LABORATORY TESTS OF CORRUGATED PLASTIC DRAINAGE TUBING WITH SMALL HOLES IN DIFFERENT SOILS

by

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To my beloved parents to whom
I shall be forever indebted

ABSTRACT

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LABORATORY TESTS OF CORRUGATED PLASTIC DRAINAGE TUBING WITH SMALL HOLES IN DIFFERENT SOILS

Investigation of the drainage and sedimentation performance of corrugated polyethylene tubings with pinholes and small slots was made in comparison with a normal slotted tube with a knitted polyester envelope in five types of soil ranging from medium sand to silt loam.

The results indicated that all drain tubes provided good drainage in the medium and fine sandy soils. The tubes with small slots and pinholes drained significantly slower than the tube with the fabric envelope in the fine and very fine sandy loam soils. All tubes, however, drained equally in the silt loam soil. Sediment entry was not a problem in the medium sand, fine sand and silt loam soils. The siltation tendency could be considered to be excessive for the tubes with small slots and pinholes placed in the fine and very fine sandy loam soils, being somewhat higher for the latter soil.

In addition, it was found that sediment weight varies exponentially with the product of the drain opening hydraulic radius and a power function of the soil D_{60} size. Furthermore, drainage rate was found to vary, in most cases, as the logarithm of the drain opening area per unit length. Studies of the hydraulic head distribution around the drain indicate that the assumption of radial flow with a uniform soil hydraulic conductivity around the drain at any radius, does not always hold true. Computed hydraulic gradients at the opening were, in general, very high and failed to explain the low sedimentation in the drains for few of the cases.

RESUME

M.Sc. Karim Chirara Génie Rural

ESSAIS AU LABORATOIRE DE TUYAUX ANNELES EN MATIERE PLASTIQUE AVEC DE PETITES PERFORATIONS DANS DIFFERENTS TYPES DE SOLS

Une évaluation des performances en drainage et en ensablement de tuyaux annelés en polyéthylène, munis de petits pertuis et de trous d'épingles, a été faite en comparaison avec celles d'un tuyau à ouvertures normales et recouvert d'une enveloppe en polyester tissé. Les essais ont été effectués sur cinq types de sol s'étalant du sable moyen à un loam limoneux.

Les résultats obtenus démontrent que tous les tuyaux concernés sont capables de drainer adéquatement les sols sableux moyen et fin. Les tuyaux à petits pertuis et à trous d'épingles ont une capacité de drainage moindre que le tuyau muni de l'enveloppe de tissu, lorsqu' installés dans un loam sableux fin ou très fin. Tous les tuyaux ont, cependant, drainé d'une manière égale le loam limoneux. L'ensablement des drains ne représente guère de problème dans le sol sableux moyen, le sable fin et le loam limoneux. Par contre, cet ensablement peut être caractérisé comme étant excessif pour les tuyaux à petites ouvertures installés dans les loam sableux fin et très fin, étant cependant, moindre pour le loam sableux fin.

De plus, il a été montré que le poids des sédiments varie exponentiellement avec le produit du rayon hydraulique des perforations et d'une puissance du D_{60} du sol. D'autre part, le taux de drainage s'est avéré croître avec le logarithme de la surface totale des ouvertures par unité de longueur du drain. Des études de la répartition de la charge hydraulique autour du drain ont montré que l'hypothèse d'un

écoulement radial avec une conductivité hydraulique du sol, uniforme autour du drain, n'est pas toujours justifiable. Enfin, les gradients hydrauliques calculés, étaient en général, très élevés et n'ont pu toujours expliqué le peu d'ensablement des drains dans certains cas.

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NOMENCLATURE

Symbol	Description	Units
A	Drain opening area per unit length	cm^2/m
a,b	Regression parameters	variable
c	Longitudinal gap (slot) spacing	mm
C_c	Coefficient of curvature $=(D_{30})^2/(D_{60})(D_{10})$	-
C_s	Coefficient = % clay/(% clay + % silt)	-
C_u	Coefficient of uniformity $=(D_{60})/(D_{10})$	-
d	Diameter Thickness of confined layer	mm, m m
D	Dry bulk density	kg/m^3
D_{15}, D_{85}	Diameter for which 15% (85%) of the soil particles by weight, are smaller.	mm or um
e	void ratio	-
h	Hydraulic head Depth from soil surface to centre of drain Height of water in well above top of confined layer	mm, m m m
H	Hydraulic head Height of piezometric surface above top of confined layer	mm, m m
HFG	Hydraulic failure gradient	-
HR	Hydraulic radius	mm
I	Hydraulic gradient	-
I_d	Density index	-
K	Hydraulic conductivity	m/d
l, L	Length of drain	m
N	No. of longitudinal rows of slots No. of observations	- -
O_{95}	Size for which 95% of the openings are smaller	mm

Symbol	Description	Units
PI	Plasticity index	-
q	Discharge per unit length	mL/s/m, m^3/d/m
Q	Total dicharge	mL/s, m^3/d
r, R	Radius	mm, cm, m
RPZ	Radial piezometric head ratio	-
s	slope	m
SEDW	Sediment weight	g
t	Depth of water ponded above soil surface Time in days	m d
T_e	Thickness of envelope	m
V	Velovity of flow	m/s
W	Slot width	mm
WIDTH	Slot width	mm
Y	Equivalent years of field drainage	yrs
Y_s	No. of years to half fill a drain with sediments	yrs
α	Relative opening area = A/A_0	-
α_e	Entrance resistance	-
$\alpha_0, \alpha_1, \beta_0, \beta_1, \gamma_1, \gamma_2, \epsilon_0, \epsilon_1, \nu_1, \nu_2$	Regression parameters	variable
β_s	Gap width	mm
β_v	Corrugation valley width	mm
γ	Parameter, = λ_p / λ_c	-
δ	Relative flow = q/q_0	-
δr	Height of corrugation	mm
Δ	Elemental	-

Symbol	Description	Units
ϵ	Measure of eccentricity of well in a confined layer	-
λ_c	Circumferential slot spacing	mm
λ_p	Slot length	mm
η	Fabric porosity	-
ρ	Fabric density	kg/m^3
μ	Unit weight	kg/m^2

Subscripts

Symbol	Description
a, b,d	Piezometers a, b and d
c	curvature
crit	critical
d	density
e	entrance, effective, envelope
i	iteration
max	maximum
min	minimum
o	drain, old
r	radial
s	cylindrical source
t	total
u	uniformity
v	valley
10, 30, 60, etc.	10%, 30%, 60%, etc.

Abbreviations

Symbol	Description
AB	Above drain
AOV	Analysis of variance
ASAE	American Society of Agricultural Engineers
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing Material
BAIN	Bainsville soil
BARB	Ste. Barbe soil
BNQ	Bureau de Normalisation du Québec
CGSB	Canadian General Standards Board
CPT	Corrugated plastic tubing
CPTA	Corrugated Plastic Tubing Association
CPVQ	Conseil des Productions Végétales du Québec
C.V.	Coefficient of variability, %
FS	Fine sand
FSL	Fine sandy loam
HFG	Hydraulic failure gradient
I.D.	Inside diameter
IN	Inside drain
MS	Medium sand
NSERC	Natural Sciences and Engineering Research Council of Canada
O.D.	Outside diameter
ON	On the drain
ORMS	Ormstown soil
PE	Polyethylene

Symbol	Description
PI	Plasticity index
PVC	Polyvinyl chloride
RPZ	Radial piezometric head ratio
SCS	Soil Conservation Service
S.E.	Standard error
SiL	Silt loam
SOPH	Ste. Sophie soil
SOUL	Soulanges soil
USBR	United States Bureau of Reclamation
USCE	United States Corps of Engineers
USDA	United States Department of Agriculture
VFSL	Very fine sandy loam

I. INTRODUCTION

1.1 Background

To improve soil conditions of poorly drained agricultural lands, artificial means such as surface drainage through ditches and subsurface drainage with clay tiles were first introduced many centuries ago. Weaver (1964), in his historical account of tile drainage in North America, states that ditches were already made by the ancient Egyptians and Babylonians. Subsurface drainage was started in the first century of the Christian era when farmers half filled the ditches with materials such as stone slabs, gravel and stone, or a rope of sprays tied together and covered the top half with earth that had been dug out. Closer to us, clay tiles for subsurface drainage purposes were installed as early as 1400 A.D. in Sussex (United Kingdom).

The shape of these cylindrical tiles took several forms such as a square, rectangle, triangle, "horse shoe" shaped or circular among others. For the last hundred years however, in North America, they were made circular for agricultural purposes and 10 to 12 in. long. Water was removed from the soil through the gap between two adjacent tiles. The width of the opening controlled the drainage rate while reducing as much as possible the accumulation of sediment inside the drains.

The tiles were successfull as reflected by the length of time they were used. However, with the ever growing population and increasing mechanisation, the handling of millions of these tiles became more difficult and costly. Thus, in 1960, drainage manufacturers in Europe came up with a new farm product in the form of corrugated polyvinyl chloride (PVC) drainage tubing (Eggelsmann, 1982). And in the late sixties, the production of corrugated polyethylene (PE) drainage tubing was started as reported by Schwieterman (1982).

PE tubings were first installed commercially in the United States in 1967. Due to their numerous advantages, PVC and PE corrugated drainage pipes became very rapidly the leading material in subsurface drainage installations in both Europe and North America, repectively.

Corrugated plastic tubing (CPT) is in general, produced in large coils up to 1200 m long by 100 mm inside diameter and perforated in the valleys and/or ridges of the corrugations. Certain criteria, developed over the years, have to be met when manufacturing CPTs. These criteria are based on the strength (deflection and elongation) and the total opening area of the perforations per unit length of drain.

No standard has been established yet for the number, location and size of the perforations. However, it is common practice to use what is known as a "standard" or "normal" tube in North America: 100 mm inside diameter (most commonly used for laterals) with 4 to 6 slots every valley or every second valley of corrugation. These slots would be 20 to 30 mm long by 1.5 to 2 mm wide.

In general, the standard drain performs well in clay loam soils. An envelope may be necessary around the pipe to prevent any sedimentation inside it, when installed in fine sandy or silty soils. This envelope could be either organic (straw fibers, coconut fibres, fibrous peat, etc...), inorganic (uniform layer of coarse sand or graded layers ranging from gravel to coarse sand) or synthetic. Over the years, more of the synthetic fibers were used as envelopes and exténsive researches have been carried out throughout the world to try to develop the ideal fabric.

Some of the problems associated with the use of synthetic fabrics are the physical damage that can be induced (cuts, stretching) and the increase in cost (up to 20% when compared to the "naked" drain). Hence, in a continuing effort to produce beneficial new drainage products, manufacturers have devised ways to produce corrugated plastic tubing with pinholes and small slots much narrower than "normal slots". It has been hoped that drain tubing with pinholes or very small slots would not require a fabric envelope as has been required for normal slotted tubing in the "problem" soils.

To test some of these new products and to make observations on the mechanics of the flow and soil movement near and into the drain, the Corrugated Plastic Tubing Association of North America (CPTA) and the Canadian Natural Sciences and Engineering Research Council (NSERC) sponsored the research reported herein. The laboratory work presented in this thesis evaluates the performance of corrugated plastic tubing with pinholes and small slots as compared to a normal slotted tubing with a knitted polyester stocking envelope. This research was started in May 1985.

