be a relevant specification if reduction of entrance resistance is envisaged or if reduction of entrance resistance is the only objective to use an envelope (see Chapter 4, Section *Entrance and approach flow resistance*). Although a thin envelope may substantially reduce the entrance resistance, the optimal reduction is obtained at a thickness of 5 mm, provided that the hydraulic conductivity of the geotextile is not the limiting factor, which will generally not be the case (Nieuwenhuis and Wesseling, 1979; Dierickx, 1980). A further increase of thickness has no marked influence on the entrance resistance, although the effective radius continues to increase since a comparatively permeable envelope replaces soil material that is usually less permeable.

When envelopes are used to reduce the exit gradient (see Chapter 4, Section *The exit gradient*), the thickness of the envelope is also a relevant design parameter. The design procedure for envelope thickness, as proposed by Vlotman *et al*. (in press) shows that even thin geotextiles (≤ 1 mm) may considerably reduce the exit gradient at the soil-envelope interface. The larger the diameter of a drain, however, the smaller hydraulic gradients near the drain will be. Hence, 'thick' or 'voluminous' envelopes (i.e. thickness > 5 mm) are generally considered to be safer than thin ones, particularly if the drains are occasionally used for controlled drainage or subirrigation (subsurface infiltration).

For PLM, the specification of a minimum thickness was introduced to guarantee a complete cover with a more or less homogeneous envelope. According to the provisional EN-standard (CEN/TC155/WG18, 1994), the following minimum thicknesses are required:

• Synthetic, fibrous PLMs:	3 mm (e.g. PP fibres).
• Synthetic, granular PLMs:	8 mm (e.g. polystyrene beads).
• Organic, fibrous PLMs:	4 mm (e.g. coconut fibres).
• Organic, granular PLMs:	8 mm (e.g. wood chips, sawdust).

The provisional EN-standard further specifies that the mean average thickness of each test piece should not deviate by more than 25 percent from that declared by the manufacturer.

Geotextiles are available from very thin, sheet-like fabrics to rather thick, mat-like materials.

Mass per unit area

The mass per unit area is not a selection criterion and therefore not specified. Mass determination can be carried out as a control measure for uniformity and conformity. According to the provisional EN-standard, the mass also may not deviate by more than 25 percent of the mass specified by the manufacturer in order to safeguard a homogeneous product.

Characteristic opening size and retention criterion

The characteristic opening size, derived from the pore size distribution or porometric curve of the envelope, is the most important selection criterion because it determines the effectiveness of the envelope to retain the surrounding soil material.

The retention of soil particles is normally not a problem since very fine fabrics are available. Laboratory research as well as practical experience, however, have revealed that fine envelopes are vulnerable to mineral blocking and clogging. Blocking of an envelope is a decrease of the number of active openings in an envelope that occurs when it is brought in contact with a soil. Clogging, on the other hand, is a decrease with time of the number of active openings in an envelope due to gradual accumulation of particles inside and on its surface, e.g. by particles suspended in turbid water. Therefore, specifications for envelopes should cover both soil retention criteria and criteria to prevent clogging and blocking of the envelope. Intensive research has resulted in criteria for soil particle retention and in recommendations with respect to the problems of blocking and clogging.

The capability of an envelope to retain the soil material is expressed as a ratio of some characteristic pore size of an envelope to some characteristic particle size of the soil in contact with this envelope. In many countries, the O_{90} is used as the characteristic pore size for organic and synthetic PLMs and geotextiles alike, with a great deal of success.

The O_{90} of a drain envelope is the pore size for which 90 percent of the envelope pores are smaller. The O_{90} value is usually obtained by dry sieving of well-known sand fractions, whereby the envelope itself is installed as a sieve and the retained amount of each fraction is recorded. Wet and hydrodynamic sieving, also applied for this purpose, use graded soil and mostly result in smaller O_{90} values than those obtained with dry sieving.

In 1994, a working group of scientists and engineers in Europe developed a new classification system for PLMs. They introduced three classes of envelopes, depending on the effective opening size of the envelope pores, O_{90}, as follows:

PLM-XF	extra fine	$100\ \mu m \leq O_{90} \leq 300\ \mu m$.
PLM-F	fine	$300\ \mu m \leq O_{90} \leq 600\ \mu m$.
PLM-S	standard	$600\ \mu m \leq O_{90} \leq 1100\ \mu m$.

In the provisional EN-standard (CEN/TC155/WG18, 1994) only two classes, namely PLM-F and PLM-S have been accepted.

In The Netherlands, practical guidelines for envelope application consider three ‘standard’ O_{90} values, namely 450, 700 and 1000 µm, 450 µm being by far the most widely applied, and servicing a great variety of soils. These figures were accepted after Stuyt (1992a), using field data, confirmed evidence of the soundness of the O_{90} parameter. In Belgium, the O_{90} of a PLM envelope should range between 600 and 1000 µm for official drainage works.

A frequently used **retention criterion**, also called filter criterion or bridging factor of an envelope, is the ratio O_{90}/d_{90}. In this ratio, d_{90} is the particle diameter of the soil in contact with the envelope where 90 percent of the particles, by weight, is smaller. Numerous other retention criteria have been proposed in the scientific literature, which have been published in comprehensive tables, by e.g. Dierickx (1993) and Vlotman *et al.* (in press). For the design engineer, however, the number of criteria is confusing, the more so because many criteria are contradictory. This fact is self-explanatory, because the criteria were developed under widely different boundary conditions, using many different techniques, equipment and so forth.

Laboratory experiments have unambiguously indicated that the likelihood of soil particle retention is greater when a fabric is thicker. Hence, the characteristic pore size of an envelope may be larger for thicker envelopes, for equal retention. Indeed, retention criteria are linked to envelope thickness.

From laboratory studies with analogue soil models, Dierickx (1987), and Dierickx and Van der Sluys (1990) derived the following simple retention criteria for subsurface drainage applications:

- $O_{90}/d_{90} \leq 5$ for ‘thick’ envelopes ≥ 5 mm (PLMs).
- $O_{90}/d_{90} \leq 2.5$ for ‘thin’ envelopes ≤ 1 mm (geotextiles).

For envelopes with a thickness ranging between 1 and 5 mm, the O_{90}/d_{90} ratio may be interpolated step-wise (Dierickx, 1992a) or linearly (Vlotman *et al.*, in press). The step-wise approach gives one value of O_{90}/d_{90} for a range of thicknesses and is somewhat more practical than a linear approach which yields a specific value of O_{90}/d_{90} for each thickness.

Retention criteria for thicknesses of PLMs and geotextiles between 1 and 5 mm, according to the step-wise approach are:

- $O_{90}/d_{90} \leq 3$ for thicknesses between 1 and 3 mm.
- $O_{90}/d_{90} \leq 4$ for thicknesses between 3 and 5 mm.

Taking into account the retention criterion of a thin envelope, most problems in subsurface drainage will be prevented by envelopes for which $O_{90} \geq 200$ µm.

Field observations of Stuyt (1992a,b) confirmed, in a large extent, the laboratory findings. Stuyt investigated the relation between the O_{90} size of envelope materials and the thickness of the sediment layer inside the pipes using a miniature video camera five years after their installation. In total, 9634 m of drains were investigated (184 laterals). The pipes had outer diameters of 60 and 65 mm. In The Netherlands, sediment layers exceeding 15 mm are generally not tolerated. The d_{90} size of the soils was approximately 150 µm in most cases. The correlation between the thickness of the sediment layer inside the pipes and the O_{90} size of envelope was significant (Table 3). Regardless of the O_{90} size, voluminous envelopes retained more soil than thin envelopes. Envelopes with larger O_{90} values, i.e. having larger openings, had poorer soil retention properties. The raw material from which the envelopes were manufactured was not significant. Stuyt (1992a) also found that the above-proposed O_{90}/d_{90} ratios were valid for the investigated problem soils. Most of the applied envelopes in the experimental fields had rather high O_{90}/d_{90} ratios (4 to 5).

TABLE 3
Fitted values for pipe sedimentation depth (mm) from a regression model, depending on effective opening size of the envelope pores, O_{90}, and envelope category (thin or voluminous) for observations made at three experimental fields in The Netherlands (after Stuyt, 1992a)

O_{90} (μm)	Experimental field					
	Uithuizermeeden		Valtermond		Willemstad	
	Thin	Voluminous	Thin	Voluminous	Thin	Voluminous
250	2.1	0.9	4.5	0.8	9.7	8.5
500	3.9	2.6	6.3	2.5	11.	10.2
1000	5.6	4.3	8.0	4.3	13.2	11.9

Experiments with turbid water or water charged with soil suspensions indicate that geotextiles are vulnerable to clogging when $O_{90}/d_{90} \leq 1$ (Dierickx, 1990; Faure, 1991). Hence, the ratio $O_{90}/d_{90} = 1$ is the lower limit for soil particle retention, regardless of envelope thickness. The phenomena of blocking and clogging of an envelope are however not so evident, neither in laboratory experiments with soils, nor in field experiments. Therefore, the lower limit $O_{90}/d_{90} \geq 1$ should be considered a recommendation rather than a rigid design criterion.

In the investigation made by Stuyt (1992a), envelopes with O_{90}/d_{90} near 1 had such low sedimentation depths that the envelopes appeared to act as filters. Hence, for thin geotextiles, the O_{90}/d_{90} ratio should preferably be near the upper limit. On the other hand, the upper limit, set to 5 for voluminous envelopes (Dierickx, 1987) appears safe for voluminous PLMs since a maximum sedimentation depth of 15 mm is tolerated in 60 and 65 mm outer diameter pipes (Table 3). In soils with some cohesion and, hence, some structural stability, voluminous envelopes with O_{90}/d_{90} ratios as high as 7 have been applied successfully.

In The Netherlands and in Belgium, the successfully applied retention criterion O_{90}/d_{90} for envelopes was therefore adopted as the major design parameter. Recommendations for envelope applications are also based on some additional considerations (Huinink, 1992; Van Zeijts, 1992) but the O_{90}/d_{90} criterion is the most important one.

In summary, the following retention criteria for both geotextiles and PLMs can be accepted:

$1 \leq O_{90}/d_{90} \leq 2.5$ for envelope thickness ≤ 1 mm.
$1 \leq O_{90}/d_{90} \leq 3.0$ for envelope thickness between 1 and 3 mm.
$1 \leq O_{90}/d_{90} \leq 4.0$ for envelope thickness between 3 and 5 mm.
$1 \leq O_{90}/d_{90} \leq 5.0$ for envelope thickness ≥ 5 mm.
$O_{90} \geq 200$ μm.

In order to minimize the risk of mineral clogging it is recommended that $O_{90}/d_{90} \geq 1$; furthermore, envelopes that have O_{90}/d_{90} ratios near the upper limit of the proposed range of values are generally preferred.

Locally made fabrics such as carpet backing, which satisfies or may satisfy the above requirements after some modifications, are equally suitable as imported geotextiles. They may therefore be trusted as envelope materials.

Hydraulic conductivity

The hydraulic conductivity of envelopes should be greater than that of the soil in order to reduce the entrance resistance of drainpipes, so that no hydraulic pressure will develop outside the envelope. From research work of Nieuwenhuis and Wesseling (1979) and Dierickx (1980) it may be concluded that a substantial reduction in entrance resistance is obtained when $K_e/K_s \geq 10$, where K_e is the hydraulic conductivity of the envelope and K_s that of the soil (see Chapter 4, Section *Drain with envelope*).

The hydraulic conductivity, perpendicularly to or in the plane of envelope, can hardly be a problem because envelopes are much more permeable than the adjacent soil that they have to retain. Even under load, the hydraulic conductivity of compressible envelopes will meet the conductivity requirements.

If, however, envelopes are brought in contact with soil, soil particles may fill pores and partly block their openings as a result of which the hydraulic conductivity at the soil-envelope interface will decrease. In addition, envelopes may clog as a result of particle deposits and/or chemical precipitates, and become less permeable with time. Evaluation of blocking and clogging of envelopes is very difficult. If the lower limit of the retention criteria is taken into account, it may nevertheless be assumed that a favourable hydraulic conductivity ratio is guaranteed.

Water repellence

PLMs do not exhibit wetting problems, yet geotextiles may do and water repellence may be a problem. Water repellence means that a minimum water head is required on top of the geotextile, before water starts to flow through it (Lennoz-Gratin, 1992). Once the water has entered the pipe through the envelope, the repellence problem is solved and will generally not return. Wettability resistance also decreases when the geotextile is brought into contact with a moist soil. Research work carried out by Dierickx (1996a) showed that the wetting problem is mainly an initial problem of dry geotextiles. The initially required head for the majority of the tested geotextiles is smaller than 2 mm. For others, it ranges from 5 to 30 mm; one geotextile required an initial head of 64 mm. Although initial water repellence of envelopes does not seem to be widespread, geotextiles that exhibit this phenomenon should not be used as drain envelope to avoid the risk of soil structure deterioration near the envelope due to the initial stagnation of water.

In accordance with the standard on the determination of resistance to water penetration of textile fabrics ISO 811 (1981), a testing procedure has been adopted in the countries of the European Union, to examine geotextiles on water repellence in a qualitative manner (prEN 13562, 1999).

Mechanical properties

Mechanical properties of envelopes are mostly of secondary importance. Geotextiles used as drain envelope do not present specific problems since they are designed for, and are normally used in more challenging circumstances. Moreover, problems that develop occasionally because of handling (e.g. tearing) can be repaired before installation.

The *compressibility* of compressible envelopes has a major effect on the characteristic opening size and the hydraulic conductivity. The opening size normally decreases in compressed state so that a safety factor is built in automatically. The hydraulic conductivity decreases also, yet the highly permeable nature of the envelope ensures that the hydraulic conductivity ratio is met in compressed state. Moreover, the compressibility of coarser envelopes, composed of coarser fibres, is small. Easily compressible thick envelopes, made of fine fibres should not be used as drain envelope.

Abrasion is the wearing of a part of the envelope by rubbing against another material, either during transportation or installation of wrapped drainpipes. Open spots due to abrasion or whatever other cause, noticed before installation, should be repaired in the field, if they are not out of proportion. Abrasion during installation is less likely to occur because of the short time that the wrapped pipe is routed through the machine.

Geotextiles are wrapped around drainpipes either manually or mechanically; therefore, a certain *tensile strength* is required. Dierickx (1994) proposed a tensile strength of 6 kN/m, determined according to the wide-width tensile test (EN ISO 10319, 1996). Geotextiles must bridge the corrugations of large drainpipes and may not sag between the corrugations under the soil load. Hence, elongation should be limited, but this requirement is only meaningful if the geotextile is tightly wrapped. Since this has never been a practical problem, elongation requirements have never been put forward.

Resistance to static puncture also is only applicable for drains with large corrugations where a tightly wrapped geotextile bridges the corrugations. The geotextile should withstand the soil load between the corrugations, and puncturing by stones and hard soil clods. These phenomena are simulated by a static puncture test. Through this test, the force required to push a flat plunger through a geotextile can be determined. Since such a problem has never occurred in subsurface drainage so far, no requirements exist.

AVAILABILITY AND COST

Cost and availability of drainage materials are strongly interrelated. Costs vary continuously since these are dependent on various, partly unpredictable factors like currency exchange rates and the cost of manual labour. For reference, various indications of the cost of drainage materials are given in this Chapter.

The cost of gravel envelopes is not specified here because the local availability of suitable granular material is rapidly declining. In addition, the cost of installation is strongly dependent on local circumstances. In the Integrated Soil and Water Improvement Project (ISAWIP) in Egypt, local gravel envelopes were four times as expensive as imported Canadian synthetic fabric envelopes (Metzger *et al.*, 1992). In the Fourth Drainage Project of the International Waterlogging and Salinity Research Institute (IWASRI) of Pakistan, the cost of synthetic envelopes was found to be 40 percent lower than that of gravel envelopes. Installation of synthetic envelopes was easier and faster, too (IWASRI, 1997). Thus, even if the price of gravel is competitive, it goes hand in hand with high costs of fuel and manual labour. It is therefore irrelevant to consider the price of the raw material only. Vlotman *et al.* (in press) quote costs of gravel envelopes (material and transport) in various projects in Pakistan. For all projects, the costs of material and shipping of synthetic materials was below the cost of gravel. Unfortunately, the high cost of gravel installation compared to that of installing prewrapped pipes is not included in this analysis. The cost/benefit ratio is certainly in favour of PLM envelopes and geotextiles.

PLM envelopes, manufactured from PP fibres and coconut fibres dominate the market in northwestern Europe. PLM envelopes, manufactured from peat fibres are now used only occasionally.

An indication of the cost of drainage materials, i.e. pipes and PLM envelopes, in The Netherlands is given in Table 4. Absolute prices are not given. Instead, the relative cost of pipe and envelope material is specified for various pipe diameters and envelope materials. The figures are based upon corrugated PVC pipe, and are quoted for contractors with high rates of turnover. The price of installation of one metre of wrapped drainpipe more or less equals that of one metre of unwrapped 60 mm pipe.

From Table 4, it can be seen that the price of even the cheapest PLM envelope comprises a substantial part of the price of a pre-wrapped pipe. This is particularly true for smaller diameter pipes. In 1998, there was a slight upward tendency of the price of polypropylene waste fibres in The Netherlands. These fibres are no longer available in such huge quantities as they used to be in the past. Dutch pipe wrapping companies are experimenting with other synthetic waste materials in an effort to be able to market competitive envelopes in the years to come.

TABLE 4
The relative cost of PLM envelopes, expressed as a percentage of the cost of the envelope plus a corrugated PVC pipe together as a prewrapped product, in The Netherlands in 1998. The cost of installation is not included. The O_{90} size is specified within brackets

		Relative cost of various envelope materials								
Pipe diameter (mm)	Coil length (m)	Typar (270)	Coconut fibres (1000)	Polypropylene waste fibres (300)	Polypropylene waste fibres (450)	Polyester knitted sock (400)	Coconut fibres (700)	Polystyrene beads in netting (1000)	Polypropylene fibres (700)	Polypropylene fibres (heavy) (700)
50	200	43	46	47	49	50	54	-	60	75
60	150	40	50	44	46	46	50	71*	57	73
65	150	35	39	39	41	41	46	62	52	69
80	100	33	37	39	41	41	43	-	49	65
100	100	31	40	40	42	37	43	-	47	64

* The external diameter of the wrapped 60-mm pipe is 100 mm, i.e. the thickness of the envelope is 20 mm.

The selection of an envelope material is determined by various factors. The price is obviously important. The ease of handling of the material is also a factor of consideration. Coconut fibre envelopes will release substantial amounts of dust particles during handling and installation, particularly in dry weather; PP fibre wrapping does not. Previous favourable experiences of farmers are important: they tend to ask for a similar envelope when ordering again.

REVIEW OF LOCAL EXPERIENCE ON DRAINAGE MATERIALS

Adequate characterization of soil properties, field conditions (e.g. groundwater table depth) and physical properties of envelope materials is essential. In this context, the term ‘problem soils’ is rather vague and calls for further definition. This also holds for envelope materials: a generic description like ‘PP envelope’ is meaningless since it may cover the whole range from thin geotextiles to voluminous PLMs.

In an envelope selection process, a systematic comparison with experience gained elsewhere is generally very useful. Synthetic envelopes, either PLMs or geotextiles, have proven to be reliable and are successfully applied in Europe, the United States, and Canada for the last 20 years. These materials have also been used satisfactorily in large-scale field experiments in Egypt and Pakistan. In the latter country, they have also been used as envelope for interceptor drains. This proves the transferability of synthetic materials from one region to another.

In Framji *et al.* (1987), the use of envelope materials is summarized for a great number of countries. These data are included in the Table 5, which is supplemented with additional

TABLE 5
Drainage materials used in a number of countries

Material	Pipes			Mineral envelopes			Organic envelopes										Synthetic envelopes		
	Clay	Concrete	Plastic	Sand and gravel	Slag	Glass fibre cloth	Chaff	Sticks	Coconut fibres	Sawdust	Straw	Rice straw	Cedar leaf	Bamboo	Palm fibres	Peat fibres	Knitted sock	Geotextiles	Synthetic waste fibres
Australia			■																
Belgium			■						■										■
Canada			■																
China	■	■	■	■		■						■			■				■
Colombia			■	■					■									■	■
Costa Rica			■															■	
Cuba	■		■	■															
Czech Rep.	■		■		■											■	■		
Denmark			■	■						■									
Egypt		■	■	■													■		■
Ethiopia			■															■	
Germany			■						■							■			■
France			■															■	
Hungary			■								■							■	
India	■	■	■	■										■			■	■	
Iran	■		■														■	■	
Iraq			■	■															
Israel			■	■														■	
Ireland	■		■	■															
Japan	■	■	■	■			■	■				■	■	■					
Jordan	■			■															
Netherlands			■			■			■								■	■	■
Pakistan	■	■	■	■													■	■	■
Peru				■															
Poland	■		■								■								
Portugal			■	■															
Romania	■		■		■						■					■			■
South Africa			■	■															
Spain	■		■	■					■								■	■	■
Thailand		■		■														■	
Turkey			■	■															
Uganda																			
USA			■														■	■	
Zambia			■	■															
Zimbabwe		■	■	■															

information from other sources, included that provided by the participants of the International Course on Land Drainage (Wageningen, 1997-1999). Some local experiences that are considered to be informative are briefly discussed below.

Arid and semi-arid zones

In the Melka Sadi Pilot drainage scheme in ***Ethiopia***, trials were conducted for evaluating drainage envelopes. Three different envelopes were tested in a pilot scheme, comprising locally available red ash, gravel and a factory made fabric filter. The cost of gravel was six times that of fabric filter. The performance of both gravel and red ash were superior to that of the fabric filter (Woudeneh, 1987).

In ***Egypt***, voluminous envelope materials that are produced locally, namely PP and PA waste fibres (O_{90} of 330 and 400 µm, respectively) performed satisfactorily (Dierickx, 1992a). Occasionally, however, the wrapping of drainpipes proves to be poor. The yarn of prewrapped pipes was slack and the envelope material did not fully cover the pipe. After shipping and handling in the field, bare spots emerged at many places. In addition, taping of the envelope at either end of coils was sometimes inadequate as a result of which the envelope was loose (DRI, 1997).

In the north-western irrigation districts of ***Mexico***, locally produced corrugated PE pipes are used, with a diameter of 100 mm for laterals and 150 mm for collectors. They must comply with ASTM standards (Chapter 9). Collector pipes are approximately twice as expensive as laterals. Polyester sock is used as drain envelope, the cost of which is 30 percent of the price of the wrapped pipe.

