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DRAIN ENVELOPES

L.C.P.M. STUYT AND L.S. WILLARDSON

GRAVEL ENVELOPES FOR PIPE DRAINS - DESIGN

R. J. WINGER

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Chapter 29 ASA Drainage Monograph

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1. Introduction

The primary reason for placing envelope material around subsurface drains is to prevent excessive movement of soil particles into the drains. The structural stability of a soil and hence the risk of mineral clogging is influenced by soil texture, soil organic matter content, natural cementing agents, the ratio between various cations, and the soil water content. Soils which are prone to mineral clogging are commonly referred to as "problem soils". In practice, all very fine sandy and silty soils with a low clay content are likely to be problem soils. Finer textured soils affected by sodium may also be difficult to drain. Each soil has its own specific characteristics and it is therefore difficult to positively label any soil a non-problem soil.

Envelope materials have both hydraulic and mechanical functions (Dierickx, 1992) that improve the efficiency of a drainage system. Hydraulic improvements are made by placement of a high permeability envelope material in the immediate vicinity of the drain openings, which facilitates water flow towards the inlet openings and consequently decreases the entrance head losses. The mechanical improvements in the drain-envelope-soil system are: the stabilizing of the soil surrounding the drain by physically supporting the soil at the interface, and, where gravel envelopes are used, the provision of suitable structural support for the drain tube.

During the early development of design criteria for drain envelopes, many scientists used existing filter criteria as a basis for their work, hence the word "filter" is often mistakenly used in reference to drain envelopes. A filter is by definition (Webster's, 1959), "a porous substance through which a gas or liquid is passed to separate out matter in suspension". A filter, used as drain envelope, would eventually become clogged because particulate matter would be deposited on or in it, thereby reducing its permeability. Microscopic suspended material in water moving toward a drain will actually pass through a properly selected 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. 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.

Means of preventing soil material from entering subsurface drains have been sought since the beginning of closed subsurface drainage. Sisson (1965) reported that in 1859, H.F. French recommended double-walled or sheathed drains with collars as one method of preventing drain sedimentation. French's second choice was clean, fine gravel. Brown (1915) reported use of gravel along the sides of wooden box drains in 1906. He concluded that unless the drain openings were protected by gravel and sand, covered drains could not be used in certain soils. Hart (1917) recommended graded gravel with particle sizes ranging from sand to small stones 30 mm in diameter as an excellent envelope. He recommended a porous fabric covering for the tile joints, such as burlap or cheesecloth, for quicksand conditions.

While the use of an envelope largely depends on soil properties, selection of the material is ultimately determined by availability, cost and soil conditions. As a result of considerable research and practical experience gained in various countries from the 1960's to the late 1980's (Stuyt, 1992a), it is now possible, by examination of soil properties and the expected flow conditions in the soil, to predict the necessity for drain envelopes, to select appropriate materials and to provide guidelines for envelope design.

2. Envelope Categories

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. Mineral envelopes consist of coarse sand, fine gravel and glass fibre membranes which are all applied while installing the drain tube. Organic envelopes include loose plant materials such as fibers, chips, or granules which may be applied directly, or may be pre-wrapped around the drain tube. Synthetic envelopes are usually pre-wrapped loose fibers and granules, or geotextile fabrics specifically manufactured for use in soil stabilization and drainage.

2.1 Gravel Envelopes

Traditionally, gravel is the most common and widely used drain envelope material. Such material is as permanent as the soil itself. The best envelope material is pit-run naturally graded coarse sand or fine gravel containing a minimum of fines. Properly designed or selected gravel envelopes fulfill all the mechanical and hydraulic functions of a drain envelope. Experiments by Lembke and Bucks (1970) and ASAE (1967) have shown that a graded fine gravel or sand envelope placed around a subsurface drain helps protect it from sediment inflow and improves its hydraulic performance.

The practice of blinding or covering subsurface drains with a layer of topsoil before backfilling the trench actually provides many humid area drains with an effective envelope material. Poorly drained surface soils in humid areas tend to have a well-developed, stable, and permeable structure that functions as a drain envelope. In stratified soils, drains are blinded by shaving the coarsest textured materials in the soil profile down over the pipe. The practice of blinding undoubtedly furnished the nucleus of the idea of using imported granular envelope materials to protect subsurface drains in arid regions. Blinding is a standard recommended part of drain installation (Hore et al.,1960; Irwin, 1960; Soil Conservation Service, 1973, p. 234.), especially in humid regions.

2.2 Glass Fibre envelopes

The first man-made (mineral) material that received attention as a substitute for a gravel envelope was fiberglass in the form of a nonwoven random fibre membrane. Fiberglass is relatively inexpensive and can be manufactured in large quantities to exact specifications. The fibers should be made of lime-borosilicate glass. Other types of glass may dissolve in the soil.

In the USA, Overholt (1959) reported the results of a tank experiment using a fiberglass filter material. The soil was a fine sand that had given some sedimentation problems in field installations of drains. A thin sheet of fiberglass was placed over the top 75% of the drain circumference for some tests and completely around the drain for others. A tile drain with no fiberglass was used as a check. Drains protected with fiberglass over 75% of their circumference had a flow rate 1.7 times that of the unprotected lines. The pipe with a complete wrap produced essentially silt-free water and had a dis-charge rate 2.26 times that of the unprotected pipe. The fiberglass material weighed 2.6 kg/100 m of pipe. By way of comparison, in some areas of California 53,500 kg of sand/100 m is specified. Shull (1967) found fiberglass mats to be superior to fiberglass sheets in filtering properties.

Rektorik (R.J. Rektorik, 1971. Personal communication) reported that between 1965 and 1971, when USDA Soil Conservation Service specifications began requiring envelopes on all drains, 90% of the drains in the Lower Rio Grande Valley of Texas were installed with fiberglass mat envelopes. The other 10% were installed with gravel envelopes. Approximately 70 km. of drains were installed there annually. Rektorik recommended careful selection of the type of fiberglass used. He reported that fiberglass mats 25 mm thick were better than fiberglass sheets 0.5 mm thick; that coarse fiberglass was better than fine fiberglass; and that the glass should be of a borosilicate type.

In The Netherlands, glass fiber sheet was introduced in early 1960's and standards for this material were formulated in 1964. Due to rumors of mineral clogging, use of fiberglass declined soon afterward. In fact, it was the limited pipe opening area, not the envelope that caused the problems. The glass fiber sheet was wrapped around 40 mm outside diameter smooth plastic tubes with sawed slots. The only area of the fiberglass membrane involved in the flow coincided with the very limited open area of these slots and the envelope material clogged directly over the slots. Due to this early experience, reluctance to apply any type of sheet envelope material persists in The Netherlands. When a fiberglass membrane is used with a corrugated pipe, the water inflow area is much greater because of the spaces between the envelope and the valleys of the corrugations.

2.3 Pre-wrapped Geotextiles

Materials known as geotextiles are widely used as pre-wrapped synthetic drain envelopes. Geotextiles are made of polyester, polypropylene, polyamide, polystyrene and nylon. Following the ISO-standard definition (ISO 10318), a geotextile is a permeable, polymeric material which may be woven, nonwoven or knitted. Woven geotextiles or geowovens are produced by interlacing and needle punching, usually at right angles, two or more sets of yarns, fibres, filaments, tapes or other elements. Similarly, knitted geotextiles or geoknitted materials are produced by interlooping one or more yarns, fibres, filaments or other elements. Nonwoven geotextiles or geononwovens are geotextiles in the form of a manufactured sheets, webs or batts of directionally or randomly oriented fibres, bonded by friction, cohesion, or adhesives. Properties of different pre-wrapped geotextiles are discussed by Stuyt (1992a).

Geotextiles differ widely in denier, smoothness, thickness, and weave density. Geotextile materials also vary in weight, opening size, fibre diameter, thickness, and uniformity. No single geotextile is suitable as a drain envelope for all problem soils. Most geotextiles are wrapped on the corrugated plastic drain tubing in the tubing plant. The finished product must be sufficiently strong to withstand normal handling in the field.

2.4 Pre-wrapped Loose Materials

Pre-wrapped loose materials, PLM, used as drain envelopes, have a permeable structure consisting of loose, randomly oriented yarns, fibers, filaments, grains, granules or beads, completely surrounding a corrugated drain tube. At the time of manufacture, a PLM envelope is assembled around a perforated drain tube as a layer of uniform thickness, held in place around the tube by netting and/or twines. PLM envelopes are usually wrapped on the corrugated plastic drain tubing by specialized companies and occasionally in a tubing plant. The finished product must be sufficiently strong to withstand normal handling that is part of the construction and installation process. The loose materials used are either organic or synthetic.

Loose organic materials, many of which are byproducts of agricultural production, have often been used as drain envelopes. Originally, they were applied as loose blinding materials. At various locations in Europe, they are still being applied in substantial quantities as pre-wrapped envelopes. The two most common materials are coconut fiber (coir) and peat fiber. Other organic drain envelope materials include straw, sawdust, corncobs, wood chips, reeds, heather bushes, chopped flax and grass sod (Juusela, 1958).

The service life and suitability of organic materials as envelopes for subsurface drains cannot be predicted with certainty. Organic matter placed as a drain envelope may also affect chemical reactions in the soil that result in biochemical clogging problems. Where iron ochre clogging of drains is expected, organic matter should be used with caution. Even organic matter accidently mixed with the trench backfill material may cause iron ochre clogging problems in some soils. Successful use of organic envelope materials will depend on the material, the installation, and the physical and chemical characteristics of the soil. Based on results of numerous field observations in The Netherlands, Van Zeijts (1992) suggests that organic materials are only temporary and should only be used in soils that become hydraulically stable before the organic material inevitably decays.

In The Netherlands, the use of fibrous peat litter as a cover layer for drain tiles was common practice for decades and lasted until the end of the 1950's. 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 often decomposed into a low-permeability layer around the pipe. At the end of the 1960's, coconut fiber (coir) was introduced. Being relatively cheap, "cocos" soon dominated the market because high quality peat litter became scarce and expensive (Meijer, 1973). At a later stage it was discovered that coconut fiber was often subject to microbiological decay (Meijer & Knops, 1977, Antheunisse, 1979, 1980, 1981), stimulating the drive to replace organic substances with synthetic alternatives. It was argued that, contrary to "organic" envelopes, "synthetic" ones could be manufactured according to design criteria which could be established by laboratory tests (Stuyt, 1992a).

Synthetic pre-wrapped loose materials include various polymeric materials. Fibers may be made of polyamide, polyester, polyethylene and polypropylene. Loose polystyrene beads, "PS", can be wrapped around drains in perforated foils or in string nettings ("geogrids" and "geonets") as pre-wrapped loose materials. The PS beads are subject to compression from soil loads that may reduce envelope permeability (Willardson et al, 1980). In The Netherlands, where drain depths are 0.9 to 1.2 m, the effect of the soil load is small. In addition, the hydraulic conductivity of PS beads envelopes is very high, so some permeability reduction has no serious impact on their functioning.

Polypropylene (waste) fibre mats are increasingly used in NW-Europe and in arid areas where they replace poor quality gravels. Properties of pre-wrapped synthetic loose materials are extensively discussed by Stuyt (1992a).

3. Principles of Drain Envelope Design

Subsurface drain tubes, either pre-wrapped or covered with an envelope material, pose special engineering design problems as a result of the complicated interactions between the drain, its envelope, the moving water and the surrounding soil. Investigation of such interactions requires spatial quantification of the processes of water flow and movement of sediment.

In 1922, Terzaghi developed a mechanics based theory for the piping and seepage forces that develop beneath hydraulic structures (Prieto, 1967). Terzaghi patented what he termed a "reverse filter" which he then used to control seepage under an Austrian dam built on a previous foundation. He developed "filter" criteria which have since been tested for applicability for envelopes around subsurface drains. He 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 such envelopes, his design criteria have been tested and modified, but his concepts have been generally accepted.

Application of Terzaghi's criteria for pre-wrapped envelopes, consisting of loose base materials has proved to be inappropriate. Therefore, notably in Belgium and in The Netherlands, efforts were made to develop special design criteria for such envelopes. This was not an easy task due to the difficulty of monitoring the flow of water and soil particles near pre-wrapped drain tubes without disturbing the system. In The Netherlands, 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 pre-wrapped loose materials (Huinink, 1992; Stuyt, 1992a; Van Zeijts, 1992) (see section 3.5).

3.1 Exit Gradients in Soil Near Drains

As water approaches a subsurface drain, the flow velocity increases as a result of convergence. The increased velocity is related to an increase in hydraulic gradient. The hydraulic gradient close to the drain may exceed unity resulting in soil instability. Luthin et al. (1968) made a theoretical analysis of exit gradients into subsurface drains. Results of their analysis indicated that exit gradients into completely permeable drains exceeded the critical gradient for nearly every condition investigated. Use of a gravel envelope increased the apparent diameter of the drain and therefore substantially decreased the exit gradient at the soil-envelope interface. High gradients in the soil near drains cause soil movement. One of the reasons for using envelope materials is to reduce the exit gradient where the water leaves the soil.

3.2 Hydraulic Failure Gradient

The phenomena of sedimentation failures of small diameter drains and the clogging of fiberglass envelope materials at drain openings lead to the an investigation of the effect of internal hydraulic gradients on the stability of the soil. Laboratory tests were conducted on a number of problem soils from both humid and arid areas. The soils were tested against different geotextile envelope materials to evaluate potential interactions between soils and envelopes. The tests were conducted using a parallel flow permeameter (Figure 1) that was developed for this purpose (Willardson and Walker, 1979). The research produced results that identified a characteristic "Hydraulic Failure Gradient" for each soil tested. The hydraulic failure gradient for a soil was essentially independent of the type of envelope material used. Table 1 shows the results of the original tests. When no difference was found between the response of different soils to different geotextile envelope materials, the soils were also tested against screens with a range of opening sizes. The soils continued to fail structurally at approximately the same internal water flow gradient. The Roosevelt soil (Table 1, Column 5) was tested with no mechanical support and failed at a gradient typical of the critical gradient for hydraulic failure defined in soil mechanics.

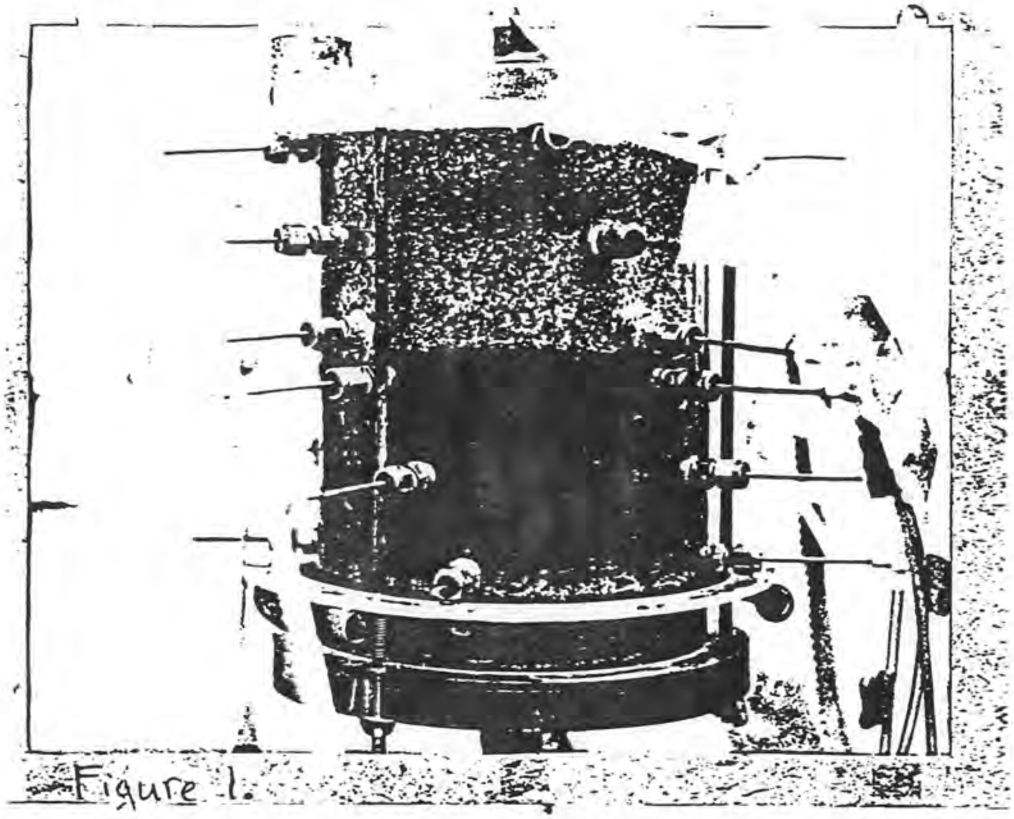

Figure 1.