1.2 Objectives

The primary objectives of this research were:

1. To measure the rate at which water drains from soil through tubing
   a) with normal slots and a knitted polyester stocking 152 g/m^2 (4.4 oz/yd^2) unit weight
   b) with pinholes and no fabric envelope, and
   c) with narrow slots and no fabric envelope.

2. To repeat the measurements indicated in Objective 1 for a range of soil particle size distributions. The five soils which were to be given priority for these tests were taken from fields where normal slotted tubing without envelopes had become filled with soil. The soils were selected to cover a range from medium sand to silt loam.

3. To measure the amount of soil passing out of the drain tubes with the drainage water.

4. To measure the amount of soil settled in the tubing corrugation valleys after a few weeks of water drainage.

5. To study the pressure distribution of the water in the soil around the tubing.

1.3 Scope of the study

Care should be exercised in applying the results of this study to soils beyond the range reported herein, namely, a Ste. Barbe medium sand, a Ste. Sophie fine sand, a Soulanges fine sandy loam, a Bainsville very fine sandy loam and an Ormstown silt loam. The drainage rates observed and sediments collected do not necessarily reflect field values. Nevertheless, tubings that performed satisfactorily in the laboratory can be tested on one or two of the soils listed above. The findings can then be used in association with the observations made in the laboratory to predict the performance of the different tubings in the other types of soil.

The effect of bacteria development and ochre formation in and around the drain were not considered as part of this research and, consequently, were not investigated. Actually, the soils used for this research have not been reported to cause ochre problems in existing subsurface drains. Also, the effect of soil structure on sediment deposition will only be assessed qualitatively.

II. REVIEW OF LITERATURE

2.1 Terminology

Dieleman and Trafford (1976), define an **envelope** as a "generic term to mean any material other than the natural earth, except perhaps the topsoil, placed on or around drains. The material may or may not completely surround the drain". They prefer the use of a more specific term such as "filter" or "surround" which implies the purpose for which the envelope is used. Thus, they define a **filter** as, quote: "an envelope placed around the drain with the express purpose of preventing the fine particles of soil from entering the drain". They further define a **surround** as: "an envelope placed on or perhaps around the drain to improve water entrance characteristics".

The term filter implies, then, the removal of all solid particles in suspension in water as emphasized by the Concise Oxford Dictionary (1985). It is not necessarily desirable to prevent all the fine particles from entering the drain. Indeed, if the envelope is too effective as a filter, clay particles may collect on the outside of the envelope and cause it to become impermeable. A filter may function well around a drain without getting clogged if the drain enrobed with a filter is installed with soil placed against the filter such that water passes through the soil without entraining any particles. Then the water can pass on through the filter into the drain tube without bringing any silt or clay particles onto the filter and block it. One might ask what the purpose of a filter is in soils engineering. To avoid any confusion on the terminology used, an engineering concept has been developed and accepted by most authors.

As used with drain tubes, a "filter" or "envelope" has three functions: 1) to stabilize the soil surrounding the drain by affording a supportive base, thus reducing internal erosion; 2) to increase the water entry area as to approach the "ideal drain" and, 3) to enhance drainage by allowing some of the fine particles to pass through the drain perforations and be washed away by the water flow inside the drain (Stuyt ,1982; Reeve, 1982; and Miller and Willardson, 1983). The "ideal drain" is represented by a drain with completely permeable walls.

When thus defined, the terms filter and envelope can be used interchangeably. The latter term will be mostly used in this thesis as it is becoming more established in recent papers as reported by Bonnell (1984).

2.2 Envelope Materials

Extensive research has been carried out over the decades on developing the ideal envelope that would have the three functions listed above. Such envelopes are, in general, required in fine sandy or silty soils. Different types of envelopes have been used on farms since the advent of subsurface drainage systems, mainly, organic, inorganic (mineral) or man-made (synthetic).

2.2.1 Organic envelopes

Long before technology permitted the use of synthetic fibres, farmers were using organic material to enhance drainage of their subsurface pipes while reducing the silting process. Willardson (1974) reports of many studies using straw, coconut fibres, sawdust, corncobs and peat litter as envelopes. The thickness of these envelopes varied from one experiment to the other but was in general in the vicinity of 10 to 15 cm (4 to 6 in.). Except for the corncobs, most of the organic materials listed above performed adequately. Timewise, straw and wood chips proved to be most effective by showing only moderate decay after 11 years and 9 years in the soil, respectively, as reported by Brownscombe (1962).

Even though organic envelopes work in the short run, few researchers would recommend using them on a long-term basis. Also, organic matter may affect chemical and biological reactions in the soil, causing clogging problems. This is especially true for soils rich in iron oxide and ochre (Asselin, 1976). Furthermore, being compressible, organic materials do not provide sufficient lateral support for corrugated polyethylene tubing. This may deflect the pipe too much, resulting in drain failure. Synthetic fabrics can be conveniently installed on corrugated plastic drain tubes at the factory and save time and labour in field installations. For these reasons among others, organic materials are seldom used nowadays, particularly in North America.

2.2.2 Inorganic envelopes

In poorly drained soils, topsoils tend to develop a stable and permeable structure. This characteristic soon made it common practice in subsurface drainage installations, to blind the drain with a layer of topsoil before backfilling. This method provides an inexpensive inorganic permeable envelope material, and was discussed by many authors (Davis et al., 1971; Willardson et al., 1973; Hwang et al., 1974; Feichtinger and Leder, 1979). However, one must keep in mind that under wet conditions, blinding and backfilling should be done carefully as soil structure can be damaged, resulting in primary silting of the drain. Primary silting is defined as the accumulation of sediment inside the drain during installation while secondary silting occurs over a period of months after installation.

The most common and widely used inorganic materials are naturally graded sands and fine gravels, which are structureless and as permanent as the soil itself. Gravel envelopes are most popular in semi-arid and arid irrigated areas where this material is abundant. These envelopes have proven to be very successful and can be designed to overcome most if not all drainage situations in problem soils (Lagacé, 1976).

Based on numerous studies reported in the literature, several criteria were developed for the design of granular envelopes by organisations such as the Conseil des Productions Végétales du Québec (CPVQ, 1984), the U.S. Bureau of Reclamation (1960), the A.S.A.E. (1982), the U.S. Corps of Engineers (Willardson, 1974). Other researchers came up with criteria based on their own research (Nelson, 1960; Broadhead, 1981; Thériault et. al., 1982). These criteria will be looked upon in detail in a subsequent section.

2.2.3 Synthetic envelopes

The unavailability of the sand and gravel in some areas combined with the high production and installation costs have led to the development of synthetic fabrics for use as a substitute to the inorganic material.

In the United States and Canada, woven and non-woven thin fabrics, 0.2 to 2 mm thick, are widely marketted. In the beginning, fiberglass had received the most attention. It was however, gradually supplanted by nylon, polyester and polypropylene bonded fabrics, as the latter ones proved more efficient in general. In Western Europe and particularly in the Netherlands, preference is given to the more voluminous types of synthetic fabrics with thicknesses varying from 3 to 10 mm (Knops et al., 1979). This difference in preference is related to the fact that approximately 85% of the lateral drains installed in Europe are between 50 and 65 mm in outside diameter as compared to 115 mm outside diameter in North America.

2.2.3.1 Fiberglass envelopes

Brouillette and Delisle (1982) mention the use of fiberglass mostly between 1957 and 1967. Overholt (1959) reported on laboratory experiments using fiberglass envelopes in a sandy soil that had given sedimentation problems in the field. Compared to unprotected pipes, drains with a complete wrap of a thin sheet produced highest flow rates and silt-free water. Drains covered on the top three quarters ranked second.

Nelson (1960) showed that randomly reinforced fiberglass sheets performed better than longitudinal reinforcements. He recommended good backfilling practices to avoid damaging the envelope, by placing a 5 cm layer of soil before backfilling. Hore and Tiwari (1962) using a Granby sandy loam, tested the following treatments: blinding with topsoil, and combinations of two fiberglass sheets, mainly Tile Guard above and below the drain, Duramat above the drain, and Tile Guard on top - Duramat under the drain. Their results showed sand from the backfill depositing in the drain while the Tile guard on top and below the drain gave highest water flows.

Similarly, Rapp and Riaz (1975) tested a gravel filter and combinations of glass fibre materials on CPT. They found that, while the gravel filter was most permeable, tubings completely wrapped with a fabric provided best protection against siltation.

Two major problems were associated with the use of fiberglass envelopes. The first, as reported by Willardson (1979), was that the types of fibres first manufactured dissolved rapidly in the soil due to chemical weathering. This problem was soon solved by using borosilicate glass fibres. The second disadvantage was the small size of the fabric openings which limited the area available for water flow. This sometimes caused the envelope to clog with soil migration into the envelope openings. Irwin and Hore (1979) measured the pore size distribution of five synthetic fabrics and found a porosity of only 17% for the fiberglass-made Tile Guard PG-90.

2.2.3.2 Bonded fabric envelopes

As a result, bonded fabric materials made of nylon, polyester or polypropylene were introduced. These fabrics can be made with controlled opening sizes which can in turn be adjusted so that the fabric will function as an envelope rather than a "filter".

Prior to marketing those bonded materials, fiberglass sheets and mats were wrapped around the drain in situ. Drainage plows and trenching machines were equipped with a device that would wrap the filter to cover the top three quarters of the drain while installing it underground. Even though flow characteristics were enhanced, this method permitted sediments to enter from below the drain. Other devices installed two strips of fabric on top and below the drain. These methods were soon abondoned by contractors as it was very difficult to check the wrapping of the filter which took place inside the machine. (Jutras, 1976).

Consequently, in the early seventies, bonded synthetic fabrics were wrapped around the drain in the manufacturing process. This method quickly became common practice. Primary silting was reduced and the fabric envelopes were more reliably installed.

Mckyes and Broughton (1974) tested four different filtering materials in a Bainsville soil with 80% of the particles between 0.07 and 0.12 mm. They found that, compared with unfiltered tubes, the polyester stocking and fiberglass sheeting offered a good protection against soil entry while keeping a high water flow for up to two months.

The other two fabrics, jute and hemp twine wrapped in the grooves of the corrugations clogged up and significantly reduced water entry after only 10 days.

Another laboratory study by Broughton et al. (1977), investigated the performance of several envelopes six of which were thin, one of coconut fibre and the last of concrete sand, in the same Bainsville sand. The thin envelopes - mainly a Remay spun polyester, a Cerex Nylon, a Superfliter 80% polyester and 20% rayon, a knitted nylon and two Typar spun polypropylene - as well as the concrete sand, did a god job in preventing sedimentation. On the other hand, concrete sand gave best results for water flow rates. The results showed decreases in drainage rates with time which were attributed to the development a filter cake just outside the envelopes. The release of air from the laboratory water giving air bubbles blocking some of the pores, and microbial growth were considered negligible. Interestingly, the drainage rates recovered temporarily after periods of no flow, a condition frequently observed in the field. Those increases in the flow rates after a dry spell would permit long-term use of synthetic envelopes as the filter cake forming around the drain would develop cracks during dry spells. However, it could be feared that the destruction of the filter cake might induce secondary silting as the cake reestablishes itself.