An encouraging result of recent envelope testing projects in ***Pakistan*** is that synthetic materials, produced in Pakistan, performed well in the laboratory and have shown their potential for field application. It is not unlikely that IWASRI will eventually recommend the Pakistan Water and Power Development Authority (WAPDA) to replace gravel envelopes with locally manufactured synthetic materials. Locally manufactured materials were found to outperform finer local and imported materials, and hence are subjected to additional field trials. In the Mardan Scarp salinity control and reclamation project in Pakistan, Dierickx *et al.* (1995) recommend envelopes with an O_{90} ranging from 200 to 400 µm.

In ***Peru***, gravel and coarse sand are available everywhere at very reasonable cost, and have been successfully installed by hand and trenching machines. The use of clay and concrete tiles has not been very successful. Many soils are very unstable, and accurate installation of drains was complicated. Installation by hand was quite slow, and the width of excavation at the soil surface was 6 to 15 times that of the trench box of a trenching machine. Concrete pipes were expensive, because they had to be made from sulphate resistant cement. Most Peruvian soils that are suitable for agriculture have a very high content of calcium sulphate. Furthermore, the rate of production of concrete pipes was quite low. Between 1983 and 1985, 400 km of 65 mm and 100 mm corrugated pipe was installed. These pipes were manufactured in Peru with an extruder, imported from Europe (De la Torre, 1987).

Humid Tropics

In ***Costa Rica***, corrugated pipes were imported from the United States to drain fruit plantations, mainly bananas, notably in medium to coarse sands. In finer soils with low structural stability, the pipes were mostly prewrapped with geotextiles, e.g. spun bonded polyamide (Murillo, 1987).

In ***India***, drainage materials are produced locally. Agricultural drainage systems are solely installed on an experimental basis. In heavy clay soils, drains are installed without envelope material, and the systems perform satisfactorily. Locally made geotextiles are used with success; problems are rarely encountered (Oosterbaan, 1998). In the mid-1980s, the functioning of subsurface drainage systems was investigated in pilot areas, using clay tiles, installed in manually excavated trenches (Singh, 1987). In 1998, the majority of the drainage systems is still being installed by manual labour.

Temperate zones

In ***Belgium***, the use of clay tiles was discontinued in 1975 when their application was superseded by corrugated PVC pipes. Since a potential risk of mineral clogging exists in nearly all soils, envelopes are used everywhere. Envelope materials have evolved from flax straw and coconut fibres to loose synthetic fibres. Currently, loose synthetic PP fibre wrapping is almost exclusively used, but coconut fibre wrapping is still available.

In the ***Scandinavian countries***, sawdust from conifer trees is very often used as an envelope material for agricultural subsurface drainage systems. In unstable soils in ***Denmark*** the pipe drain is protected against mineral clogging by a synthetic sheet beneath the pipe, and gravel or sawdust aside and on top of the pipe. In ***Norway***, 50 percent of the sawdust has usually decayed after 20 years. Still, some drains have a service life of over 30 years, which will be due to the low temperatures in Scandinavia. The sawdust is applied in a 50 to 70 mm thick layer (Mortensen, 1987).

Approximately 60 percent of the installed drainpipes in the then ***West-Germany*** were prewrapped (Eggelsmann, 1982). Organic envelopes like peat, rye straw and coconut fibre wrappings have been extensively used. Even envelopes made from tannin-containing wood chips to prevent or reduce ochre formation have been developed (Eggelsmann, 1978). Various kinds of synthetic fibre and granule wrappings have been applied, yet geotextile and loose PP fibre wrappings are the most widely used materials.

Only 5 percent of the drainpipes installed in ***France*** need an envelope material. Envelopes have evolved simultaneously with drainpipes and drainage mechanization. Originally, coconut fibre wrappings have been widely used. The risk of microbiological decay of the coconut fibre wrapping has prompted the introduction of loose synthetic fibre wrappings and, at a later stage, geotextiles. Currently, geotextiles are used almost exclusively (Lennoz-Gratin, 1987).

In ***The Netherlands***, the recommendations for the selection of PLMs are as follows (Huinink, 1992; Van Zeijts, 1992):

- Envelopes containing peat fibres and ‘PP-450’ should not be used in case of possible iron ochre hazard and/or if the drains are also used for subsurface irrigation purposes during the summer season.
- Mature or ‘ripened’ clay soils with a clay content greater than 25 percent do not require envelopes.
- For most other soils, such as immature clay soils with a clay content greater than 25 percent, (loamy) sand, (sandy) loam, silt loam and peat soils, any envelope may be selected following the recommendations, specified in Table 6.
- Exceptions are made for clay soils with a clay content below 25 percent, silts and very fine sands which should be drained with ‘PP-450’ or, in case of iron ochre, with ‘PP-700’ only.

TABLE 6
Applicability of the most popular prewrapped drain envelopes in The Netherlands (adapted from Huinink, 1992)

Envelope material	**Soil type**[1]						
	Soils with clay content > 25% down to drain depth		Soils with clay content <25%, loams and very fine-textured soils, structurally unstable sands (median particle diameter < 120 μm)		Loamy sands and eolic deposits	Sandy soils (median particle diameter > 120 μm)	Peaty soils and peats with clayey topsoils
	Soil profile matured to drain depth?						
	Yes	No	Yes	No			
'voluminous' envelopes (i.e. thickness ≥ 1mm)							
Cocos (O_{90} = 700 or 1000 μm)	None[2]	Yes			Yes	Yes	Yes
Peat/cocos mix, peat fibres	None[2]	Yes[3]			Yes[3]	Yes[3]	Yes[3]
Polypropylene fibres 450 μm	None[2]	Yes[3]	Yes[3]	Yes[3]	Yes[3]	Yes[3]	Yes[3]
Polypropylene fibres 700 μm	None[2]	Yes	--[4]	--[4]	Yes	Yes	Yes
Polystyrene beads	None[2]	Yes			Yes	Yes	Yes
'thin' envelopes (i.e. thickness < 1mm)							
Glass fibre sheet, Cerex, Typar, knitted sock envelope	None[2]		Yes[3,5]			Yes[3,5]	

[1] In layered soil profiles, envelope selection should be based on the layer with the lowest clay content.
[2] No envelope required; soil is structurally stable and the risk of mineral clogging of the drainpipe is small.
[3] Do not install this envelope material if there is a risk of iron ochre clogging, or if the drains are used for controlled drainage or for subirrigation purposes.
[4] Use this envelope material only if there is a serious threat of iron ochre clogging the drains.
[5] Do not use a thin envelope if the soil profile to drain depth contains peaty layers.

In The Netherlands, 'thin' envelope materials are used with great caution only, and only in highly unstable very fine sandy soils (median soil particle diameter < 120 µm). For a variety of reasons, this category of envelopes has never become very popular. The price of thin envelopes is not competitive, and most farmers simply prefer envelopes to have a 'visible and substantial thickness' because they are convinced that such envelopes provide better service than thin ones. Reliable data, retrieved from pilot area research projects that convincingly prove that this 'traditional' viewpoint is not always justified, have not had an appreciable effect. *Tradition is indeed a strong factor when it comes to selecting drainage materials, particularly envelopes.*

In the Marismas area, located in the Guadalquivir estuary in southern ***Spain,*** clay pipes are mainly used although corrugated plastic pipes are installed as well. The clay pipes have an inside diameter of 80 mm, yet a square outside circumference with a small longitudinal hole in each corner, which is introduced to assure thorough heating of the clay during the manufacturing process. The corrugated PVC drains have a diameter of 50 mm. The cost difference between clay and PVC drains is small, and farmers, therefore, prefer the larger diameter clay pipes (Martínez Beltrán, 1987). Drains are installed during the dry season when the groundwater table is below drain level. Drains do not require envelopes because the Marismas soils are very stable due to their clay content greater than 65 percent. Mineral clogging of drainpipes has never been observed except for drains whose outlets into open collectors were submerged during periods of heavy rainfall.

In silty loams and loamy clay soils of the Ebro basin in north-eastern ***Spain***, corrugated PVC drains with coconut fibre wrapping have been installed in the seventies. There is no information on the performance of these drainage materials. Corrugated PVC drains and synthetic fibre wrapping have been used in the sandy soils of the Ebro delta as well.

Chapter 4

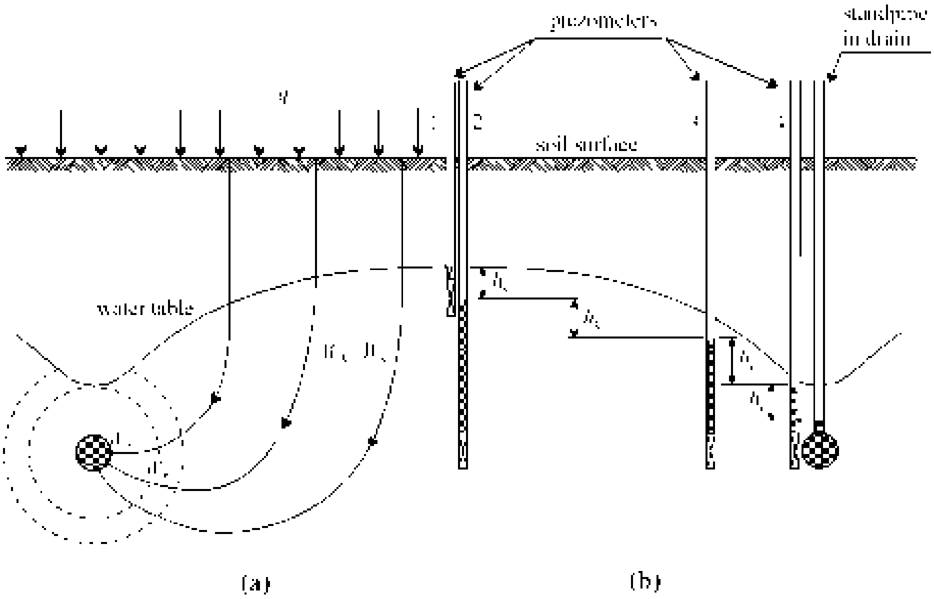
Water flow into and inside the drain

FLOW TOWARDS THE DRAIN

According to Ernst (1954), the flow towards a subsurface drain can be described by a vertical flow (from the groundwater level downward to drain level), a horizontal flow towards the vicinity of the drain, a radial flow to the drain and an entry into it. Each of these flows is subject to a corresponding *resistance* (Figure 22a). For steady-state flow, the total resistance can thus be roughly classified into vertical, horizontal, radial, and entrance resistances. These resistances can be measured by strategically located piezometers (Figure 22b). Piezometers consist of unperforated narrow pipes with a short filter at the bottom end in which the water level represents the hydraulic head in the soil near the filter end. Differences in heads are a measure of the resistances mentioned. The total loss of head, h_t, is the sum of all differences indicated in Figure 22b:

- The *vertical head loss*, h_v, is the difference in water level between piezometers 1 and 2, located midway between two drains, with filters at respectively groundwater level and drain depth.
- The *horizontal head loss*, h_h, due to (mainly) horizontal flow towards the drain, is the difference in water level between piezometers 2 and 3, with filters at drain level respectively midway between two drains and in the vicinity of the drain.

FIGURE 22
Flow resistances towards a drain flowing at full capacity (a) and their corresponding head losses (b)



- The *radial head loss*, h_r, is the difference in water level between piezometers 3 and 4, with filters at drain level respectively some distance away from the drain and at the drain.
- The *entrance head loss*, h_e, is the difference in water level between piezometer 4 and an open standpipe in the drain.

The relationship between head loss and corresponding resistance is given by:

$$h_* = q\,L\,W_* \tag{1}$$

where h = difference in head (m);
L = drain spacing (m);
q = specific discharge (m/d);
W = resistance (d/m); and
$_*$ = subscript v (vertical), h (horizontal), r (radial), e (entry) or t (total).

Thus the total head loss is:

$$h_t = h_v + h_h + h_r + h_e \tag{2}$$

Sometimes the resistances W are replaced by the dimensionless quantities α which are independent of the hydraulic conductivity of the soil:

$$\alpha_* = K_* W_* \qquad \text{or} \qquad W_* = \alpha_* / K_* \tag{3}$$

where K = hydraulic conductivity (m/d); and
α = geometrical factor (dimensionless).

Hence, the total head is given by:

$$h_t = q\,L\,(W_v + W_h + W_r + W_e) = q\,L\,(\alpha_v / K_v + \alpha_h / K_h + \alpha_r / K_r + \alpha_e / K_e) \tag{4}$$

This and other drainage theories are used for calculating drain spacings. They are based on a set of assumptions concerning the drain and the physical properties of the soils involved. Although these assumptions are approximate, the outcome is usually sufficient for practical applications. One of these assumption is that of an ‘ideal drain’, without entrance resistance, whereby the drain is considered as an equipotential. Generally, it is assumed that the drain surround (envelope material and loosened soil in the trench) has such a high hydraulic conductivity compared to the undisturbed soil, that the entrance resistance may be neglected. Practical experience has shown that this cannot always be taken for granted. There is still need for a query, both theoretically and empirically, in which cases substantial entrance resistances may be encountered.

Ponding and excess soil water during heavy rains, in spite of the presence of a drainage system, may also result from a low permeability layer near the soil surface that causes a suspended or perched water table. Another cause may be compaction due to heavy machinery, to slaking during heavy rains and, on sports fields, to playing actions. This low permeability layer simply prevents the water from reaching the groundwater table, but has nothing to do with the subsurface drainage system itself.

Procedures and programs for the design of subsurface drainage systems are in preparation by FAO. Therefore, this analysis will be limited to the influence of the entrance resistance and pipe flow on drain performance.

ENTRANCE AND APPROACH FLOW RESISTANCE

Water enters a real drain through a finite number of perforations, which represent at most only 1 to 2 percent of the total wall area. Although a real drain does not alter the general radial flow pattern, the streamlines converge to the inlet perforations in the immediate vicinity of the drain. This causes an *entrance resistance*, W_e, leading to a head loss on entry, h_e.

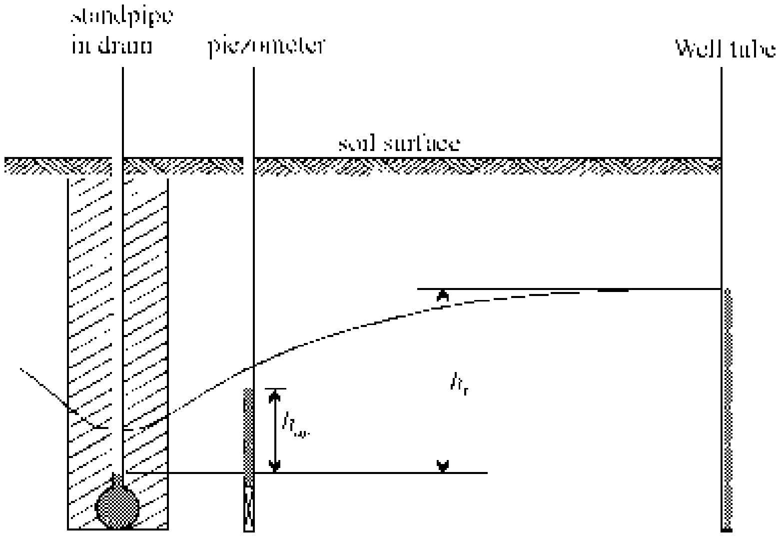
> As compared to flow to an imaginary, ideal drain, the convergence of streamlines to the inlet perforations of a real drain invokes an additional flow resistance and head loss. The additional flow resistance is called entrance resistance and the corresponding head loss is the entrance head loss.

According to Eq. (1) and taking into account Eq. (3) the relationship between entrance head loss and entrance resistance is given by:

$$h_e = qLW_e = \frac{qL}{K_e}\alpha_e \tag{5}$$

The entrance resistance of a real drain can be calculated theoretically for some simple perforation shapes and patterns, or can be obtained if the flow pattern towards both the ideal and real drain can be accurately modelled (Section *Entrance resistance of drainpipes*). In most cases, the entrance resistance is obtained empirically from the entrance head loss. Theoretically, the entrance head loss can be obtained directly from piezometer readings outside and inside the drain (Figure 22b). Practically, however, piezometer 4 will be placed at some short distance away from the drain to avoid the disturbance of the soil caused by installing the drain (Figure 23) and therefore, the measured head loss involves not only the entrance head loss, but also part of the radial resistance.

FIGURE 23
Approach flow and total head loss to evaluate drainage performance in experimental fields



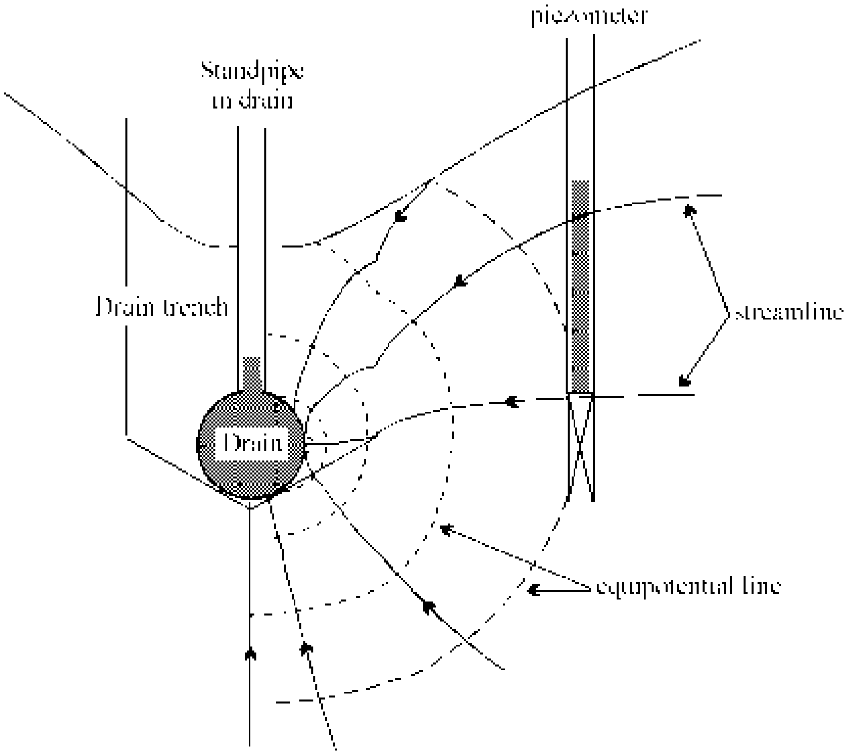
> Entrance resistance, resistance of the disturbed soil and the radial resistance are theoretical concepts, which cannot be physically separated, nor separately measured in the field. The measured head loss is the 'lump sum' of all the head losses which may be theoretically considered in the approach flow region.

Cavelaars (1967) introduced the concept of 'approach flow resistance' (W_{ap}) and 'approach flow head loss' (h_{ap}) for the flow in the approach region (Figure 23). Similar to Eq. (5), the relationship between both quantities for approach flow can be written as:

$$h_{ap} = qLW_{ap} = \frac{qL}{K_{ap}}\alpha_{ap} \tag{6}$$

The measured head, h_{ap}, results from entrance resistance, resistance of the disturbed soil surrounding the drain, and the radial resistance in the undisturbed soil as shown in Figure 24 for a drain installed in a trench. This also holds for trenchless drainpipe installation, but the disturbed zone will not be so clearly bounded compared to that created by a trencher.

FIGURE 24
Drain with or without envelope, disturbed trench backfill and undisturbed soil constitute the approach flow region



The head loss determined in experimental fields is the approach flow head loss, though it is usually called 'entrance head loss', and is used to calculate the 'entrance resistance', e.g. by Dieleman and Trafford (FAO, 1976).

The entrance resistance as defined by Dieleman and Trafford (FAO, 1976) is in fact an approach flow resistance and differs fundamentally from the theoretical concept of entrance resistance.

It can also be useful to express the approach flow head loss as a percentage of the total head loss. To determine the total head loss, either a piezometer (piezometer 1) as in Figure 22b or a well tube as in Figure 23 can be installed midway between drains. Unlike the piezometer, which is perforated at the bottom over a limited length only, the well tube is perforated over almost its entire length.

The flow pattern near the drain is very complex due to the disturbed soil where physical characteristics are heterogeneous and change with time and are therefore difficult to predict. The approach flow head loss, h_{ap}, is affected by the physical properties of this disturbed soil which surrounds the drain (K_{ap}), the drain spacing and the drainage materials used. A good envelope material, however, can reduce α_{ap} to such low values that the drain will act as almost an ideal drain.

The same holds if the soil around the drain is highly permeable, say K_{ap} = 10 m/d. This is mostly the case in backfilled trenches in clayey soils or after trenchless drainage in well-structured clays and clay-loams. Thus, entrance resistance is seldom a problem in these soils, even in the absence of a drain envelope. The reason for this behaviour is that water in the immediate vicinity of the drainpipe often follows preferential pathways. It will be routed through either the trench backfill, if present, or through cracks and fissures, created by a trenchless drainage machine. The occurrence of preferential flow is determined by the conductivity ratio of the disturbed and the undisturbed soil. The disturbed soil may have a permanently higher hydraulic conductivity. Yet after settling, some disturbed soils may become less permeable than the undisturbed soil. Soil disturbed in dry conditions will in most cases favourably affect drainage performance, regardless of whether the soil is homogeneous or heterogeneous, and whether the water follows preferential flow paths or not.

Any effective subsurface drainage system requires good physical soil conditions in the immediate vicinity of the drain. Only then will drainage materials, which are by themselves appropriate, do a good job. In this context, *‘good physical soil conditions’* is synonymous with a physically stable and hydraulically permeable soil. Such a soil, which consists of stable soil aggregates is often referred to as a *‘well-structured soil’*.

The installation of subsurface drains causes major changes in the physical properties of soil material abutting the drain. These properties are difficult to quantify, mainly because they cannot be accurately observed. Still, the physical properties of the soil are crucial for the future success or the failure of the drainage system. After installation, a balance has to be re-established, as the soil will settle around the drain in some way or another. The major force that governs this process is the drag force of the flowing groundwater that is discharging into the drain. The forces between soil particles and aggregates that resist this drag force are also important. Furthermore, the retentive property of the pipe or the drain envelope plays an important role. Depending on the way the drains were installed (trencher or trenchless), the structure of the soil around the drain will be ‘damaged’, that is, weakened. Consequently, the natural ability of the soil to resist the detrimental forces of the groundwater will be undermined. An additional complicating factor is the fact that the flux density of the groundwater is the highest where the structural stability of the soil is often weakest, namely near the drain, where the flow converges.

The soil may be locally compacted, especially when drains are laid under wet conditions. If drains are installed with a trenchless machine, which employs a vertical plough, the detrimental effect on the structure of the soil depends on the depth of installation and the soil water content at the time of installation. Up to a certain depth, the plough is able to lift the soil, creating fissures, and macropores. Yet, below the so-called critical depth the overburden of the soil prevents it from being lifted. Instead, the soil is pushed aside, compacted and smeared and natural fissures and macropores are locally destroyed (Van Zeijts and Naarding, 1990).