TABLE 1. Failure Gradients for Soils against Different Scrrens and Envelope Materials.

Material or screen (1)	Openings in milli-meters (2)	Soil: Hydraulic Failure Gradient St. George[a] (3)	Rich-field (4)	Roose-velt[b] (5)	Delta (6)	Cache (7)
None	--	--	--	0.8	--	--
8	2.360	--	--	6.90[c]	--	--
Screen	1.6	2.4[c]	--	6.4	--	--
30	0.600	2.00	7.0	6.1[c]	3.5	3.8
60	0.250	2.6	--	6.8[c]	--	--
120	0.125	2.1	--	--	--	--
230	0.063	1.9	--	--	--	--
Drainguard	--	2.2	--	7.1	--	--
Typar	--	2.1[c]	--	6.2	--	--
Mirafi	--	2.7	--	--	--	--

[a]Maximum particle size = 0.124 mm.
[b]Maximum particle size = 0.1 mm.
[c]Test period longer than 24 hr.

Table 1. Failure Gradients for Soils against Different Screens and Envelope Materials

The tests showed the importance of envelope use for drains placed in problem soils. As long as the flow rate (and the associated hydraulic gradient) in the soil was low, there was no soil particle movement. The results suggested that if the velocity of water flow toward drains could be kept below the hydraulic failure gradient of the soil, no failure of the drain and envelope system would occur.

Correlations between hydraulic failure gradient and various soil parameters such as clay content, clay mineralogy and organic carbon content for individual soils were inconclusive. Plasticity Index was found to correlate with hydraulic failure gradient for arid region soils or for humid region soils, but the relation was not transferrable between the different climatic areas (Samani and Willardson 1981). A good correlation, useful for both humid and arid areas, was found between hydraulic failure gradient and the combination of Plasticity Index and Hydraulic Conductivity of the soil. Equation 1 can be used to estimate the hydraulic failure gradient of soils from easily determined soil parameters. Table 2 from Samani and Willardson (1981) shows the range of data used to develop Equation 1.

$$HFG = EXP(0.102 - 0.108K + 1.09 \ln PI) \quad . \ . \ . \ . \ (1)$$

where HFG is the hydraulic failure gradient, EXP is the power of e, K is the hydraulic conductivity of the soil in meters per day, PI is the Plasticity Index of the soil and ln is the natural logarithm. Plasticity Index is the difference between the soil water content at the liquid limit (ASTM D-423) and at the Plastic Limit (ASTM D-424) (Dunn et al, 1980).

When the hydraulic failure gradient for a soil is known, the gradients that will develop in the system at the point where the water exits from the soil and enters the drain can be estimated to determine whether there will be a structural failure of the soil. Soil failure would result in sediment entry into a drain through any unprotected perforations, or clogging of the envelope material.

Steps that can be taken to reduce the hydraulic gradients in the soil near the drain are: increasing the effective diameter of the drain by using a gravel envelope, increasing the perforation area of the drain, reducing the drain depth and spacing to decrease the possible magnitude of the gradient, and use of a geotextile to make the full surface of the corrugated drain pipe permeable (this assumes a perforation in every corrugation) (Willardson and Walker, 1979; Salem and Willardson, 1992). If there are only perforations in every other corrugation, the exit gradients are effectively doubled.

TABLE 2. Plasticity Index, Hydraulic Conductivity and Hydraulic Failure Gradients for Different Soils

Soil (1)	Bulk density g/cm^3 (2)	Plasticity Index (3)	Hydraulic conductivity cm/min (4)	Hydraulic failure gradient measured: SAMANI* (5)	Hydraulic failure gradient measured: BATISTA** (6)	Hydraulic failure gradient calculated using eq. (7)
Roosevelt	1.03	19	3	-	0.5	0.11
	1.08	19	2.3	-	0.6	0.4
	1.28	19	0.24	-	11	22.21
	1.47	19	0.18	-	28	25.07
	1.17	19	1.1	-	4	3.98
	1.16	19	0.9	-	2.4	3.98
Delta	1.24	16	0.05	-	3.5	24.61
St. George	1.41	3	0.28	-	0.7	2.65
Cache	1.28	26	0.05	-	40	41.37
Liberty Sand	1.35	1.0	0.4	-	0.5	0.65
	1.35	1.0	0.37	-	0.45	0.69
	1.33	1.0	0.5	-	0.45	0.54
Millville	1.48	3.8	0.28	2.2	-	3.41
	1.53	3.8	0.05	5.0	-	5.29
	1.50	3.8	0.08	4.5	-	4.99
Sterling	1.54	1.7	0.8	0.8	-	0.53
CAPAC	1.52	15	0.001	29	-	25.22
Jurek	1.30	1.5	0.7	0.8	-	0.56
Brookston	1.24	25	0.00042	40	-	43.61
Keowns	1.63	5	0.0006	19	-	7.79
Sebewa	1.82	4.7	0.00098	14	-	7.29

*Samani, 1979
**Batista, 1978

Table 2. Plasticity Index, Hydraulic Conductivity and Hydraulic Failure Gradients for Different Soils

If a soil has a high hydraulic failure gradient, a drain envelope may not be necessary. Many humid area soils do not require use of drain envelopes. If the drain tubes have an open or perforation area equivalent to 20 to 50 cm 2 per meter of drain length, the drains function well without sedimentation problems in structurally stable soils. In some areas, criteria based on soil clay contents have been successful as a means of determining whether drain envelopes are required. Such criteria are based on local experience and field observations.

3.3 Gravel Envelope Design

The general procedure for designing a gravel envelope for a given soil is to make a mechanical analysis of both the soil and the proposed envelope material, compare the two particle size distribution curves, and then decide, by some set of criteria,whether the envelope material is satisfactory. The first criteria proposed by Terzaghi (U.S. Corps of Engineers, 1941) for what he termed a "filter" are:

1) The particle diameter of the 15% size of the filter material should be at least 4 times as large as the diameter of the 15% size of the base material. (This would make the filter material roughly more than 10 times as pervious as the base material.)
2) The 15% size of the filter material should not be more than 4 times as large as the 85% size of the base material. (This would prevent the fine particles of the base material from washing through the filter material.)

The 15% size is the particle diameter such that 15% of the material by weight is of a smaller diameter;similarly, 85% of the material by weight is of a smaller diameter than the 85% size.

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

The design of gravel packs for wells is similar to the design of envelopes for subsurface drains. Kruse (1962) reported on investigations of gravel pack designs where the criteria used were based on pack-aquifer ratios of the 50% sizes.

The uniformity coefficient, which is the ratio of the 60% finer size to the 10% finer size of a granular material, was also considered as a design factor. A low uniformity coefficient indicates a uniform material. Kruse (1962) considered a material with a uniformity coefficient of 1.78 to be uniform. He noted that sand movement was reduced by increasing the uniformity coefficient (i.e. decreasing the uniformity)of the gravel pack at all pack-aquifer ratios. The reported investigations indicated that, in order to prevent excessive movement of aquifer materials, the largest permissible pack-aquifer ratios are:

Aquifer	Gravel Pack	Pack-Aquifer Ratio
Uniform	Uniform	9.5
Uniform	Nonuniform	13.5
Nonuniform	Uniform	13.5
Nonuniform	Nonuniform	17.5

Pillsbury (1967) reported on the use of the standard deviation of the envelope material as one criterion of effectiveness of a drain envelope. The standard deviation can be calculated from the difference between the 95% and the 50% size of the envelope, divided by 1.645. It can also be obtained from a plot of the grain size distribution data on logarithmic probability paper. The other criterion he used was the 50% size ratio of the filter to the aquifer material. This ratio corresponds to the pack-aquifer ratio used by Kruse

(1962) for wells. Pillsbury presented a figure showing two zones on a graph of envelope-aquifer ratio vs. standard deviation. An envelope that falls below a given lower limit line is 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 ASTM standard concrete sand with a 50% size less than 1 mm and a standard deviation greater than 1 mm would be a satisfactory envelope material under most conditions.

The Soil Conservation Service (1991) has combined the results of the research reported above into a specification for evaluating pit run and artificially graded granular materials for use as drain envelope materials. The recommendation is for naturally graded pit-run materials or a mixture of medium and coarse sand with fine and medium gravel. The maximum size should not be more than 38 mm, no more than 30 percent of the material should be smaller than 250 um (#60 sieve) and not more than 5 percent should be smaller than 75 um (#200 sieve). They also suggest the additional criteria (Soil Conservation Service, 1988):

D15 size smaller than 7 times the d85 size but not smaller than 0.6 mm,

D15 size larger than 4 times the d15 size,

to prevent excessive fineness of the envelope material used for finer textured soils.

For rigid non-perforated pipes, the 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, 1984) contains graphs which take all these factors into consideration. Table 3 from the Drainage Manual is a table of recommended envelope gradations for soils with different 60 percent passing sizes.

TABLE 3. Gradation relationship between base material and diameters of graded envelope material

Base material, 60 percent passing (diameter of particles, mm)	Gradation limitations for envelope (diameter of particles, mm)											
	Lower limits, percent passing						Upper limits, percent 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

Table 3. Gradation relationship between base material and diameters of graded envelope material

For some fine textured problem soils the USBR criteria have produced envelope materials that are too coarse, allowing excessive amounts of fine soil materials to enter the drains.

Sherard et al. (1984a, 1984b) published two papers related to filters. The research was done to check filter criteria for protection of hydraulic structures. Although not intended for application in subsurface drainage, the principles have direct application to the design of gravel envelopes and also to selection of synthetic envelope materials. The filter criteria $D15/d85 < 5$ was found to be slightly conservative, where D15 is the 15% finer particle size of the envelope material and d85 is the 85% finer particle size of the soil. They stated that the D50/d50 and D15/d15 ratios were meaningless. Another finding of interest was that rounded and angular particles gave equivalent results. Their findings also showed that if a filter did not fail with the initial flow of water, it was probably permanently safe. They determined that the size ratios were critical and materials with a D15/d85 ratio greater than 9 always failed. Well-graded materials were more successful than uniform sized materials. In their second paper, Sherard et al. (1984b) reported on tests using fine textured soils and concluded the following with respect to filter and base soil sizes:

1. Sandy silts and clays (d85 of 0.1-0.5 mm)
   $D15/d85 \le 5$ is conservative
2. Fine-grained clays (d85 of 0.03-0.1 mm)
   $D15 < 0.5$ mm is conservative
3. Fine-grained silts of low cohesion
   (d85 of 0.03-0.1 mm)
   $d15 < 0.3$ mm is conservative
4. Exceptionally fine soils ($d85 < 0.02$ mm)
   $D15 < 0.2$ mm or smaller is conservative

They stated that sands and gravelly sands containing fine sand sizes and having a D15 of 0.5 mm or less would be a suitable filter for even the finest clays. For clays with some sand content ($d85 > 1.0$ mm), filters with a $D15 = 0.5$ mm satisfy the $D15/d85 \le 5$ criterion. For finer clays, the $D15/d85 \le 5$ is not satisfied, but the finer soils tend to be structurally stable and are not likely to fail.

Sherard et al (1984b) also found that well-graded gravelly 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.

Dierickx (1992) presented a summary of gravel envelope criteria from the United States and the United Kingdom. Excerpts from his summary are shown in table 4.

TABLE 4. Overview of existing design criteria for the use of sand and gravel around drain pipes.

A. USBR-CRITERIA (Batti and Vlotman, 1990)		
USBR filter design (Karpoff, in Willardson, 1974) for inverted filter with hydraulic structures		
Uniform envelope (natural)	D_{50}/d_{50} = 5-10	
Graded envelope (natural)	D_{50}/d_{50} = 12-58	
	D_{15}/d_{15} = 12-40	
Graded envelope (crushed rock)	D_{50}/d_{50} = 9-30	
	D_{15}/d_{15} = 6-18	
General	$D_{100} \leq 80$ mm	to minimize segregation and bridging during placement
	$D_5 \geq 0.07$ mm	to prevent movement of fines
	$D_{opening} \leq 0.5\ D_{85}$	opening of drain perforation to be adjusted to filter material used
B. SCS-CRITERIA (Batti and Vlotman, 1990)		
SCS criteria for envelope (SCS, 1971)*		
Graded envelope	D_{50}/d_{50} = 21-58	minimal thickness 3"
	$D_{10} \geq 0.25$ mm	0.25 mm = sieve #60**
	D_{15}/d_{15} = 12-40	
Uniform envelope		$D_{15}/d_{85} < 5$
	$D_{85} \geq 0.5\ D_{opening}$	
SCS criteria for filter gradation(SCS, 1988)		
	$D_{15} < 7\ d_{85}$	but not smaller than 0.6
	$D_{15} > 4\ d_{15}$	
	$D_5 > 0.074$ mm	% passing sieve #200 less than 5%
SCS criteria for envelope (surround)(SCS, 1988)		
	$D_{100} < 38.1$ mm	the whole sample should pass the sieve of 1.5"
	$D_{30} > 0.25$ mm	% passing sieve #60 less than 30%
	$D_5 > 0.074$ mm	% passing sieve #200 less than 5%
C. UNITED KINGDOM ROAD RESEARCH LABORATORY CRITERIA (Spalding, in Boers en Van Someren, 1979)		
For filtration	1. $D_{15} \leq 5d_{85}$	
	2. $D_{15} \leq 20\ d_{15}$	
	3. $D_{50} \leq 25\ d_{50}$	
For permeability	4. $D_{15} \geq 5d_{15}$	
Only for uniform soils ($C_u \leq 1.5$) criterion 1 changes into		$D_{15} \leq 6d_{85}$
and for well-graded soils ($C_u \geq 4$) criterion 2 changes in		$D_{15} \leq 40\ d_{15}$
		$D_{85} \geq$ perforation width /0.83

* Superceded by more recently published SCS standards (SCS, 1988)
** Sieve numbers refer to standard sieve set of the US

Table 4. Overview of Existing Design Criteria for the use of Sand and Gravel around Drain Pipes.

Gravel envelopes that have a D15 of 0.3 mm and a D15/d85 <= 5 with less than 5 percent of the material finer than 0.074 mm will be satisfactory as envelope materials for most problem soils (Sherard et al, 1984b).

Figure 2 shows particle size distribution curves for two typical problem soils in Pakistan. Soil A is finer than soil B, but both caused serious sedimentation of drains surrounded with gravel envelopes that met USBR envelope specifications. The curves labeled USBR Upper and USBR Finer are the accepted limits for suitable envelope material based on the gradation curves of the soil. Conventional theory would allow use of any gravel envelope material falling between the USBR Upper and USBR Finer curves. In the field, the drain envelope did not function properly and the drains filled with sediment in a very short time.In an effort to solve the problem empirically a natural material called Qibla Sand was mixed with the USBR Finer envelope and also with some crushed gravel that was available. The addition of the Qibla Sand produced an envelope that successfully protected the drains from sediment inflow. The D15 size of the new envelope mixture was approximately 0.4 mm, which is appropriate for both the Sherard and the new Soil Conservation Service specifications.