The filters tested by Benz et al. (1977) were the following: a Typar, Mirafi, Cerex, knitted nylon and polyester stockings, SCS and USBR-designed gravel envelopes. Short-term flow tests showed that natural and synthetic envelopes were effective, but gravel usually had a slightly higher flow rate and occasionaly would not retain the aquifer. They also observed a reduction in flow rates with time for all envelopes in long-term tests. Ohrun and Luthin (1979) tested a Drainguard spun-bonded nylon fabric using a sand tank. Their experiment was inconclusive and they recommended field tests to determine the suitability of the material.

Broughton and Gibson (1977) and Gibson (1978) furthered the study presented by Broughton et al. (1977). They evaluated the performance of five envelopes and two unwrapped drains with different openings in a farm at Notre-Dame-du-Bon-Conseil, Québec. The soil was a Ste. Sophie sand. The envelope materials were a Cerex spunbonded nylon, a Reemay spunbonded polyester, a knitted nylon, a Typar spunbonded polypropylene and a gravel and sand envelope. The first envelope-free tubes had openings 1.6 mm wide by 30 mm long, while the second tube had smaller openings 0.75 x 8 mm. With the drains spaced 16.8 m and 134 m long, all treatments gave drainage rates 15 mm/day and over. However, the two envelope-free tubings showed lowest drainage rates and presented the largest amount of sediment deposition and the highest head losses near the drain.

A field evaluation of synthetic envelopes was carried out by Johnston et al. (1982) in the San Joaquin Valley (California). The authors used a three-inch gravel envelope, a knitted polyester sock envelope, a spun-bonded nylon as well as a soviet-made non-woven synthetic envelope. The 200 m long drains were spaced 56.6 meters and placed 2.1 m deep. The authors concluded that synthetic drain envelope materials were less effective than gravel envelopes, in terms of water and salt removal as well as peak flows. In his discussion of the paper presented by the above authors, Broughton (1982) shows that there was no statistical significant difference at the 0.10 level of probability for the data presented by Johnston et al. (1982), on peak flows, water and salt removal. Broughton explains that the high coefficient of variation of the data comes from the fact that only three replicates were used. In a large area of land, much soil variation can be expected. Therefore, five or six replicates should be installed to get significant results. He concludes that laboratory experiments should be made to give preliminary results on envelope materials before field tests are carried out using the more promising materials.

The efficiency of thin envelopes is still argued by some researchers. Zaslavsky (1979) favours coarse voluminous envelopes. He explains that particles smaller than the envelope 's pore migrate into it while the larger ones remain behind. This process would continue until the soil stabilizes. At the same time, an inverted natural soil filter would gradually form outside the envelope, changing from coarse to fine. If this envelope is thin with large pores, the erosive process may continue before the soil stabilizes, causing sedimentation. On the other hand, with small pores, all small particles will be stopped, clogging the envelope. With a thick coarse envelope, fine particles leaving the soil will be stopped at random places in the envelope and at different depths. This process would reduce the probability of clogging the envelope.

In contrast, Sweetland (1977), as cited by Stuyt (1982), argues in favour of thin fabrics. The latter believes that the size of the fabric openings controls the size of the particles migrating. If the fabric consisted of several layers, continuous pores would become tortuous and reduce the maximum size of the migrating particles. Therefore, the thicker the fabric, the lower the probability of having continuous pores for migrating soil particles. Sweetland (1977) suggests that the probability of clogging the envelope increases with increasing envelope thickness.

2.2.4 Soil conditioners

When the topsoil is not cohesive enough for use as drain blinding material or the subsoil is unstable, the structure can be improved by using soil conditioners. According to Zaslavsky (1979), the purpose of a soil conditioner is to produce a highly aggregated thin layer of soil around the pipe that would act as an envelope. This could be done by using cement, lime, polymer solutions or polymer emulsions.

Polymer solutions consist of a complex material having a treadlike structure which would hold the soil particles together and thus form small aggregates. On the other hand, electrically charged micelles from polymer emulsions, would glide over thin water films (surrounding mineral particles) into the menisci at the point of contact between particles when the soil is drying out (Dierickx and Goossens, 1979). Soil particles would thus stick together due to the circular micelles in the dried-out menisci.

Soil conditioners could be used on fine textured soils to increase their permeability especially in the backfill trench, while they would stabilize the highly permeable coarse-textured soils.

Dierickx and Goossens (1979) tested three types of polymer solutions and three others of the emulsive type. Using permeameters, they found that for sandy loam and clay soils, the polymer solutions gave best results when compared to the emulsive types, as no drying period was required to obtain optimal stabilizing action. The permeability of the stabilized samples increased by a factor of 10 to 100. Sandy soils treated with either conditioner, needed a drying time of several days before the formed aggregates were able to resist breakdown when put in contact with water.

Soil conditioners present good prospects for the future, but much research is still needed to answer some of the questions. Their durability, the load carrying capacity of the formed aggregates, the effect of soil chemicals and soil microbiological activities need to be investigated in more details. Also, a suitable and economical method should be developed for use of soil conditioners in subsurface drainage applications.

2.3 Envelope Design Criteria

In 1922, Terzaghi, developed filter criteria for hydraulic structures which have been tested for and found applicable for envelopes around the drains (Willardson, 1974). He recommended the filter material be made many times more permeable than the bulk soil material but not so coarse as to allow soil particle movement into the filter. The criteria he proposed and adopted by the U.S. Corps of Engineers in 1941, are:

1) D_{15} (filter) / D_{15} (base) ≥ 4

   (this implies that K(filter) $\geq$ 16K(base) since the permeability varies as the square of the particle diameter)

2) D_{15} (filter) / D_{85} (base) ≤ 4

where the D_{15} is defined as the effective particle diameter for which 15% of the soil sample by weight is smaller. Similarly, the D_{85} is the diameter for which 85% of the soil sample is smaller. K is the hydraulic conductivity.

Other criteria are developed in detail in Willardson's review of envelope materials (1974). Terzaghi's criteria have been tested and modified but have been generally accepted. The most widely used criteria in North America are the ones adopted by governmental agencies or associations. In Québec, the legal specifications for a granular envelope follow the ones established by the Soil Conservation Service (SCS) or the U.S. Bureau of Reclamation (USBR) but with a minimum thickness of 75 mm (3 in.). For synthetic fabrics, it is required that the mean fabric opening be less than or equal to the D_{50} of the soil (C.P.V.Q., 1984). The USBR (1978) present granular filter criteria as under:

1) D_{15} (filter) / D_{15} (base) ≥ 5
2) D_{15} (filter) / D_{85} (base) ≥ 5
3) D_{85} (filter) / Max. size of drain opening ≥ 2

They have also established a gradation relationship between base material and diameters of graded envelope material which goes along with the above criteria. The criteria used by the SCS (1973) are as follows:

"1) D_{50} (filter) = 12 to 58 times D_{50} (base)

2) D_{15} (filter) = 12 to 40 times D_{15} (base)

3) All of the filter material shall pass the 1.5 inch sieve; 90% shall pass the 0.75 inch sieve and no more than 10% shall pass the No. 60 sieve.

4) For more or less uniformly graded envelope material

D_{15} (filter) / D_{85} (base) ≤ 5

5) For placement around a perforated tubing,

D_{85} (filter) / Average drain opening size $\geq$ 0.5"

Broadhead (1981) reported on a group of laboratory experiments where he tried to retain soils of various particle size distributions on a series of nylon ("Nytex") square mesh ranging in opening size from 250 to 1000 microns (0.25 to 1.0 mm). He found that the ratios of the critical opening sizes to prevent excess sedimentation to the D_{60} size of the soil sample ranged from 2.40 to 4.05. For the samples with a D_{60} of 100 microns, the average ratio was 3.26 and for samples with a D_{60} of 200 microns, the average ratio was 2.49. He suggests the use of the conservative guideline that the openings in drain tubes or envelope fabrics not be greater than 2.40 times the D_{60} size, if sedimentation is to be prevented.

When the soil is less uniform such that the D_{85} size is much larger than the D_{60}, the criterion is, generally, based on the D_{85} size. The criteria for the size of envelope-free drain openings are more or less the same as for envelope materials. Thériault et al. (1982) reported on field investigations of 24 drainage systems where drains were dug up at 72 locations. The drain tubes which had more than 2 cm of sediment, all had slots wider than 2 times the D_{85} of the soil around the tube. They recommend that the openings in the drain tubes meet the CPVQ standards, that is, that the perforations be no larger than twice the D_{85} of the base soil to be restrained.

Willardson (1979) hypothesizes that bridging across the tube holes occurs if the soil particles are one third the size of the circular opening or larger. There is some controversy about the comparison of the diameter of circular drain hole with the width of a slot. A three dimensional dome would develop over a circular hole whereas a two dimensional arch of a smaller span develops over a slot with the same material acting. The above author explains that "a slot has the same effective size as a circular hole with a diameter three times the narrow dimensions of the slot".

In contrast, Broadhead (1981) indicates that a circular hole could have a diameter larger than the side of a square mesh and give the same effect. He implies that the equivalent circle diameter should probably be less than the diagonal of the square, that is, less than 1.4 times the slot width. The US Corps of Engineers, as reported by Kovacs (1981), recommends a more conservative criterion for drain pipes in dams, where a gravel envelope is used around the drain pipes. Kovacs states that the

D_{85} of the gravel envelope should be greater than 1.2 times the width of the slot, or greater than the diameter of a circular hole.

From this controversy, the necessity is seen to carry out more research in order to investigate the effect of drain opening shape on sedimentation inside the drains. The present research may help to verify or reject some of the above theories.

Giroud (1982), as an attempt at complementing experimental findings, presented a theoritical analysis of the filtration mechanism related to geotextiles (synthetic fabrics). He found that although the involved mechanism is similar to the filtration mechanism of a granular envelope, the derived criteria for permeability and opening size of geotextiles are different. His findings are sumarized in Table 2.1 and plotted in Figure 2.1.

2.4 Envelope Requirement Versus Siltation Tendency

Before installing an envelope, the question that arise is "what soil conditions require an envelope in subsurface drainage systems. This question has no specific answer, but attempts have been made by many researchers to establish definite criteria. These citeria were usually based on the soil texture, while the effect of soil structure was only qualitatively assessed.

2.4.1 Soil texture and soil structure

A) Soil texture

Table 2.1. Retention criterion for geotextile. The criterion is represented graphically in Figure 2.1. (After Giroud, 1982).