WATER FLOW INTO THE DRAINPIPE

The exit gradient

Darcy’s law describes the flow of water through porous media under laminar flow conditions and expresses the proportionality between the discharge over a cross-section and the hydraulic head loss, or between the discharge and the hydraulic gradient:

$$Q = KA\frac{dh}{dl} = KAi \tag{7}$$

where Q = discharge (m^3/d);
A = area of cross-section (m^2);
K = hydraulic conductivity (m/d);
dh = hydraulic head loss (m);
dl = distance over which dh is measured (m); and
i = hydraulic gradient or head loss per unit of distance (= dh/dl).

The exit gradient i_{ex} is the hydraulic gradient at which water leaves one medium and enters another. The flow media at the interface may be soil-water, soil-air, soil-envelope, envelope-water, or envelope-air. When the water enters the drain, the medium it leaves can be the soil or the envelope material. The medium it enters may be water or air.

If the streamlines are parallel (Figure 25), the hydraulic gradient i is given by:

$$i = \frac{\Delta h}{\Delta l} = \frac{Q}{AK} \tag{8}$$

In this case, for a given Q, the hydraulic gradient i is the same anywhere in the flow region since A and K are constants. Thus, the exit gradient i_{ex} or the gradient where the water leaves the soil is equal to the hydraulic gradient throughout the system, which is a constant.

However, in case of radial flow (Figure 26), the cross sectional area per unit drain length at a distance r from the drain centre is $2\pi r$ and the streamlines converge. The discharge per unit drain length is given by:

$$qL = 2\pi rK\frac{dh}{dr} \tag{9}$$

and the hydraulic gradient by:

$$i = \frac{dh}{dr} = \frac{qL}{2\pi rK} \tag{10}$$

(9)

FIGURE 25
Horizontal flow

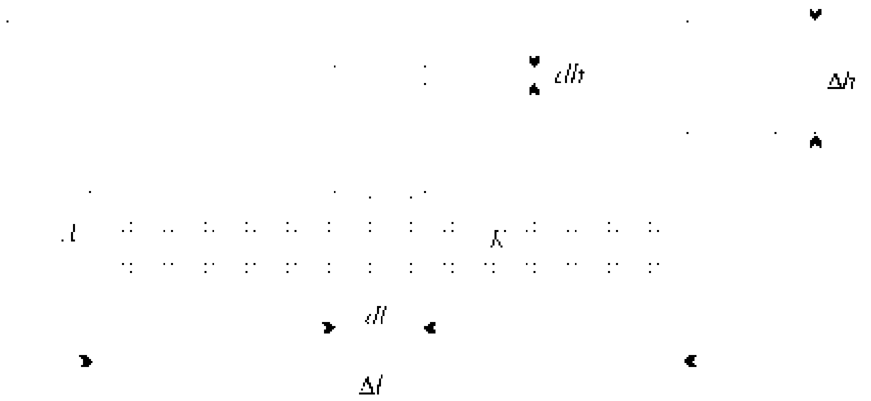
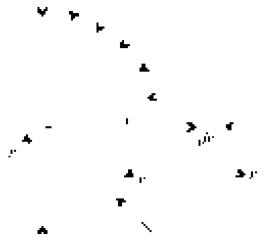


FIGURE 26
Radial flow



where q is the specific discharge (for steady state flow equal to rainfall or irrigation excess in m/d), L the drain spacing (m), and qL the discharge per unit drain length (m^2/d). In this case, the hydraulic gradient i is no longer a constant for a given discharge per unit drain length, but increases with decreasing r and vice versa.

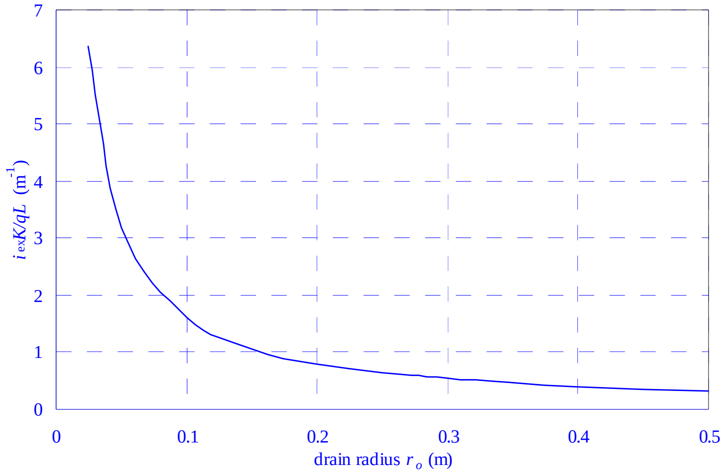
Considering radial flow towards an ideal drain, i.e. a completely permeable drain, the exit gradient i_{ex} where the water leaves the soil and enters the drain will be greater than anywhere else in the flow system. It is inversely proportional to the drain radius (Figure 27). For non-ideal drainpipes, the flow lines further converge toward the perforations in the drain wall, so that the exit gradient at the drain perforations will be even greater. However, an ideal drain with a smaller diameter r_o can 'replace' a perforated real drain in drain spacing calculations (Section *Plain drain*). In theory, the exit gradient at the boundary of such a hypothetical (and smaller) ideal drain equals the exit gradient at the perforations of a real drain.

The concept of radial flow is based upon simplifying assumptions concerning the real situation. Usually, however, the flow pattern near a drain is not fully radial; it may indeed be very different, e.g. irregular, depending on the hydraulic properties of the soil near the drain. Hence, the equipotentials in the groundwater are not necessarily concentric, relative to the drain centre. Instead, they are more likely to be eccentric and even irregular. This fact often complicates the assessment of the actual exit gradient in real situations.

The critical hydraulic gradient

Flow of water at a high exit gradient is rapid and powerful. It may exert enough drag force to overcome the resistance of the soil against shear. In this case, movement of soil particles will

FIGURE 27
Exit gradient i_{ex}, expressed as the ratio $i_{ex}K/qL$ for radial flow as a function of the drain radius, r_o



start and local erosion will occur around the drain. The hydraulic gradient at which these phenomena occur, is called *critical hydraulic gradient.*

The shearing resistance of a soil, which opposes the movement of soil particles or soil erosion, is given by Coulomb's equation:

$$\tau_f = c_o + \sigma_e \tan\phi \qquad (11)$$

where τ_f = shearing resistance per unit area (Pa);
c_o = cohesion (Pa);
σ_e = effective stress of the soil particles or intergranular stress (Pa); and
ϕ = angle of internal friction or shearing resistance.

Cohesive soils (like clays) possess firm bonds between soil particles and are mostly composed of soil aggregates. Cohesionless soils (like sands) lack bonds between individual particles ($c_o = 0$) and consist of individual soil particles, hence:

$$\tau_f = \sigma_e \tan\phi \qquad (12)$$

Soil load and water pressure determine intergranular stresses σ_e. Greater soil loads and smaller water pressure increase the effective stress and reduce the risk of erosion. However, stable bridges may occur in sands. They form arches, that span about 5-8 grain diameters (Peschl, 1969). Sand, therefore, does not normally enter openings less than 5-8 grain diameters (except for a few grains that escape while the arches are being established).

Water flowing through a porous medium exerts a pressure on the soil particles in the direction of movement. This pressure is called *flow pressure*. If the flow pressure acts in the direction of gravity (downward flow) the effective stress of the soil particles is increased and the risk of erosion is lessened. If however the flow pressure acts against gravity (upward flow) the intergranular stress may decrease substantially or even be cancelled, resulting in a highly unstable situation which is known as 'quick sand'. Examples of such flows are 'mud volcanoes' being formed in places of strong upward water movement. Flow pressure perpendicular to gravity causes a lateral movement of soil particles when the shear resistance is overcome. The hydraulic gradient at which the structural strength of the soil becomes negligible is called the *critical gradient*, i_c.

> The critical gradient depends on the effective stress and on the cohesion of the soil. For cohesionless soils without soil load, the critical hydraulic gradient equals approximately unity. This situation occurs in case of upward flow of groundwater. For cohesive soils, the cohesive force has to be considered as well. For these soils, the critical hydraulic gradient will be greater than that of cohesionless soils. It is related to the strength of the cohesive bonds between soil particles and/or aggregates.

If the flow pressure exceeds the shearing resistance of the soil, erosion will occur because the soil loses its structural strength. Since the flow pressure is proportional to the acting hydraulic gradient, erosion will start as soon as the exit hydraulic gradient i_{ex} reaches the critical hydraulic gradient i_c of the soil (Terzaghi and Peck, 1965).

Internal erosion in which soil particles move in the soil itself is not considered. It usually occurs in alkali soils, especially when the soil reacts on phenolphthalein (*pH* above 8.5). In such soils, internal erosion may occur if fine soil particles can detach themselves from the skeleton formed by the coarser fractions. With the water flow, they move through cracks and other macropores in the soil. This may cause a turbid drain outflow, resulting in a 'milky' appearance of such waters and internal clogging of the soil skeleton.

Hydraulic failure gradient

The critical hydraulic gradient will be greater in case of overburden load and with increasing soil cohesion. In accordance to these assumptions, Samani and Willardson (1981) have proposed the concept of the *hydraulic failure gradient*, i_f, which is the hydraulic gradient at which a confined or supported soil cannot resist the drag force of the flowing water. The soil loses its structural stability and starts moving into, and possibly through envelopes. Then the drainage system is very likely to fail because this process may substantially reduce the hydraulic conductivity of the envelope.

Samani and Willardson (1981) found that the hydraulic failure gradient depends on the plasticity index of a soil (Chapter 6). The associated relationship was however not transferable between soils originating from humid and arid regions. Yet, if the hydraulic conductivity is incorporated in the i_f -concept a good correlation was found between the hydraulic failure gradient and the combination of plasticity index and hydraulic conductivity of the soil. This correlation was valid both for humid and arid regions. Vlotman *et al.* (in press) used the data of Samani and Willardson (1981) to derive an empirical relationship, which is only slightly different from the original one:

$$i_f = e^{(0.332 - 1.14K + 1.07 \ln I_p)} \tag{13}$$

where i_f = hydraulic failure gradient;
K = hydraulic conductivity of the soil (m/d); and
I_p = plasticity index of the soil.

The plasticity index is a measure for the plasticity of a soil. It is defined as the difference in water content, as a percentage of the mass of oven-dried soil, of a soil at its liquid limit and at its plastic limit (ICID, 1996):

$$I_P = 100\left(W_{LL} - W_{PL}\right)/W_{DS} \tag{14}$$

where W_{LL} = mass of soil sample at liquid limit (g);
W_{PL} = mass of soil sample at plastic limit (g); and
W_{DS} = mass of oven-dried soil sample (g).

Eq. (13) considers however only soil properties. Overburden effects and envelope types are not considered, otherwise i_f cannot be constant for a given soil condition. Therefore the i_f-concept is, in essence, the same as the critical hydraulic gradient.

The i_f-concept can be useful as a decision tool for the application of a voluminous envelope to increase the radius r and so to reduce the exit gradient i_{ex} near the drain to a value inferior to the i_f-value of the soil. Still, the i_f-concept has never found widespread application. The experience obtained so far with the i_f as a tool for drain envelope design is therefore very limited.

ENTRANCE RESISTANCE OF DRAINPIPES

In the section *Entrance and approach flow resistance*, it was established that the head loss which is observed near a field drain is associated with the *approach flow resistance*, which is the *lump sum* of the *entrance resistance* and the *flow resistance* in the adjacent soil. Hence, the effect of (wrapped) subsurface drains on drainage performance cannot be determined as such. It is, however, important that the hydraulic properties of drainpipes and envelopes on drainage performance can be assessed as well. These properties are therefore discussed in this section.

Plain drain

The flow towards a drain can be established if this flow can be modelled analytically. This can be done for radial flow. The head loss, associated with radial flow to an ideal, full flowing drain in a homogeneous and isotropic soil (Figure 28a) with hydraulic conductivity *K*, reads:

$$h_r = qLW_r = \frac{qL}{K}\alpha_r = \frac{qL}{2\pi K}\ln\frac{r}{r_o} \tag{15}$$

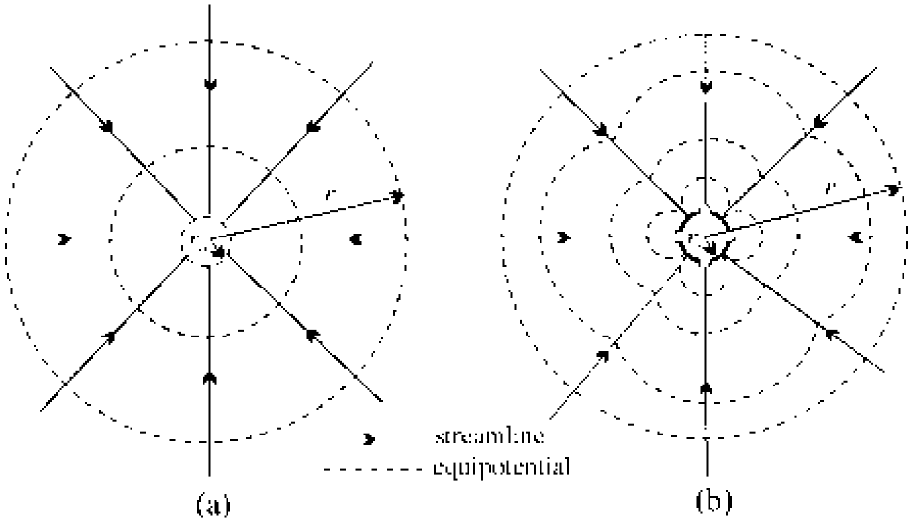
in which:

$$\alpha_r = \frac{1}{2\pi}\ln\frac{r}{r_o} \tag{16}$$

where r = the radius of a circular equipotential (m); and
r_o = the radius of the ideal drain (m).

The radius *r* should be chosen such that the equipotential has indeed a circular shape, and the flow towards the drain is radial. That is, the effect of the pipe perforations on the chosen equipotential must be insignificant. The approach flow head loss, associated with radial flow to a *real drain* (Figure 28b) is given by Eq. (6) which can also be written as:

FIGURE 28
Radial flow to (a) an ideal and (b) a real drain



$$h_{ap} = qL(W_r + W_e) = \frac{qL}{K}(\alpha_e + \alpha_r) \qquad (17)$$

Since radial flow to an ideal drain is described by Eq. (16) the entrance resistance results from:

$$\alpha_e = \alpha_{ap} - \alpha_r \qquad (18)$$

In this case, the entrance resistance of a *real drain* is the difference between the approach flow resistance to a real drain and the radial flow resistance to an *ideal drain.*

The entrance resistance α_e is fully associated with the drainpipe and therefore is a constant dependent on the perforation shape and pattern of the drainpipe if the radial flow occurs over the whole drain circumference. If radial flow occurs over only a section of the drain circumference (Figure 29), the flow resistance depends on the sector area where the radial flow to the drainpipe really occurs (Boumans, 1963). The actual entrance resistance, α_e^*, is inversely proportional to the flow sector:

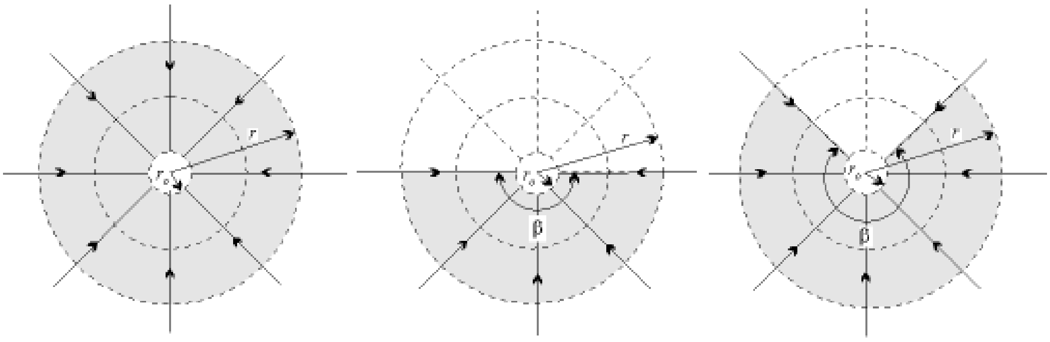
$$\alpha_e^* = \frac{2\pi}{\beta}\alpha_e \qquad (19)$$

where β = angle of the sector where radial flow occurs (radians, 0-2π).

The transitional boundary of the soil with the pipe perforations also affects the entrance resistance since the entrance resistance is invoked by the convergence of streamlines to these perforations. The entrance resistance increases due to any type of clogging, and decreases because of the washing out of soil particles. The boundary between soil and pipe perforations may have manifold geometrical configurations. The following boundaries may exist (Figure 30):

- the perforations are filled with soil;
- the soil forms a plane boundary with the perforations (plane boundary conditions);

FIGURE 29
Influence of a partly radial flow pattern on the entrance resistance of real drains



$\beta = 2\pi$, $p = 1$, $\alpha_e^* = \alpha_e$

$\beta = \pi$, $p = 2$, $\alpha_e^* = 2\,\alpha_e$

$\pi < \beta < 2\pi$, $2 > p > 1$, $2\,\alpha_e > \alpha_e^* > \alpha_e$

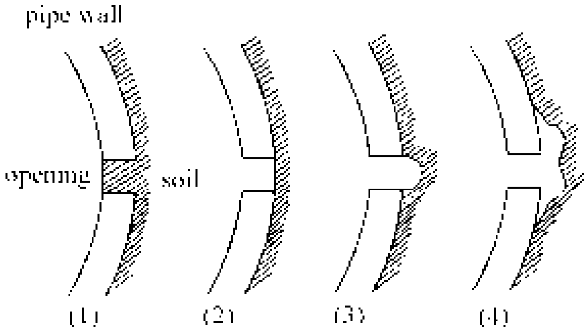
- the soil near the perforations is washed out and forms an arched boundary (arched boundary conditions); and
- the soil near the perforations is washed out and forms an irregular boundary.

In the field, the arched boundary is the most likely configuration (Peschl, 1969). According to Stuyt (1992a) this boundary may have a more complex three-dimensional configuration. The openings shown in Figure 30 may represent either:

- gaps between tile drains;
- circular perforations in plastic pipes; and
- rectangular slots in plastic pipes.

The shape of the outer pipe wall (smooth or corrugated) affects the entrance resistance, especially if the perforations lie in the valley of the corrugations which is normally the case. The greatest effect stems from whether the corrugations are filled with soil or not. If the corrugations are filled with soil, the geometry of the boundary of the soil with the perforations is quite relevant. For corrugations without soil the boundary with the corrugations will be decisive for the entrance resistance. The shape of the corrugations (‘wave’ or ‘block’) exerts only a minor influence.

FIGURE 30
Possible boundaries between soil and drain openings (after Cavelaars, 1970)



For some patterns and shapes of perforations in smooth outer pipe walls, the entrance resistance can be modelled analytically for plain and arched boundary conditions. Dierickx (1980) made an extensive review of the analytical solutions and checked their correctness with an electrolytic model. The simplest but still sufficiently accurate solutions are summarized in

Dierickx (1999). In many cases however, and for corrugated drains, the entrance resistance follows from model research. Accurate results can be obtained with an electrolytic model since both boundary conditions and hydraulic conductivity are known very accurately. This is not the case when sand models are used, because the configurations are less well defined.

Analytical solutions and model research have revealed that for *circumferential openings* between clay and concrete tiles, the entrance resistance is largely related to the gap spacing and the outer drain diameter and only slightly to the gap width. Thus, increasing gap width between tiles is an ineffective way to reduce the entrance resistance while the risk of soil invasion is enhanced. The provision of segmented pipes with holes also reduces the entrance resistance. Such pipes are used exclusively in the United States. Because the gap spacing of *tile drains* cannot be reduced, the only way to decrease their entrance resistance is the use of a larger diameter tile.

The most effective way to decrease the entrance resistance of drainpipes with *circular perforations* is to increase the number and diameter of the perforations. Although drains with *continuous longitudinal slits* do not exist, their properties can be simulated in mathematical models. As such, investigation of their properties is useful: increasing the number of slits is more effective than increasing the slit width and the drain diameter. Hence, increasing the number of slit rows is the most effective way to reduce the entrance resistance of drains with *discontinuous longitudinal slits*. The entrance resistance of drains with *discontinuous circumferential slits* can be reduced by decreasing the spacing between the rows of slits and by increasing the drain diameter. The slit width is less important.

According to Childs and Youngs (1958), a real drain can be replaced by an ideal drain with a smaller radius, the so-called *equivalent* or *effective radius*, r_{ef}. Substitution of α_r from Eq. (16) into Eq. (18) yields:

$$\alpha_{ap} = \frac{1}{2\pi}\ln\frac{r}{r_o} + \alpha_e \tag{20}$$

Similarly to Eq. (16), the radial flow resistance for flow to the ideal substitute, which results in the same flow resistance, is given by:

$$\alpha_{ap} = \frac{1}{2\pi}\ln\frac{r}{r_{ef}} \tag{21}$$

from which it follows that:

$$r_{ef} = re^{-2\pi\alpha_{ap}} = r_o e^{-2\pi\alpha_e} \tag{22}$$

As the effective radius depends on the entrance resistance, the effective radius can be used as an alternative to the entrance resistance: the smaller the entrance resistance, the larger the effective radius.

Values of entrance resistances associated with various drainpipes are given in Table 7. The values of Dierickx (1993) result from electrolytic model research with the assumption that the corrugations of flexible pipes are filled with soil, and that the soil forms a plane boundary with the perforations. Smedema and Rycroft (1983) do not quote any reference yet the values they present are most likely established from sand tank models. The table also contains the ratio r_{ef}/r_o (= $e^{-2\pi\alpha_e}$) to show the effect of entrance resistance on the effective radius of a drain.

TABLE 7
Entrance resistances and r_{ef}/r_o-ratios of plain drainpipes

Type of drainpipe	Dierickx (1993)		Smedema & Rycroft (1983)	
	α_e (dimensionless)	r_{ef}/r_o (dimensionless)	α_e (dimensionless)	r_{ef}/r_o (dimensionless)
Clay and concrete	1.0 – 3.0	$1.9\ 10^{-3}$ – $6.5\ 10^{-9}$	0.4 – 2.0	$8.1\ 10^{-2}$ – $3.5\ 10^{-6}$
Smooth plastic	0.6 – 1.0	$2.3\ 10^{-2}$ – $1.9\ 10^{-3}$	0.4 – 0.6	$8.1\ 10^{-2}$ – $2.3\ 10^{-2}$
Corrugated plastic	0.3 – 0.6	$1.5\ 10^{-1}$ – $2.3\ 10^{-2}$	0.05 – 0.1	$7.3\ 10^{-1}$ – $5.3\ 10^{-1}$

> Although different entrance resistance values are found in the literature, segmented pipes with gaps usually have a greater entrance resistance than smooth plastic pipes with more uniformly distributed perforations. In turn, smooth plastic pipes have greater entrance resistances than corrugated plastic pipes with more perforations and a greater perforation area.