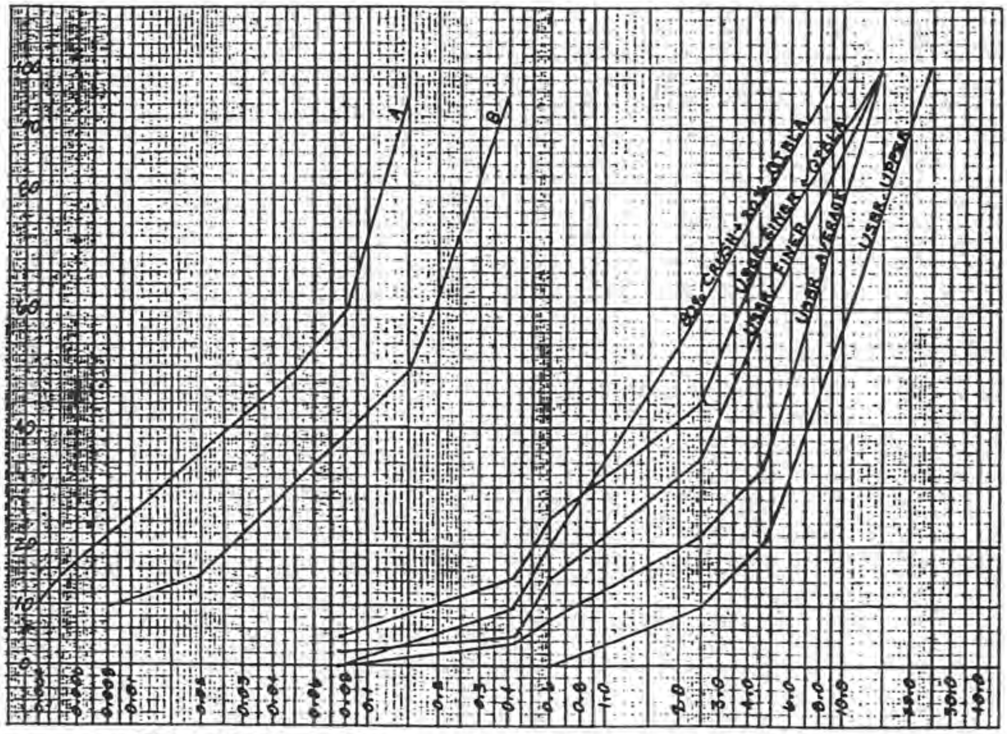

Figure 2.

3.4 Design of Geotextile Envelopes

The ability of a geotextile to retain soil particles is usually expressed as the ratio of a characteristic pore size of the geotextile to a characteristic particle size of the soil. This ratio is called the retention criterion, also known as bridging factor or filter criterion. It is a measure for determining the mechanical support which envelopes provide to the surrounding soil.

A widely used criterion is the O90/d90 ratio, where O90 is the pore size of the geotextile at which 90% of the pores have a smaller diameter, and d90 the particle size of the soil at which 90% of the particles by weight have a smaller diameter. The O90 size of geotextiles is related to the D10 size for gravel envelopes. The O90 size of a geotextile is determined by a sieving test wherein the envelope material itself is installed as a sieve. Wet and hydrodynamic sieving mostly result in smaller O90-values than those obtained with dry sieving.

In a study of bridging of particles at drain openings, Willardson (1979) used the O50/d50-ratio and found bridging factors ranging from 3 to 21 for dry sandy soils; Davies et al. (1978) suggest an O50/d50 of 5. Dierickx et al. (1990, 1992) concluded that the particle retention capability of thin geotextiles is satisfactory if O90/d90 < 2.5. For thicker geotextiles,with a thickness of at least 5 mm, he found a ratio of O90/d90 < 5 to be acceptable (Dierickx, 1987).

Geotextiles which are made too fine will act as filters. On both the outside and inside such very fine textured materials, soil particles with average and finer sizes are retained in a dense network of stable arches, bridging over the openings in the geotextile. Subsequently, comparatively fine soil particles will also be retained, reducing the hydraulic conductivity of the envelope. Under such conditions there is an enhanced risk that the soil surrounding the drain, which is in fact a very fine natural filter, will also clog internally (Stuyt, 1992a).

It is difficult to set a lower limit for detrimental soil bridging, but envelopes for which O90/d90 < 1 are considered inappropriate (Faure, 1991). Experiments, made in the Antwerp Harbour (Belgium)showed that geotextiles with O90/d90 < 1 rapidly clogged when placed in turbid water, whereas no obvious clogging was observed for materials with O90/d90 of approximately 1.25 (Dierickx, personal communication).The ratio O90/d90 <= 1 is a minimum beyond which no noticeable passage of particles occurs, i.e., the envelope material becomes a filter. Geotextiles which have O90/d90 ratios near the higher (i.e. safer) end of there commended range of values are generally preferred,thus minimizing the risk of mineral clogging of the envelope while providing adequate mechanical support for the soil (Dierickx, personal communication). Stuyt(1992a) investigated the functioning of various geotextiles installed in experimental fields and found that the O90/d90 ratios as proposed by Dierickx were valid for three Dutch problem soils. Most of the applied envelopes had comparatively high O90/d90 ratios(4 to 5).

Dierickx (1992) summarized existing retention criteria for geotextiles, reported by Fischer et al.(1990). These criteria are summarized in Table 5.

3.5 Design of Pre-wrapped Loose Materials

Subsurface drain envelopes, using pre-wrapped loose materials may be characterized by porometry,thickness and hydraulic conductivity. When using loose granular materials, particle size distribution parameters may also be used. In The Netherlands,recommendations for design and application of pre-wrapped loose materials (PLM) have been developed on the basis of concurrent research projects,theoretical studies, mathematical modeling, empirical studies in experimental fields, analog modeling in laboratories and practical experience covering a 30 year period (1960-1990). Private studies have also been carried out by various companies and institutions(Stuyt, 1992a).

TABLE 5. Existing filter criteria for geotextiles

Reference	Geotextiles	Soils	Criteria	Remarks
Calhoun (1972)	woven	cohesionless ($d_{50} \geq 74$ μm) cohesive ($d_{50} < 74$ μm)	$O_{90}/d_{85} < 1$ $O_{90} \leq 200$ μm	dry sieving, glass bead fractions
Ogink (1975)	woven nonwoven	sand sand	$O_{90}/d_{90} \leq 1$ $O_{90}/d_{90} \leq 1.8$	dry sieving, sand fractions
Zitscher (1975) in Rankilor (1981)	woven	$C_u \leq 2$ $100\ \mu m \leq d_{50} \leq 300\ \mu m$	$O_{50}/d_{50} \leq 1.7$-2.7	
Sweetland (1977)	nonwoven	$C_u = 1.5$ $C_u = 4.0$	$O_{15}/d_{85} \leq 1$ $O_{15}/d_{15} \leq 1$	
ICI Fibers (1978) in Rankilor (1981)	nonwoven	$20\ \mu m < d_{85} \leq 250\ \mu m$ $d_{85} > 250\ \mu m$	$O_{50}/d_{85} \leq 1$ $O_{15}/d_{15} \geq 1$	
Schober and Teindl (1979)	woven and thin nonwoven ($T_g \leq 1$ mm) thick nonwoven ($T_g \geq 1$ mm)	sand sand	$O_{90}/d_{90} \leq B_1\ (C_u)$ $O_{90}/d_{50} \leq B_2\ (C_u)$	dry sieving, sand fractions $B_1(C_u) < B_2(C_u)$ and are factors depending on the coefficients of uniformity C_u $B_1\ (C_u) = 2.5 - 4.5$; $B_2\ (C_u) = 4.5 - 7.5$.
Millar, Ho and Turnbull (1980)	woven and nonwoven		$O_{50}/d_{85} \leq 1$ $O_{50}/d_{15} \geq 1$	
Giroud (1982)	needle-punched nonwoven woven and heat bonded nonwoven	cohesionless less dense $1 < C_u < 3$ $C_u > 3$ moderate dense $1 < C_u < 3$ $C_u > 3$ dense $1 < C_u < 3$ $C_u > 3$ $1 < C_u < 3$ $C_u > 3$	 $O_{95}/d_{50} < C_u$ $O_{95}/d_{50} < 9/C_u$ $O_{95}/d_{50} < 1.5\ C_u$ $O_{95}/d_{50} < 13.5/C_u$ $O_{90}/d_{50} < 2\ C_u$ $O_{95}/d_{50} < 13.5/C_u$ $O_{95}/d_{50} < C_u$ $O_{95}/d_{50} < 9/C_u$	
Heerten (1983)	woven and nonwoven	cohesionless ($d_{50} \geq 60$ μm) $C_u > 5$ $C_u < 5$ cohesive ($d_{50} \leq 60$ μm)	 $O_{90}/d_{50} < 10$ $O_{90}/d_{90} < 1.0$ $O_{90}/d_{50} < 2.5$ $O_{90}/d_{90} < 1$ $O_{90}/d_{50} < 10$ $O_{90}/d_{90} < 1$ $O_{90} \leq 100$ μm	wet sieving, graded soil
Carroll (1983)	woven and nonwoven		$O_{95}/d_{85} \leq 2$-3	
Cristopher and Holtz (1985)		dependent on C_u	$O95/d_{85} \leq 1$-2 $O_{95}/d_{15} \geq 3$	
CFGG (1986)	woven and nonwoven	 $C_u > 4$ $C_u < 4$ less dense dense $I < 5$ $5 < I > 20$ $20 < I < 40$ filter filter and drainage cohesive	$O_{95}/d_{85} \leq C$ $C = C_1C_2C_3C_4$ $C_1 = 1$ $C_1 = 0.8$ $C_2 = 0.8$ $C_2 = 1.25$ $C_3 = 1$ $C_3 = 0.8$ $C_3 = 0.6$ $C_4 = 1$ $C_4 = 0.3$ $O_{95} \geq 50$ μm	hydrodynamic sieving, graded soil

Table 5. Existing Filter Criteria for Geotextiles

The major factors which affect the success of synthetic envelopes in humid areas, following Dutch experience, are: soil structural stability, soil texture, particle size distribution, rate and depth of ripening of the soil, organic matter content of the soil and iron (Fe) content of soil and groundwater.Knops et al. (1979) published the first set of comprehensive guidelines for the selection of envelopes, made of pre-wrapped loose materials, for use in Dutch soils. Several years later, the number of complaints about excessive mineral clogging of drain tubes increased substantially. Over

1000 excavations were made to investigate this problem (Blom, 1987). It was found that envelopes manufactured from organic substances performed worse than those made from synthetic fibers and geotextiles. As a result, the guidelines were modified and the O90-value, the effective opening size of envelope pores, was adopted as the major design parameter. This criterion choice was supported by concurrent laboratory and field research.

Recently, Stuyt (1992a, 1992c) completed research on a series of projects to evaluate envelope performance. He used a CAT-scanner to investigate 45 field samples of pre-wrapped drains that had been installed in weakly-cohesive, very fine-sandy soils with a d90 of approximately 150 um. Among other things, this research yielded three-dimensional (3D) mappings of heterogeneous patterns of mineral clogging inside envelopes and showed soil structural features in the abutting soil. Much was revealed about the functioning of pre-wrapped envelopes. Effects of soil properties exceeded those of envelope properties.Patterns of water flow into drains were, unlike theoretical concepts, were heterogeneous and were strongly correlated with the macropore network in the adjacent soil. Figures 3 and 4 show examples of macropore systems with enhanced permeability that have developed around drains wrapped with envelope materials. The water does not approach the drains through a homogeneous soil cross-section. Figure 5 shows patterns of mineral clogging inside an envelope. For computational reasons, the images had to be processed independently yielding separate upper and lower sections.

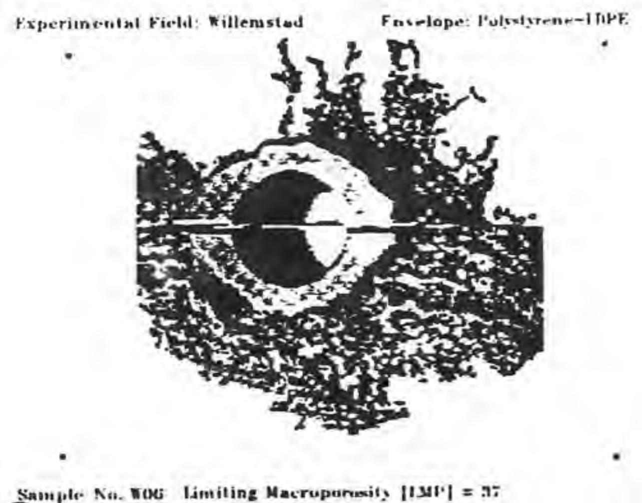

Figure 3.
Image areas containing all voxels with Limiting Macroporosity LMP ≥ 37%. This drain was installed in a soil layer with a relatively high conductivity. Water flow through the trench is restricted at this LMP, possibly due to structural deterioration of the backfill material. Experimental field: Willemstad, envelope material: Polystyrene beads "PS-LDPE", sample No. W06. See also Plate 5.

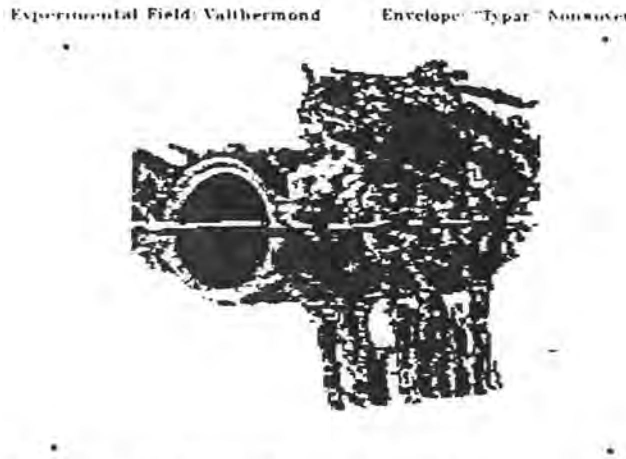

Figure 4. Sample No. V01 Limiting Macroporosity [LMP] = 41

Image areas containing all voxels with Limiting Macroporosity LMP ≥ 41%. Water access to this drain proceeds through a series of parallell vertically oriented macropores. Not all macropores are involved at this LMP, however, see Figure 11 and Plate 2. Experimental field: Valthermond, envelope material: "Typar" nonwoven, sample No. V01. See also Plate 7.

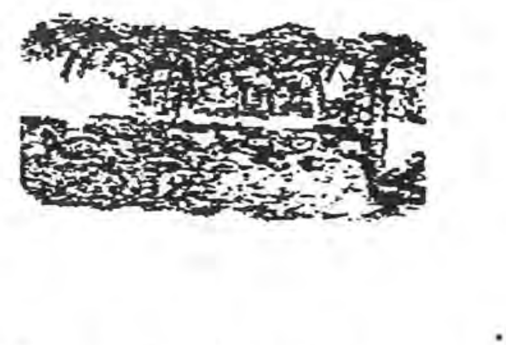

Figure 5. Sample No. W09 Permeable Envelope Areas

Image areas containing all voxels where the most permeable envelope areas are mapped. The envelope is mainly clogged at the interface area with the trench. Experimental field: Willemstad, envelope material: Peat/Coconut fibre mixture, sample No. W09. See also Plate 8.

Using a miniature video camera inspection system, Stuyt (1992a, 1992b) investigated the relation between the O90-size of envelope materials and the thickness of the sediment layer inside drain tubes, 5 years after installation. The d90-size of the soils was approx. 150 um in most cases. The correlation between soil particle size and envelope opening size was significant. Regardless the O90-size, voluminous envelopes restrained more soil than thin envelopes. Envelopes with larger O90 values, i.e. having larger openings, had poorer soil retention properties (Table 6).