	Density index of the soil (Relative index)	Linear coefficient of uniformity of the soil $1 < C_u < 3$	$C_u > 3$
Loose soil	$I_d < 35\%$	$O_{95} < D_{50} C_u$	$O_{95} < 9 D_{50}/C_u$
Medium to dense soil	$35\% < I_d < 65\%$	$O_{95} < 1.5 D_{50} C_u$	$O_{95} < 13.5 D_{50}/C_u$
Dense soil	$I_d > 65\%$	$O_{95} < 2 D_{50} C_u$	$O_{95} < 18 D_{50} C_u$

$I_d = (e_{max} - e)/(e_{max}-e_{min})*100$, e = void ratio , $C_u = D_{60}/D_{10}$

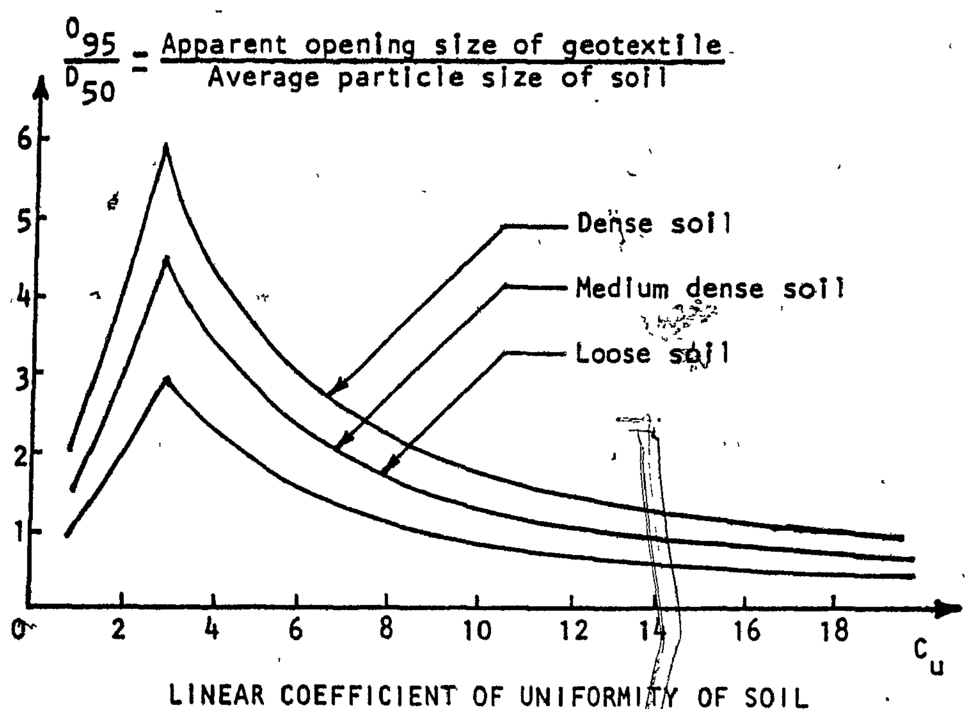


Figure 2.1. Retention criterion for geotextile filter (see Table 2.1).

Willardson and Walker (1979) have shown how the particle size distribution greatly affects the soil sensitivity to internal erosion. As water approaches a subsurface drain, the flow velocity increases as a result of convergence towards the drain openings. This increase in velocity, accompanied by an increase in hydraulic gradient, tends to move the soil particles towards the drain if they are not held together. The velocity at which particles are carried away depends upon their dimension and cohesion forces (Trafford et al., 1974).

High velocities are needed to drag the coarser particles (coarse sand, gravel) and the finer these particles are, the lower the velocity required. However, there comes a point when particles are so fine (clay) that the phenomenon is reversed (high velocity needed), as the clay particles are held together by strong cohesive forces. Consequently, soils with a high proportion of coarse sand or clay are the most resistant to tractive force, as depicted by Table 2.2.

Generally, characteristics like the D_{10}, D_{15}, D_{50}, D_{60} and D_{85} as well as the coefficients of uniformity (C_u) and curvature (C_c) are used to determine the problem soils. Trafford et al. (1974) cites the following ones as being widely used:

1)

	Siltation tendency
$C_u > 15$	none
$5 < C_u < 15$	moderate
$C_u < 5$	strong

Table 2.2. Soil type and siltation tendency. (After Kuntze, 1974).

Soil type	Silting: Primary	Silting: Secondary
Coarse sand	0	0
Medium sand	1	1
Fine sand	2	2
Silty sand	3	3
Loamy sand	1	1
Silt	3	3
Sandy silt	3	3
Loamy silt	2	2
Sandy loam	1	0
Loam	1	0
Sandy clay	0	0
Clay	0	0

0 : no tendency to sedimentation = envelope not required

1 : slight tendency to sedimentation = envelope required

2 : moderate tendency to sedimentation = envelope required

3 : strong tendency to sedimentation = envelope strongly recommended

2) If $C_s < 0.50$, there is a danger of internal erosion,

where $C_u = D_{60}/D_{10}$ and

C_s = %clay / (%clay + %silt)

In the United States, the A.S.A.E. (1982) recommends the use of an envelope for:

" 1) Soils that easily fill a drain with sediment, such as fine and medium sand in the range of 0.05to 1.0mm

2) Soils that do not provide a stable foundation such as saturated sands in quick condition, and

3) Soils that tend to seal or clog drain opening and limit water entry into drain."

Broughton et al. (1977) have shown that soils having a large amount (80%) of particles ranging from 0.05 mm to 0.15 mm present siltation problems. In general, non-saline soils having 20% clay do not exhibit that tendency. Thus, in Québec, envelopes are required for (C.P.V.Q., 1984): 1) soils for which the D_{85} of the soil is less than half the width of the drain slots, and 2) soils with less than 20% clay that do not have a stable structure. Figure 2.2 shows a range of particle size distribution for soils that have been known to cause sedimentation inside drains.

B) Soil structure

Although the particle size distribution is important for identifying a soil type, it is not sufficient to classify a soil type as

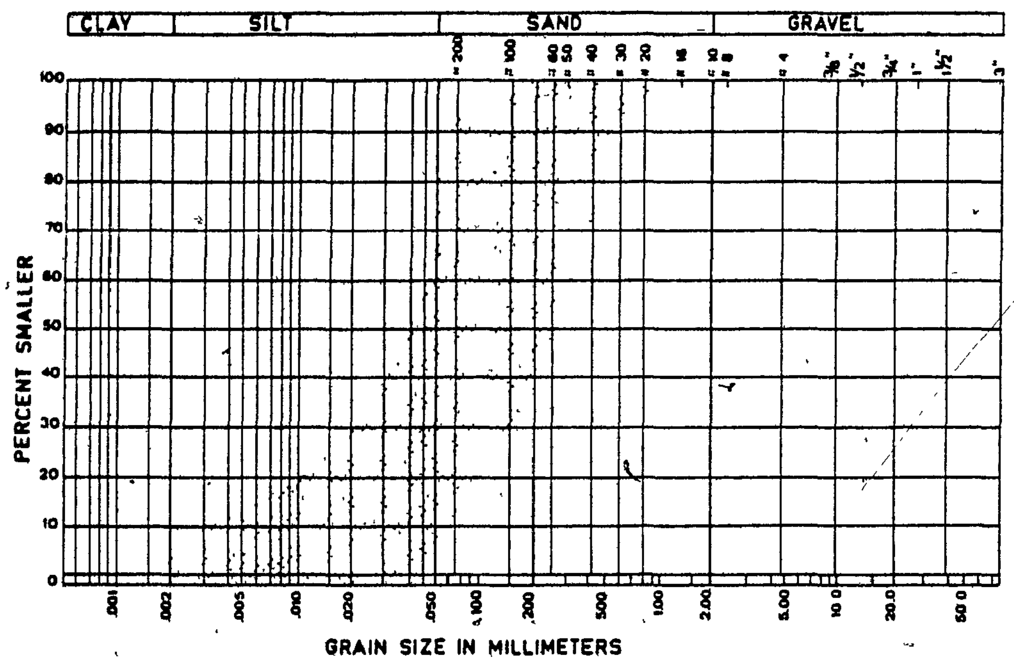


Figure 2.2. Range of particle size distribution for problem soils in Ontario and Québec. (After Irwin and Hore, 1979).

a problem soil. Soil structure plays an important role, as soil sensitivity to siltation is also dependent upon cohesive forces between soil particles (Dierickx, 1982b; Stuyt, 1982; Samani and Willardson, 1981). However, even though many authors agree that the structure of a soil has a definite impact on the phenomenon of sedimentation, most studies were limited to the textural aspects.

Consequently, further research was necessary to evaluate the effect of soil structure on sedimentation, and henceforward, establish a criteria based on both quantitative measures of the individual effects of aggregate and particle sizes.

With this consideration in mind, Lagacé and Skaggs (1982) tried to predict drain silting using both particle size and aggregate size distribution. They fitted a linear regession between the depth of sediment inside drains and particle size analysis parameters and/or aggregate size parameters. They found a better correlation with particle size analysis parameters (R^2=0.85) than with aggregate size analysis parameters (R^2=0.55). However, the regression of both parameters gave the best relationship (R^2=0.94). Furthermore, using both particle and aggregate size analyses, and a stepwise discriminant analysis method, they were able to determine good criteria for predicting when a filter material was needed. Based on actual observations of the depth of sediment deposited inside the drain, the authors classified the siltation as low, medium and high. Considering only particle size distribution parameters and using the discriminant analysis, 87% of the observations were correctly classified, with the misclassified by one class. A misclassification by one class indicates that if the sediment depth was actually low, the discriminant analysis would classify it as being medium. If the procedure predicted that it would be high, it was misclassified by two classes. When considering aggregate size parameters, 23% were misclassified by 1-class and 4% were misclassified by 2-classes. However considering both particle and aggregate size distributions, only 6% of the data were misclassified by 1-class and none by 2-classes.

The discriminant method seems to work but it is time-consuming and requires computer facilities. Consequently further research might be necessary to determine simpler criteria that would include quantitative measures of both soil structure and soil texture. To the author's knowledge no simple methods have yet been reported.

In this research, the effect of soil texture on sedimentation will only be investigated qualitatively, as it is otherwise considered beyond the scope of this study.

2.4.2 Importance of installation conditions

Installation conditions play an important role in determining the rate of silting up. Under unfavourable conditions, soil aggregates may be destroyed leading to a reduction of permeability of the trench. Furthermore, under high water-table, muddy water moving through the backfill material directly onto the envelope (under high hydraulic heads), may clog the envelope openings (Willardson, 1974). It may also induce primary silting in the drain. This is especially true for sand, silt, loamy sand, sandy loam and silty clay loam as reported by Knops et. al (1979). The implication is that whether or not an envelope is installed, careless backfilling might be harmful to the performance of subsurface drainage systems.

2.5 Filtering Drains

Despite being effective, farmers would rather avoid installing envelopes because of the high costs involved. Therefore, many manufacturers have produced drains with much smaller holes than conventional drains, mostly to be installed in the problem areas. Of course, nothing prevents installing those drains in stable soils. More, the drains with small perforations have to act as envelopes at the same time. That is, besides providing a suitable support for the surrounding soil, they would have to prevent a critical accumulation of sediments while unrestricting drainage. For this reason, they have been qualified as "filtering filterless drains" or simply "filtering drains".