Drain with envelope

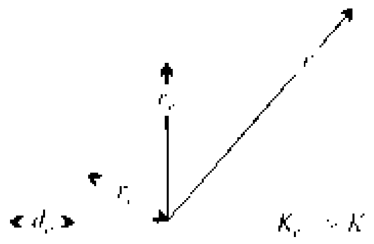
Since the entrance resistance of drainpipes can be of the same order as the total flow resistance in the soil (Widmoser, 1968), any change of permeability in the immediate vicinity of the drain will markedly influence drainage performance. Drain envelopes normally have a greater hydraulic conductivity than the surrounding soil. Hence, they contribute to the decrease of the entrance resistance of drainpipes.

If an envelope with thickness d_e and a hydraulic conductivity $K_e > K$ surrounds an ideal drain (Figure 31), the total radial flow resistance is given by:

$$\alpha_r = \frac{1}{2\pi}\ln\frac{r}{r_e} + \frac{1}{2\pi\kappa_e}\ln\frac{r_e}{r_o} \qquad (23)$$

where r_e = radius of the soil-envelope interface (m); and
κ_e = K_e/K, is the relative hydraulic conductivity or the hydraulic conductivity ratio of the envelope and the surrounding soil.

FIGURE 31
Theoretical flow towards an ideal drain surrounded by an envelope



Defining the entrance resistance presents no particular difficulty for drains without envelopes (Section *Plain drain*). However, the entrance resistance of a drain with envelope is affected by both the hydraulic conductivity of the envelope relative to that of the surrounding soil, as well as by the envelope thickness. When an envelope is used, several definitions of the entrance resistance can be given.

Alternative 1

If the entrance resistance is related to the drainpipe itself, an envelope does not cause any change in the entrance resistance. Only the total flow resistance is changed. As long as the thickness and the hydraulic conductivity of an envelope allows for radial flow in the surrounding soil, the entrance resistance α'_e of a drainpipe itself is given by:

$$\alpha'_e = \frac{\alpha_e}{\kappa_e} \tag{24}$$

while the radial flow resistances in the envelope and in the soil form the other components of the approach flow resistance, hence:

$$\alpha_{ap} = \frac{1}{2\pi}\ln\frac{r}{r_e} + \frac{1}{2\pi\kappa_e}\ln\frac{r_e}{r_o} + \alpha_e^{'} \tag{25}$$

and, if the effective radius, r_{ef}, is considered:

$$\alpha_{ap} = \frac{1}{2\pi}\ln\frac{r}{r_{ef}} \tag{26}$$

Hence the effective radius becomes:

$$r_{ef} = \frac{r_o^{1/\kappa_e}}{r_e^{(1/\kappa_e)-1}} e^{-2\pi\alpha_e^{'}} \tag{27}$$

Alternative 2

The entrance resistance may alternatively be expressed as the resistance of both drain and its surrounding envelope. This is equal to combining the last two terms in Eq. (25) into:

$$\alpha_{e,e} = \alpha_e^{'} + \frac{1}{2\pi\kappa_e}\ln\frac{r_e}{r_o} \tag{28}$$

The approach flow resistance now reads:

$$\alpha_{ap} = \frac{1}{2\pi}\ln\frac{r}{r_e} + \alpha_{e,e} \tag{29}$$

For an ideal drain where $\alpha_e' = 0$, the entrance resistance given by Eq. (28) yields the envelope resistance to radial flow. The effective radius can be calculated by combining Eqs. (26) and (29):

$$r_{ef} = r_e\, e^{-2\pi\alpha_{e,e}} \tag{30}$$

Alternative 3

Widmoser (1968) defined the entrance resistance, $\alpha_{(e,e)W}$, as the difference in flow resistance between a drain with an envelope and an ideal drain of the same diameter, r_o. Thus:

$$\alpha_{(e,e)W} = \left(\frac{1}{2\pi}\ln\frac{r}{r_e} + \frac{1}{2\pi\kappa_e}\ln\frac{r_e}{r_o} + \alpha_e^{'}\right) - \frac{1}{2\pi}\ln\frac{r}{r_o} \tag{31}$$

which, after some simplifications, finally results in:

$$\alpha_{(e,e)W} = \alpha_e^{'} + \frac{1}{2\pi}\left(\frac{1}{\kappa_e}\ln\frac{r_e}{r_o} - \ln\frac{r_e}{r_o}\right) \tag{32}$$

while the approach flow resistance is given by:

$$\alpha_{ap} = \alpha_{(e,e)W} + \frac{1}{2\pi}\ln\frac{r}{r_0} \tag{33}$$

Combination of Eqs (26) and (33) yields the effective radius:

$$r_{ef} = r_o e^{-2\pi\alpha_{(e,e)W}} \tag{34}$$

Though Widmoser (1968) might have given the right definition on the entrance resistance of a drain with envelope, from the above analysis it is obvious that the effective radius of a given drain with a well-specified envelope is independent of whatever definition is used for the entrance resistance.

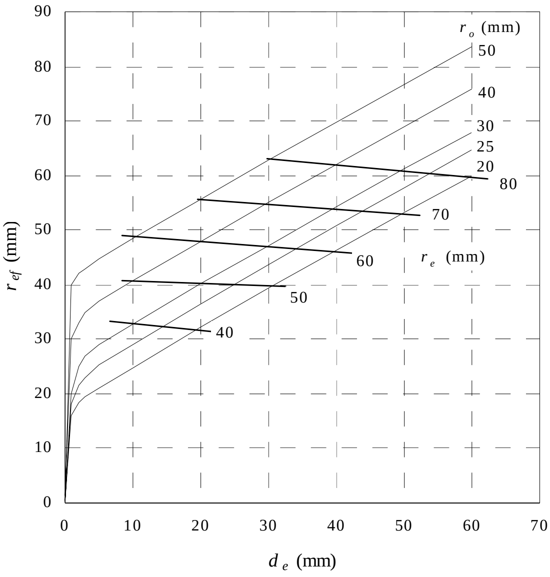
Corrugated plastic drain pipes with a perforation in each corrugation and wrapped with a thin envelope ‘sheet’ which spans the corrugations and keep them free from soil makes the drain surface much more permeable and reduces the entrance resistance considerably (Willardson and Walker, 1979; Salem and Willardson, 1992). A substantial reduction of the entrance resistance is obtained if an envelope is installed which has a hydraulic conductivity at least 10 times higher than that of the surrounding soil. The thickness of the envelope should, preferably, be at least 5 mm (Nieuwenhuis and Wesseling, 1979; Dierickx, 1980). More favourable specifications do not significantly decrease the entrance resistance any further. Still, greater envelope thickness enhances the effective radius, because the soil around the drain is replaced by a comparatively more permeable envelope.

The effective radius of a wrapped drain increases, if the hydraulic conductivity and/or the thickness of the envelope are made larger. The use of a sufficiently permeable envelope ($\kappa_e \geq 10$) which is adequately thick ($d_e \geq 5$ mm) around a plain drain reduces the entrance resistance drastically. If $\kappa_e \geq 10$ and $d_e \geq 5$ mm, drains wrapped with envelopes which have the same external radius, r_e, have almost the same effective radius, r_{ef}, regardless the pipe radius, r_o, and the envelope thickness, d_e (Figure 32). Thus, it may be more cost efficient to select the minimum drain diameter required to satisfy the discharge capacity, and to wrap with a relatively thick envelope, than selecting a greater diameter pipe, wrapped with a relatively thin envelope. This is because larger diameter pipes are much more expensive than a larger amount of envelope material, required to arrive at the same external diameter r_e.

Drain with a less permeable surround

It is generally accepted that drainage works must be carried out under circumstances that do not challenge the structural stability of a soil. The moisture content of the soil is a critical factor because drainage works carried out with trenchers in wet conditions may result in deterioration of the structure of the excavated soil. As a result, the drain surround becomes less permeable than that of the surrounding natural soil. Trenchless and mole drainage techniques can locally

FIGURE 32
Effective radii, r_{ef}, for drains of different pipe radii, r_o, and provided with four continuous longitudinal slits as a function of the envelope thickness d_e for K_e = 10



compact the soil around the drain or mole channel, inducing a less permeable zone around it. Invasion of soil particles into the envelope and/or chemical deposits can result in a partial blocking of the pores and a decreased hydraulic conductivity of the external envelope surface.

Experimental research shows that, if an envelope has a substantial thickness, e.g. >5 mm, and if its hydraulic conductivity is less than 10 percent of that of the surrounding soil, the entrance resistance may be very large, and consequently the effective radius of the drain reduces to extremely small values. This is mainly due to impeded flow in the less permeable layer surrounding the drain. If the drain is wrapped with an envelope, smearing and compaction of the surrounding soil influences the entrance resistance less than envelope clogging, yet the effective radius may be reduced to intolerable values.

A less permeable layer surrounding either a plain drain or a drain with a more permeable envelope has an adverse influence on the performance of drain materials and must therefore be avoided at all times.

Mutual differences between the entrance resistances of various types of drainpipes may be important if these drains are installed without envelope. The hydraulic characteristics of the abutting media (either the soil or the envelope and the soil) are, however, much more relevant than the specifications of these pipes.

DISCHARGE CAPACITY OF DRAINPIPES

The discharge capacity of drainpipes is an important component of any design procedure for land drainage systems, and is described in all major drainage textbooks. The available information ranges from exhaustive (Cavelaars *et al.*, 1994) to straightforward treatment, which is limited to the fundamentals only and some useful examples (Smedema and Rycroft, 1983). In this guide, only the most relevant material is discussed, following Dierickx (1993). Readers who want to be informed further on the subject are referred to the above publications. Additional information on design procedures (i.e. formulae) in various countries is given in Framji *et al.* (1987). Pipe diameter nomographs, which are quite useful for a ‘quick scan’ analysis of the required pipe diameter(s), are given in Smedema and Rycroft (1983). A computer program for calculating the diameter of drainpipes is in preparation by FAO.

It is often financially attractive to increase the pipe diameter of collector drains and even of lateral drains in the flow direction. In doing so, the diameter is adjusted for the discharge, which increases in the direction of the outlet. This issue is discussed in depth by Cavelaars (1979), and illustrated in a simple case by Smedema and Rycroft (1983). The forthcoming FAO-publication on drainage design also includes the design of such composite drains.

The hydraulic design of drainpipes is based on formulae that relate the discharge of water to the pipe diameter, the hydraulic roughness of the pipe wall and the hydraulic gradient. Different formulae are used for smooth and corrugated pipes.

Clay, concrete and smooth plastic pipes are considered hydraulically smooth pipes. Their discharge capacities can be calculated from the Darcy-Weisbach equation. The discharge capacity of corrugated pipes can be calculated from the Chézy-Manning equation. For laterals, a minimum pipe diameter is advisable to compensate for less accurate grade and alignment, and eventually for some settlement that may occur, thus assuring the discharge capacity of the drainage system. In European countries, a minimum diameter of 50 or 60 mm is accepted; elsewhere the minimum diameter is 80 mm and in the United States the smallest diameter is 100 mm. For collector drains the length covered by a given pipe diameter for a specified hydraulic gradient is calculated.

In the Chézy-Manning equation, the hydraulic roughness (or ‘friction resistance’) of the pipe wall is expressed as Manning’s coefficient, n, or its reciprocal parameter, k_M. For drainpipes with diameters ranging from 50 to 200 mm and small corrugations, the roughness coefficient $n = 0.0143$ s m $^{-1/3}$ (or the reciprocal value $k_M = 70$ m$^{1/3}$ s^{-1}). From the results of Irwin (1982, 1984), Boumans (1988) established that the k_M-value of larger diameter pipes with large corrugations can be expressed as:

$$k_M = 18.7d^{\,0.21}S^{\,-0.38} \tag{35}$$

in which d (m) and S (m) are the internal pipe diameter and the pitch length, respectively. For most pipes with large corrugations, a roughness coefficient $n = 0.02$ s m$^{-1/3}$ (or $k_M = 50$ m$^{1/3}$ s^{-1}) can be accepted.

The type of pipe and the hydraulic gradient determine the discharge capacity of drainpipes. The calculation of the discharge capacity of drainpipes may be based upon two principles (Wesseling and Homma, 1967; Wesseling, 1987):

- the *transport principle* with *uniform flow*, whereby a drainpipe is assumed to transport a fixed discharge along its length, while the pipe itself is flowing full; and
- the *drainage principle* with *non-uniform flow*, whereby a constant inflow of groundwater into the drain along its length results in a discharge which increases along the length of the pipe.

Application of both principles and pipe characteristics yields the following set of equations:

Transport principle		Drainage principle	
Clay, concrete and smooth plastic pipes			
$Q = 50\, d^{2.714}\, s^{0.572}$	(36)	$Q = 89\, d^{2.714}\, s^{0.572}$	(37)
Corrugated pipes with small corrugations (usually pipes ranging from 50 to 200 mm in diameter)			
$Q = 22\, d^{2.667}\, s^{0.5}$	(38)	$Q = 38\, d^{2.667}\, s^{0.5}$	(39)
Corrugated pipes with large corrugations (usually pipes with a diameter beyond 200 mm)			
$Q = 15\, d^{2.667}\, s^{0.5}$	(40)	$Q = 27\, d^{2.667}\, s^{0.5}$	(41)

with Q = discharge ($m^3\ s^{-1}$);
d = internal diameter (m); and
s = hydraulic gradient (dimensionless).

All equations are derived for clean pipes. Comparison of these equations reveals that the assumption of the *transport principle* for the determination of the diameter of drainpipes implies that a safety factor is automatically incorporated in the design. The equations based upon the *drainage principle* yield larger discharge capacities, and, as such, larger surfaces that can be drained with a given pipe diameter. Adoption of some safety factor is indeed required to incorporate the risk of possible mineral and/of chemical clogging of the pipe in its hydraulic design. Usually, pipes are ‘over designed’ to allow for subsequent partial mineral or chemical clogging, and for misalignment during installation.

When applying the *drainage principle*, a safety factor must be imposed because this principle is based on a more realistic physical concept, which leads to a more economical yet risky design. For practical application, the discharge capacities as calculated with the formulae based upon the drainage principle are commonly reduced to 60 percent of the calculated values to include a safety factor for possible mineral and/of chemical clogging of the pipe (Cavelaars, 1974). This means that, in the end, both principles result in approximately the same discharge capacity (Dierickx, 1993). For collector pipes, the theoretical capacity is usually only reduced to 75 percent. Hence, an extra safety of 15 percent is built in when using the formulae based upon the transport principle.

Additional reduction factors up to 50 percent may still be advisable to compensate for pipe clogging, misalignment and an erroneous assessment of the pipe roughness coefficient (El Atfy *et al.*, 1990). The reduction factor may be conservative (25 percent) if corrugated plastics pipe is installed in stable soil, yet must be comparatively large (50 percent) for tile drains laid in unstable soil.

Too small a drain or a drain partially filled with sediment causes a reduced transport capacity. The pipe section will then be too small for discharging the groundwater properly, and the water in the drain will be flowing under pressure. Water may be standing above the drain and the groundwater table midway between drains will be too high. Too small a diameter or a reduction in transport capacity can be observed by a piezometer to measure the water head in the drain, and observation wells for the height of the water table transversal to and near the drain.

Chapter 5

The problem of clogging of pipes and envelopes

MINERAL CLOGGING

Processes in soils around drains

A major problem that is often encountered on subsurface drains is mineral clogging of pipes and envelopes. This physical process occurs as the result of sudden drastic changes in soil-water conditions near the pipes caused by their installation. Immediately after installation, a new equilibrium begins to be established at the vulnerable area near the interface between the backfilled soil and the surface of the drainpipe or the surface of the envelope. The area is vulnerable because the physical strength and the structural stability of the soil has been weakened by the installation process. Moreover, groundwater starts flowing towards the drain, whereby the hydraulic gradients and the flux densities, being high in this area, induce substantial drag forces on the soil particles.

Soil movement at the interface between soil and envelope (or pipe wall) caused by flowing water is often referred to as internal soil erosion. Ziems (1969) made an extensive study of this phenomenon. He indicated that soil particle movement at the interface between two media may be, in fact, caused by three different physical phenomena, namely the washing out of fine soil particles (creating a *'natural filter'*), contact erosion and soil collapse. The physical process leading to the development of a natural filter in a soil has been discussed by various authors (Stuyt, 1982, 1992a; Cavelaars *et al.*, 1994). Another phenomenon, which adversely affects water entry into drains, is the development of a so-called 'filter cake'.

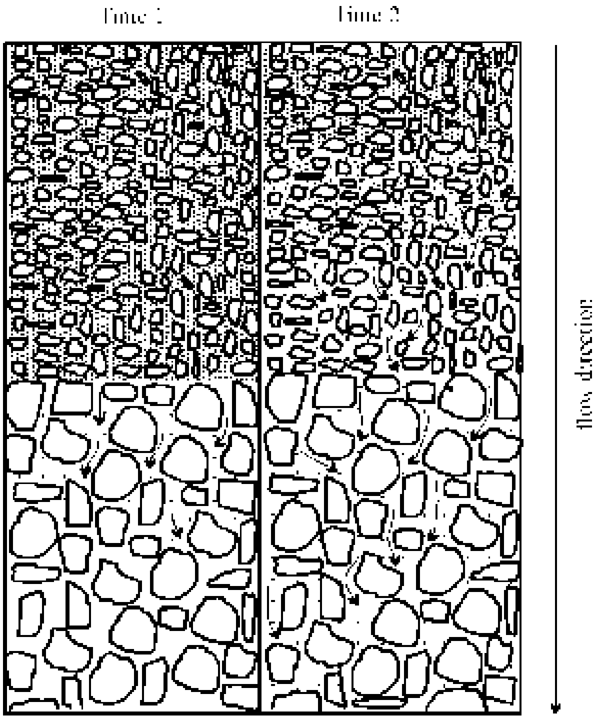
The phenomena just mentioned may be characterized, in brief, as follows:

Natural filter. If only fine soil particles are washed out, a coarser soil skeleton is left behind that bridges over the openings in the drain or in the envelope. The formation of a natural filter, for instance in soil backfilled on top of a granular envelope, is illustrated in Figure 33. The drag force of the water that flows toward the drain causes small soil particles to move into and through the envelope while those of larger sizes are retained (Time 1). After some time, a highly permeable 'natural filter' will develop in the soil adjacent to the envelope (Time 2), with an enhanced hydraulic conductivity. If coarser particles are washed out also, the formation of a natural filter in the soil may be superseded by excessive soil particle movement, which will locally undermine the physical strength of the soil skeleton. This process, in turn, promotes contact erosion.

Contact erosion means that particles of nearly all sizes are washed out locally, resulting in modification of the skeleton which transfers the effective stresses within the soil. The result of contact erosion is shown in Figure 34. Here, the drag force of the water that flows toward the drain causes soil particles of all sizes to move into and through the envelope (Time 1). After some time, macropores will develop at the interface between the envelope and the soil (Time 2).

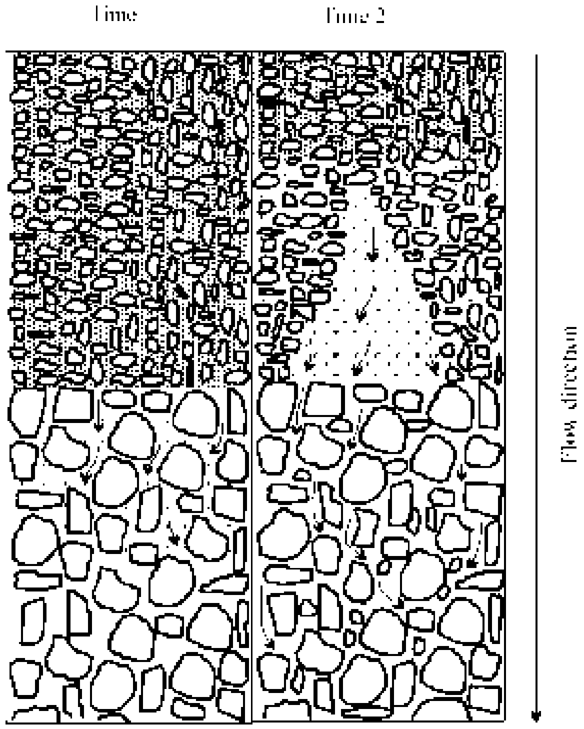
Filter cake. A filter cake is a dense layer of soil particles which develops if suspended, fine soil particles accumulate at or near the interface between the soil and the envelope. The greater part of this area is often located in the soil rather than in the envelope (Stuyt, 1992a). Figure 35 shows the development of a filter cake in the course of which fine soil particles move toward but do not enter the envelope (Time 1). Many particles accumulate in the soil near the interface between the soil and the envelope (Time 2). This condition occurs when the envelope openings are too small and act as a filter for the small soil particles moving with the water. The hydraulic conductivity of filter cakes is often considerably smaller than that of the original soil, because fine soil particles clog the soil pores at the soil-envelope interface.

FIGURE 33
Natural filter (after Stuyt, 1982)



Soil collapse. When the drag force of the water surpasses the cohesive forces and intergranular stresses of a soil, the soil collapses and may consolidate. Soil collapse is illustrated in Figure 36. It shows that, after installation of the drain, the cohesion of the soil prevents soil material from moving toward and into the envelope (Time 1). At a later stage, soil aggregates are dislocated and soil particles move through the envelope towards the drain (Time 2). Some secondary bridging may occur at the soil-envelope interface that stops further soil movement into the envelope.

FIGURE 34
Contact erosion (after Stuyt, 1982)



Soil collapse implies local soil structural failure, dispersion of soil aggregates and movement of soil particles of all sizes at the interface between the soil and the envelope. Soil collapse is most likely to occur in heavy, cohesive soils at high hydraulic gradients. The drag force of the water and the soil load, induced at drain depth, may even cause the saturated soil material near the drain to be pressed through the envelope and into the pipe perforations, as a muddy substance (Van der Louw, 1986; Stuyt, 1992a).

Until recently, *contact erosion* was considered harmful to the successful functioning of subsurface drains (Stuyt, 1982). Later observations however indicated that a low rate of contact erosion is favourable in that it promotes the formation of a macropore network around the drain. This network plays an important role in the conveyance of water into the drain.