In The Netherlands and in Belgium, the retention criteria O90/d90, used for geotextile envelopes (see paragraph 3.4) has proved to be valid for pre-wrapped loose materials as well. These countries have adopted the O90/d90 criteria for such materials, but recommendations for their application is based on some additional considerations. (Huinink, 1992; Van Zeijts,1992). The lower limit, O90/d90 = 1, is still subject to discussion. Envelopes with O90/d90 near 1 had such low sedimentation depths in drain tubes that they seem to act as filters (Table 6). A lower limit for the O90/d90 ratio of 1.5 or 2 for thin geotextiles might be preferable. On the other hand, the higher limit, set to 5 for voluminous geotextiles, appears conservative for voluminous pre-wrapped loose materials since a maximum sedimentation depth of 15 mm can be tolerated in 60 and 65 mm outer diameter tubes (Table 6). In soils with some cohesion and, hence, structural stability,voluminous envelopes with O90/d90 ratios as high as 7 have been applied successfully.

Table 6. Pipe Sedimentation depth (mm); fitted values from a regression model, depending on effective opening size of the envelope pores, O90 (um) and envelope category (thin or voluminous) for observations made at the experimental fields at Uithuizermeeden, Valthermond and Willemstad. Sediment depths > 15 mm are not tolerated. The tubes had outer diameters of 60 and 65 mm. (From Stuyt 1992a).

	Uithuizermeeden		Valthermond		Willemstad	
O90(um)	thin	volum.	thin	volum.	thin	volum.
sedimentation rates (thickness of sediment layer (mm))						
250	2.1	0.9	4.5	0.8	9.7	8.5
500	3.9	2.6	6.3	2.5	11.4	10.2
1000	5.6	4.3	8.0	4.3	13.2	11.9

Hydraulic conductivities of pre-wrapped loose materials are generally so high that they have no effect on envelope design. The most important selection criterion is the porometry or pore size distribution of the actual envelope in a natural compressed condition.

In The Netherlands, the following, standardized,pre-wrapped loose materials are used: polypropylene(waste) fibres, "PP-450" and "PP-700" (O90: 450 and 700 um), coconut fibres "Cocos-700" and "Cocos-1000" (O90:700 and 1000 um), polystyrene beads in synthetic netting (O90: 1000 um), peat fibres, and mixtures of peat fibres and coconut fibres. Synthetic fibers comprise the greater part of the market but organic fibers will continue to be used in various regions because they function satisfactorily and are available at competitive prices. Figure 6 shows some frequently used PLM envelopes.

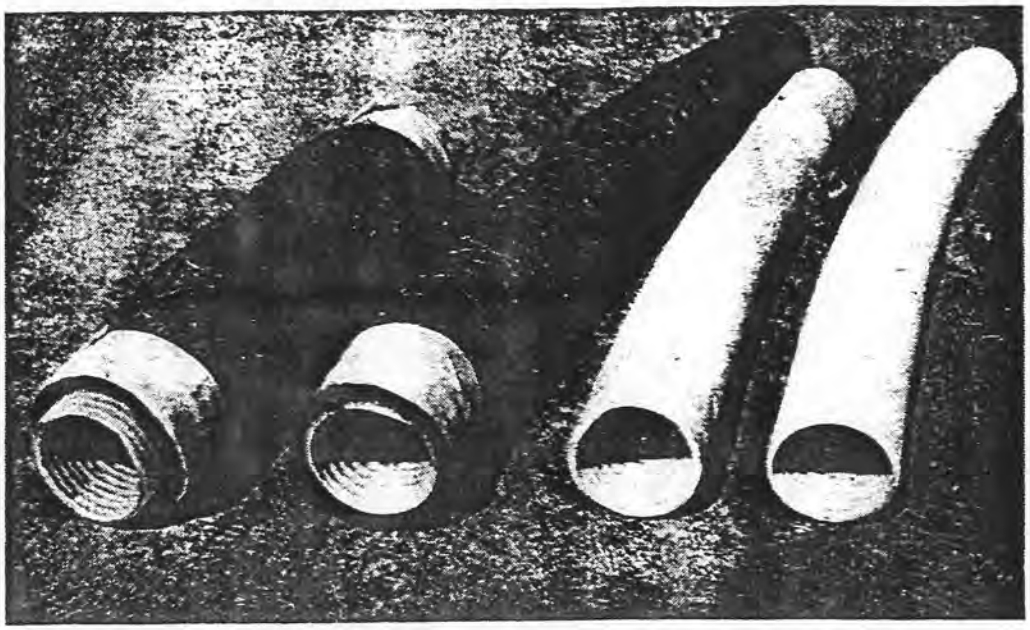

Figure ~~2~~ 6. From left to right: pipe (outer diameter 60 mm) with a voluminous organic envelope, with a voluminous synthetic envelope, with a thin envelope and without an envelope.

The Dutch recommendations for the application of pre-wrapped loose material envelopes are summarized as follows (Huinink, 1992; Van Zeijts, 1992).

1. Envelopes containing peat fibres and "PP-450" should not be used: i) in case of possible iron orchre hazard, and ii) if the drains are also used for subsurface irrigation purposes during the summer season.

2. Ripened clay soils with a clay content > 25% do not require envelopes.

3. For most other soils, such as unripened clay soils with a clay content > 25%, (loamy) sand, (sandy) loam, silt loam and peaty soils, any envelope, mentioned above, may be selected.

4. Exceptions are made for clay soils with a clay content < 25%, silts and very fine sands which should be drained with "PP-450" or, in case of iron ochre, with "PP-700" (see above) only.

A working group of scientists and engineers in Europe recently developed a new classification for drain envelopes made from pre-wrapped loose materials.They introduced three classes of envelopes, depending on the effective opening size, O90, as follows:

PLM-XF:	XF = extra fine:	100 um =< O90 < 300 um
PLM-F :	F = fine:	300 um =< O90 < 600 um
PLM-S :	S = standard:	600 um =< O90 < 1100 um

Tubing coil ends are labeled with tape, imprinted with identification "PLM-XF", "PLM-F", or "PLM-S" on it.

In addition to these O90-ranges, the following minimum envelope thicknesses are required:

1. Synthetic, fibrous materials: 3 mm. (e.g. PP fibres),

2. Synthetic, granular materials: 8 mm. (e.g. polystyrene beads),

3. Organic, fibrous materials: 4 mm. (e.g. coconut fibres),

4. Organic, granular material: not yet fixed (e.g. wood chips, sawdust).

The minimum thickness was introduced to guarantee a complete cover with a homogeneous envelope. The above classification is scheduled to be introduced in all European countries as an official "CEN" (Commission Europeene de Normalisation) standard in 1993. Following this standard, "PP-450" will be classified as PLM-F(fine) and "PP-700" as PLM-S (standard).

3.6 Design of Composite Envelopes

Although no design criteria are available for combinations of inorganic and synthetic materials, they have been used successfully in practice. In highway drainage, the practice of lining a narrow shallow trench with a geotextile and then backfilling the trench with single-sized gravel (9.5 mm) is an accepted solution for some pavement drainage problems, (Figure 7). In agricultural areas, where clean sand is plentiful, but graded gravel is not available, a composite sand-geotextile envelope system can be used.Where a large diameter envelope is needed to reduce the exit gradient to a value below the hydraulic failure gradient of an unstable soil, it is possible to surround the drain tube with a geotextile having an appropriate O90 to prevent movement of sand into the pipe perforations. A clean sand that meets the D15/d85 criterion or the D15 < 0.3 mm gradation recommended by Sherard et al. (1984a) can then be used to make a sand envelope with the outside diameter required control the exit gradient and prevent movement of the soil into the sand.

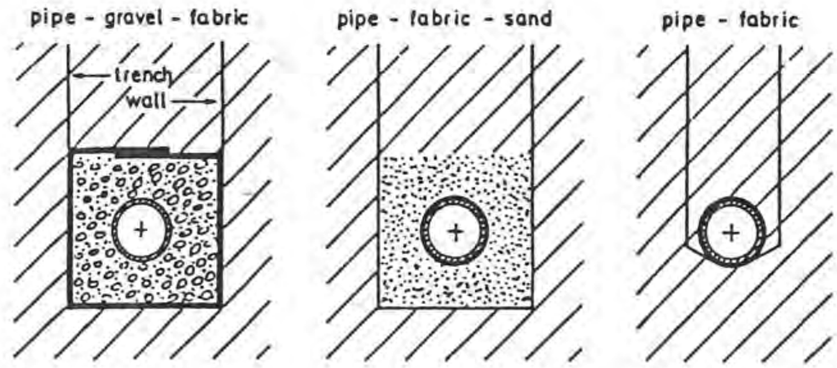

Figure 7 Three possibilities to use geotextiles as drainage envelope.

3.7 Envelope Material Testing

Field tests of large numbers of envelope materials are time consuming and expensive. It is recommended that some form of permeameter testing be done to eliminate envelope-soil combinations that are obviously unacceptable. A state-of-the-art permeameter test apparatus is shown in Figure 8. The permeameter tests must cause some of the envelope materials being tested to fail in order to be certain that the test is representative of the hydraulic gradients that may develop at the drains in the field. When a suitable envelope system has been designed or selected, then some pilot drains should be installed to check the system under field installation and operation conditions (Dierickx, 1991). Local experience is also valuable in selection of envelope materials if careful observations are made and if drain envelope failures were not caused by unfavorable installation conditions.The uncertainties of field installations make dependence on permeameter tests alone somewhat questionable (Stuyt, 1992a).

4. Installation of Envelopes

Even the best envelope materials cannot compensate for improper installation, especially in saturated,fine, weakly-structured soils. Envelope materials, that are otherwise reliable, will only be successful if installed under favorable physical soil conditions.General excess wetness of a soil may adversely affect its structural stability. The soil manipulation that occurs during the trenching operation while installing drains may destroy its structure, leading to soils laking, enhanced risk of mineral clogging of envelope sand pipes, and a low hydraulic conductivity of the soil. Gravel envelopes tend to be less susceptible to poor installation conditions, but they can also fail due to adverse conditions at the time of installation.Stuyt (1992a, 1992c) found increased rates of pipe sedimentation in the "Willemstad" experimental field where drains were laid after a prolonged period of excess wetness (see table 6). Geotextile envelopes are normally pre-wrapped and have sufficient mechanical strength to withstand the stresses of installation, so, during installation, attention should be focussed entirely on preserving the hydraulic function of the drain envelope-pipe system.

Fig 8

The ideal condition for installation of subsurface drains is to place the drains in an unsaturated soil.If the soil has a high water table that cannot be lowered prior to installation, every effort should be made to preserve the existing soil structure and to protect the drain from trench wall failure. Adjusting the forward speed of the machine can be done to limit the damage to soil structure. Observation of the condition of the excavated material 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 a slurry. Simultaneous and instantaneous backfilling (see Figure 9) will help prevent trench wall failure. Drain plows have been developed that will install drains with synthetic or gravel envelopes. Plowed-in drains, Figure 10, avoid many of the problems of trenched or backhoe excavated drain installations.

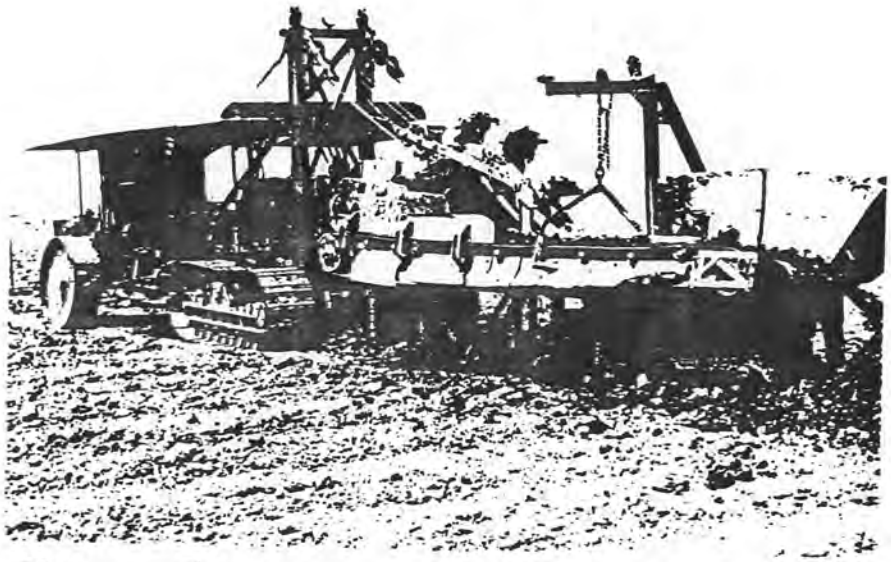

Figure ~~8~~ 9

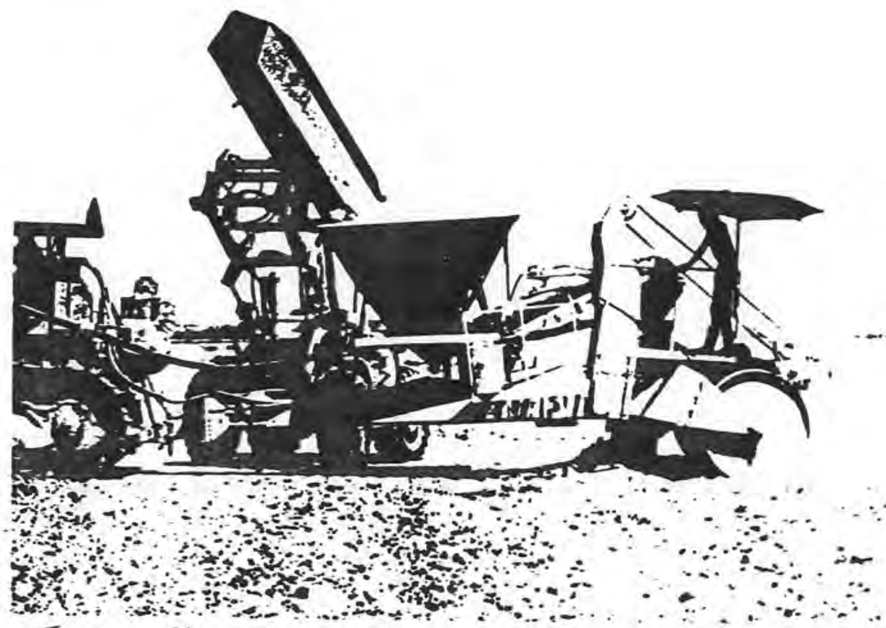

Figure ~~9~~ 10

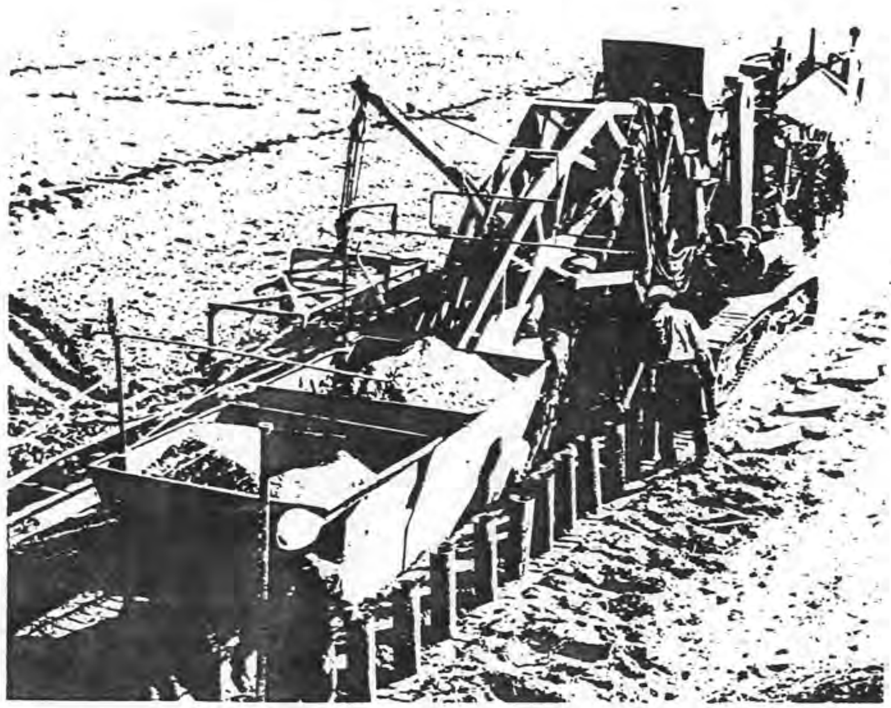

Figure 10.11

4.1 Installation of Gravel Envelopes

Most of the water entering a subsurface drain moves through openings in the sides and bottom of the drain, below the hydraulic grade line inside the drain.The hydraulic gradients that develop at unprotected drain openings are often high enough to cause a quick condition at the opening and, consequently, piping of the soil material may occur. The noncohesiveness of many soils makes them particularly susceptible to movement when saturated. For these reasons, an adequate amount of envelope material is needed under the drainpipe, as well as on top and along the sides.