Brouillette and Delisle (1982) report of filtering drains being installed as early as 1976 in Québec. Their findings have also been published under Thériault et al. (1982). The authors investigated the performance of 24 subsurface drainage systems with filtering drains that were installed on unstable sandy and silty soils in Southern Québec. For each farm, they measured the depth of sediment inside drains, slope and drain spacing as well as drain characteristics among others. Drain openings varied between 0.51 and 1.14 mm with 62% of the openings being less than 0.80 mm. Standard deviations were quite high though, in the range of 0.03 to 0.20 mm. The authors suggested that a better performance could be achieved if the openings were made more uniform. Further, they found that for soils presenting ochre problems, the filtering drains ended up being clogged: up to 63% of the openings were clogged by the formation of bridges of ochre and soil particles. In sandy soils (80% sand and over), the drains performed very well provided the CPVQ standards were met. In silty soils (30% silt and over) however, high levels of sedimentation were encountered.

Recall the unwrapped drain with small slots (0.75 x 8 mm) tested by Broughton and Gibson (1977) and Gibson (1978). This drain did not perform well in the Ste. Sophie sand. The authors predicted that the drain would have probably clogged after a series of wet periods spread over 4 to 6 years.

Fausey (1982) reports on small diameter tubing for shallow drainage application. In May 1977, 50 mm drains were installed in a Clermont silt loam with 70% silt. The drains had an opening area of 3.4 cm^2/m with individual openings 9.5 mm long by 0.13 mm wide. It was found that these drains performed satisfactorily in the unstable soil, in terms of sedimentation and water removal. Reeve (1982) presents results for slotted corrugated tubing with different opening areas. He does not give any indication on slot characteristics. However, one of the drains seems to have had small perforations as the total opening area was 29 cm^2/m for 302 slots/m. 48-hr midpoint drawdown between two drains was calculated for drains installed in a 2 m soil profile with a hydraulic conductivity of 50 mm/hr and at a depth of 1 m and a drain spacing of 30

m. The tube of interest lowered the water table by 14.2 cm. Drawdown values ranged from 13.5 to 18.1 cm for inlet areas varying from 12 to 3600 cm^2/m for the ideal drain. The author concluded that a small amount of inlet area is enough to produce considerable lowering of the water table.

Lagacé (1983) investigated the effect of installation conditions (dry and saturated) on the performance of four drain types: small slotted, medium slotted and two large slotted P.E. CPT. Under dry installation conditions, the small slotted drain (0.69 x 5.0 mm) gave 0 to 2 mm of sediments as compared to the medium type (1.2 x 6.8 mm) and the larger ones (2.0 x 27.0 mm; 2.0 x 8 mm) which gave up to 75 mm of sediments. Under saturated conditions, all tubings performed equally with 1-2 mm of sediments entering the tubes. In terms of flow rates, the small slotted drain competed very well with the other three drains. The soil used, a St. Damase sandy loam with 70% of the particles in the range 0.02-0.10 mm, had produced heavy silting in several fields.

Literature on the performance of corrugated plastic tubing with small perforations and pinholes is scarce. Much information is still needed to improve on the manufacturing of these tubings. Hence, in an effort to help manufacturers find out about the suitability of their new product, the CPTA sponsored a preliminary laboratory study on the performance of corrugated tubing with pinholes and small slots that was to be carried out by Bolduc, Dvorsky and Broughton (1984).

Three tubes were tested: 1) a normal slotted tubing enrobed with a knitted polyester stocking, 2) a 50 mm nominal inside diameter corrugated P.E. tubing for use in golf courses with very narrow slots (i.e. 0.224 x 1.21 mm) and an opening area of 7 cm^2/m, and 3) a 100 mm nominal inside diameter pipe with circular perforations 0.39 mm in diameter giving 5 cm^2/m of opening area. The soils used were a Ste. Barbe medium sand and a Bainsville very fine sandy loam; different from the Bainsville sand used by Broughton et al. (1977). It was found that, as expected, tube 1) above gave higher flowrates due to the presence of the envelope. Interestingly, tube 2) gave higher flowrates than tube 3). One would have expected the opposite because of the smaller diameter of tube 2) and the convergence of the streamlines near the tube. The authors explained this behaviour by the possible clogging of pinholes (tube 3) by soil particles and by the very small opening area of 5.0 cm^2/m, only 1/3 of the minimum recommandations listed in Table 2.3. However, all tubes gave satisfactory results for flowrates and sediment entry in the medium sand. This was not the case for the pinhole pipe and the small slotted one in the Bainsville very fine sandy loam soil.

The CPTA considered sponsoring a second study that would cover a broader range of soils and tubings, tubings which would meet at least one of the requirements given in Table 2.3. The findings of this research are reported herein.

2.6 Ochre Deposition

Ochre deposition inside and around drains has been recognized as affecting the performance of subsurface drainage systems over a century

Table 2.3. Area of drain openings required by various standards.

Standard	cm^2/m of length	in^2/ft of length
ASTM F405 (Anonymous, 1982)	21	1.00
USDA SCS 606 (Anonymous, 1980)	21	1.00
Canadian General Standards Board CGSB 41-GP-29Ma (Anonymous, 1983)	16	0.75
Bureau de Normalisation du Québec BNQ3624-115 (Anonymous, 1985)	32	1.50

ago (Ford, 1975). Iron ochre or iron sludge is a red to yellow, gelatinous, filamentous, amorphous, sticky mass of ferric hydroxide plus an organic matrix (Ford, 1979a). This iron deposit tends to form in the first three years after installation of the drains, thus reducing the flow to and sometimes blocking the drains (Sojak and Invarson, 1977). This is especially true if the soil pH is higher than 5.5.

Regamey and Jaton (1976) and Jaton (1977) describe the phenomenon of ochre formation as occuring in three steps. Initially, iron in the soil profile changes from the ferric state to the soluble ferrous state under water-logged, anaerobic conditions. It then migrates through the soil towards the drain to finally precipitate and deposit in and around the drain, due to the presence of oxygen.

Ford (1975) found that the precipitation of ferrous hydroxide at drain level, was primarily due to the presence of microorganisms and not to physico-chemical reactions as reported by other authors. Since then, many bacteria have been identified. The most important ones affecting ochre deposition in Ontario and Québec are of the genera Gallilionella and Sphaerotilus (Gameda, 1981; Gameda et al, 1983).

The types of soil in which this problem occurs, are primarily sandy soils and muck soils underlain with sand containing ferrous iron in the groundwater (Ford, 1975).

When installed in such soils, synthetic envelopes with small pores are likely to be clogged or loose much of the inflow area. On the other hand, organic envelopes and envelopes made with easily decomposable organic fibers will not suffer ochre clogging. This is because of their ability to produce iron reducing agents, such as phenols.

Consequently, special fabrics were made that incorporated a substance capable of inhibiting the formation of ferric hydroxide. However, the initial desintegration of the organic material releases large amounts of phenols such as tannins which are drained into rivers and lakes. Pollution problems are then generated as fish is affected by this highly toxic compound. (Ford, 1979b).

Happily, other control measures have been established (Ford, 1975; Kuntze, 1978; Sojak and Invarson, 1977). These measures can be classified as preventive, controlling and corrective. Preventive measures include soil aeration by subsoiling and/or the use of loose and well aerated gravel envelopes which allow sludge to form in the soil and not inside the drain. Controlling measures consist of using shorter laterals and maximum grades, increasing the minimum drain opening size (i.e. 1.2 mm), and submerging the drain so as to prohibit drain aeration. Drain submersion requires deep drains to avoid water-logging the root zone or narrowly spaced drains. Finally, chemical treatments by flushing the drains with an acid forming gaz or acid solution, and mechanical treatments such as jet cleaning, make up the corrective measures. These methods are described in more details by Kuntze (1978).

III. THEORIES OF FLOW TO DRAIN

Before proceeding with the experimental procedure, let us consider a few aspects of theories describing the flow to drains. Many of those theories have been developed over the decades, using different approaches. Only the relevant ones will be discussed in this chapter. Details of the mathematical development can be found in most drainage textbooks and original papers (Schwab et al., 1981; Luthin, 1973; Van Schilfgaarde, 1974; Kirkham, 1949, 1950; etc). Furthermore, only radial flow theory in a saturated homogeneous isotropic soil will be covered as it is directly relevant to the research carried out and presented in this thesis.

3.1 Drains in Homogeneous Soil Saturated to the Surface

Using the potential flow theory and Darcy's law, Kirkham (1949) developed analytical and flow net solutions for unlined subsurface drains placed in a homogeneous soil overlying an impervious layer, with water ponded above the soil surface. For this situation, flow into an individual drain is given approximately by:

$$q = \frac{2 \pi K (t+h-r)}{\ln(2h/r)} \qquad \text{(see Figure 3.1)} \qquad (3.1)$$

where,

q = flow into a unit length of drain per unit time, $m^3/d/m$

K = soil hydraulic conductivity, m^3/d

t = depth of water ponded on soil surface, m

h = depth from soil surface to centre of drain, m

r = radius to ouside of drain, m

Figure 3.1 shows the flow net for parallel drains 180 mm in diameter, 12 m apart and 1.35 m deep. In the right hand half of the figure, equipotentials are labelled in meters of water. In the left half, streamlines are given in fraction of the total flow which occurs between the given streamline and the zero streamline, midway between the drains. This flow net shows that 60% of the inflow at the soil surface enters the drain within 0.60 m on either side of the drain. Notice how the streamlines are closer together immediately over the drain than at some distance from it. This indicates a rapid increase in water flow over the tile than midway between them. The closeness of the equipotentials over the drains shows that nearly half of the total potential is used up within two diameters of the drain.

Equation (3.1) is a close approximation for cases when the depth to the impermeable layer is at least twice the depth of drains, and when the drain spacing is at least five times the drain depth.

3.2 Radial flow from a cylindrical source

The oldest approach for the development of equations simulating the operation of gravity wells in unconfined aquifers with horizontal replenishment, is that of Dupuit (Luthin, 1973). The Dupuit assumptions are that the streamlines in a system of gravity flow towards a shallow sink, are horizontal and that the velocity along the streamlines is

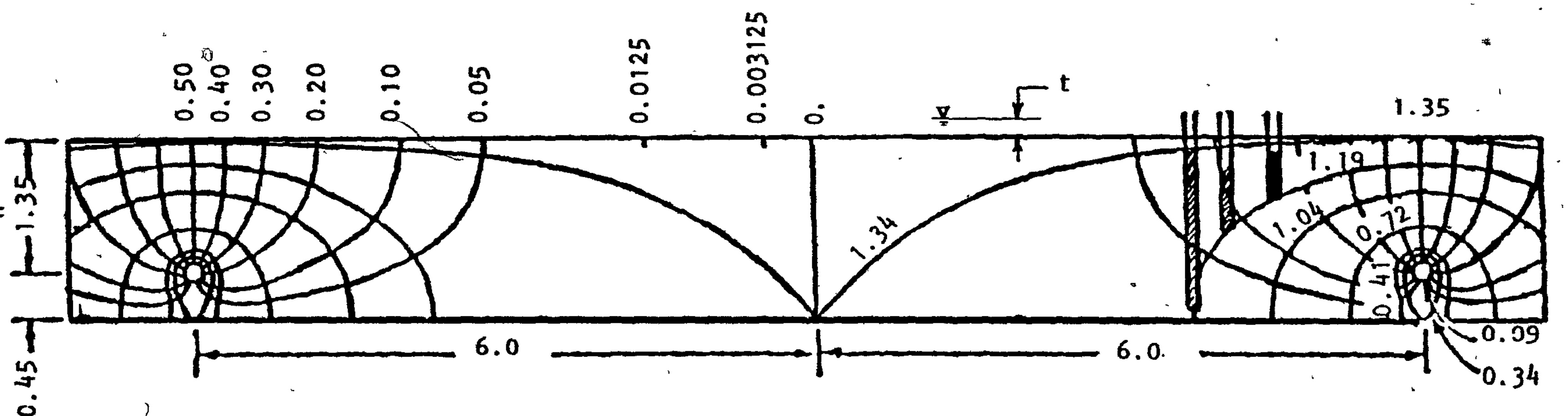


Figure 3.1. Flow net for seepage to parallel drains from ponded water over a saturated soil overlying an impervious layer. (Redrawn from Kirkham, 1949; original drawing labelled in feet).

proportional to the slope of the free water surface but independent of the depth of the saturated flow layer. Ignoring the seepage surface around the well and using the above assumptions, the flow rate into a gravity well, is:

$$Q = \frac{\pi K (H^2 - h^2)}{\ln(R/r)} \tag{3.2}$$

where Q = rate of flow, m^3/d

K = hydraulic conductivity, m/d

H = hydraulic head at radius R or height of the static water level above the impervious layer, m

h = hydraulic head at the well or height of the water level inside the well, m

R = radius of influence, m

r = radius of the well, m

The distance from the well to where the static water table is not lowered by drawdown, is known as the radius of influence.