Stuyt (1992a) made a serious attempt to gain insight into the *physical processes, associated with mineral clogging.* A CT scanner was used to obtain three-dimensional (3-D) digital images of soil cores, containing 300 mm long sections of wrapped drainpipes with the surrounding soils. After a service life of five years, 45 drain sections were retrieved from three experimental fields, located in areas in The Netherlands where the soils at drain depth consist of very fine sands: indeed problem soils with low structural stability. Each CT-sequence is a 3-D, geometrically precise mapping of the interior density variations inside drain envelopes and the surrounding soils. In the 3-D images, two major types of soil pores could be distinguished, namely *textural pores* inside soil aggregates and *macropores* (voids, cracks) which separate these aggregates. In 40 percent of all cases, the average macroporosity in the trench was lower than that in the subsoil. Two types of soil structural features were found in the subsoil: horizontal layering and vertically oriented macropores (Figure 37).

FIGURE 35
Filter cake

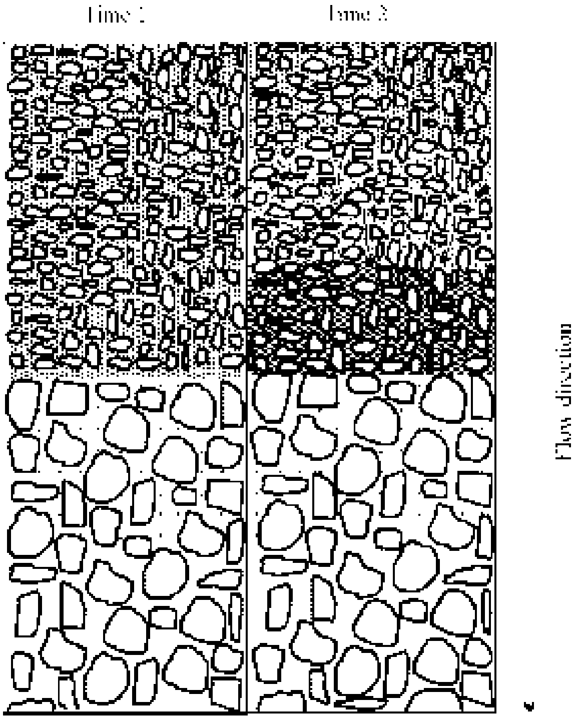


FIGURE 36
Soil collapse (after Stuyt, 1982)

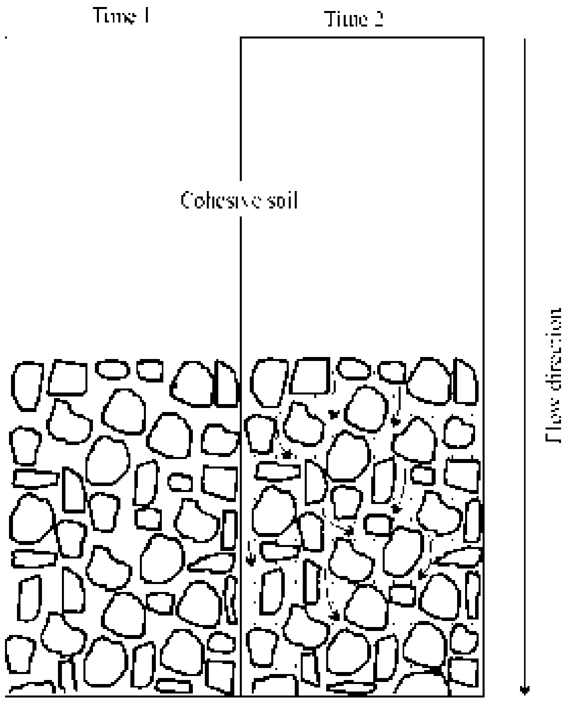


FIGURE 37
Example of a layered subsoil (left) and of a subsoil with vertically oriented macropores, that had developed at former root channels (right) (after Stuyt, 1992b)

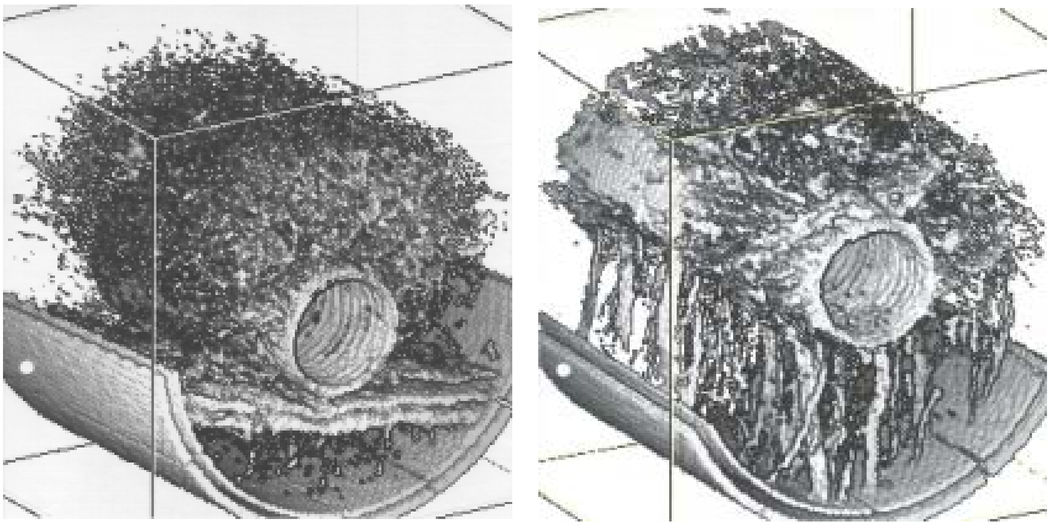
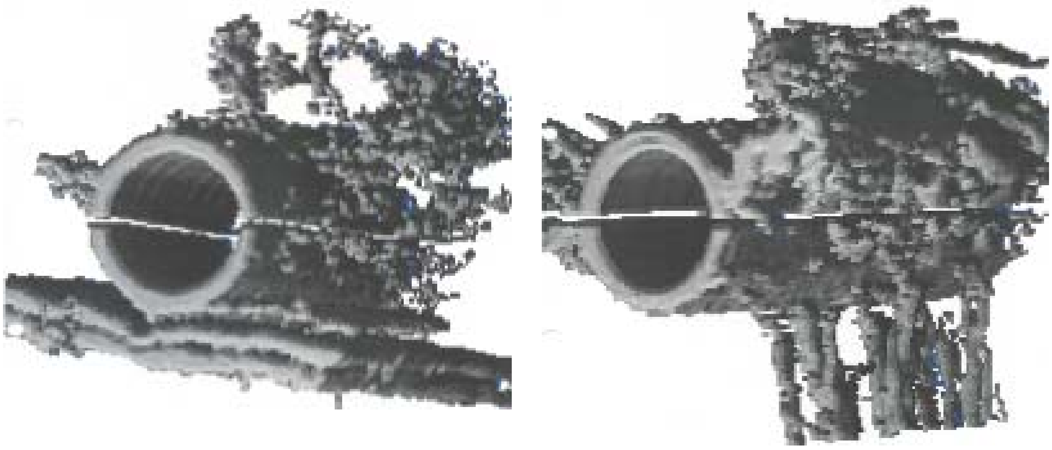


FIGURE 38
Image areas displaying drain envelopes and active macropores (after Stuyt, 1992b)



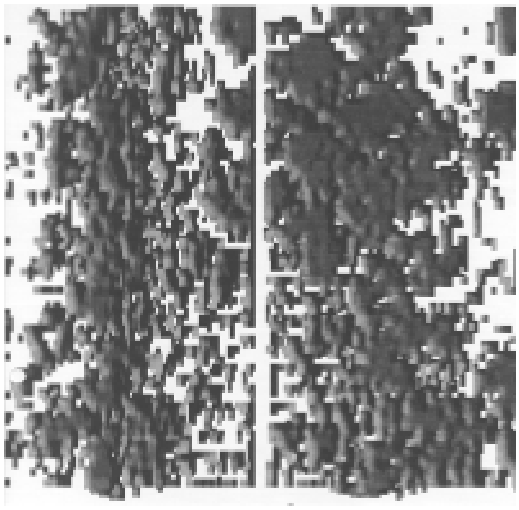
In Figure 37, only the relatively permeable areas in the soil around the drain are depicted. There is no relation between soil permeability and the intensity of the grey shading. The latter is induced by image processing techniques in order to facilitate visual interpretation of the highly complex image. Parts of the Plexiglas rims of both the sample container and the sample holder of the CT scanner were cut away by image processing techniques.

Not all the permeable areas depicted in Figure 37 are physically connected to the drain and, as such, conveying water into it. Using a 3-D image analysis technique, the areas that are connected to the drain - the so-called *active macropores* - could be detected. In Figure 38, these active macropores are displayed. The depicted samples in Figure 38 are the same as the ones displayed in Figure 37. It can be clearly observed that only a minority of all the detected permeable areas is actively conveying water into the drain. These active macropores are partly developed through contact erosion processes that must have taken place during soil settlement after installation.

Subtle banding is evident underneath the drain, indicating comparatively permeable soil layers, and the drain trench contains some geometrically complex macropores (Figure 38 left). Water access to the drain on the right proceeds through a series of parallel, vertically oriented macropores.

The heterogeneity of mineral clogging of voluminous envelopes, as detected on field samples is illustrated in Figure 39 in the form of transformed CT-images that depict the envelopes as flat surfaces. Areas that are not seriously clogged are grey. Clogged envelope areas are not depicted and appear white.

FIGURE 39
Illustration of the heterogeneity of mineral clogging patterns as detected inside voluminous envelopes (after Stuyt, 1992b)



Contrary to theoretical assumptions, the effect of an envelope on the water flow pattern towards a drain is often limited, as is its effect on the radial and the entrance resistance. Study of all water flow patterns into the drains revealed that there is no evidence that envelope specifications have a significant effect on the geometry of such patterns. Variation of the flow resistance near a subsurface drain is therefore likely to be largely associated with structural features of the soil, i.e. its macroporosity and the geometric arrangement of the macropore network near the drain. The so-called effective opening size, $O_{90,}$ appeared to be the only crucial design parameter for an envelope. Unlike any other envelope specification, the O_{90} value had a significant effect on the rate of mineral clogging of drainpipes (Stuyt, 1992a).

Envelopes largely act as soil ‘retainers’ or permeable constraints that physically support the soil near the drains. Given the importance of the physical properties of soils in relation to the process of mineral clogging, good installation practice will favourably affect the service life of wrapped drains. On the other hand, well-designed envelopes cannot cancel the unfavourable physical properties of the surrounding soils, nor can they compensate for poor installation practice. Installation under general wetness must therefore be avoided as much as possible.

Pipe clogging

Sedimentation in drainpipes does not depend only on the intrinsic characteristics of the soil. Other factors such as the conditions and the quality of installation and inadequate maintenance of the drains, e.g. high pressure jetting, can cause sedimentation in drains.

Mineral deposits in drains are due to soil grains passing the envelope (if any) and the openings in the pipes. Fine particles (< 20 µm) are usually carried in suspension, causing a turbid outflow. Sand remains in place and - if abundant - will cause pipe clogging. In flat country, with drain gradients around 0.2 percent (0.2 m per 100 m) even very fine sand (median particle size 50 μm) will stay near the entry point in the pipe. Self-cleaning of the pipe may be expected only at much steeper gradients.

CHEMICAL AND BIOCHEMICAL CLOGGING

In subsurface drains, there are four known types of deposits that are associated with bacterial activity. These are ochre deposits, manganese deposits, sulphur slime and iron sulphide. Gelatinized, voluminous oxidized iron deposits, named ochre, are the most serious and widespread. Other known deposits are lime and gypsum, which mostly occur in subsurface drains of irrigated areas as a result of the chemical composition of the soil and the quality of the irrigation water.

Iron ochre

The gelatinous slimes, associated with ochre deposits are usually yellow, red, or tan in colour. Ochre is filamentous (from bacterial filaments), hydrated (more than 90 percent water), and its dry matter has a high iron content (2-65 percent dry weight). They usually contain an organic matrix (2-50 percent dry weight) (Ford, 1979, 1982a).

There are two main categories of ochre problems:

1. ***Ochre as a temporary problem, called autochthone (of local origin).*** Temporary ochre as a clogging factor may disappear over a period of three to five years. It usually occurs rapidly and can be often detected at drain outlets soon after drain installation. If the drains can be maintained in working order, the concentration of Fe^{2+} reaching them will gradually decrease.
2. ***Ochre as a permanent problem, called allochthone (of foreign origin).*** Permanent ochre is the most hazardous condition because it continues to be a clogging agent for the service life of the drainage system, regardless of treatment. Permanent ochre occurs in soils that contain extensive quantities of residual iron and natural energy. The soluble reduced iron originates from surrounding areas, hence the name, and is transported by seepage into the drained area. There are ochre locations where the soluble iron originates 4 to 6 km from a drainage site. Thus, it is important to consider topographical terrain features when estimating the potential for permanent ochre formation. In general, sites considered to have permanent ochre potential should not be tile-drained without modifications in design and provisions for continuous maintenance.

Ochre can be found in the soil abutting the drain envelope, the envelope itself, the pipe perforations and within the drain pipe. Most clogging in corrugated pipes can be traced to sealing of the perforations and accumulations within the valleys of the corrugations. Within the pipes, the heaviest accumulation of ochre appears to be in the lower third of the drain length, although the lower third is usually not the region of maximum ochre formation. Ochre can usually be detected at drain outlets or in manholes as a voluminous and gelatinous mass. However, it may be present in the drains, while not visible at the outlet.

Ochre formation

The development of ochre requires reduced or *ferrous* iron (Fe^{2+}) flowing into drains as raw material. The minimum concentration of ferrous Fe^{2+}, necessary for growth of the iron bacterium *Leptothrix,* is 0.12 mg/l (0.12 ppm) (Ford, 1980).

It must be in solution in the groundwater rather than located on soil particles. It is present mostly as iron hydroxide ($Fe(OH)_2$) or as iron sulphide (FeS_2), and will precipitate when oxidation takes place after contact with air, e.g. near and inside subsurface drains (Smedema and Rycroft, 1983). Many soils contain substantial quantities of iron, yet the conditions, required to create ochre problems in drains vary considerably.

Bacteria are required to convert the insoluble *ferric iron* (Fe^{3+}), which is located on soil particles, to a soluble form (Fe^{2+}) which can be transported to the drains by groundwater advection. *Ferrous iron* (Fe^{2+}) can only exist in groundwater if the oxygen in the soil has been depleted, e.g. after a soil is flooded for a considerable time, or when micro-organisms have used all available oxygen. If this condition is met, iron-reducing bacteria reduce the insoluble ferric iron (Fe^{3+}). This biological action of the bacteria is energy intensive, and energy sources must therefore be present. The major sources are organic material like remnants of plants and plant roots, and certain acids like malic, citric, tannic and lactic acids. Hence the higher the organic content in the soil, the faster and more widespread the conversion from Fe^{3+} to Fe^{2+} by bacteria will be.

Soluble Fe^{2+} flowing in groundwater enters a different environment as it approaches the drain and passes through the drain envelope. If some oxygen is present in this area, certain filamentous and rod-shaped bacteria will precipitate some of the Fe^{2+} as insoluble Fe^{3+} and incorporate it into ochre. Iron-precipitating bacteria must be present for extensive clogging to occur, even when other conditions are just right for chemical precipitation of the iron. *Iron alone does not have serious sticking properties.* The reaction inside drains is a combination of bacterial precipitation and the incorporation of chemically precipitated iron into the sticky slimes of the bacterial masses involved in the ochre matrix.

There is a type of ochre that forms only at low pH, in *pyritic* soils (acid sulphate soils). These soils are found in many coastal areas as well as in mine dumps and in certain shales. Pyrites are formed from iron and hydrogen sulphide in flooded marine deposits. When such soils are drained, the pyrites first oxidize to Fe^{2+} and sulphates. These sulphates change to sulphuric acid, which lowers the soil pH below 3.5. The rod-shaped bacterium *Thiobacillus ferrooxidans*, which can function only in an acid environment, then converts the soluble iron into ochre.

In Egypt, Iraq and Pakistan no serious ochre problems have been reported. The absence of ochre there is due to the generally alkaline soil environment. In alkaline soils, ferrous iron (Fe^{2+}) cannot exist in solution in the groundwater. In Israel, severe ochre problems have been encountered when draining certain swampy areas. The drainage systems were designed such that anaerobic conditions were maintained by placing an elbow at the drain outlets to create submergence. These systems have operated successfully for several years (Henkin, 1987). The same procedure was introduced in The Netherlands in the 1960s, yet with limited success (Huinink, 1991).

Prediction of ochre problems

The following on-site observations may give clues to potential ochre problems inside drains (Ford, 1979):

1. Soil types that appear to show the highest potential for ochre formation are fine and silty sands, organic soils, soils with organic pans and mineral soil profiles with mixed organic matter.

2. Sites being utilized for sprinkling of sewage effluent usually furnish sufficient energy for reduction reactions. Such sprinkled soils are potentially serious for ochre hazard if the profiles are subjected to long term flooding.
3. Some topographical features indicate possible ochre problems. If there is land of higher elevation close to the proposed drainage site, permanent ochre potential may be a problem due to permanent seepage. Valleys at the base of escarpments are typical for permanent ochre.
4. Flood plains of rivers and gullies are suspect, particularly if the site is a mixture of sand and organic matter.
5. Depressions containing organic residues are ochre prone sites.
6. Blue-coloured clays or bog-like, decomposable organic matter between 0.6 and 1.2 m below the soil surface suggest permanent ochre sites.
7. Oil-like films floating on surface water in canals may indicate ochre and may contain ochre forming bacterial filaments.
8. Gelatinous ochre that has precipitated on ditch banks and/or canal bottoms is an important indicator for potential ochre problems.
9. The amount of Fe^{2+} in groundwater is usually higher in soils with organic pans and a pH below six.
10. Based on practical experience, the least likely candidates for ochre problems are silty clays, clay loams and clay soils.
11. In arid areas, ochre is seldom a problem.

Ochre potential ratings

It is possible to estimate the maximum potential for ochre before installing drains, as well as to estimate whether specific soil types or profiles can be considered susceptible (Ford, 1982b). Analysing the *soils* for total iron is of no value because the values do not indicate soluble Fe^{2+} or the complex interactions between the soil pH and the soil type. The Fe^{2+}-content of the *groundwater* flowing into a drain is a reliable indicator of the potential for ochre clogging. The simplest way to determine the ferrous (Fe^{2+}) iron content of the groundwater is using paper indicator strips, which are immersed in a groundwater sample. The colour can be used to assess the concentration of the ferrous iron. The concentrations are colour-coded into the following classes: 2, 5, 10, 25, 50, and 100 mg Fe^{2+}/l.

Ford (1982a) developed a reliable yet elaborate testing procedure to assess the ochre clogging potential of soil profiles before installing drains. This procedure is independent of pH and soil type. The method has been developed and tested extensively at numerous locations in the United States (Ford, 1982a). Using this method, it is possible to determine whether a soil layer may release much or little ferrous (Fe^{2+}) iron, once water saturated, and whether the ferric iron (Fe^{3+}), which is adhered to the soil particles, can be easily reduced to soluble Fe^{2+}.

Scholten and Ven (1987) have compared the ochre potential ratings, assessed with the Ford method, with the method using indicator strips. They found a strong correlation of the detected ferrous iron content, determined with both methods. However, the content indicated by the strips is consistently higher than the content indicated by the Ford method (ratio 3 to 4). Yet, for routine measurements, the simple method with indicator strips will suffice. In spite of the insufficient number of readings in their investigations, Scholten and Ven (1987) present a table (Table 8) to assess the ochre potential. The figures in this table are in reasonable agreement with the figures, proposed by Ford (1982a).

How to minimize ochre clogging of drains

There is no known economical, long-term method for effectively controlling ochre clogging in drains. Although options are limited, the emphasis must be on ‘living with the problem.’ The following recommendations may be useful (Ford, 1982a, 1982b).

TABLE 8
Ochre potential according to the Ford-method and the method of indicator strips

Ochre potential	Ferrous (Fe^{2+}) in groundwater (mg/l) Ford method	 Indicator strips
Very high	>10	>25
High	5-10	10-25
Moderate	2-5	5-10
Little	0.5-2	1-5
Negligible	<0.5	<1

1. *Precipitating iron in the soil by promoting oxidation.* Iron cannot be dissolved in groundwater until it is reduced. Hence, all measures that minimize the development of anaerobic conditions are acceptable. Soil aeration prevents reduction. Closer spacing and shallower depth of drains may be beneficial for certain sites.

2. *Size of the perforations in drainpipes.* The larger the pipe perforations, the longer the period before drain discharge may be severely restricted. Ochre adheres to frayed plastic edges of perforations. Cleanly cut inlet perforations are essential. Small perforations limit the effectiveness of jet cleaning as a method for cleaning drains installed with synthetic envelopes.

3. *Drain envelopes.* A graded gravel envelope is best. It may however still clog under conditions of severe ochre potential. Soil compatible, coarse structured PLMs may also reduce the risk of clogging by ochre. Relatively thin synthetic envelopes like geotextiles present the greatest risk. Surveys of selected drainage sites show that ochre clogging of drains, wrapped with synthetic materials occurs first in the slots and valleys of pipe corrugations, and can be present in amounts sufficient to cause drain failure. These materials clog relatively easily by ochre deposits because the iron precipitating bacteria easily grow across the voids in the fabrics. Of all thin synthetic envelopes, knitted polyester envelopes are the least vulnerable to ochre clogging.

4. *Organic envelope materials*. Envelopes, manufactured from pine, oak and cypress sawdust delayed ochre development at drain inlet openings for extended periods in Florida (United States). Sawdust creates an anaerobic environment and appears to be toxic to ochre enhancing bacteria. Sawdust may contain aromatic hydroxyl compounds that complexes iron. The use of peat and other organic envelope materials should be avoided. They usually increase ochre problems and enhance clogging.

5. *Submerged outlets*. Submerged drains in groundwater with high ochre risk prevent the soluble ferrous iron (Fe^{2+}) to oxidize to the insoluble clogging ferric iron components (Fe^{3+}) (Rozendaal and Scholten, 1980). This is an old recommendation that has been used with some success when the entire drain is permanently under water. The drain line must be completely under water over its entire length throughout the year. This may require that the drains be installed on a flat grade or horizontal.