Where drains are laid by hand, a layer of envelope material is placed in the bottom of the trench and is leveled to the design grade before the drain is laid.The drain pipe is then put into place and covered with envelope material to the required depth. The trench is then backfilled with soil. Some trenching machines(see Figure 11) have been fitted with two hoppers for placing envelope material under and over a drain on a continuous basis. One hopper near the digging device covers the trench bottom with the required thickness of envelope material. The pipe is put into place and the second hopper at the rear of the machine covers the pipe with envelope material.

Drainage contractors have recently developed procedures for placing envelope material completely around a drain pipe in one operation using a single gravel hopper. Single hopper placement is used for both rigid and flexible pipe. The pipe within the machine is suspended above the bottom of the trench until the granular envelope material can flow around the pipe.This single-stage placement has resulted in economies of material since it is possible to make an approximately concentric envelope by pre-shaping the trench bottom. Drain plows that install flexible corrugated plastic drain tubing with gravel envelopes have uniformly concentric envelope placement.

In unstable soils, the drain pipe and envelope are sometimes displaced by soil movement before and during backfilling. The sides of the open trench may fall or slough causing lateral misalignment of the pipes. If the soil around or in the bottom of the trench is saturated and unstable it may move as a fluid, displacing the envelope material and pushing the pipe out of line. Simultaneous backfilling, as illustrated in Figure 8, is particularly desirable in unstable soil conditions. Movement of saturated unstable soil may also cause puddling of the backfill material and plugging of the envelope material during construction. A slurry in the bottom of a trench will cause immediate and complete failure of synthetic envelope materials.

Protection of the envelope-drain system following installation is important. No heavy loads, mechanical or hydraulic, should be imposed until the soil in the trench is consolidated. The loose backfill material will settle naturally with time.Passage of a light weight vehicle wheel in the trench will speed up the process, but care must be taken to avoid crushing the pipe.

Application of irrigation water to unconsolidated material in the trenches to settle the backfill is a practice that should be done very carefully. Muddy water moving through the porous backfill material directly into the envelope under high hydraulic heads can cause plugging of the envelope material at the drain openings. Such plugging will reduce the effectiveness of the drain envelope. It may also result in sedimentation of the drain or even complete plugging and failure of the envelope.

Other installation problems to be considered are:lack of uniform gravel quality; segregation during transportation and installation; gravel flowability problems in the supply tube; unequal distribution around the drain pipe; and lack of a natural gravel supply appropriate to the soil, therefore requiring screening or blending. Naturally graded pit-run materials with a minimum of fines make ideal envelope materials.

4.2 Envelope Thickness

One of the benefits of envelope placement is the increase in permeability along the pipe that enables water to flow more easily to the perforations (or joints between clay or concrete tiles). The effect of a drain envelope is similar to converting the pipe from one with limited openings to one that approximates a completely permeable "ideal drain". Nieuwenhuis and Wesseling(1979) and Dierickx (1980) showed that the entrance resistance for water flow near the pipe, i.e. the resistance caused by the convergence of flowlines toward perforations and joints is related to the permeability of the envelope.

Kirkham (1949) has shown theoretically that increasing a drain diameter will increase inflow. Increasing the diameter of an envelope effectively reduces the water flow velocity and exit gradient at the soil-envelope interface (Willardson and Walker,1979) thereby decreasing the probability of soil particle movement. If a permeable envelope material is considered to be an extension of the pipe diameter, then the thicker the envelope the better. There are however, practical limitations to increasing envelope thickness. The perimeter of the envelope through which flow occurs increases as the first power of the diameter of the envelope, while the amount of envelope material required increases as the square of the diameter. Doubling the diameter of the envelope and consequently decreasing the inflow velocity or exit gradient at the soil-envelope interface by half, would require 4 times the volume of envelope material. Studies, made by Nieuwenhuis and Wesseling (1979)(theoretical) and Dierickx (1980) (theoretical and analog modeling) demonstrate that the favorable effect of increasing envelope thickness is inversely proportional to the thickness itself.

Recommendations for minimum thickness of geotextile and PLM envelopes are based on the studies mentioned above, and to guarantee a complete cover with a homogeneous envelope. CEN-standards for minimum envelope thickness are given in section 3.5.

Recommendations for gravel envelope thickness have been made by various agencies. The USBR (1984) recommends a minimum thickness of 100 mm around the pipe. The Soil Conservation Service (1991) recommends an 80 mm minimum thickness. The Edward E. Johnson Company (1966) recommends a minimum thickness of 80 mm and a maximum thickness of 200 mm as a gravel pack fora well. Des Bouvrie (Pillsbury, 1967) related envelope thickness to the envelope-aquifer ratios at the 50 % grain size and suggested a 130 to 250 mm thick envelope for an envelope-aquifer ratio of 12.0. For an envelope-aquifer ratio of 12.0 to 24 the envelope thickness should be 80 mm. Envelope-aquifer ratios of 24.0 to 28.0, 28.0 to 40.0, and 40.0 to 52 would require envelope thicknesses of 150, 230, and 300 mm, respectively.

The development of corrugated plastic drain pipes with close perforation spacing has reduced the requirement for a permeable envelope material to transport water to widely spaced openings that were common when 0.3 to 1.0 m lengths of rigid pipe were used for drainage. The practical problems of placement probably dictates a design minimum gravel envelope thickness of approximately 80 mm. The principal reason for a thicker envelope in a problem soil would be to help reduce the exit gradient to a value below the hydraulic failure gradient of the soil.

5. Conclusions

The natural variability of soils and the complicated nature of the interactions between water and soil in the vicinity of a drain opening make absolute prediction of need and appropriateness of drain envelope materials very uncertain. Differences between envelope materials add another dimension of uncertainty to the problem. Attempts to adapt filter criteria developed for hydraulic structures to drain envelope design have resulted in criteria that have been used successfully under many circumstances, but there have been some serious failures. The introduction of synthetic materials in the form of bulk fibers or in geotextiles has resulted in the need for a new set of criteria for thin envelopes. The best information currently available is summarized above. The $D15/d85 <= 5$ for gravel materials and the $O90/d90 < 5$ for thick synthetic materials ($O90/d90 < 2.5$ for thin geotextiles) should be used as the main guidelines. Estimates of the exit gradients for water leaving the soil and entering the drain and the hydraulic failure gradient of the soil can give an indication of whether an envelope material will be needed to protect a drain. The final test is a field installation under natural conditions.

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GRAVEL ENVELOPES FOR PIPE DRAINS - DESIGN

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SUMMARY: Subsurface drains constructed for agricultural drainage function best when installed in an envelope designed for the specific characteristics of the soil to be drained. Methods have been developed for determining the proper envelope gradation and permeability.

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GRAVEL ENVELOPES FOR PIPE DRAINS - DESIGN

Introduction

Pipe drains designed and constructed for the drainage of irrigated lands should accept ground water moving to them without a water table buildup above the drain. To accomplish this, the pipe must be surrounded by an imported material (envelope) designed with a gradation and permeability compatible to those of the material being drained, which throughout this paper will be called the base material.

It has only been the last 20 years that agricultural research scientists and drainage engineers have recognized the need for the development of a criteria for the design of an envelope material to be used primarily for agricultural drainage.

Material engineers began studying the criteria required for protective filters used for toe drains in dams and large canals early in the 1920's about the time Karl Terzaghi published his work on the design criteria for weighted filter. 7/ With no other studies or information available, drainage engineers used filter design criteria for envelopes for agricultural drains. Many drains functioned satisfactorily, but field studies conducted on drains that were not draining the lands satisfactorily indicated that the envelope could not handle all the ground water converging at the pipe joints, and water stood above the envelope material following an irrigation or heavy rainfall. This in turn caused a higher water table than desirable midway between drains. Drainage engineers and drain contractors found that by removing part of the fines from a designed protective filter, the envelope still acted as a partial filter, but the permeability was increased sufficiently so no water stood above the drain during any part of the irrigation cycle.

With part of the fines removed, the envelope no longer qualified as a designed protective filter which caused a great deal of concern to the material engineers. They maintained that the design criteria for an envelope must be based on a form of ratios which control the gradation of the envelope in reference to the size of the base material so that the envelope: (1) contains sufficient fine material to prevent the movement of fines from the base material into the envelope; and (2) contains enough coarse material so that the permeability is adequate to move the ground water into the

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Footnote indicators refer to references listed at the end of report.

drain with a negligible loss of head at the joint opening. This ratio, developed by laboratory tests for toe drains for dams was based on the assumption of relatively high gradients in the range between 7.5 and 45.

Drainage engineers agree that for all types of subsurface drainage a large quantity of fines should not be allowed to move into the envelope, and the permeability must be adequate to move all ground water converging at the joint into the pipe. However, if the envelope is to be used only for agricultural drainage, the gradients would be low in the order of one or less. Therefore, the design criteria for agricultural drainage envelopes must recognize that the velocity between the base material and the envelope is low, and less fines are required than for the design of a protective filter. By reducing the amount of fines to specified gradation limitations, the permeability will be increased, which is an important requirement for an envelope material used for agricultural drainage. Well-graded envelopes meeting the gradation limitation requirements should be tested for permeability and the results compared with the inflow capabilities of the base material before they are used.

Gradation Requirements

Envelope gradation requirements for base materials consisting of silt loams, sandy clay loams, and loams can usually be more flexible than for base materials that have textures of fine sands and very fine sands. The velocity at the interface between the finer textured base materials and the envelope are so low that the fine textured base material will not move into the envelope even under excessive leaching conditions. Waste slag and even broken-up concrete envelope material have been used for silty clay loam base material with little of the finer textured soils moving into the envelope. However, this type of envelope would have been entirely unsuitable for fine sands and very fine sands because the potential ground-water velocity in these materials can be great enough to move some sand particles if unrestricted by some fines in the envelope.

Gradation requirements should not be changed as different textured soils are encountered. From borings taken about every 600 feet along the centerline of the drains, the most permeable base material for significant lengths of the drain should be determined and the envelope designed for this material. Different gradation requirements can be specified if there are long sections of drain where the gradation and permeability of the base material indicate less expensive or easier obtainable envelope material can be used.

However, the proper envelope must be used for the right sections or the effectiveness of that entire section of the drain might be nullified.

There have been many methods used to establish the most desirable gradation relationship between the envelope and the base material. Most of the available data are for a protective filter and are too restrictive for use in the design of an envelope for agricultural drains. The method proposed in this paper is based on observation of a number of operating field drainage systems and has been verified by limited laboratory experimental data using a graded fine sand as the material to be drained. 3/

An envelope to function properly should be reasonably well graded, free of vegetable matter, clays, and other deleterious substances which could with time change the permeability. In addition, for the sieve analysis, 100 percent should pass the 1-1/2-inch clear square sieve openings and not more than 5 percent should pass the Number 50 U.S. Standard Series screen. Since very few pit run sands and gravels meet these requirements, most envelopes must be machine sorted. Washing is required only when sand and gravel are not plentiful and the only source is from pits containing silt or clay coated material.

An envelope material is considered well graded when there is a representation of all the particle sizes from the largest allowable to the smallest permitted. To determine whether or not a material is well graded, coefficients describing the slope and shape of the gradation curve have been defined as follows 2/:

$$\text{Coefficient of uniformity, } Cu = \frac{D_{60}}{D_{10}} \qquad (1)$$

and

$$\text{Coefficient of curvature, } Cc = \frac{(D_{30})^2}{(D_{10})(D_{60})} \qquad (2)$$

where D_{60}, D_{10}, and D_{30} = Diameter of particles in millimeters passing the 10, 30, and 60 percent on the base material gradation curve

To be well graded, the coefficient of uniformity must be 4 or greater for gravels and 6 or greater for sands, and the coefficient of curvature must be between 1 and 3 for both gravels and sands.

The gradation curves of the base material are drawn from the sieve and hydrometer analyses data using samples taken on the drain centerline and at about drain depth. Since both the coefficients of uniformity and curvature use the diameter of particle size at the 60 percent passing point (D_{60}) a relationship has been established between D_{60} of the base material and the D_{60} of the envelope as shown in Table 1. The D_{10} and D_{30} values have been computed from Equations 1 and 2.

Table 1

GRADATION RELATIONSHIP BETWEEN BASE MATERIAL AND ENVELOPE

Base material 60% passing (diameter of particles, mm)	Gradation limitations for envelope (diameter of particles, mm)											
	Lower limits						Upper limits					
	Percent passing						Percent 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

These limitations give the widest spread consistent with the criteria for a well-graded material.

Selecting D_{60} sizes of 2.0 to 5.0 millimeters for the envelope lower limits should normally provide an adequate permeability for appropriate gradations of base material. The upper limits for D_{60} sizes of 10 to 20 millimeters have been established from observations on the success and failure of envelopes due to fines in the base material moving into the envelope. With the current concepts of water table control for normal rooted crops of 3 or 4 feet below ground surface for 7- to 8-foot-deep drains, higher upper limits might be used for all gradation of base materials. However, there is always the possibility of overirrigation or ponding for leaching which might increase the head sufficiently to cause some of the smaller soil particles in the base material to move into the coarser textured envelope and decrease its permeability below the computed minimum.

To complete the gradation curves, the permissible largest and smallest particle sizes must be established. For the upper limit curve, it has been observed that any coarse gravel passing the

100 percent point and larger in diameter than about 1-1/2 inches could crack or break clay pipe if it falls directly on the pipe from the top of the trench. Also gravel sizes larger than 1-1/2 inches lying underneath the pipe could cause grade and alinement problems during construction. For the lower limit curve, there should be some gravel up to about 3/8-inch size passing the 100 percent point to assure adequate permeability. The fines for the upper limits can vary considerably, but it has been observed that when most of the envelope consists of the larger diameter particles, part of the sand particles passing the No. 30 screen will eventually move into the pipe. Smaller sand particles can be permitted in the lower limit curve, but obtaining adequate permeability might be a problem if more than about 5 percent is allowed to pass the No. 50 screen. Figure 1 shows the upper and lower limits of a well-graded envelope for four different base materials.

Permeability Requirements

Until a few years ago, envelope material was believed satisfactory if it had equal or a little better permeability than the base material. Any pit run material that satisfied this condition and qualified as a protective filter was used as an envelope. However, it was observed that for a number of drainlines using envelope material with about the same permeability as the base material, ground water stood over the envelope during construction. It was also observed that observation wells, installed on the drain centerline after backfilling the trench, indicated the drawdown curve did not start at the top of the envelope but above it. Therefore, any rule-of-thumb method used for determining the minimum permeability for the envelope was not always reliable and a mathematical method, based on field observations, was developed to calculate the required minimum envelope permeability for any base material. The mathematical solution takes into account the effect of joint width, length and diameter of pipe, the maximum possible rate of inflow to the pipe considering soil characteristics and drain spacing, and the thickness of the envelope material.