The flow to a well completely penetrating a confined aquifer, can be analyzed in a manner similar to the unconfined flow, It is described as:

$$Q = \frac{2 \pi K d (H - h)}{\ln(R/r)} \tag{3.3}$$

where d = thickness of the confined layer, m

H= height of the piezometric surface above the top of the confined layer, m

h= height of the water in the well above the top of the confined layer, m

For steady flow, the entire discharge of a well must pass through a concentric cylinder at any radius. Thus, it can be shown that the flow rate for radial flow from a cylindrical source to a subsurface drain with completely open walls is very similar to Eq. (3.3):

$$Q = 2\pi LK \cdot \frac{(h_s - h_0)}{\ln(r_s/r_0)} \qquad (3.4)$$

where L = length of the drain, m

h_s = hydraulic head of the cylindrical source, m

h_0 = hydraulic head inside the drain, m

r_s = radius of the source from centre of drain, m

r_0 = radius of the drain, m

3.3 Effective Drain Tube Radius

Equation (3.4) assumes a completely permeable drain which offers no resistance to the flow. This is not the case in reality and many authors have developed formulae taking into account the effect of drain tube opening dimensions on water flow. Kirkham and Schwab (1951) present a complex mathemical solution for the effect of circular perforations on flow into smooth drain tubes. They verified their model with experimental electric analogues (Schwab and Kirkham, 1951). Similarly, analytical solutions were derived for the gap width between two adjacent clay tiles by Kirkham (1950), Sneyd and Hosking (1976), Bravo and Schwab

(1977) among others. The latter authors included a formulation for discontinuous slots on smooth drains and compared the theory with results from electric analogues.

All these analytical expressions compared very well with their electric analogue. However, they are quite complex and difficult to use. Consequently, approximate solutions were derived to determine the rate of flow into real drains. The concept of "effective drain radius" was thus introduced. It is defined such that the flow to a completely permeable tube with radius r_e, is the same as that of the real drain with radius r_0. Taking into account the effective drain radius, Eq. (3.4) becomes:

$$Q = 2\pi LK \frac{(h_s-h_0)}{\ln(r_s/r_e)} \tag{3.5}$$

The effective drain radius is useful in comparing the performance of unlike drains. Other practical applications of the effective radius, as reported by Skaggs (1978), are its inclusion in the equations presented by Moody to determine the equivalent depth to the impervious layer; the equivalent depth can then be used to estimate the water table drawdown from solutions to the Boussinesq equation.

Mohammad and Skaggs (1982) determined the effective radius of several tubes with circular openings and different number, location and total opening area. They found that the location of the openings on the wall had little effect on the effective radius. However, the existence of a gravel envelope around one of the tubes, greatly increased the effective radius but not sufficiently as to equal the radius of the envelope.

3.4 Entrance Resistance

Another method for characterizing the effect of drain tube opening is the concept of entrance resistance which helps to calculate the head loss at the drain wall. The total flow resistance can be divided into four components: a vertical, a horizontal, a radial and an entry resistance. The first two components would depend on the porous medium (i.e the bulk soil) while the last two depend on both the soil and the type of drain and/or envelope used. The sum of the radial and entrance resistance is known as the "approach flow resistance" (Cavelaars, 1967). The approach flow resistance can be narrowed down to a radius of 0.5 - 0.7 m around the drain (Eriksson, 1982).

In a field situation where the water table is above the drain, radial flow would start about 50 to 70 cm away from the drain centre. Eq. (3.4) can thus be applied only within this radius. Considering the head loss due to radial flow resistance, Eq. (3.4) can be rewritten as:

$$\Delta h_r = \frac{q}{2\pi K} \ln(r_s/r_o) = q\, W_r = \frac{q}{K}\, \alpha_r \qquad (3.6)$$

where Δh_r = hydraulic head loss for radial flow, m

W_r = radial resistance, m

α_r = radial flow resistance for a soil with a hydraulic conductivity of unity, m

The entry resistance to a drain with a limited number of openings is :

$$\Delta h_e = q\,W_e = \frac{q}{K}\,\alpha_e \qquad (3.7)$$

where Δh_e = hydraulic head loss due to entrance resistance, m

W_e = entrance resistance, m

α_e = entrance resistance for a soil with a hydraulic conductivity of unity, m.

Thus, the total head loss due to radial flow into a real drain becomes:

$$\Delta h_t = \Delta h_r + \Delta h_e$$

$$= \frac{q}{K}\,(\alpha_r + \alpha_e) = \frac{q}{K}\,\alpha_t \qquad (3.8)$$

and

$$\alpha_t = \frac{1}{2}\,\ln(r_s/r_o) + \alpha_e \qquad (3.9)$$

where α_t is the total flow resistance in a soil with ~~K=1.~~ α_e can be determined once α_t and α_r are known. Replacing the real drain by a drain with an effective radius of r_e, Eq. (3.9) changes to:

$$\alpha_t = \frac{1}{2}\,\ln(r_s/r_e) \qquad (3.10)$$

therefore,

$$r_e = r_s\;e^{(-2\pi\alpha_t)} \qquad (3.11)$$

or

$$r_e = r_o\;e^{(-2\pi\alpha_e)} \qquad (3.12)$$

Eq. (3.11) shows that the effective radius of a drain decreases exponentially with an increasing resistance. Attempts have been made to find analytical expressions for the entrance resistance which depends on the number, shape and location of the perforations. It also depends on the type of bridging over the perforation, usually an arch type as observed by Zaslavsky and Kassiff (1965) among others. The area covered by a an arch type of bridging is greater than in a flat bridging by a factor of $\pi/2$. This will reduce the convergence of the streamlines towards the opening which in turn offers less resistance to the flow of water.

The following expressions for the entry resistance - Eq. (3.13) to (3.17) - were taken from Dierickx (1982a) who studied the effect of corrugations on entrance resistance. We have:

$$\alpha_e = \frac{c}{2\pi^2 r_o}\left(\ln\frac{2c}{\pi\beta_s} - \frac{c}{4\pi r_o}\right) \qquad (3.13)$$

$$\alpha_e = \frac{c}{2\pi^2 r_o}\left(\ln\frac{2c}{\pi\beta_s} + \frac{1-\gamma}{\gamma}\left(\ln\frac{16\lambda_c}{\beta_s} - F(\gamma,\epsilon)\right)\right) \qquad (3.14)$$

Eq. (3.13) represents the case for a smooth pipe with continuous circumferential slits simulating a gap between clay tiles. In this case, c=gap spacing (m); r_o=outside drain radius (m); and β_s=gap width (m).

Eq. (3.14) is the expression for rectangular discontinuous slits on a smooth drain. $\gamma = \lambda_p/\lambda_c$ and the other symbols are as defined in Figure 3.1. Figure 3.2 is a graphical representation of the function

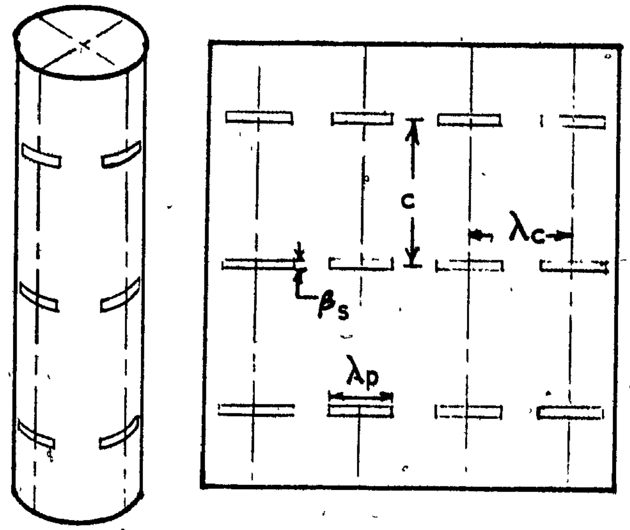


Figure 3.2. Rectangular perforation pattern of discontinuous transverse slits. (After Dierickx, 1982a).

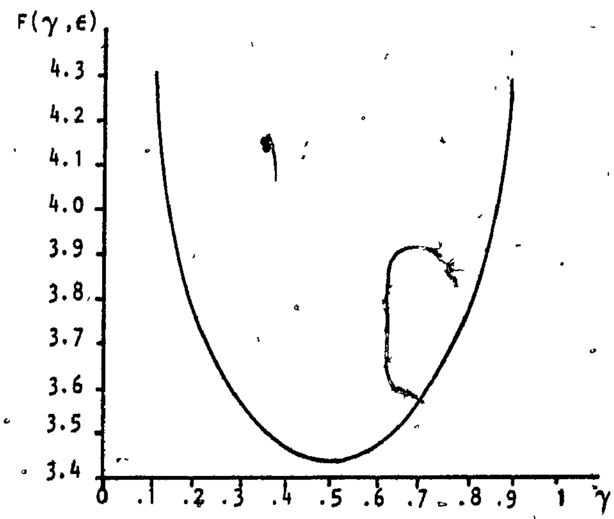


Figure 3.3. The function $F(\gamma, \epsilon)$ with $\epsilon = 0$ for flow towards a partially penetrating well in a confined aquifer. (After Dierickx, 1982a).