Ochre removal from drains

Data on jetting of drains, wrapped with synthetic envelopes, are scarce. In The Netherlands, medium pressure jetting of ochre clogged drains has generally not been very successful. The dewatering capacity of jetted drains was not significantly enhanced, or only for a very short period. Jetting water must pass through the pipe perforations and be deflected by the envelope in order to clean the valleys. In structurally unstable soils, the pressure at the nozzle should not exceed 20 bar, otherwise the soil near the drains may destabilize and flow into the drain (see Chapter 7, Section *Maintenance of drainpipes*). The larger the pipe perforations, the better the potential for cleaning the valleys and envelope. Jet cleaning is unsatisfactory if delayed until the ochre has aged and become crystalline and/or sticky. ‘Dry’ rodding (with a scratcher at the end without extra water) can also be applied successfully, provided that:

- the operation is carried out when the ochre is still slimy, before it had the opportunity to harden during a prolonged dry period (summer); and
- rodding is done while the drain is carrying water (wet period). Thus the (still slimy) ochre is easily loosened and will be carried away by the drain discharge (Cavelaars, personal communication).

As ochre clogging is usually most severe shortly after installation, it is recommended to jet the drains during the first year if ochre problems are suspected, rather than wait until the drains are clogged. Drains should discharge into open ditches rather than through closed collector systems. The access of single drains through open outlets greatly facilitates jetting. Herringbone or similar drain designs should have entry ports for jet flushing.

Lime and gypsum depositions

Whereas ochre is a prominent problem in humid temperate regions, which has been investigated extensively on a large scale for many decades, the deposition of slightly soluble salts, such as calcium carbonate ($CaCO_3$) and calcium sulphate as gypsum ($CaSO_4.2H_2O$), within drainpipes and envelopes is a not systematically investigated problem. There is ample scope for systematic investigation on lime and gypsum depositions with pipe drains; this would include an inventory of the extent of the problem and the conditions under which it is likely to develop. Lime and gypsum deposition is most likely a chemical process. The hard and crystalline deposits are likely to build up comparatively slowly so that adverse effects only appear after a long time.

The problem may occur in gypsiferous soils and soils with a high content of calcium carbonate, which are common in arid and semi-arid areas, or result from the salts applied with the irrigation water. Depending on the dissolved Ca^{2+}-content of the groundwater, it may however also occur in non-irrigated areas like Belgium where $CaCO_3$ is reported to have cemented the gravel around a drainpipe of a road drainage system to a compact, impervious mass. Calcareous deposits in and around drains installed in soils that convey groundwater rich in dissolved Ca^{2+} also are reported in France (CEMAGREF, 1983). In arid regions, Cavelaars *et al*. (1994) found gypsum in excavated drains. No deposition of lime was however found in horizontal drainage systems, in spite of the lime deposition hazard - ‘*incrustation*’ - of tube wells.

Precipitation of lime and gypsum may take place if the concentration of calcium compounds (carbonates, bicarbonates or sulphates) exceeds their solubility. Many waters, particularly in arid regions, are partly or nearly saturated with calcium bicarbonate, ($Ca(HCO_3)_2$), which, upon concentration, precipitates in the soil as $CaCO_3$. Precipitation of $CaCO_3$, and of $CaSO_4$ will occur if the soil solution is concentrated by water removal during plant growth, and the solubility of the relatively insoluble $CaCO_3$ and the more soluble $CaSO_4$ is exceeded.

This physical process does not explain the precipitation of $CaCO_3$ in the drain envelope and at the perforations which may result from the conversion of $Ca(HCO_3)_2$ through the loss of carbon dioxide, (CO_2). For tube wells, the precipitation hazard may be explained by the pressure decline in the groundwater at the entrance of the envelope or the tube openings.

Complete prevention of the deposition of $CaCO_3$ and $CaSO_4$ in a horizontal drainage system will not be possible, yet some measures can be taken to reduce the precipitation hazard of these calcium salts. Keeping drainage systems under water will reduce the risk of more concentrated solutes near the drainage system and the release of CO_2 from the groundwater.

Manganese deposits

Manganese, if dissolved in groundwater under suitable reducing conditions, can form a bacterially enhanced, gelatinous black clogging deposit.

Sulphur precipitate

Sulphur slime is a yellow to white stringy deposit formed by the oxidation of hydrogen sulphide that may be present due to reduction of sulphates dissolved in groundwater. Sulphur bacteria oxidize the H_2S to H_2O and elemental sulphur S. Globules of elemental sulphur and masses of whitish, sticky slime are deposited within the filaments of these bacteria and forms a precipitate of sulphur at the drain outlets (Martínez Beltrán, 1978; Ford, 1980).

Sulphur slime has not been a serious problem in most agricultural drains. It is found most often in muck soils. It may also be present at sites designed for subirrigation through drainpipes if the well water used for irrigation contains hydrogen sulphide (H_2S).

Iron sulphide

Iron sulphide (FeS_2) may be found under chemically reduced conditions, e.g. when drains are buried in mixed soil profiles, in gullies and river plains, or when topsoil or organic debris are used to cover the drains during installation. It is a gelatinous black precipitate formed by the reaction between ferrous iron (Fe^{2+}) and hydrogen sulphide (H_2S). It will usually not stick to light sandy soil particles. It becomes a clogging agent if it is present in amounts that can block soil pores. In general, iron sulphide should not be a serious problem for most installations that do not blind the drains with topsoil or debris of organic matter.

PENETRATION OF ROOTS INTO DRAINPIPES

Field data concerning *root penetration* are scarce. Penetration of roots of field crops is rare in arable lands. Such roots may temporarily obstruct drain discharge and slightly enhance pipe siltation, but they will die after harvesting. Roots are more challenging in drains installed under perennial plants like trees and shrubs, e.g. under shelterbelts, which border orchards. They may fill the entire drain over a considerable length, trapping suspended materials and seriously obstructing drain discharge. Installing unperforated pipe sections at locations where such roots occur may prevent the problem (see Chapter 2, Section *Rigid pipes*).

In arid countries, drains are installed at 1.5 to 2 m depths and occasionally deeper, hence, root growth into the drains is less likely as compared with drains that are installed at shallow depths.

Quantitative information on root growth inside drains is scarce.

- In *Belgium*, during a dry spell, deep rooting cabbage caused problems in a shallow drainage system that was used to control a perched water table.
- In *Egypt*, the Eucalyptus tree is known to cause trouble (Cavelaars *et al*., 1994).
- In *Israel*, the roots of certain types of Tamarix trees tend to clog drains. The roots of Tamarix and of some other types of trees cannot be removed, especially when gravel envelopes have been used (Henkin, 1987).

- In *Pakistan*, all trees located within a distance of 35 m from the drains were removed as a way of precaution in the Mardan Scarp project.
- In *Spain*, very fine roots of saline shrubs (*Suaeda fruticosa*) which grow on the banks of collector ditches were found to grow into laterals, causing serious clogging. This problem may be solved by installing unperforated pipe sections with a minimum length of 3 m at the downstream end where the laterals discharge in these ditches (Martínez Beltrán, 1987).
- In *Surinam*, an Asiatic vine called kudzu caused substantial problems of root growth inside drains (Van der Molen, 1972).
- In *Peru*, sugar cane was reported to grow into pipes at a depth of 1.5 m (Cavelaars, 1987).
- In *The Netherlands*, the occurrence of roots in agricultural lands is linked to the type of crop, the type of envelope, and the site that is drained. Roots penetrated easily into drains wrapped with organic envelopes (a mixture of peat and coconut fibres), glass fibre sheet envelopes, knitted sock envelopes, and a PLM envelope consisting of polystyrene granules. Thin synthetic envelopes however provided good protection. Root penetration was generally lower when the envelope thickness was greater (Stuyt, 1992a). Fruit trees (apples, pears) do not cause many problems, yet poplar (*Populus canadensis)* is known to be harmful.

Chapter 6

Guidelines to predict whether an envelope is required

Due to the drag force of water flowing toward a drain, soil particles may be carried into the drain from all sides. Drainpipe siltation may be due to particle invasion of cohesionless soil, to soil dispersion of cohesive soil at drain level, or to downward transport of dispersed or suspended material through soil pores, cracks and voids. This process can never be prevented completely, but it can be counteracted by installing an envelope material around the drainpipe. The need of envelope materials around drainpipes will depend on the physical and chemical properties of the soil, on the chemical composition of the water to be drained and on the conditions under which the pipes are installed. However, whether or not a soil presents problems is not easy to tell, because it cannot easily be derived from soil properties and conditions. Soil heterogeneity and the complicated nature of the physical interactions between water and soil near drain openings make prediction of the need for drain envelope materials very difficult.

Attempts have been made to define and identify soils that are prone to cause mineral clogging of drainpipes. Although many soil types have been identified as being more susceptible to sedimentation than others, sound criteria as to whether drains require an envelope or not have not yet been established. With the current state of knowledge, it is virtually impossible to determine universal criteria and fixed parameters to predict the tendency of mineral drain clogging for a given soil and the associated need of an envelope. Nevertheless, the experience gained during four decades of investigations and practice allows for a number of conclusions to be drawn. These are existing criteria, usually based on local experience and only valid for the regions where they have been established. They may therefore not be directly transferred to other regions without verification of their applicability.

Permeameter experiments with soil samples taken at design drain depth may provide information on the need of drain envelopes, by giving evidence of the structural stability of a soil and the risk of soil particle invasion into drainpipes. Permeameter research has been performed in the United States (Willardson and Walker, 1979; Samani and Willardson, 1981), the Netherlands (Stuyt, 1992a), Belgium (Dierickx and Yüncüoglu, 1982), France (Lennoz-Gratin and Zaïdi, 1987) and is currently being conducted in Egypt, Pakistan, and India. Permeameter experiments on samples of soils and potentially suitable envelope materials are carried out with increasing hydraulic gradients. If the soil resists high gradients, a drain envelope is not required. An application is the assessment of the hydraulic failure gradient of a soil (e.g. Samani and Willardson, 1981). From comparison of permeameter results with those of field drains, Lennoz-Gratin *et al.* (1992) consider the permeameter flow test a reliable means to predict mineral clogging of drainpipes. The results of Stuyt (1992b), however, indicate that the association between laboratory data and field data may be quite ambiguous.

Apart from laboratory experiments, very simple field observations may give clues to the need to install envelopes in future drainage projects. Auger holes, intended for the determination of the hydraulic conductivity of the soil, may yield useful information in this respect. If such holes collapse rapidly, so that a screen must be used, installation of an envelope is vital to protect future drains against mineral clogging. The occasional occurrence of soil layers or lenses of loose soil material at drain depth in a soil profile where drainpipes do not normally require an envelope may be a reason to wrap all drains with envelopes as a safety measure, in spite of the higher costs.

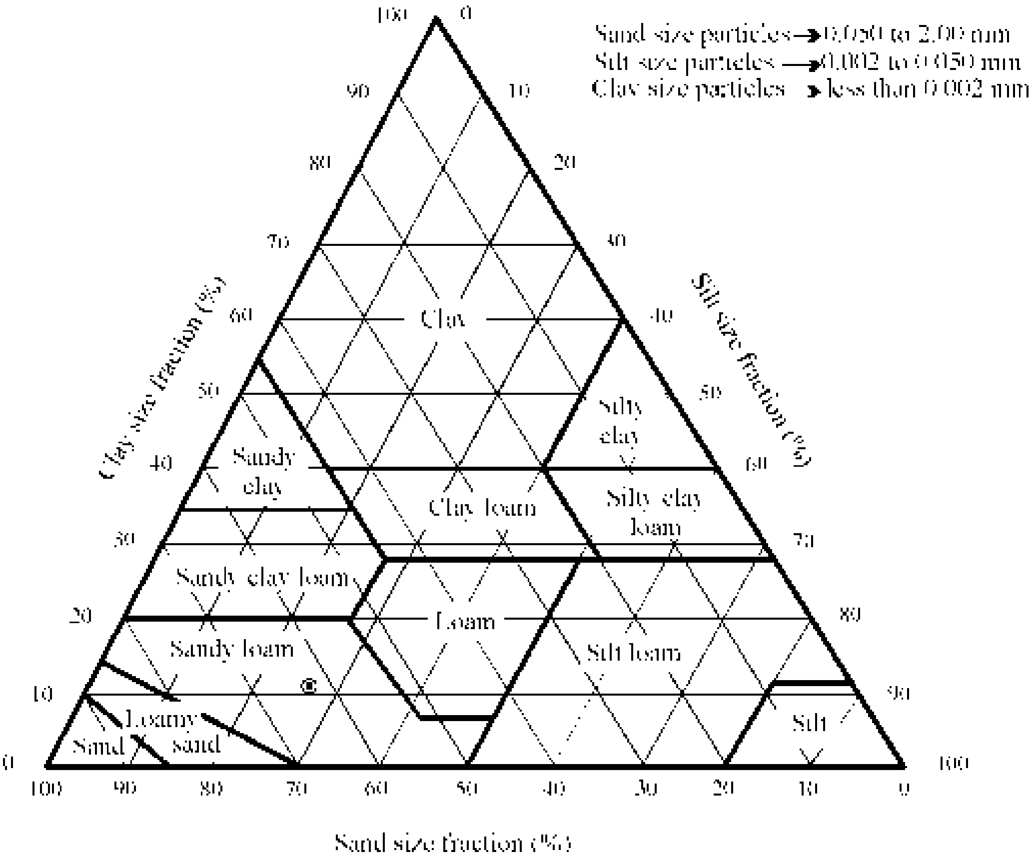
In the following sections the main soil properties related to the risk of soil particle invasion into drainpipes and the associated need to protect drainpipes against siltation are described. In addition, the influence of water quality on soil chemical composition has been considered. Finally, some prediction criteria for the need of drain envelopes have been defined.

PHYSICAL PROPERTIES OF THE SOIL

Soil texture

A soil consists of a skeleton of mineral particles with voids or pores, which contain air and water. Organic matter may be present as well, particularly in shallow soil layers. Mineral particles of soils vary widely in shape, size, mineralogical composition, and surface-chemical characteristics. The particle size distribution of a soil, often referred to as *soil texture*, is an important indicator for soil stability. It can be found by mechanical soil analysis. Soil particles

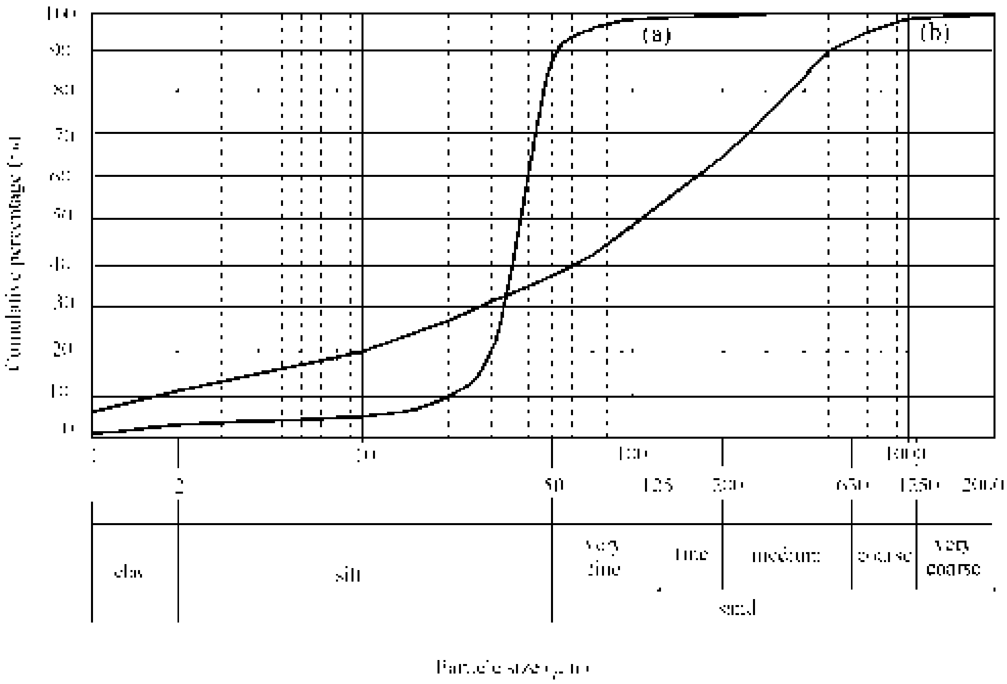
FIGURE 40
Textural classes (FAO, 1990)



are normally classified as clay (< 2 µm), silt (2-50 µm) and sand (50-2000 µm). The dry weight percentages of sand, silt, and clay can be plotted in a triangular graph (Figure 40). Drawing these percentages on a line parallel to the base *opposite* to the indicated corner (which represents 100 percent sand, silt, or clay) the textural class can be found by the intersection of the three lines inside the triangle. Figure 40 shows that a soil with a clay fraction of 11 percent, a silt fraction of 27 percent and a sand fraction of 62 percent would be classified as sandy loam.

The cumulative particle size distribution curve (Figure 41) gives information on the cumulative percentage of soil particles (on dry weight basis) that is smaller than a given diameter. For example, d_{10} and d_{50} are the particle diameters for which respectively 10 and 50 percent of the soil particles (by dry weight) have a smaller diameter. A uniform soil has a ‘steep’ particle size distribution curve (curve `a` of Figure 41), whereas a well-graded soil curve is less steep (curve `b` of Figure 41). The latter has a d_{10} of 1.7 and a d_{50} of 105 µm.

FIGURE 41
Particle size distribution curves



The coefficient of uniformity (C_u) of a soil is a measure of the bandwidth of the sizes of the soil particles that it contains. This coefficient, which is reflected by the inclination or slope of its particle size distribution curve, is given by:

$$C_u = d_{60} / d_{10} \tag{42}$$

The greater the C_u value is, the less uniform or the better graded the soil will be. A uniform soil, with all particles of the same size, has $C_u = 1$.

Particle size distribution and soil texture classification can give a first indication of the need for a drain envelope. For loose soils like sands, the C_u coefficient is often employed to predict the need for drain envelopes. If the soil is cohesive, the clay percentage is a more significant indicator.

In various regions, criteria based on the clay content of a soil have been successful as a means of determining whether drain envelopes are required. In Quebec, drainpipes do not need envelopes in soils with a clay content of at least 20 percent (CPVQ, 1989) while in the Netherlands, the clay content should be at least 25 percent (Van Zeijts, 1992). In Egypt and in India, the clay content should be 30 percent or higher (Abdel-Dayem, 1987; Rajad Project Staff, 1995). Nevertheless, some of these soils still exhibited mineral clogging. This is caused by the fact that soil stability is not only depending on the physical, but also on the chemical composition of the soil (Section *Chemical properties of the soil*).

In fine cohesionless sandy soils, drains normally require an envelope. However, in Quebec (CPVQ, 1989) no envelope is recommended if the width of the perforations in the pipe wall is smaller than 2 d_{85} (the particle diameter for which 85 percent of the soil particles by dry weight have a smaller diameter). Instead of 2, other values of this factor ranging from 0.5 to 10 have been accepted as well. Attempts to adapt the perforation width to a characteristic particle size diameter of the surrounding soil have failed because of the variability of both. Therefore, in cohesionless sandy soils, drain envelopes should be recommended under all circumstances.

Although texture alone is insufficient as a decision parameter for envelope application, it is generally accepted that soils with d_{50} between 50 and 150 µm are mechanically quite unstable and, as such, sensitive to erosion (Dierickx and Leyman, 1991). They will therefore require an envelope.

Given the fact that soils with a great bandwidth of particle sizes do not present serious siltation problems, Olbertz and Press (1965) proposed the C_u coefficient as an *erosion likelihood* parameter:

- $1 < C_u < 5$: very uniform and very sensitive to erosion.
- $5 \leq C_u \leq 15$: moderately uniform and sensitive to erosion.
- $C_u > 15$: no danger of erosion.

The ratio clay/silt percentage of a soil is also important. According to Dieleman and Trafford (FAO, 1976), the risk of mineral pipe clogging decreases rapidly when this ratio exceeds 0.5, where the particle size of silt ranges from 2 to 20 µm.

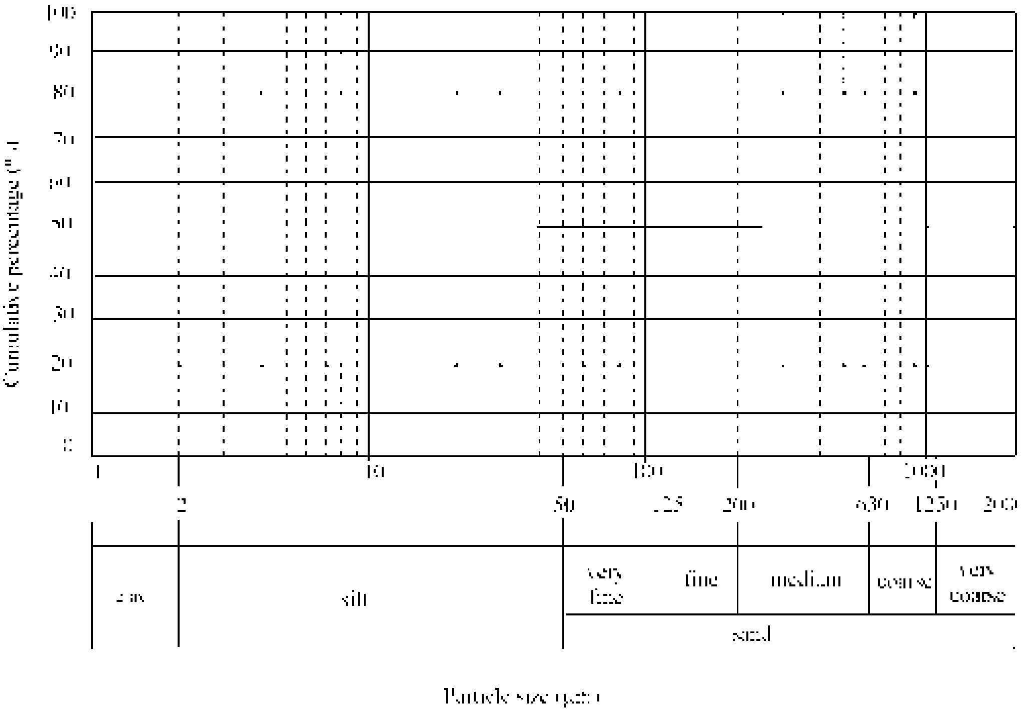
In any case, soils with an important quantity of silt and a small amount of clay offer a great risk for mineral clogging of drains. A range of particle size distributions of such soils is presented in Figure 42. Any soil having a cumulative particle size distribution that lies completely or largely in the shaded area is likely to cause problems with drain clogging (Stuyt, 1982; Veldhuijzen van Zanten, 1986). The reason is that these soils have particles which are generally too big to be cohesive yet not big enough to be stopped from being washed into drain openings not protected by an envelope.

Structural stability

In the Netherlands, field data indicate that soils may differ widely with regard to the rate of mineral clogging even though they have a comparable texture (Stuyt, 1992a). It has become obvious, over the years, that the structure of a soil is at least as important as its texture. However, it is rarely possible to interpret soil structure in terms of clogging risks, let alone clogging rates.