The procedure developed by W. T. Moody, Bureau of Reclamation, 5/ is based on the loss which occurs as the flow converges in the gravel envelope immediately surrounding the joint opening. Only the convergence loss at the joint was considered because the thickness and permeability requirements of the envelope for flow along the pipe proved insignificant compared to the convergence requirements. Disregarding the flow requirements along the pipe permitted the solution to be given as a single set of curves.

Including this parameter involved the summation of an infinite series of Bessel function which complicated the solution without adding significantly to its accuracy.

The region of convergence is assumed to be the volume enclosed by semicircles of radius R equal to the thickness of the gravel envelope, and c equal to one-half the joint width as they rotate about the centerline of the pipe (Figure 2). The centers of the semicircles coincide with the center of the joint opening and lie at a distance from the axis equal to the outside radius b of the pipe.

If a free water surface is maintained in the gravel in the vicinity of the joint opening at a distance H (where $H > b$) above the centerline of the pipe (Figure 3), a constant potential difference of H exists between the outer limits of the water surface and the centerline of the pipe when the pipe is empty. With the pipe flowing full, but not under pressure, the constant difference in potential is very nearly given by $H - a$, where a represents the internal radius of the tile. For the intermediate case where water is flowing at depth d in the pipe (where $0 \leq d \leq 2a$) the average potential difference, $\overline{H}$, per unit circumference is given by:

$$\frac{\overline{H}}{H} = 1 - \left\{ \left(\frac{d-a}{H}\right) \left[1 - \frac{1}{\pi}\cos^{-1}\left(\frac{d-a}{a}\right)\right] + \frac{1}{\pi}\sqrt{\frac{d(2a-d)}{H}} \right\} \qquad (3)$$

This relation is closely approximated by the considerably simpler empirical expression

$$\frac{\overline{H}}{H} = 1 - \frac{d}{160H}\left(22 + 29\frac{d}{a}\right) \qquad (4)$$

Ground water entering the envelope is assumed to converge in two directions between: (a) meridian planes of the region of convergence and (b) cones whose elements pass through the circumferential centerlines of the joint opening and intersect the region of convergence in parallel circles. The elementary cross section area of a stream tube (Figure 2) is therefore,

$$dA = (b + r\cos\theta)\, d\psi\, r d\theta. \tag{5}$$

If the elementary rate of flow into this area is dQ, then by Darcy's law

$$dQ = K(b + r\cos\theta)\, r d\theta\, d\psi \frac{dh}{dr} \tag{6}$$

where h represents the potential at a point in the stream tube.

This can be rewritten as

$$dh = \frac{dQ}{K d\theta\, d\psi} \frac{dr}{r(b + r\cos\theta)} \tag{7}$$

Integrating (7) subject to the conditions

$$r = c,\ h = o;\ r = R,\ h = \overline{H} \tag{8}$$

gives

$$\overline{H} = \frac{1}{Kb}\left[\ln \frac{R(b + c\cos\theta)}{c(b + R\cos\theta)}\right] \frac{dQ}{d\theta\, d\psi} \tag{9}$$

Rearranging (9) and integrating over the entire volume to get the total flow into one opening results in

$$Q = 2b\bar{H}K \int_0^{2\pi} \int_0^{\pi/2} \frac{1}{\ln \frac{R(b+c\cos\theta)}{c(b+c\cos\theta)}}\, d\theta\, d\psi \tag{10}$$

To put this in dimensionless form let

$$\begin{aligned} c &= mb \\ R &= nb \end{aligned} \tag{11}$$

which, after carrying out the integration on ψ, gives

$$Q = 4\pi b\bar{H}K \int_0^{\pi/2} \frac{d\theta}{\ln \frac{n+mn\cos\theta}{m+mn\cos\theta}} \tag{12}$$

Finally, place

$$\varphi(m,n) = 4\pi \int_0^{\pi/2} \frac{d\theta}{\ln \frac{n+mn\cos\theta}{m+mn\cos\theta}} \tag{13}$$

so that

$$Q = b\bar{H}K\varphi \tag{14}$$

Equation (13) was integrated numerically to obtain value of φ for a series of values of m and n to provide data for the curves in Figure 3. These curves define a dimensionless function, φ of the joint width and thickness of envelope. This function gives the rate of inflow, Q, to the pipe, through a single opening of width 2mb. Q is given in units of $b\overline{H}K$ where b is the external radius of the pipe, $\overline{H}$, the average potential difference, and K the permeability of the envelope. The quantity $\overline{H}$ is the average potential difference acting between the outer and inner surface of the region where the flow is assumed to converge. This region is a partial torus of envelope material immediately surrounding the joint. Back pressure due to flow within the pipe will reduce the effective potential. For the case where the minimum permeability permissible for the envelope must be determined, the effective potential will be for the pipe flowing full but not under pressure.

The following calculations show how the minimum permeability permissible for the envelope can be determined using easily measurable soil characteristics of the base material and known pipe measurements.

Joint width 2mb - Use 1/8-inch (Can vary from 1/16 to 1/4 inch, but increasing the joint width is an ineffective method of increasing the rate of flow, and also wider joints will permit a greater amount of the finer material in the envelope to move into the pipe.)

Envelope thickness nb - Use 4 inches (Can vary from 2 inches up, but must consider availability and cost of envelope and installation. Present installation methods cannot maintain a uniform thickness of less than about 2 inches.)

Drainpipe - Use 4-inch-diameter concrete bell and spigot drainpipe 30 inches long. (Clay pipe will have essentially the same envelope permeability requirement. Other types of joints can be used but tongue and groove and straight end allow more fines in the envelope to fall through the joint opening into the pipe if not covered on top with plastic or asphalt-saturated felt.

Therefore: Inside pipe diameter, 2a = 4 inches = 0.333 foot
Joint width, 2mb = 1/8 inch = 0.0104 foot
Envelope thickness, nb = 4 inches = 0.333 foot
Outside pipe diameter, 2b = 4 + 1 = 5 inches = 0.416 foot

$$\text{Outside pipe radius,} \quad b = \frac{0.416}{2} = 0.208 \text{ feet}$$

$$m = \frac{0.0104}{0.416} = 0.025$$

$$n = \frac{0.333}{0.208} = 1.60$$

When the pipe is running full:

$$\bar{H} = H - a = b + nb - \frac{2a}{2} = 0.208 + 0.333 - \frac{0.333}{2} = 0.374$$

From Figure 3 when $m = 0.025$ and $n = 1.60$, $\varphi(m,n) = 5.70$

The inflow from base material, $Q = b\bar{H}K\varphi$ and the required permeability for the envelope, $K = \frac{Q}{b\bar{H}\varphi} = \frac{Q}{0.208 \times 0.374 \times 5.70}$

$$K = \frac{Q}{0.444} = 2.25\ Q$$

The smallest diameter pipe used in the system will require the highest permeability in the envelope.

Table 2 shows the required permeability and inflow relationships, using different joint widths, pipe diameters, and envelope thickness.

Table 2

REQUIRED PERMEABILITY AND INFLOW RELATIONSHIPS FOR CONCRETE AND CLAY PIPE USING DIFFERENT JOINT WIDTHS, PIPE SIZES, AND ENVELOPE THICKNESSES

Joint width and envelope thickness	Concrete drainpipe K equals			Clay drainpipe K equals		
	4" diam	6" diam	8" diam	4" diam	6" diam	8" diam
1/16" joint 3" envelope	3.38Q	2.31Q	1.71Q	3.45Q	2.41Q	1.83Q
1/16" joint 4" envelope	2.73Q	1.89Q	1.42Q	2.84Q	1.97Q	1.51Q
1/16" joint 6" envelope	1.97Q	1.38Q	1.05Q	2.02Q	1.43Q	1.09Q
1/8" joint 4" envelope	2.25Q	1.60Q	1.19Q	2.32Q	1.65Q	1.25Q
1/8" joint 6" envelope	1.65Q	1.17Q	0.88Q	1.70Q	1.23Q	0.95Q

The inflow from the base material can be computed from measured and selected drainage data using the following equations 1/:

when drains are above the barrier

$$Q = \frac{2\pi \ Ky_o \ D'}{L} \tag{16}$$

and when drains are on a barrier

$$Q = \frac{4 \ Ky_o^2}{L} \tag{17}$$

where Q = inflow from base material in cubic feet per lineal feet per day

K = permeability of base material in feet per day

y_o = Maximum permissible water table height midpoint between drains

D' = Average flow depth corrected for loss of head due to convergence of the flow lines as they approach the drain $(d' + \frac{y_o}{2})$

L = Drain spacing in feet

The required permeability of the envelope should be determined using the same data as were used to determine the drain spacing. If one section of the drainage system has wider spacing and higher permeabilities than other sections, data from this section should be used to determine the required envelope permeability for the entire system.

To compute Q assume the following:

K = 5 inches per hour or 10 feet per day

Drain depth = 8 feet

Maximum y_o = 4 feet

Depth to barrier = 30 feet

Depth from drain to barrier d = 22 feet

Depth from drain to barrier corrected for convergence using method developed by Hooghoudt, d' = 20 feet

Average flow depth, $D' = d' + 1/2\ y_o = 20 + 2 = 22$ feet

Drain spacing, L = 900 feet

$$Q = \frac{2\pi\ K y_o\ D'}{L}$$

$$Q = \frac{6.28 \times 10 \times 4 \times 22}{900}$$

Q = 6.16 cubic feet per lineal feet per day

Using a 4-inch-diameter pipe drain, 4 inches of envelope material, 1/8-inch joint opening and a 2.5-foot length of pipe, the permeability of the envelope must be equal to or greater than:

$$K = 2.25 \times 6.16 \times 2.5 = 35 \text{ feet per day}$$

This method of determing the minimum acceptable permeability for the envelope should be used only for relief and interceptor spaced drains. Drain spacings greater than about 2,000 feet will have a high base material permeability (50 to 100 feet per day). For these conditions, the base material permeability will be great enough to handle all ground water that can converge at the joint, and imported envelope material will not be required. Envelopes are not usually placed around collector pipe drains, but when a pipe drain serves both as a collector and relief or interceptor, the envelope permeability required for the smallest diameter pipe in the system should be used.

In some gravel pits the waste of undesirable fines can amount to a large percentage of the processed envelope material. Some of these fines can be used in the envelope if an asphalt-saturated felt or plastic sheet is placed over the upper half of the joint opening to keep them from moving into the pipe. The felt, or plastic material, is inexpensive, and as long as the minimum permissible permeability in the envelope is maintained this practice is acceptable. However, R. W. Ribbens, Bureau of Reclamation, has developed a mathematical solution, based on Moody's original work, that shows the minimum permissible permeability must be increased when the felt or plastic cover is used. 6/ Figure 4 shows the curves developed for determining φ when the top half of the joint opening is covered with felt or plastic.

Assuming the same conditions as shown in the preceding problem with the pipe running full:

$$b = 0.208 \text{ foot}$$

$$m = 0.025$$

$$n = 1.6$$

$$\overline{H} = 0.374$$

$$Q = 6.16 \text{ cubic feet per lineal feet per day}$$

From the curves shown in Figure 4:

$$\varphi = 3.08$$

The inflow from base material, $Q = b \bar{H} K \varphi$ and the required permeability for the envelope equals:

$$K = \frac{Q}{bH\varphi} = \frac{Q}{0.208 \times 0.374 \times 3.08}$$

$$K = \frac{Q}{2.40} = 4.17\,Q \qquad (18)$$

Using a 4-inch-diameter pipe drain, 4 inches of envelope material, 1/8-inch joint opening, and a 2.5-foot length of pipe, the permeability of the envelope must be equal to or greater than:

$$K = 4.17 \times 6.16 \times 2.5 = 64 \text{ feet per day}$$

This is almost twice the 35 feet per day required when no felt or plastic covers the top half of the pipe.

Table 3 shows the required permeability and inflow relationship using different joint widths, pipe diameters, envelope thicknesses, and a felt or plastic cover over the top half of the pipe.

Table 3

REQUIRED PERMEABILITY AND INFLOW RELATIONSHIP FOR CONCRETE AND CLAY PIPE WHEN TOP HALF OF DRAIN IS COVERED

Joint width and envelope thickness	Concrete drainpipe K equals			Clay drainpipe K equals		
	4" diam	6" diam	8" diam	4" diam	6" diam	8" diam
1/16" joint 3" envelope	6.40Q	4.50Q	3.36Q	6.67Q	4.74Q	3.57Q
1/16" joint 4" envelope	5.18Q	3.64Q	2.80Q	5.38Q	3.79Q	2.95Q
1/16" joint 6" envelope	3.82Q	2.68Q	2.06Q	3.90Q	2.78Q	2.15Q
1/8" joint 4" envelope	4.17Q	3.01Q	2.30Q	4.34Q	3.13Q	2.42Q
1/8" joint 6" envelope	3.06Q	2.25Q	1.73Q	3.14Q	2.33Q	1.80Q

The first drain downslope from a leaking canal or lateral (Figure 5) will have a greater inflow to the joint opening than equally spaced drains. This inflow will be the summation of the canal or lateral seepage, the irrigation recharge to be drained between drain and edge of irrigated area above drain, and irrigation recharge that will enter the drain from the downslope area, which normally would be from one-half the area between the equally spaced drains.

The canal or lateral seepage can be determined from the equation

$$q_s = \frac{K_2 D_2 h_s}{x} \tag{19}$$

where (Figure 5): q_s = Seepage in cubic feet per lineal foot of canal or lateral per day when the selected root zone depth at edge of the irrigated area is controlled by the first downslope drain

K_2 = Weighted permeability in feet per day between root zone depth and barrier

D_2 = One-half the sum of the distance between barrier and water surface in canal and between barrier and selected root zone depth at edge of the irrigation area in feet

h_s = Difference in elevation between selected root zone depth at edge of irrigated field and water surface in canal in feet

X = Distance from centerline of canal to edge of irrigated area in feet.

The irrigation recharge to be drained between drain and edge of irrigated area above drain can be determined by the equation:

$$q_i = q_d(R - X) \tag{20}$$

where

q_i = Irrigation recharge in cubic feet per lineal foot of canal or lateral

q_d = Deep percolation per irrigation in cubic feet per square foot divided by the minimum days between irrigations

R = Distance in feet from canal centerline to first required drain

$$\frac{K_2(H^2 - h^2)}{2\, q_s} + X$$

where: H = Distance in feet between barrier and bottom of root zone at edge of irrigated area

h = Distance in feet between drain and barrier

q_s = Computed from equation 19

X = Distance from centerline of canal to edge of irrigated area

The irrigation recharge that will enter the drain from one-half the area between the equally spaced drains can be estimated from

$$Q = \frac{\pi\, K y_o\, D'}{L} \qquad (21)$$

where Q, K, y_o, D', and L have the same designation as shown for Equation 16.

After determining the minimum permissible permeability, samples from available envelope material sources must be tested to see which ones most nearly meet the required permeability and gradation requirements.

Equipment required for determining the envelope permeability includes:

a. Round gallon container with bottom cut out and a brass screen (18 to 20 openings per inch) soldered on the bottom

b. Constant headwater supply device

c. Container graduated in cubic inches

d. Measuring tape graduated in hundredths of a foot

e. Watch or clock

f. Two permeability test tubes 1 inch in diameter and a constant headwater supply device

The following is a suggested envelope permeability testing procedure:

a. Divide the envelope material into two samples.

b. Using one-half the sample, fill the gallon container with envelope material to within 3 inches of the top edge. Drop container on hard rubber pad 10 times from about 1 inch above pad. Refill to 3 inches from the top.

c. Slowly immerse gallon container into a larger container of water until free water stands on top of the envelope sample.

d. By the use of a constant headwater supply device, usually nothing more than a hose, control valve, and velocity dissipator connected to an adequate water supply, hold the water at the top of the container for a 5-minute interval and then still keeping a constant head, catch, measure, and record the effluent for a 1-minute interval. Then hold the constant head for another 5 minutes and again catch, measure, and record the effluent for 1 minute. If the volume of water passing through the material is about the same at the end of 10 minutes as it was at the end of 5 minutes, the test can be terminated, and the permeability computed.

e. To check the effect of the fines on the long time use of the material, sieve the remaining portion of the sample, and save all material passing the Number 30 U.S. Standard sieve.

f. Following accepted laboratory permeability determination procedures, run a 48-hour permeability test on two test tube samples of the material passing the Number 30 sieve. Collect, measure, and record the volume of effluent for the 1-, 24-, and 48-hour time intervals and compute the permeability for each. If the permeability remains about the same during the 48-hour test for both samples, the envelope probably does not contain deleterious substances that could seal the envelope material with time.