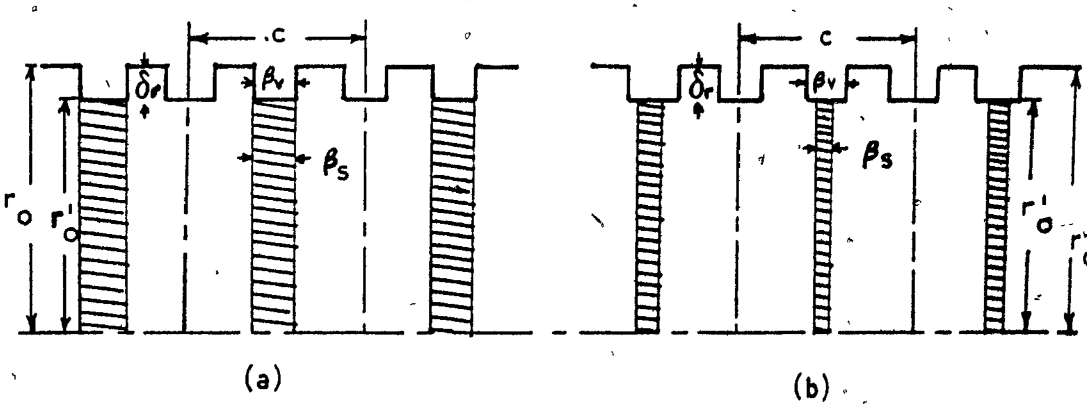


Figure 3.4. Corrugated drains with (a) a gap width equal to valley width and (b) a gap width smaller than valley width. (After Dierickx, 1982a).

$F(\gamma, \epsilon)$.

The presence of corrugations on a drain increases the entrance resistance as the streamlines experience additional convergence towards the opening between two corrugations. Hence, for a corrugated drain with a rectangular block wave profile and continuous circumferential openings with a width equal to the valley width, the entry resistance is:

$$\alpha_e = \frac{c}{2\pi^2 r_o}\left(\ln\frac{2c}{\pi\beta_s} - \frac{c}{4\pi r_o}\right) + \frac{c}{2\pi\beta_s}\ln\frac{r_o}{r_o'} - \frac{1}{2\pi}\ln\frac{r_o}{r_o'} \qquad (3.15)$$

For circumferential openings with a width less than the valley width, the entry resistance approach is approximated by:

$$\alpha_e = \frac{c}{2\pi^2 r_o}\left(\ln\frac{2c}{\pi\beta_v} - \frac{c}{4\pi r_o}\right) + \frac{c}{4\pi^2 r_o'}\ln\frac{2\sinh\dfrac{2\pi\delta_r}{\beta_v}}{\sin^2\dfrac{\pi\beta_s}{2\beta_v}} - \frac{1}{2\pi}\ln\frac{r_o}{r_o'} \qquad (3.16)$$

For discontinuous slits with a width less than the valley width, the expression becomes:

$$\alpha_e = \frac{c}{2\pi^2 r_o}\left(\ln\frac{2c}{\pi\beta_v} - \frac{c}{4\pi r_o}\right)$$

$$+ \frac{c}{2N\lambda_p}\ln\frac{2\sinh\frac{2\pi\delta_r}{\beta_v}}{\sin^2\frac{\pi\beta_s}{2\beta_v}} - \frac{1}{2\pi}\ln\frac{r_o}{r_o'} \qquad (3.17)$$

The symbols are as indicated in Fig 3.4 and N represents the number of longitudinal rows of slots. Notice that Eq. (3.17) is equal to Eq. (3.13) plus two other terms. The second term in Eq. (3.17) takes into account the convergence of the streamlines inside the valley of the corrugations. The last term is a correction for the radial flow in that valley. Dierickx (1982a) tested the validity of these equations using electric analogues and found very good agreement between the experimental and theoritical values.

3.5 RPZ Ratio

Up to this point, it has been assumed that the hydraulic conductivity of the soil in the area of "flow resistance approach" was constant all around the drain. Lagacé (1983) and Lagacé and Skaggs (1985) have shown that this assumption does not hold true in the vicinity of the drain for the cases they studied. To do so, the authors defined the "RPZ ratio" which stands for "radial piezometric ratio". Denoting "a" the inner piezometer (0.7 to 1.5 cm away from the drain) and "b" the outer piezometer (20 cm away from the drain in the same direction); and assuming an average hydraulic conductivity between piezometer a and the drain (K_a) different from the one between piezometer b and the drain (K_b), equation (3.8) can be rewritten as:

$$\Delta h_a = h_a - h_o = \frac{q}{K_a} \alpha_{t_a} \qquad (3.18)$$

$$\Delta h_b = h_b - h_o = \frac{q}{K_b} \alpha_{t_b} \qquad (3.19)$$

where h_a = hydraulic head at piezometer a, m

h_b = hydraulic head at piezometer b, m

h_o = hydraulic head at drain opening, m

α_{ta} = total flow resistance at piezometer a

α_{tb} = total flow resistance at piezometer b

and

$$\alpha_{ta} = \frac{1}{2} \ln(r_a/r_o) + \alpha_e \qquad (3.20)$$

$$\alpha_{tb} = \frac{1}{2} \ln(r_b/r_o) + \alpha_e \qquad (3.21)$$

Taking the ratio of the two equations (3.18) and (3.19), we have:

$$\frac{\Delta h_a}{\Delta h_b} = \frac{K_b}{K_a} \frac{\alpha_{ta}}{\alpha_{tb}} \qquad (3.22)$$

The RPZ ratio is defined as:

$$RPZ = \frac{\Delta h_a / \Delta h_b}{\alpha_{t_a} / \alpha_{t_b}} \quad \frac{\text{(observed)}}{\text{(theoritical)}} = \frac{K_b}{K_a} \qquad (3.23)$$

Actually, the authors made the hydraulic head at the opening (h_o) equal to zero by moving the reference line. This would reduce the numerator to h_a/h_b. The RPZ ratio, as defined, is independent of drain characteristics and of the radial distance to the drains. It is however, the expression of the ratio of the hydraulic conductivity between each piezometer and the drain. Thus, for a uniformly compacted layer of soil, the RPZ ratio should be equal to one. Should it be less than unity, this would indicate that the soil between the drain and the inner piezometer is more permeable than the soil outside the first piezometer. The authors found all RPZ values to be less than one for their experiment (above, below and on each side of the drain). However, the values were closer to unity on the top quarter while the bottom quarter gave lowest results. The situation would be that the soil tends to settle properly in the corrugations on top of the drain whereas the opposite seems to take place below the drain. The authors explain that above the drain, tractive forces and gravity help pushing the soil particles towards the opening while under the drain, gravity is acting against the flow of water, thus reducing the effective pressure on the soil particles.

3.6 Hydraulic Gradient

Water flows from one point to another because of a difference in potential (i.e. hydraulic head). The difference in potential divided by the distance separating the two points is termed the hydraulic gradient. At drain level the hydraulic head is maintained at its lowest level by contant removal of water in the tubing when drainage takes place. Therefore, the gradient will be highest at the drain as a result of convergence of the streamlines. The gradient at the opening for a real drain is called the exit gradient. When the forces exerted by moving water exceeds those which hold the soil particles around the openings, particle movement takes place and sedimentation occurs. The gradient at which erosion occurs is known as the critical gradient or hydraulic failure gradient. It follows that erosion would occur in cohesive soils at critical gradients much higher than would be expected in structureless soils.

Several formulae are given in the literature for the expression of the critical gradient. Of interest to us, is the hydraulic failure gradient at a drain opening, which Samani and Willardson (1981) have developed through empirical means. The formula was derived from studies of critical gradients done over a wide range of soils from sandy to clay loam soils. It is expressed as:

$$HFG = \exp(0.332 - 11400\ K + 1.07\ \ln(PI)) \qquad (3.24)$$

where HFG = hydraulic failure gradient

K = hydraulic conductivity of the soil (m/d)

PI = plasticity index of the soil (decimal)

From Darcy's law, the hydraulic gradient at the drain for a completely porous drain is:

$$I = \frac{\Delta h}{\Delta r} = \frac{Q_t}{K\ A_t} = \frac{q_t}{K\ A} = \frac{q_t}{2\ \pi\ K\ r} \qquad (3.25)$$

where A_t is the total drain opening area and A the drain opening area per unit length. The other symbols are as defined previously. For a real drain, r can be replaced by the effective radius, r_e, and the hydraulic gradient near the drain be estimated. Comparing the predicted gradient as determined by equation (3.25) with the expected hydraulic failure gradient, one can decide whether an envelope is required on the drain in order to stabilize the soil or to reduce the exit gradient.

IV. MATERIALS AND METHODS

4.1 Tubing Used

The four types of tubings to be tested, were supplied by different manufacturers. These 100 mm (4 in.) nominal diameter tubings, are:

a) Pinhole tubing A,

b) Pinhole tubing B with slightly less open area than pinhole tubing A,

c) Pipe with very small slots, and

d) Normal slotted tubing with a knitted polyester stocking, 152 g/m^2 (4.4 oz/yd^2) of unit weight.

The total opening area per unit length of the above drains is given in Table 4.1. Other drain characteristics such as openings dimensions and number of holes per unit length are indicated in Table 4.2. Also, histograms of drain openings are presented in Figures A1 and A2 in Appendix A, for the tubes with small slots and pinholes. The openings histogram of the bare normal slotted tubing is not shown as it is the fabric envelope wrapped around the drain that has a direct effect on the drainage rate rather than the slots themselves.

The openings histograms of Figures A1 and A2 have been presented in Figure 4.1 as the opening size distribution. Also, this graph depicts the pore size distribution of the knitted polyester stocking as measured by the ASTM draft procedure (Papineau, 1985).

Table 4.1. Measured area of drain openings for the tubes used in the laboratory.

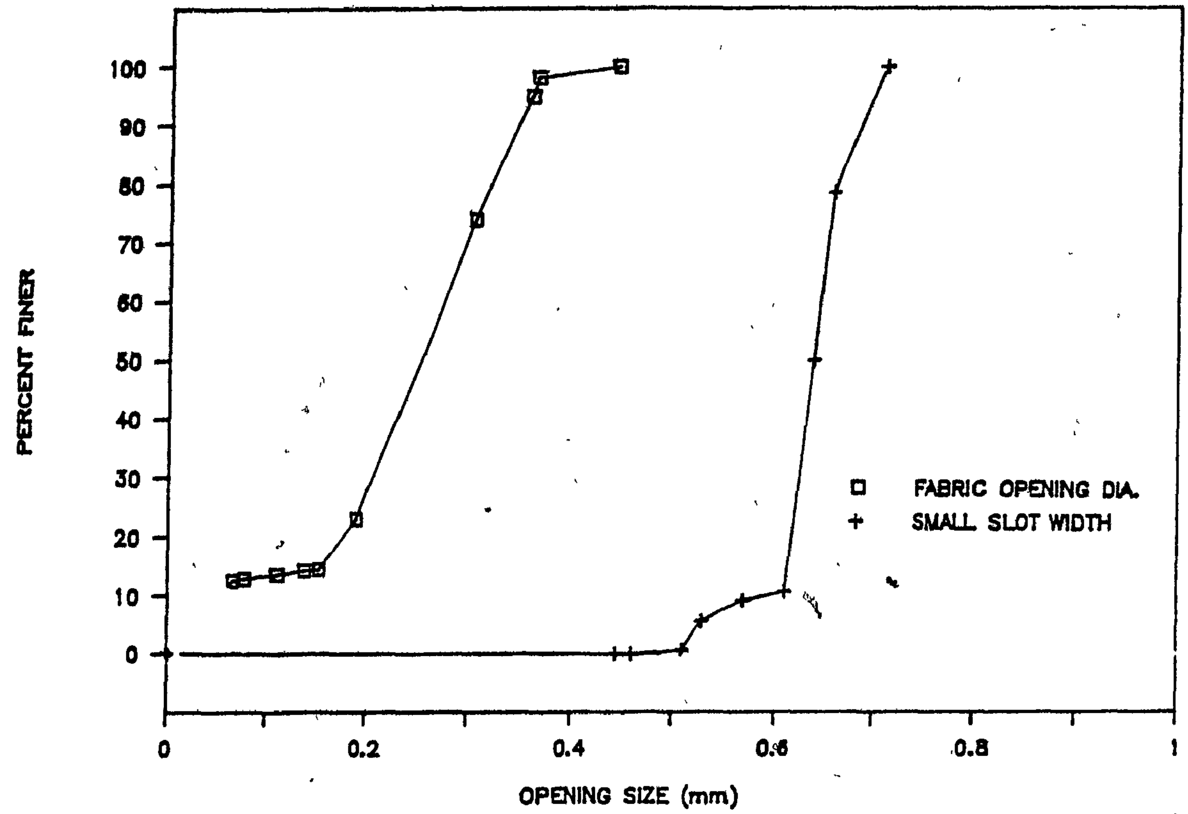
Tubing	Holes/m	Holes/ft	cm^2/m	in^2/ft
Normal slotted tube without envelope	244	76	51.5	2.4
Normal slotted tube with sock envelope[a]			1427.5	67.4
Tube with small slots	2528	768	56.9	2.7
Pinhole tube A	6231	1905	29.7	1.4
Pinhole Tube B	5376	1728	21.0	1.0