Soil structure refers to the way soil particles are bound together into natural, more or less porous compounds or aggregates. It is conditioned by the soil texture, the presence of organic

FIGURE 42
Range of particle size distribution of soils that may cause clogging of drains



and other cementing substances, and the ratios between various cations that are present in the soil. Soil aggregates may be classified depending on the strength of the bonds between soil particles, which can range from loose, weak, moderate to strong bonds. Soil structure consisting of loose, individual soil particles is typically associated with sandy soils, yet the finer grained silts may also exhibit this type of structure. Such soils are structureless and have virtually no cohesion. Clay soils are generally cohesive and may be massive or develop blocky and prismatic structures. In some cases, however, they lose their cohesion and get dispersed (Section on *Chemical properties of the soil*). Soil structure governs, among other things, water flow toward drainpipes.

The firmness of the bonds between soil particles is called cohesion. Soil consistency refers to the behaviour of a soil at various moisture contents and largely depends on cohesion. Two well-known consistency limits are the *liquid limit* and the *plastic limit,* which form the so-called Atterberg limits. The difference between these two limits gives the plasticity index (I_p). The I_p index is an indicator for the firmness of the bonds between soil particles.

The structural stability of soil aggregates is related to the attracting forces between the soil constituents, and determines the resistance of a soil to mechanical and physical-chemical destructive forces. To a certain extent, the structural stability of soil aggregates is determined by the amount of clay particles. Aggregate stability is an important soil characteristic when it comes to the assessment of the risk of mineral clogging of drainpipes, and it is known that drainpipes installed in stable structured soil do not require envelope materials. In spite of the availability of various methods to determine aggregate stability, e.g. by wet sieving, a straightforward, unambiguous procedure to classify the structural stability of soil aggregates into significant figures is not available. The reason for that is that stability of aggregates is not an intrinsic property of the soil but depends on various conditions such as moisture content and chemical properties. Slaking of dry soil aggregates upon wetting is well known. However, if this soil remains in the plastic state at drain depth, it will largely resist slaking. Hence the structural stability of a soil is not a very reliable indicator when it comes to derive guidelines for the assessment of envelope requirement to prevent mineral clogging of drain lines.

The I_p index, mentioned above, is used to predict the sensitivity of a soil to mineral clogging of a drainpipe. Dieleman and Trafford (FAO, 1976) report the following:

- $I_p < 6$: high tendency to siltation.
- $6 \leq I_p \leq 12$: limited tendency to siltation.
- $I_p > 12$: no tendency to siltation.

There are various modifications of this approach, sometimes in combination with other criteria (e.g. Lagacé, 1983).

Moisture content

Under general wetness the structure of the soil is detrimentally affected when a subsurface drainage system is installed. Putting drains under wet conditions may destroy the structure of a soil almost completely and enhance the risk of mineral clogging of the pipes. Therefore, drains should not be installed under too wet conditions. Unfortunately, stopping the work during wet spells is often ignored for financial considerations. Moreover, drains must sometimes be installed at locations where the groundwater table is permanently above the envisaged drain level.

The warning not to install drains, if possible, during periods of excess wetness, or when the water table is quite shallow is not new. Cavelaars (1966) was one of the first to mention that the performance of a drain under field conditions is determined to a far greater extent by the actual condition of the soil around the drain, than by the type of drain or envelope material. His major conclusion was that installing drains under wet conditions could have a very harmful effect on the performance, especially in soils of low structural stability.

CHEMICAL PROPERTIES OF THE SOIL

Structural stability of a soil is affected by its salt and sodium content. In addition, cementing agents in sands and silts are lime ($CaCO_3$) and sesquioxides (Al- and Fe-oxides). Lime precipitates around the contact points between soil particles. The binding capacity of Fe-oxides is ill-defined, but Al-oxide is probably effective. Apart from these inorganic deposits, soil organisms and their organic by-products may also keep soil particles together.

The chemical composition of a soil is also quite relevant because of potential clogging of drainpipes and/or envelopes due to iron, lime and sulphate compounds (Chapter 5, Section on *Chemical and biochemical clogging*). Although drain envelopes cannot prevent chemical clogging, this phenomenon must be duly considered in any envelope selection procedure.

Assessment of the risk of mineral clogging of drainpipes as a result of the chemical composition of the soil requires knowledge of the cation exchange capacity, and the salinity and sodicity of the soil.

Cation Exchange Capacity

Clay particles and humus have adsorptive properties. Clay particles are colloids that are so small that surface effects are dominant. Phenomena affected by soil colloids are dispersion, swelling, shrinkage, flocculation, cohesion, and plasticity of soils. Clay particles have a negative charge and thus they adsorb positively charged cations such as Na^+, K^+, H^+, Ca^{2+}, and Mg^{2+}.

Organic matter has a stabilizing influence on the physical and chemical properties of soils, despite its generally modest quantity. It promotes the development and the stability of soil structure. The finer components of organic matter are converted into humus, as a result of their decomposition by micro-organisms. Like clays, humus is also a colloidal material. Its capacity to hold ions exceeds that of clay but clay is generally present in larger amounts. Hence, the contribution of clay to the chemical soil properties usually exceeds that of humus, except in very sandy soils.

If soil colloids contain a high proportion of Ca^{2+} and other divalent ions, firm bonds are formed between mineral particles, leading to stable soil structure. In soils rich in Na^+-ions (*sodic soils*) the bonds are unstable, which results in a weak soil structure.

The total amount of cations that a soil can adsorb is determined by the negatively charged soil colloids clay and humus. This amount is called the *Cation Exchange Capacity* (*CEC*) of a soil and usually expressed in meq/100g of dry soil.

Soil salinity

Soils may contain slightly soluble salts such as lime and gypsum and highly soluble salts such as sodium chloride and sodium sulphate. These salts may be contained in the soil parent material (primary salinization) or be transported dissolved in water and deposited after the soil has dried (secondary salinization). The major sources of secondary salinization are salts added with the irrigation water and through capillary rise of groundwater, mainly if the groundwater table is recharged by seepage. Salt contained in precipitation is negligible in comparison with the salt content of the irrigation water and the groundwater.

The anions predominantly present in salty soils are Cl^- and SO_4^{2-}, yet some HCO_3^- at *pH* values of 6-8 and CO_3^{2-} at *pH* values higher than 8.5 may be found. Na^+, Ca^{2+} and Mg^{2+} are the predominant cations.

The total dissolved solids (*TDS*) can be assessed from measuring the electrical conductivity (*EC*). The *EC*-value and *TDS* are linearly related (Richards, 1954), and given by:

$$TDS = 640\ EC \tag{43}$$

where TDS = total dissolved solids (mg/l); and
EC = electrical conductivity (dS/m).

The electrical conductivity of the soil extract is usually determined in a soil paste saturated with water up to the liquid limit. This conductivity (EC_e) is comparatively easy to measure. For most soils the *EC* of the soil solution at field capacity (EC_s), some time after a rain or irrigation, is about twice the EC_e-value.

Soil sodicity

The relative amount of adsorbed Na^+-ions, compared to the total amount of cations that a soil can adsorb is called the Exchangeable Sodium Percentage (*ESP*):

$$ESP\ (\%) = (Na^+_{ads}/CEC) \times 100 \tag{44}$$

where Na^{+}_{ads} is the quantity of adsorbed Na^{+}-ions (meq/100 g of dry soil). The *ESP* expresses the sodicity and hence the dispersion tendency of a soil.

Information on the chemical properties of the soil adsorption complex can be obtained from the soil solution since there is equilibrium between the adsorbed cations and the dissolved cations. Hence, another measure for the sodicity is the *Sodium Adsorption Ratio* (*SAR*), derived from the concentration of sodium, calcium, and magnesium in the soil solution.

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}} \tag{45}$$

where the cation concentration is expressed in meq/l.

The *SAR* can be determined more easily than the *ESP*. The *ESP* can however be calculated easily from the *SAR* since they are related as (Richards, 1954):

$$ESP\,(\%) = \frac{100(-0.0126 + 0.01475SAR)}{1 + (-0.0126 + 0.01475SAR)} \tag{46}$$

Within the range 2-30, *SAR* and *ESP* values are almost equal, so *SAR* = *ESP* is a practical approximation. Outside this range, Eq. (46) must be used.

High *ESP* or *SAR* values are usually an indication of poor physical soil conditions and high *pH*. An easy field method, therefore, is testing *pH* with the indicator phenolphthalein. If this turns pink (*pH* above 8.5), the soil has probably a high *ESP*.

Dispersion problems are generally more severe when the *ESP* or *SAR* values are greater. Dispersed material may be transported by groundwater and will enter the drainpipe. In general, under arid climates, problems are not experienced in soils with *ESP* values below 15 percent. In India, the clay content of soils, for which no envelopes around drains are required, is increased from 30 to 40 percent for soils with *SAR* exceeding 13 (Rajad Project Staff, 1995).

As the salt concentration of the soil solution has an influence on dispersion, the *ESP* of a soil cannot be used as a single indicator of soil stability. Soils having an *ESP* greater than 15 percent will not disperse as long as the salt concentration in the soil solution is high. When this high salt concentration in the soil solution decreases, e.g. due to leaching by rain or irrigation water, dispersion problems may arise (Smedema and Rycroft, 1983).

The sensitivity of soils to dispersion also depends on the type of clay mineral (swelling or non-swelling type of clay). Swelling clay types are more susceptible to dispersion problems than non-swelling clays. But vertisols (strongly swelling and shrinking clay soils) in Gezira, Sudan and elsewhere, are examples of soils which do not exhibit dispersion problems in spite of *ESP*-values ranging from 20 to 25 percent (Smedema and Rycroft, 1983).

In humid areas, where leaching by rain water is dominant, difficulties with soil structure may already arise at *ESP*-values as low as 5 percent, whereas soils leached by irrigation water will usually tolerate 10 percent *ESP* (cf. Table 9).

WATER QUALITY

The chemical composition of a soil largely depends on the quality of the irrigation water, the amount of rainfall and on the chemical composition of the groundwater. The latter may be recharged by irrigation water, rainfall or seepage, causing the water table to rise far enough to influence the soil.

Irrigation water

The stability of the soil structure in the arable layer and the root zone depends in the long run on salts added with the irrigation water. In the long run, the EC and SAR of the soil solution at field capacity (EC_s and SAR_s) depend on the EC and SAR of the irrigation water (EC_{iw} and SAR_{iw}) with which the soil has been irrigated:

$$EC_s = n\,EC_{iw} \tag{47}$$

and

$$SAR_s = \sqrt{n}\,SAR_{iw} \tag{48}$$

where n = factor of concentration of the irrigation water in the soil. It depends on the leaching fraction (the fraction of irrigation water drained).

For high leaching fractions ($LF \approx 0.3$) the n-value is approximately 2. If the EC and SAR are expressed in terms of the saturated paste $EC_e \approx EC_{iw}$ and $SAR_e \approx SAR_{iw}$ (Ayers and Westcot, FAO, 1985). For medium leaching fractions (LF ranging between 0.15 to 0.20) $EC_e \approx 1.5\ EC_{iw}$ and $SAR_e \approx 1.22\ SAR_{iw}$.

The effect of the quality of irrigation water on the stability of soil structure may be diagnosed on the basis of its EC_{iw} and SAR_{iw}-values. Guidelines to evaluate the impact of the chemical composition of irrigation water on the infiltration rate of water into the soil were given by Ayers and Westcot (FAO, 1985). These guidelines, which are summarized in Table 9, may be used to assess the effect of the quality of the irrigation water on soil stability in the arable layer and the root zone.

TABLE 9
Problems with the infiltration rate of water into a soil as related to SAR_{iw} and EC_{iw} of irrigation water (after Ayers and Westcot, FAO, 1985)

SAR_{iw}	EC_{iw} (dS/m)		
	No problems	Moderate problems	Severe problems
0 – 3	> 0.7	0.7 – 0.2	< 0.2
3 – 6	> 1.2	1.2 – 0.3	< 0.3
6 – 12	> 1.9	1.9 – 0.5	< 0.5
12 – 20	> 2.9	2.9 – 1.3	< 1.3
20 – 40	> 5.0	5.0 – 2.9	< 2.9

Irrigation with water of low salinity will decrease soil stability if the salt concentration of the soil solution is substantial. Rainwater dilutes the soil solution and may cause greater dispersion than most irrigation waters.

Groundwater

Salinity problems and dispersion of clays, as encountered in irrigated agriculture, are very frequently associated with an uncontrolled water table within one to two metres below the ground surface. If the groundwater is too close to the surface, it rises by capillary action in dry periods and salinizes the soil surface. If the groundwater contains salts, a continuous load of salt accumulates into the root zone. The combination of high groundwater with salts especially arises in places where upward seepage occurs. Unless the excess groundwater is removed by an adequate drainage system its level must be kept below the critical depth. This is the depth below which capillary rise can be neglected: about 1 m in sands (because of low capillary rise), about 2 m in most clays (where the velocity is limiting), and 3 m or more in silt loams (with high capillary rise and sufficient velocity).

If the groundwater table is controlled by a subsurface drainage system, both the *EC* and *SAR* of the groundwater (EC_{gw} and SAR_{gw}) may have a profound effect on the structural stability of the soil at drain level. This is because the *EC* and the *SAR* of the soil solution will be similar to the EC_{gw} and the SAR_{gw} if the soil at drain level is permanently saturated. However, the *EC* and the *SAR* of the soil solution may be substantially higher if the soil at drain level is unsaturated, and salt accumulates due to capillary rise.

Effective salinity control must therefore include not only adequate drainage to control and stabilize the water table and to prevent salt accumulation in the shallow soil layers, but also a net downward movement of water to prevent salinization by capillary rise.

PREDICTION CRITERIA

The prediction criteria defined in the above sections are summarized below. These rules are merely guidelines or recommendations that do not guarantee 100 percent certainty.

- If at drain depth, auger holes can be made only with the use of a screen, because their walls collapse rapidly, installation of an envelope is vital to protect future drains against mineral clogging.
- In cohesionless sandy soils drain envelopes should be recommended under all circumstances.
- Any soil having a cumulative particle size distribution that lies completely or largely in the shaded area of Figure 42, is likely to cause problems with clogging of drains without envelopes.
- In temperate areas, drainpipes do not usually need envelopes in soils with a clay content of at least 20-30 percent, providing that drains are not installed under general wetness.
- Soils with a plasticity index of at least 12 show no tendency to siltation.
- In irrigated areas, drainpipes installed in soils with a clay content exceeding 40 percent do not need an envelope, regardless the *SAR* of the soil solution.
- The need for an envelope in soils with a clay content ranging from 20 to 40 percent depends on the *ESP*, which is approximately equal to the *SAR* of the soil solution (or somewhat higher). This *SAR* is greatly influenced by the quality of the irrigation water and sometimes by the groundwater composition (the latter in case of dominant capillary rise). Generally, no envelope is required in all cases where SAR_{iw} and EC_{iw} appear to exclude soil stability problems, following the guidelines specified in Table 9. In cases, where *SAR* and *EC* of the irrigation water and/or groundwater will presumably invoke soil stability problems, an envelope is recommended.
- If there is net upward movement of saline groundwater there will be problems with salinization and dispersion of clays. Maintaining a net downward water movement is the key measure to avoid such problems in soils with or without drainage systems.

Chapter 7

Guidelines for installation and maintenance of drainage materials

INSTALLATION OF SUBSURFACE DRAINAGE MATERIALS

Installation procedures

Drainage machinery

The success of a drainage system does not only depend on the design and the properties of the soil and the envelope. It is also determined by soil wetness during installation, trench backfilling and the general quality of the work.

Manual installation of drains and *installation with backhoe machines* are a valid option for small drainage projects. Backhoes make wider trenches than drainage machines commonly used in large projects. They are also used for wide and deep excavations for large collectors. Drainage machines either make narrow trenches in which the drains are laid (trench method) or they put the drain directly into the ground (trenchless method). *Trenching machines* are either wheel or chain trenchers. They are appropriate for a wide range of working depths and widths. *Trenchless machines* can be classified in either vertical or V-ploughs. The trenchless installation method, however, has some practical limitations with respect to drain types, drain sizes, gravel application and installation depth. Therefore, trenchless drainage has not yet been widely implemented in irrigated areas (Zijlstra, 1987).

Installing drains by manual labour or with classic excavators requires a series of successive operations: excavating the trench, installing the pipe, applying the envelope material and backfilling the trench. These operations are done simultaneously by trenching machines. Sometimes, backfilling is done by a separate auger or blade on a tractor. Backfilling can also be done by an implement, attached on the drainage machine when driving backward to begin excavating a new trench (Ochs and Bishay, 1992).

Contemporary drainage machines are equipped with laser grade control, which has significantly contributed to the efficiency and accuracy in the installation of subsurface drains. The maximum digging speed, however, should be adjusted to the speed of the hydraulic system that is used for automatic depth regulation, otherwise the installation accuracy will be poor. Although a certain deviation from the design grade can be tolerated, it should not exceed half the pipe diameter. Larger deviations promote air locks in high and sedimentation in low places, which obstruct water movement through the drain. Similarly, drain sections with a reverse grade cannot be tolerated.

Blinding

Since the risk of sedimentation is largest during installation and in the immediate subsequent period as long as the backfill has not settled and stabilized, drains are normally covered with friable topsoil to create a stable and highly permeable soil surround, and to preserve the alignment. Therefore trenching machines are equipped with cutters to bring a layer of topsoil or soil from another suitable layer from the sides of the trench on top of the drain. Its thickness should be at least 100 to 250 mm, depending on the drain diameter. Granular envelope material (like gravel) can also be used to achieve a highly permeable drain surround and to prevent vertical and horizontal displacement once the pipe is installed. Any envelope material to be used must be in place around the pipe before blinding is done.

Blinding, the initial covering of the drain with topsoil, is not recommended when organic envelopes are used, because topsoil with organic matter and intensive microbiological activity enhances the risk of microbiological decomposition of these envelopes. In such cases, soil from another suitable layer, with low organic matter, can be used for blinding. Further backfilling of the trench should be done as soon as possible and, at the latest, at the end of each day if there is a risk of surface water entering the trench.

Soil conditions

Since soil cohesion is strongly correlated with its water content, installation of the drainage system should preferably be done in unsaturated soil conditions with the water table below installation depth and outside periods of general wetness. In addition, the backfill should have settled before heavy rain or irrigation. In some situations, however, these conditions are not, or cannot be fulfilled. Drainage installation in wet conditions is discouraged, yet it is not always possible to drain under favourable or ideal circumstances.

When *cohesionless soils* are drained in saturated conditions, an envelope must be wrapped immediately around the drain and the drain covered with backfill material before the liquid sand flows into the trench. Caving of the trench wall, which often occurs in cohesionless or low cohesive soils, may damage and/or displace the drain. In every case, the drain and the envelope should be in place before the trench box has passed. Possibly, a longer trench shield may be used to protect a greater length of the trench. The drain should be blinded immediately. Simultaneous and instantaneous backfilling will help to prevent trench wall failure. However, the trench may collapse as soon as the trench box has passed and, therefore, a chute should be provided at the end of the trench box to convey the caving soil down to the top of the drain in order to avoid damage by falling clods and stones.

In cohesionless soils, drainage machines should be kept moving at all times. If not, fluid sand is likely to enter the trench box and cause problems with sedimentation as well as with alignment and grade of drains (Ochs and Bishay, 1992). Many problems, encountered with trenchers or backhoe excavators in saturated cohesionless soils, can be avoided by trenchless drainage installation.

Drainage of physically stable, *well-structured soils* under general wetness may destroy the soil structure during excavation and create a less permeable trench backfill (Stuyt, 1992a). Moreover, such conditions also promote mineral clogging of pipe and envelope. In any case, the use of an envelope cannot compensate for the ‘adversely affected’ soil conditions. Every effort should be made to preserve the existing soil structure and to protect the drain from soil failure. Adjusting the forward speed of the machine can be done to limit the destruction of the soil structure. Observation of the condition of the excavated soil can be a guide to the proper machine speed. The machine should move fast enough to preserve the structure of the soil and not turn the excavated soil into slurry (Stuyt and Willardson, 1999).

Structural deterioration of an originally stable, well-structured soil can be avoided with trenchless drainage installation. The functioning of drains installed with the trenchless technique depends very much on the changes in soil structure brought about by the passing of the blade (Zijlstra, 1987). This depends on the soil, the circumstances (not wet) and the depth (not over approximately 1.5 m). Drainage of clay soils in wet conditions will unavoidably result in smearing and reduction of the hydraulic conductivity where the machine has physical contact with the soil. Drainage of cohesive soils in wet conditions must be avoided, regardless of the available drainage machine.

The installation conditions for laterals of a composite drainage system in saturated soil are improved if the time span between the installation of “permeable” collectors and installation of the laterals is long enough. This is because much of the local groundwater has the opportunity to drain out before the laterals are installed. In severe cases, where the construction of collectors is difficult because of quicksand, a temporary drain (at greater depth) may be helpful. It is usually far cheaper than using well-points.

Backfilling

Backfilling and finishing of trenches should ensure a minimum of later land subsidence and preclude the occurrence of piping. The piping phenomenon may occur as a result of internal erosion of trench backfill by water flowing from the soil surface directly to the drains through the loose backfill material (Van Zeijts and Zijlstra, 1990). This is crucial in irrigated lands, where irrigation water that can flow freely through the trench or drain plough fissures into the drainpipe, will dramatically lower the irrigation efficiency. Furthermore, soil piping may cause soil material to be carried by the flowing water into the drain, creating sinkholes at the soil surface and/or mineral clogging of drains and envelopes, if present. Proper backfilling of the trench or plough fissures is therefore essential. It is easier to backfill and compact V-plough fissures than trenches. Fissures, created by vertical ploughs cause the most problems (Van Zeijts and Naarding, 1990).

Neither heavy loads, nor significant flooding should be imposed on newly installed drains until the soil in the trench is consolidated. The loose backfill material will settle naturally with time. Since backfilling is usually done with a tractor equipped with a dozer blade, passage of the tractor wheel over the backfilled trench, filling it up, and running over it again will speed up the process, yet care must be taken to avoid crushing the pipe. This procedure ensures that only the top part of the trench backfill is compacted, and that the deeper part of the backfill retains a good permeability and a low entrance resistance. In case of trenchless drain installation with a vertical plough, compaction of the upper part of the disturbed soil is equally important. A common procedure is that one track of the drainage machine runs over the drain line on its way back to the outlet drain to begin installing the next lateral. In dry soil, the rate of compaction following this procedure may not be sufficient. Application of irrigation water to unconsolidated material in trenches to settle the backfill is a practice that should be done very cautiously, however.