The permeability of the envelope material can be calculated using Darcy's flow equation in the form

$$K = \frac{QL}{TAh} \tag{22}$$

where:

K = permeability in inches per hour

Q = Volume of water passing through the material in cubic inches per hour

A = Cross-sectional area of test container in square inches

T = Time in hours for which sample was collected

L = Length of material column in inches

h = Length of material column plus height of water above column in inches

Figures 6 amd 7 show the gradation and permeability of envelope material that has been used for drain construction in various base materials compared with the well-graded limitations and permeabilities computed or suggested in this paper. Sand designations are as follows:

Coarse sand - 25 percent or more very coarse and coarse sand, and less than 50 percent of any other one grade of sand

Medium sand - 25 percent or more very coarse, coarse and medium sand, and less than 50 percent of fine or very fine sand

Fine sand - 50 percent or more fine sand (or) less than 25 percent very coarse, coarse and medium sand and less than 50 percent of very fine sand

Very fine sand - 50 percent or more of very fine sand

Figure 6 shows a fine sand base material with a permeability of 38 feet per day. The envelope used, when placed in the trench, had a permeability of about 150 feet per day. The required minimum permeability computed for the envelope was 105 feet per day. The envelope material falls a little outside of the suggested upper limit gradation curve, and soon after construction some base material moved into the envelope material and on into the drain causing considerable expensive drain cleaning. The permeability and gradation were not determined after the base material and envelope material became stabilized, but the drain now appears to function satisfactorily. The original envelope could be considered a poor design for a fine sand base material. The envelope would have been more effective if it had fallen between the gradation limits and maybe a little toward the lower limits.

The base material in Figure 7 was a coarse silt loam with a permeability of 4 feet per day. As there were no gravel pits in the area, a graded coarse sand was used which had a permeability of about 50 feet per day. Although the gradation of the envelope falls a little below the suggested gradation limits, the permeability was still greater than the 28 feet per day required when an asphalt-saturated felt sheet was placed over the upper half of the joint openings. This was considered a satisfactory envelope for the coarse silt loam base material with the upper half of the pipe covered with felt.

Summary

Pipe drains designed and constructed for the drainage of irrigated lands must be surrounded by an imported material (envelope) designed with a gradation and permeability compatible to those of the material being drained.

Envelopes for agricultural drains are not designed as protective filters, but principally to provide adequate permeability for the ground water to converge into joint openings without a significant loss of head. To be stable with the base material, the envelope should also be well graded according to an established relationship between the 60 percent passing of the material being drained and the 60 percent passing of the envelope material.

Mathematical methods were developed to calculate the required envelope permeability for any base material. The mathematical solutions take into account the affect of joint width, length and diameter of pipe, the maximum possible rate of inflow to the pipe considering soil characteristics and drain spacing, the thickness of the envelope material, and use of a plastic or asphalt-saturated felt cover over the top half of the pipe.

Every envelope material should be tested for permeability before it is used. Deleterious substances can reduce the permeability in the envelope with time until it no longer has an adequate permeability to provide for the convergence at the joint opening.

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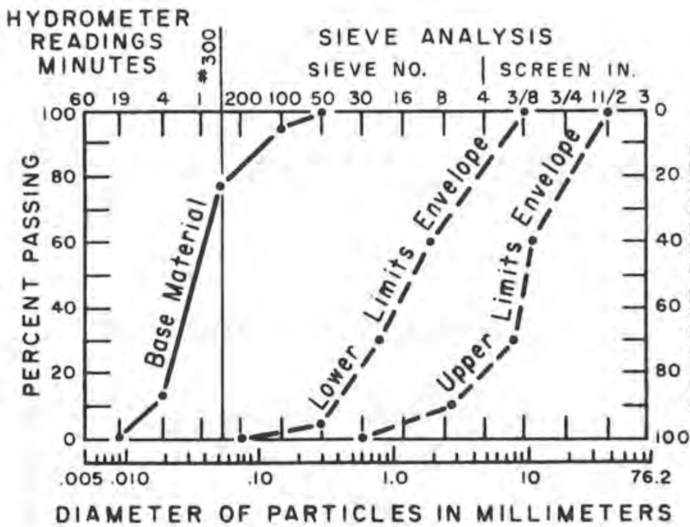
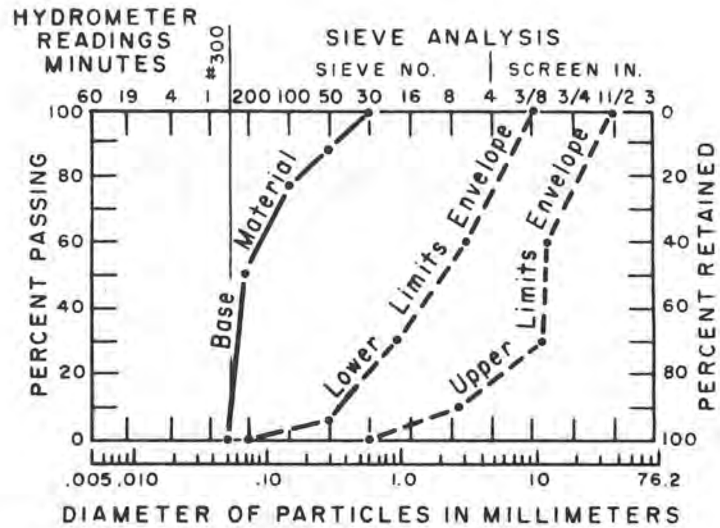
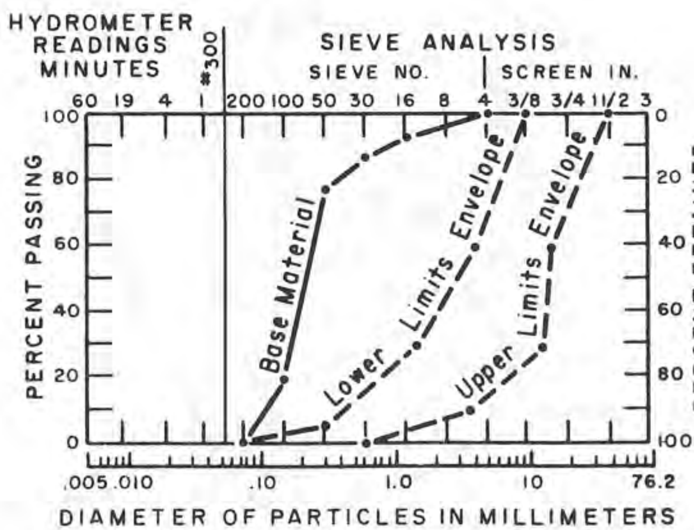


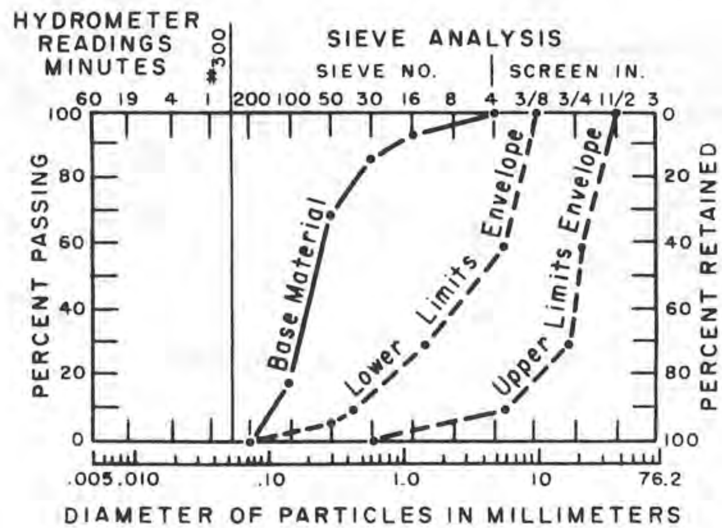
(A) COARSE SILT LOAM BASE MATERIAL
(D_b 60 = 0.04 MM)



(B) VERY FINE SAND BASE MATERIAL
(D_b 60 = 0.098 MM)



(C) MEDIUM SAND BASE MATERIAL
(D_b 60 = 0.24 MM)



(D) COARSE SAND BASE MATERIAL
(D_b 60 = 0.44 MM)

FIGURE 1. GRADATION LIMITATIONS FOR WELL GRADED ENVELOPE

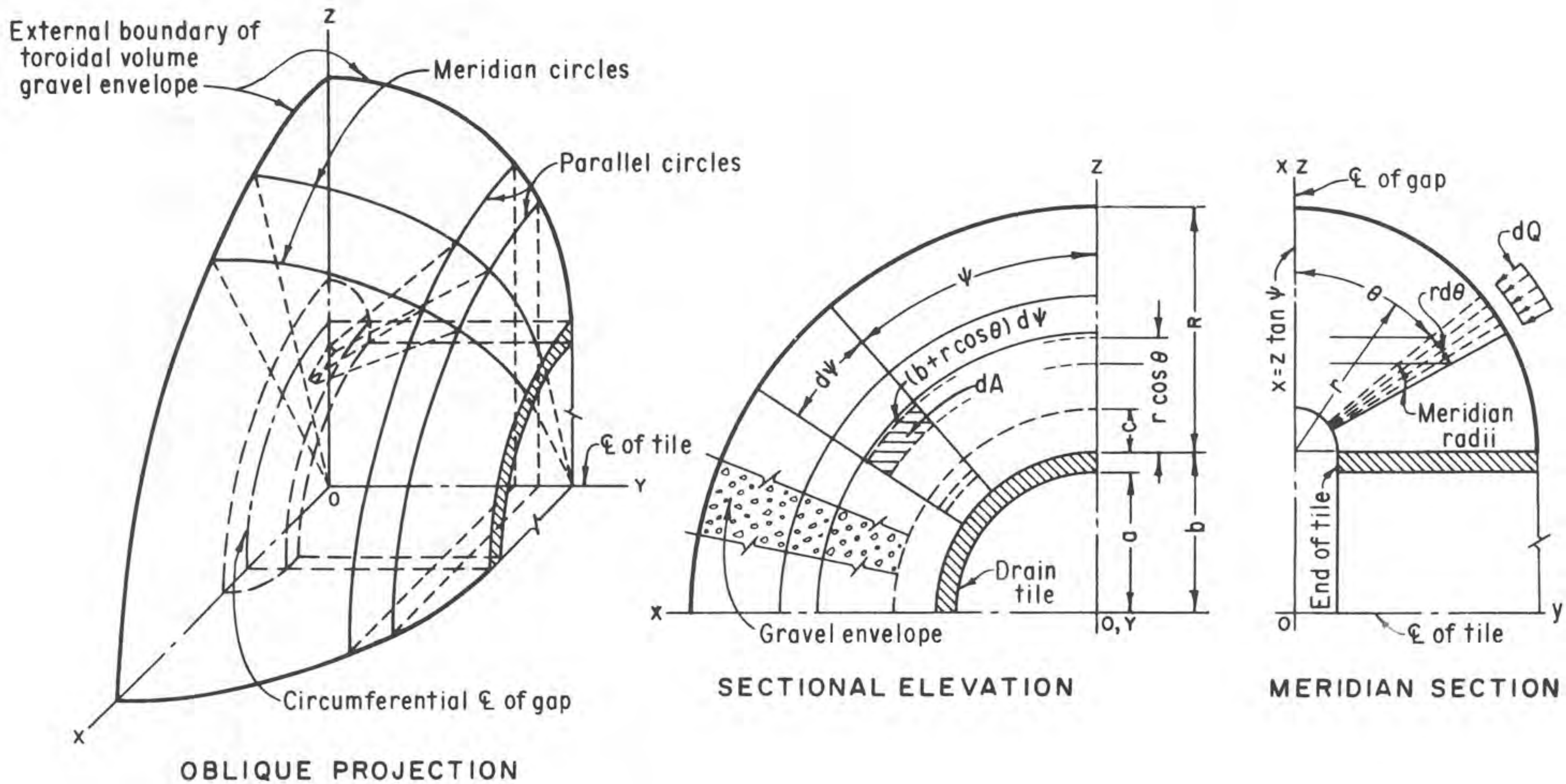


FIGURE 2. SKETCHES DEFINING ELEMENTS OF THE REGION OF CONVERGENCE

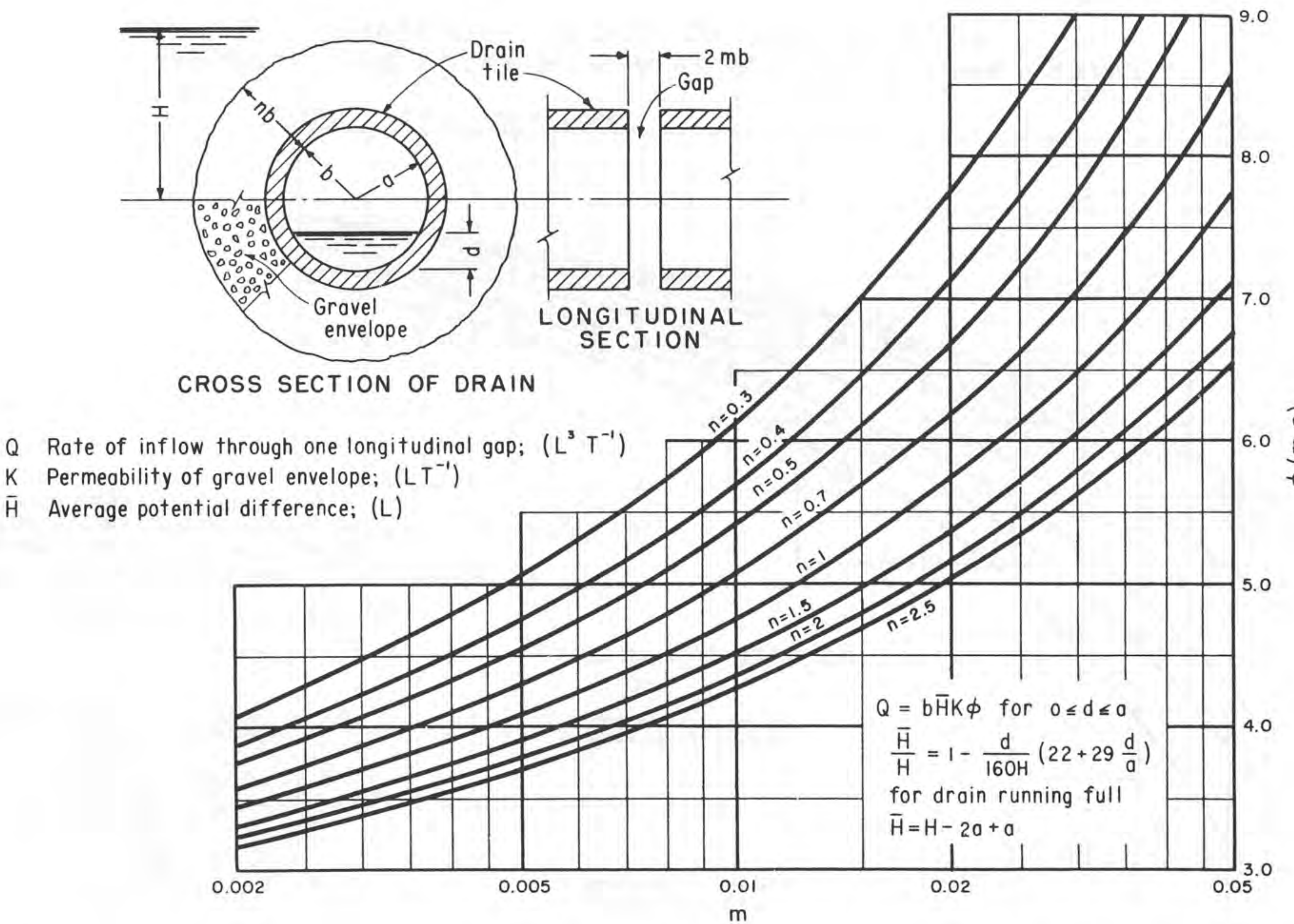


FIGURE 3. FLOW ENTERING SPACED DRAIN TILE FROM GRAVEL ENVELOPE

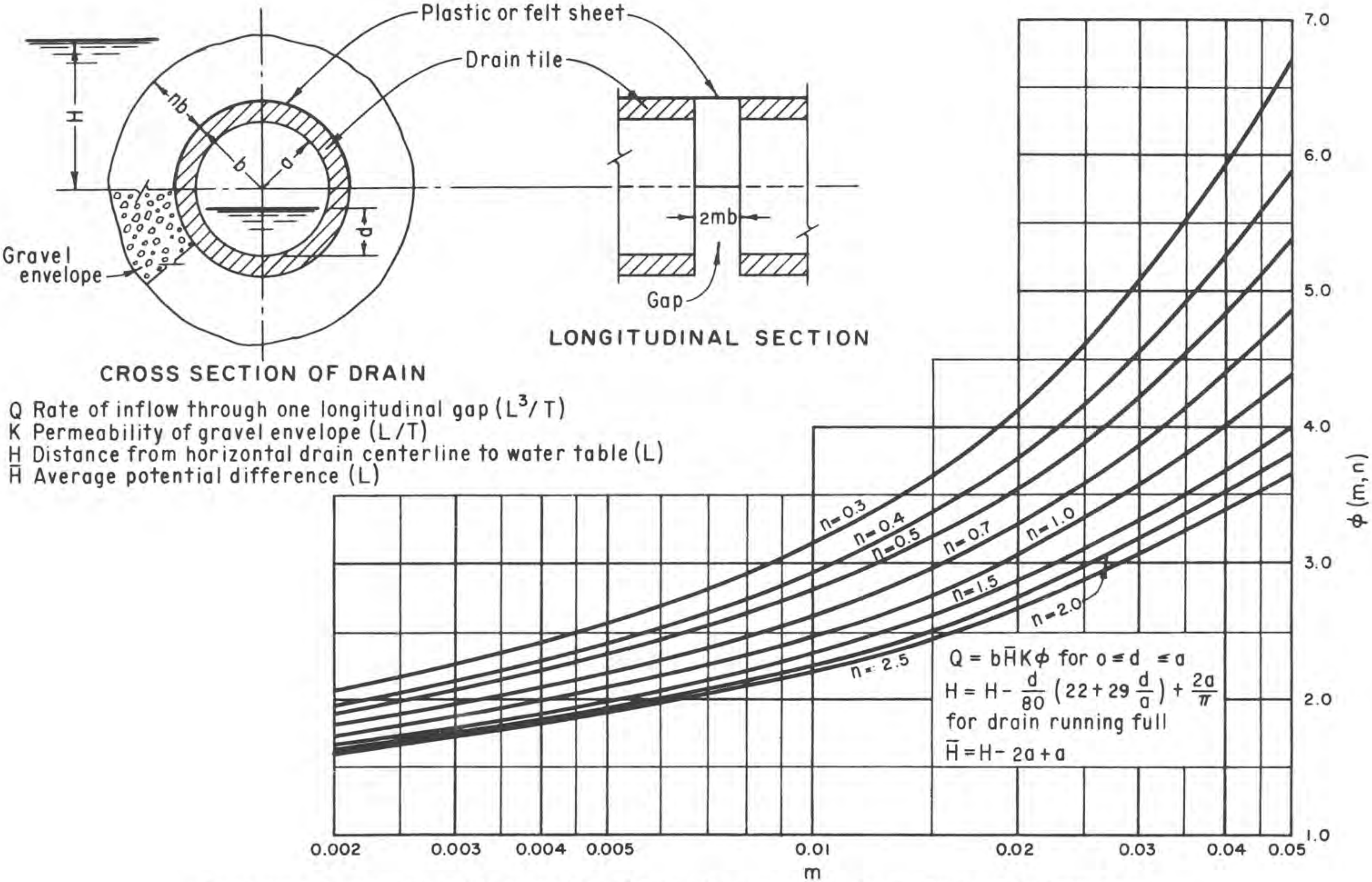


FIGURE 4. FLOW ENTERING SPACED DRAIN TILE FROM A GRAVEL ENVELOPE - TOP HALF OF DRAIN COVERED

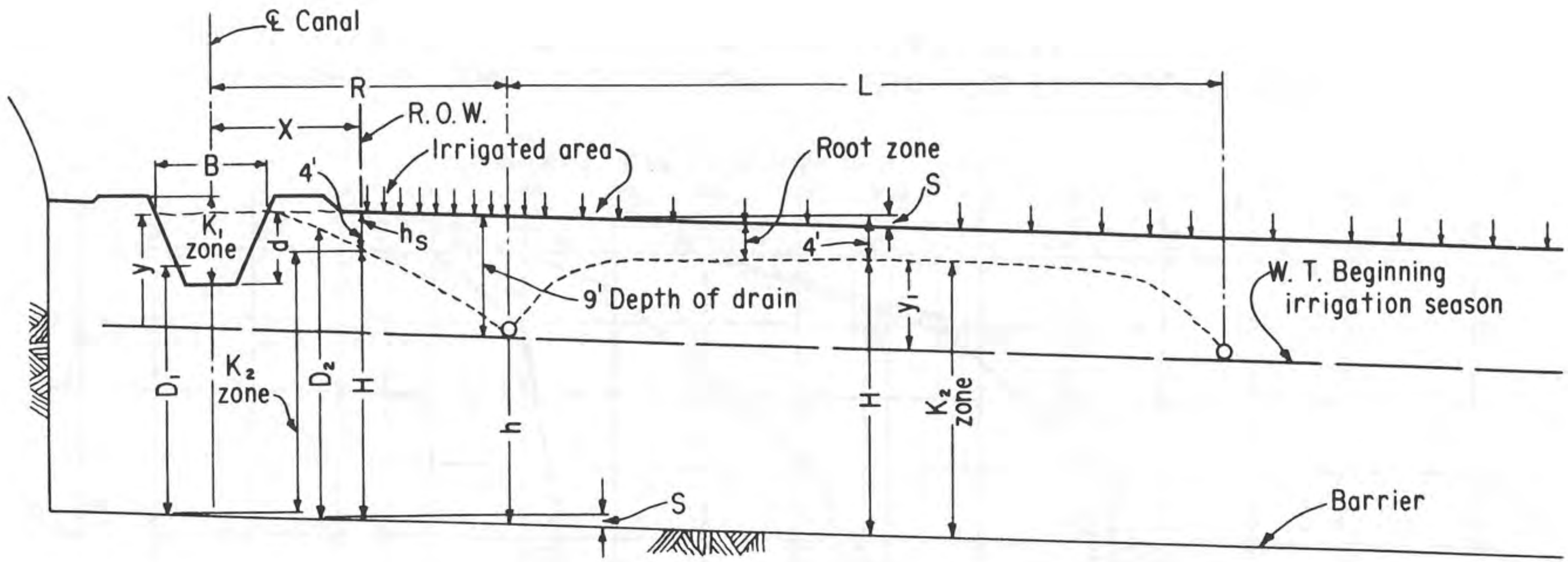


FIGURE 5. MEASUREMENTS USED FOR ESTIMATING DRAINAGE REQUIREMENTS RESULTING FROM CANAL OR LATERAL SEEPAGE

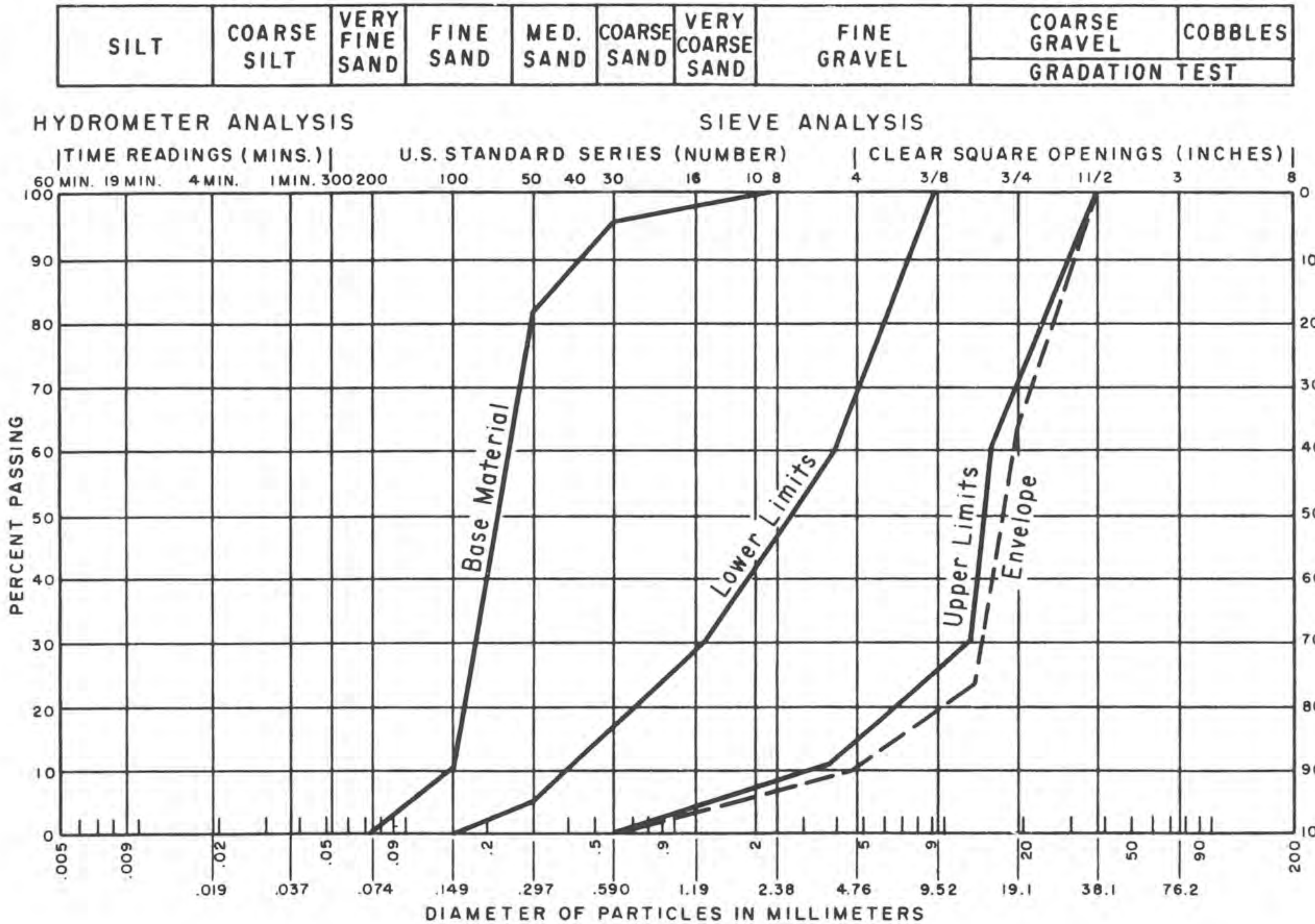


FIGURE 6. UNSATISFACTORY DESIGNED ENVELOPE FOR A FINE SAND BASE MATERIAL

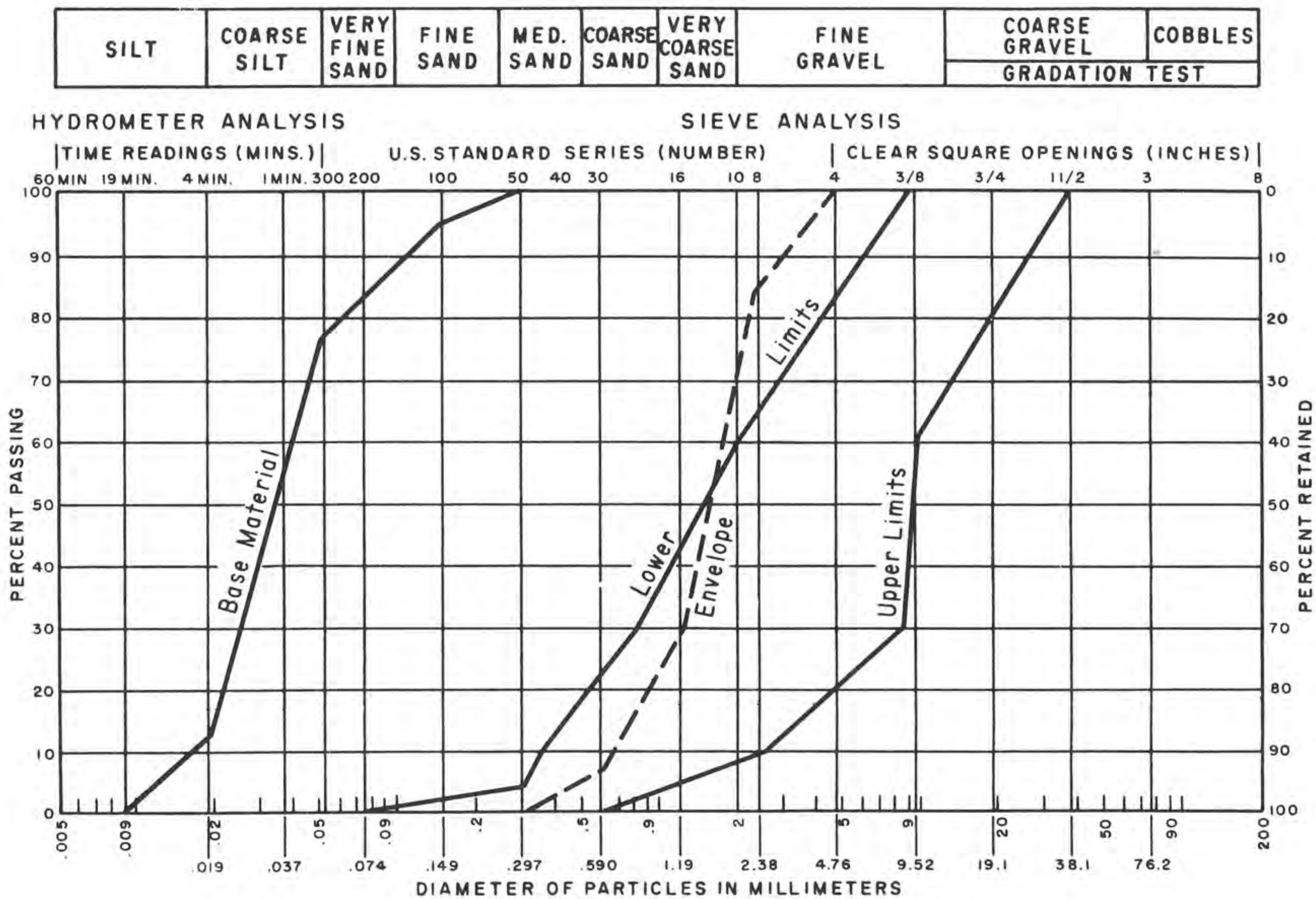


FIGURE 7. SATISFACTORY DESIGNED ENVELOPE FOR A COARSE SILT LOAM BASE MATERIAL