If a field is to be flood irrigated before the trench backfill is consolidated, direct entry of uncontrolled surface water into the trench should be avoided by raising temporary ridges along both sides of the trench (Stuyt and Willardson, 1999).

Guidelines with respect to drainpipes

Trenching machines can install clay, concrete, or plastic pipes. *Clay and concrete pipes* are manually placed on a chute that conveys the tiles down into the trench shield where they automatically move into the right position on the bottom of the trench. The tiles should be installed in the trench in such a way that a perfect junction between drains is obtained. For drains of larger sizes, an inspector, standing or sitting in the shield, checks for correct laying. The maximum gap between drains may not be more than 3 mm except for sandy soils or soils with a sandy layer on drain depth where it should be not more than $2d_{85}$. Clay and concrete tiles without gravel or appropriate synthetic envelopes are not recommended in cohesionless fine sand (CPVQ, 1989).

Plastic drains are normally fed through a conducting pipe, mounted just behind (wheel trencher) or above (chain trencher) the digging mechanism of the trencher. Trenchless machines have been developed to install only corrugated drains of not too large a diameter. They should not be installed with a curvature radius less than five times the pipe diameter, particularly if the pipe is wrapped with an envelope.

For machine installation, the quality of drainpipes is of utmost importance. Drainpipes with fissures, cracks or other visible shortcomings and badly formed pipes or torn envelope material, which do not allow a proper installation or assure a reliable performance, should not be used. Furthermore, all drains and collectors must be closed at the upward end to avoid soil invasion (see Chapter 2, Section *End caps*). Failures that may occur during installation of corrugated drains are crushed or collapsed pipes, twisted pipe sections, couplings pulled apart and snapped-off pipes (Van Zeijts and Zijlstra, 1990). In such cases, the discharge is obstructed. Although the water may finally find its way through the soil to a properly functioning downstream part of the drain and to neighbouring drains, stagnation occurs. Upstream the blockage, water may stand above the drain and a higher groundwater table will result.

Coils of smaller diameter pipes are usually carried on a reel on either trenching or trenchless machine and wound off as installation proceeds. Larger diameter pipes are usually laid out on the field beforehand, and then guided through the trenching machine.

Excessive pulling can result in connections becoming loose or pipes breaking off. During the uncoiling of the pipe, pipe breakage can be easily overlooked, yet the missing piece of drain will cause local wetness. Therefore, trenchless drainage machines must be equipped with guides to facilitate smooth entrance of the drainpipe into the feeder tube. Gravel envelope application can entail substantial, undesirable elongation of the drainpipe if the gravel does not flow smoothly downward through the supply tube.

While cleaning corrugated PVC drains by jetting (Section *Maintenance of drainpipes*), it is sometimes observed that drains were not laid in a straight line, but spiralled slightly. This phenomenon is attributed to the tension in the pipe material generated in the unwinding of the rolls at installation (Van Zeijts, 1987), and may enhance the development of unwanted airlocks inside the drain.

PVC pipes should not be installed at temperatures below 3°C because of their brittleness at low temperatures. Storage at temperatures exceeding 40°C for PE and 80°C for PVC pipes, as well as installation at temperatures above 40°C should be avoided in order to prevent pipe deformation as a result of load and longitudinal stress. Exposure to UV rays of solar radiation also affects the strength properties of corrugated plastic pipes (Desmond and Schwab, 1986; Dierickx, 1998a). Stored pipes should therefore be protected from the influence of direct sunlight if not installed within one week (tropical climates) or one month (temperate climates) after delivery (see Chapter 2, Section *Plastic drainpipes*).

Guidelines with respect to envelopes

Whatever envelope material is used, and by whatever method it is installed, envelopes must fully surround a drainpipe, unless the drain is installed on an impervious layer. An envelope merely on top of a drain does not suffice because mineral clogging also occurs from underneath if water enters the drain from all around. Bulky envelopes can be spread out by hand in the bottom of the trench before the pipe is placed, but this is only possible in stable soil where trench walls do not collapse. If drains are laid by hand and a layer of the bulky envelope should surround the drain, the envelope is placed on the bottom of the trench and levelled first. Next, the drain is installed and covered further with bulky envelope to the required height. This also holds for machine installation of drains with a bulky envelope. Envelope strips, delivered on rolls, should be applied below and on top of the drain. The material at the bottom needs not necessarily be the same as the material on the top. Prewrapped drains, however, are preferred since they protect drains from all sides, and offer a greater safety than bulky envelopes or envelope strips can do. Envelopes that are good and reliable, however, will only be successful if properly installed under favourable physical soil and weather conditions. Slurry in the bottom of a trench will cause immediate and complete failure of the envelope material and hence of the drain.

The general use of *gravel* envelopes has decreased continuously in spite of all efforts to mechanize and perfect installation by e.g. introducing a gravel auger at the end of the trench box. This gravel auger reduces pipe stretch but gravel-feeding problems are still not completely solved (Vlotman *et al*., in press). Theoretically, it is also possible to apply gravel with the vertical drain plough as well as with the V-plough. However, the risk of stagnation of gravel in the supply tube of the machines makes the trenchless technique less suitable for gravel installation. The installation of gravel remains a difficult and labour-intensive operation. Practical experience shows shortcomings causing base soil intrusion and pipe siltation. The major shortcomings are (Dierickx, 1993):

- segregation during transportation and installation;
- flow problems in the supply tube;
- unequal distribution around the drainpipe; and
- accidental incorporation of soil into the gravel on the bottom of the stockpile.

Coarse, well-graded *sand* can also be used as a drain envelope. However, the shear resistance of sand, especially if it is not completely dry, will hamper mechanical installation even more seriously than gravel does.

Organic and synthetic envelopes, pre-wrapped around corrugated drainpipes can be installed adequately with both trenching and trenchless machines. They are however prone to damage, caused by transport and/or rapid machine installation, especially when materials of inferior quality are used or when the pipe is not carefully wrapped. In order to avoid local spots of soil particle invasion, prewrapped envelopes cover the entire drain circumference. Furthermore, they should not be damaged during handling and installation. Therefore, the layer of loose material before wrapping should be sufficiently thick and as uniform as possible to avoid open spots.

Geotextiles that are used for the wrapping of drainpipes are usually supplied on rolls. The sheets should be wide enough to facilitate adequate overlap so that the pipes are completely wrapped, without open joints. If both longitudinal edges of a geotextile sheet are sewn, the sheet should be wide enough to facilitate this. If a geotextile sock is pulled manually over the drain laid out on the field, both the geotextile and the seam, if any, should be strong enough to resist this handling without damage. Geotextiles usually have adequate mechanical strength to resist mechanical loads during installation.

Machine installation requires adequate drainage materials to assure a straightforward installation and a proper drainage performance. Therefore high-quality materials are required and their properties need be checked prior to installation according to well-considered standard specifications. Quality standards of drainpipes and drain envelopes are therefore of paramount importance (Chapter 9). Neither PLMs nor prewrapped geotextiles show particular problems during installation with both trenching and trenchless machines. Their light weight makes them suitable in soft soils where the use of gravel creates problems because of the weight of the gravel.

MAINTENANCE OF DRAIN PIPES

Jet flushing

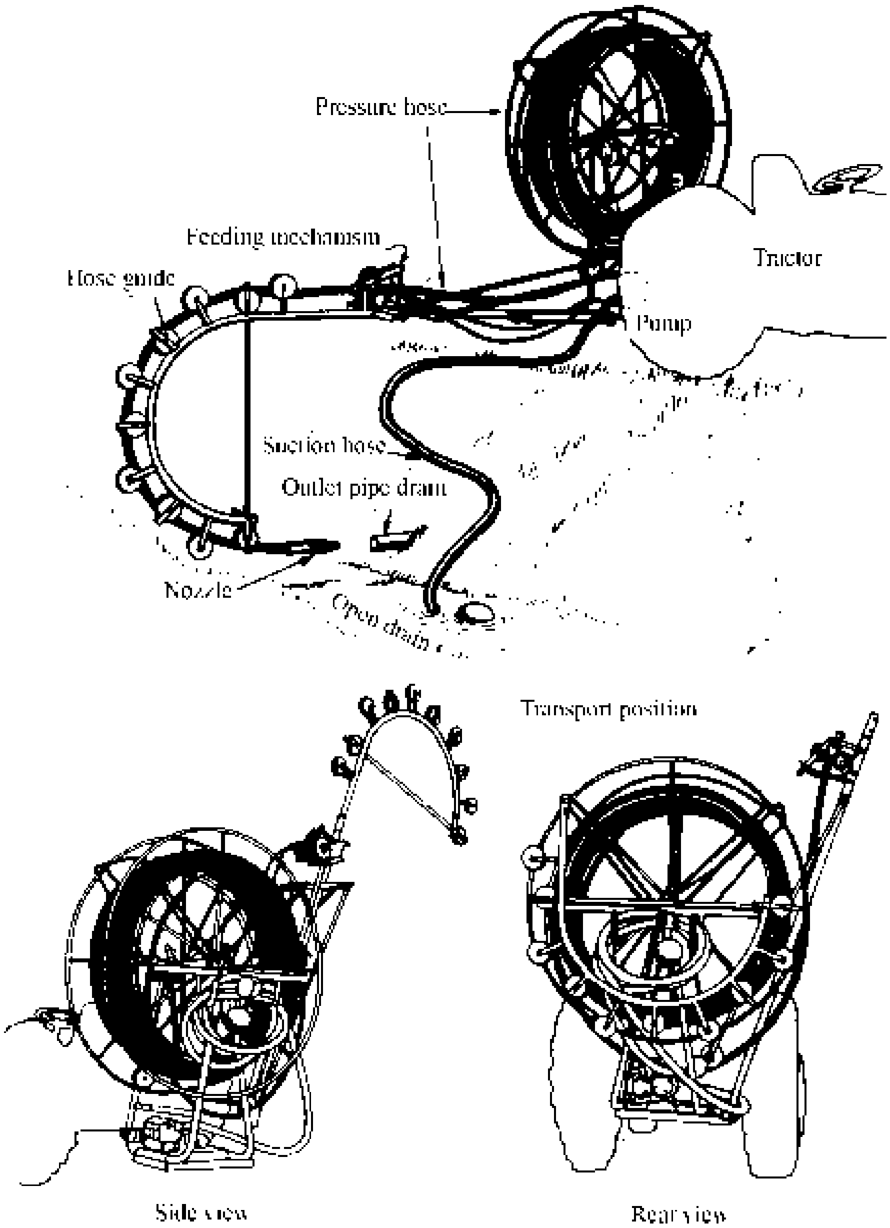
Maintenance is obvious when there is severe clogging. If done regularly it may extend the service life of the system and enhance its performance. In case of light obstructions in pipes (like fresh ochre) *dry rodding* may be helpful: a long series of coupled rods, with a scratcher at the end, is pushed into the drain and removed later. If done during a period of considerable discharge, the loosened materials will be discharged. For more serious forms of clogging, *jet flushing* has to be used. Jet flushing is a technique used to remove clogging and precipitating agents (e.g. soil particles and microbiological deposits, including iron ochre) from drainpipes through the impact of water jets. More particularly, the functions of jet flushing are:

- lifting of blockages inside the pipe drain;
- removal of deposits from the inner wall surface of the drain;
- cleaning of clogged perforations;
- removal of loose smaller roots of agricultural crops and weeds; and
- supply of sufficient water to carry the loosened agents, including sand and clay particles towards the drain outlet.

Ideally, the water that discharges from the drain evacuates the major part of the clogging agents. Particles, larger than approximately 75 μm may be dislodged, yet are generally too heavy to be removed from the drain (Busser and Scholten, 1979). It is not clear to what extent pipe perforations can be cleaned efficiently and non-destructively. It is assumed that jet flushing has a negligible effect on clogged envelopes.

A typical jetting device is operated from the power takeoff of an agricultural tractor. It consists of a pump, a suction pump inlet, and a reel with a 200-400 m long pressure hose fitted with a nozzle, as shown in Figure 43. The nozzle is fed into the pipe drain from the downstream end. Therefore, the pressure hose is pointed to the drain outlet with the help of an adjustable hose guide. Access of the outlets of laterals is easy if they discharge into open collector ditches. Contrary to these singular drainage systems, as common in humid temperate zones, drainage systems in semi-arid countries often have a composite layout, whereby laterals discharge into pipe collectors instead of open collectors. If the junctions between laterals and collectors are located at manholes, these can be used to accept a jetting hose, provided that the diameter of the manhole is at least 0.3 m. In some countries, e.g. Egypt, laterals are accessible at their upstream end (Figure 14).

FIGURE 43
Jet flushing with a medium pressure unit (after Bons and Van Zeijts, 1991)



On average, jetting requires 1-2 m^3 of water per 100 m of drain. The water can be pumped from a drainage ditch, an irrigation supply canal, or a tanker must supply it. Saline water is a harsh and corrosive environment for flushing machines. If saline water must be used, the flushing machine should be made of high quality salt resistant machine parts. The use of salt water for flushing must be avoided: it damages the soil structure around the drain and it is harmful for the machine.

During the jetting procedure, the nozzle must be inserted into the pipe as fast as possible. The pulsating action of the piston pump enhances the forward movement of the nozzle. After the nozzle has reached the upstream end of the drain, the hose is retreated by reeling, at a steady pace of approximately 0.3 m/s while pumping continues (Van Zeijts and Bons, 1993). The cleaning action is influenced by the cleaning force, the angle of attack of the water jets, the duration of cleaning, the water temperature and the use of chemicals (Heeres *et al*., 1985). The cleaning force is proportional to the flow rate times the square root of the water pressure at the nozzle (Lechler, 1980). Environmental restrictions as well as cost considerations generally preclude the use of chemicals while jetting.

A balance must be found between the pressure and the flow velocity of the water jets coming from the nozzle, preferably on site. The optimum ratio is likely to depend on the inside diameter of the drains; however, no data are available to support this assumption. On many commercial jet flushing units, the ratio between flow rate and pressure can be adjusted. Flow rates are adjusted by changing the pumping speed. The water pressure is adjusted by selecting an appropriate nozzle (number, size and orientation of holes).

Jet flushing will temporarily increase the water pressure in the drainpipe and thus in the surrounding soil, possibly affecting soil stability around the drain. The increased water pressure causes a reduction of cohesive forces between soil particles, which may lead to instant and hazardous quicksand conditions. Notably in weakly cohesive soils, there is a risk of the development of quicksand. After the nozzle has passed, structureless soil material may flow into the pipe. In addition, the hydraulic conductivity of the soil may be adversely affected. Regardless of the discharge from the nozzle, dislodged substances are more easily evacuated from small than large diameter drains due to the higher flow velocities in the smaller diameter pipes.

As far as the water pressure is concerned, three categories of jet flushing units are being manufactured:

- high pressure equipment : > 100 bar at the pump;
- medium pressure equipment : 20-35 bar at the pump;
- low pressure equipment : < 20 bar at the pump.

High-pressure units cannot be recommended, because empirical experience evidenced that this type of flushing machine destabilizes the soil around the drain and destroys its structure.

Water pressure at the nozzle is approximately 50 percent of the pressure at the pump. Hydraulic data of nozzle, pump pressure, and flow rates provided by a commercial flushing unit manufacturer for a flexible hose with an inside diameter of 20 mm and a length of 300 m, are given in Table 10 (Bons and Van Zeijts, 1991). The highlighted line contains recommended figures (i.e. pressures and discharges).

TABLE 10
Relation between pump pressure, nozzle pressure and discharge for a flexible hose with an inside diameter of 20 mm and a length of 300 m (after Bons and Van Zeijts, 1991)

Pump Pressure (bar)	Nozzle with 2-mm holes		Nozzle with 1.5-mm holes	
	Pressure at nozzle (bar)	Discharge (l/min)	Pressure at nozzle (bar)	Discharge (l/min)
20	3.2	47	6.0	50
25	4.5	65	8.5	56
30	5.5	70	10.0	61
35	6.7	76	12.5	67
40	8.0	82	14.5	71
45	9.5	87	16.5	76
50	10.0	90	18.5	80

The maximum flow of water that can be employed depends on the cross section of the drain. Empirically it was found that a discharge of approximately 70 l/min is satisfactory for 50 to 70 mm pipe diameters. Such discharges are indeed realized with the highly popular medium pressure units. Higher discharges may force too much water through the pipe perforations, which is hazardous for the envelope and the structure of the abutting soil.

The cost/benefit effects of regular maintenance of drains by jet flushing are hard to quantify. Still, some figures may be informative. The cost of jet flushing in The Netherlands, at medium pressure, is approximately US $0.15 per m of drain which is 12 percent of the installation cost of $1.25 per m. With a typical drain length of 800 m per hectare and a flushing frequency of once in every three years, the annual cost amounts to $40 per hectare per year. The average annual gross yield of arable land is approximately $2500 per hectare. The calculated maintenance cost is therefore less than 2 percent of the annual gross yield.

Empirical experience with jetting in northwestern Europe

Dry rodding and jetting of drains are useful for removing ochreous substances but generally not for removing roots from drains, with the exception of loose, tiny ones (agricultural crops, some weeds). Before jetting, some drains should be examined internally first, e.g. with a miniature video camera, in order to check the kind of clogging and to assess the jetting efficiency. In case of ochreous substances, preventive jetting may be useful in order to prevent total blocking of pipe perforations. Ochre is a soft substance when precipitating, but becomes dense and sticky with time, making it difficult to remove (Cestre and Houot, 1984). Jetting cannot generally re-open pipe perforations that were clogged with encrusted ochreous substances. Ochre deposits should therefore be removed before drying out by frequent flushing with medium pressure (Von Scheffer, 1982). Based on recently acquired experience in The Netherlands, this recommendation is nowadays relaxed somewhat in the sense that flushing is recommended only if the ochre deposits do noticeably impede proper functioning of the drain. This recommendation also holds for other kinds of microbiological deposits inside drains.

The following conditions may enhance the risk of drain sedimentation through jetting:

- the use of high pressure equipment;
- jetting shortly after drain installation (soil not yet settled nor stabilized);
- damaged pipes and/or decomposed envelopes;
- non-cohesive and weakly-cohesive soils; and
- slow pace of movement or (temporary) blockage of the nozzle.

In The Netherlands, approximately 600 000 hectares of agricultural lands are provided with a subsurface drainage system. No precise data about the area periodically flushed is available. In 1998, the number of flushing units in operation was estimated at several thousands, so a considerable area is regularly maintained. The medium pressure unit (35 bar at the pump and 10 to 15 bar at the nozzle, highlighted in Table 10) is by far the most widely used.

In the past, jet flushing has been reported to have a positive effect on drain performance in a pilot area, where drains were prone to excessive biochemical clogging due to intense upward seepage of ferrous groundwater (Ven, 1986). As long as the drains were jetted periodically, the drainage system met the design criteria in terms of drawdown of groundwater and discharge. After jetting was discontinued, the plots suffered from waterlogging. Van Hoorn and Bouma (1981) investigated the effect of jetting on drains, installed in clay soils, which had been submerged regularly and clogged by mineral particles and biochemical substances. The effect was quite positive. At another pilot area in The Netherlands with comparable conditions, however, Huinink (1991) established that drain performance could not be restored, despite the implementation of an extensive jetting project.

Experiences with high-pressure equipment in northwestern Europe are unfavourable, while substantial pipe sedimentation is occasionally reported with intermediate pressure equipment (Brinkhorst *et. al*, 1983). Practical experience of farmers and contractors learned that flushing with high pressures enhances sedimentation rates. The next flushing had to be done sooner than in case medium or low pressure was used. Around 1980, therefore, the use of high-pressure equipment was gradually discontinued.

During the nineties, the frequency of jet flushing as advised to the farmer varied from annually to once in every five years. During this decade, farmers have gradually become somewhat suspicious towards jetting of drains. Intense monitoring of drain performance in various pilot areas revealed that the assumed beneficial effects were not so obvious as was assumed for a long time (Huinink, 1991). If any improvement in drain performance could be noticed at all, it would generally last for a very short time. This fact has induced some reluctance towards preventive jetting of drains.

Drainage experts nowadays give the following advice to the farmers: do not jet any drain as a form of preventive maintenance, unless there is a substantial risk of ochre clogging. On the other hand, jetting is useful if the performance of drains has significantly deteriorated, as observed by the farmer. Drains, prewrapped with suitable and lasting envelopes should however be practically maintenance free (Dierickx, 1993). A likewise observation was made in the United States some 20 years earlier (Winger, 1973).

Because of this development, the number of Dutch manufacturers of high and medium pressure equipment went down from six in 1991 to two in 1998. Comparatively simple low pressure jetting equipment is however manufactured at various locations.

Guidelines for jetting

In summary, the following guidelines for jetting were empirically developed in Denmark, Germany and The Netherlands for various types of drainpipes with diameters ranging from 40 to 90 mm:

1. Jetting must preferably be done when the groundwater table is at or above drain level. This is because wet sediment is easier to remove, and because a wet soil will restrict the undesirable penetration of the jetted water into envelopes and soils.
2. Satisfactory results were achieved with the following machine specifications and settings:
   - a middle pressure pump (35 bar at the pump and 12 to 15 bar at the nozzle);
   - a standard nozzle with one hole forward and 12 holes backward;
   - a flow rate of 50 to 70 l/min;
   - an advance (penetration) rate of 0.5 m/s; and
   - a withdrawal rate of 0.3 m/s.
3. When the movement of the nozzle is obstructed, the pump should be stopped immediately to prevent local physical damage to the drain, envelope, and to the soil structure.
4. Neglected drains that contain hardened clay and silt deposits should be jetted with a special nozzle with less yet larger diameter holes (e.g. one forward and four to the rear). The high impact water jets will ‘cut’ grooves in the sediments, breaking them up into pieces, which facilitates their removal.
5. Sediments consisting of fine sands must be removed with a nozzle with smaller jet angles, e.g. 30^{o}. Wet sand can be loosened relatively easy, but is more difficult to remove from the pipe than deposits that consist of finer particles like silts and clays. The sand must be kept moving by large quantities of water.
6. Drains that are severely clogged should be cleaned in stages with an interval of several weeks. These intervals are required to allow the soil around the drains to stabilize after jetting.
7. If the rate of mineral clogging of drains is so high that installation of new drains must be considered, a last, drastic attempt may be made to restore them. In such cases, the drain must be jetted by repeatedly inserting and pulling back the nozzle, each time a few metres further, whereby application of high pressures may be considered. In order to minimize the risk of destabilizing the surrounding soil, the speed of insertion of the nozzle into the drain should be maximum with low water flow, whereas the pace of withdrawal and the pumping rate should be such that the sand is kept in front of the jet sprays. It is crucial to establish and maintain a substantial discharge velocity in the drain.