[a] Determined as shown in Appendix C.

Table 4.2. Measured dimensions of drains openings in tubes tested.

Designation	No. of holes per ring		Average mm	Minimum mm	Maximum mm
Normal slot without enve.[a]	4 (valley)	width	1.50	1.30	1.63
		length	14.08	5.66	18.19
Small slot[b]	32 (valley)	width	0.65	0.51	0.71
		length	3.56	3.18	3.79
Pinhole A[c]	48 (valley)	dia.	0.66	0.00	1.02
	45 (ridge)	dia.	0.88	0.00	0.99
	mean		0.77		
Pinhole B[c]	48 (valley)	dia.	0.69	0.00	0.99
	48 (ridge)	dia.	0.67	0.00	0.91
	mean		0.68		

[a] 80 slots measured (20 rings)
[b] 320 slots measured (10 rings)
[c] Holes measured on 10 ridges and 10 valleys



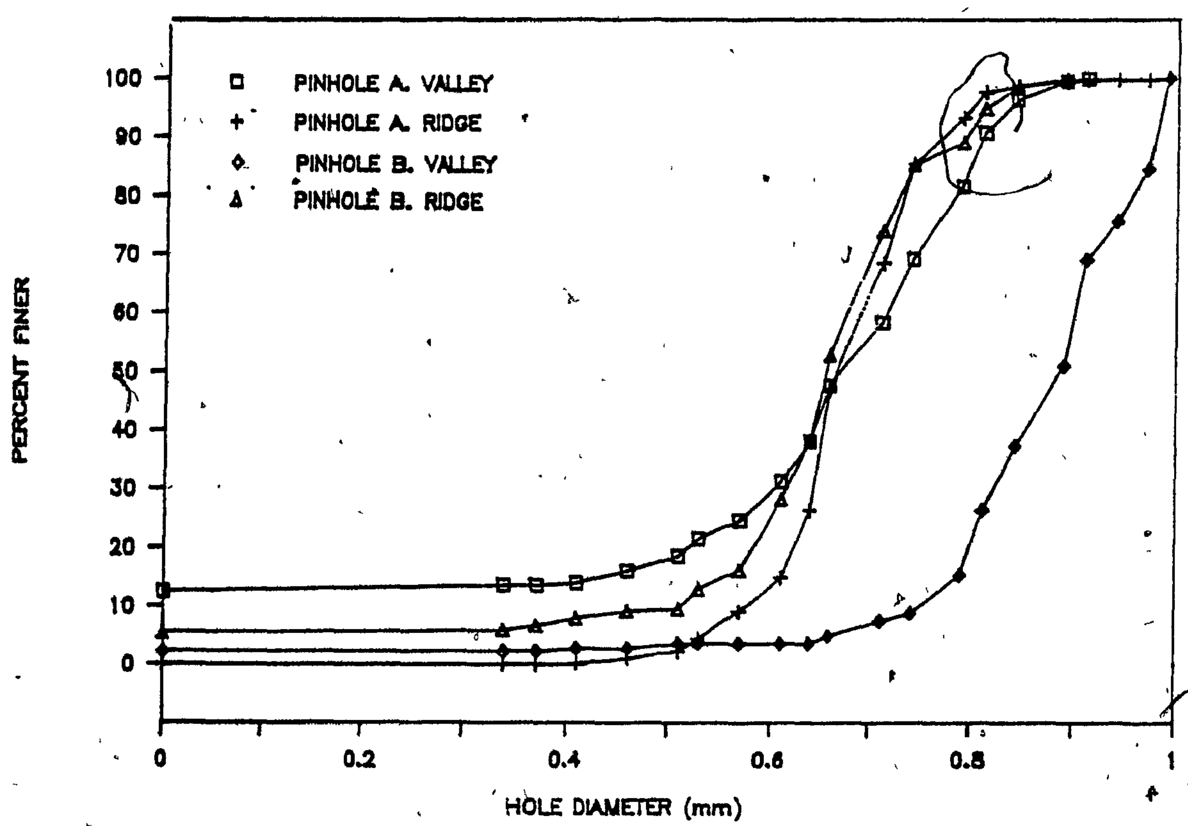


Figure 4.1. Opening size distribution for fabric envelope and tube with small slots (top); and pinhole tubes A and B (bottom).

4.2 Soils Used

The soils were obtained from near drain depth, 60 to 120 cm deep from soil areas where fabric envelopes are normally recommended for use on drain tubes. Particle size distributions for these soils are given in Figure 4.2. The percentages of sand, silt and clay in each of the soils, and their position in the soil classification Textural Triangle, is given in Figure 4.3. These curves are the average data of approximately 20 samples from above drain pipe. There was very little difference between samples in any soil type as will be discussed in the next chapter.

The Ormstown soil comes from a farm where drain tubes with normal slots 1.8 mm wide x 14 mm long and no envelope were blocked with sediment. Figure 4.2 shows that the soil used had 10% clay. It was first intended to obtain the soil from near a lateral where an envelope was installed. The soil in that area had only 5% clay. But as the field was already cultivated and planted, soil from near a field boundary was used and it is the one represented in Figure 4.2. This latter soil was kept for the research as its clay content was below the upper limit of 20% for which no envelope is required (Québec standards - CPVQ, 1984).

Soils much coarser than the Ste. Barbe medium sand are seldom used for agriculture, or seldom need drain tubes because their water holding capacity is so low that they usually suffer from droughtiness. Where they are used for agriculture, it is frequently for tree crops with irrigation. If drains are needed, the soil is usually coarse enough to serve as its own envelope material for drain tubes with pinholes or

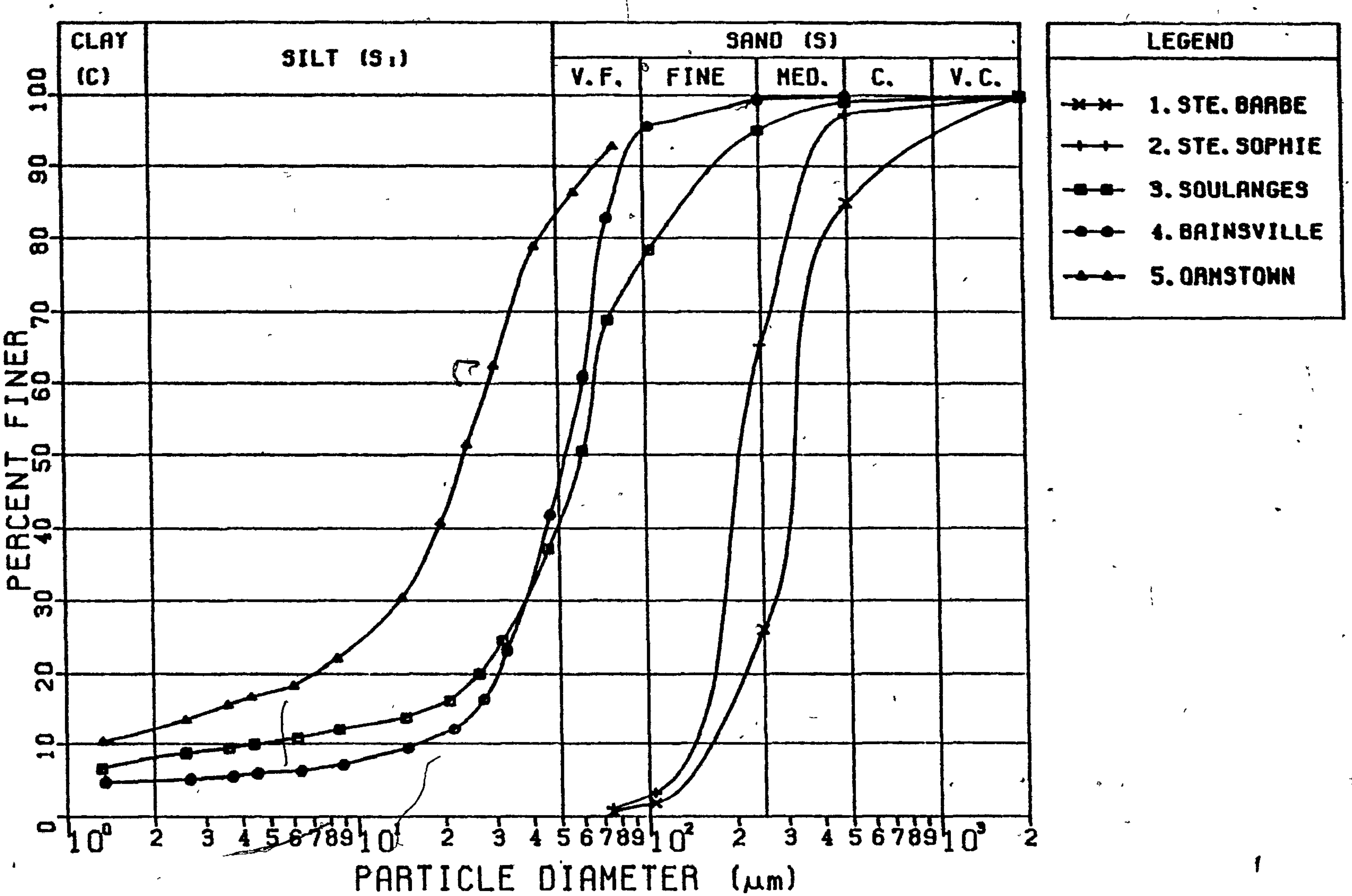
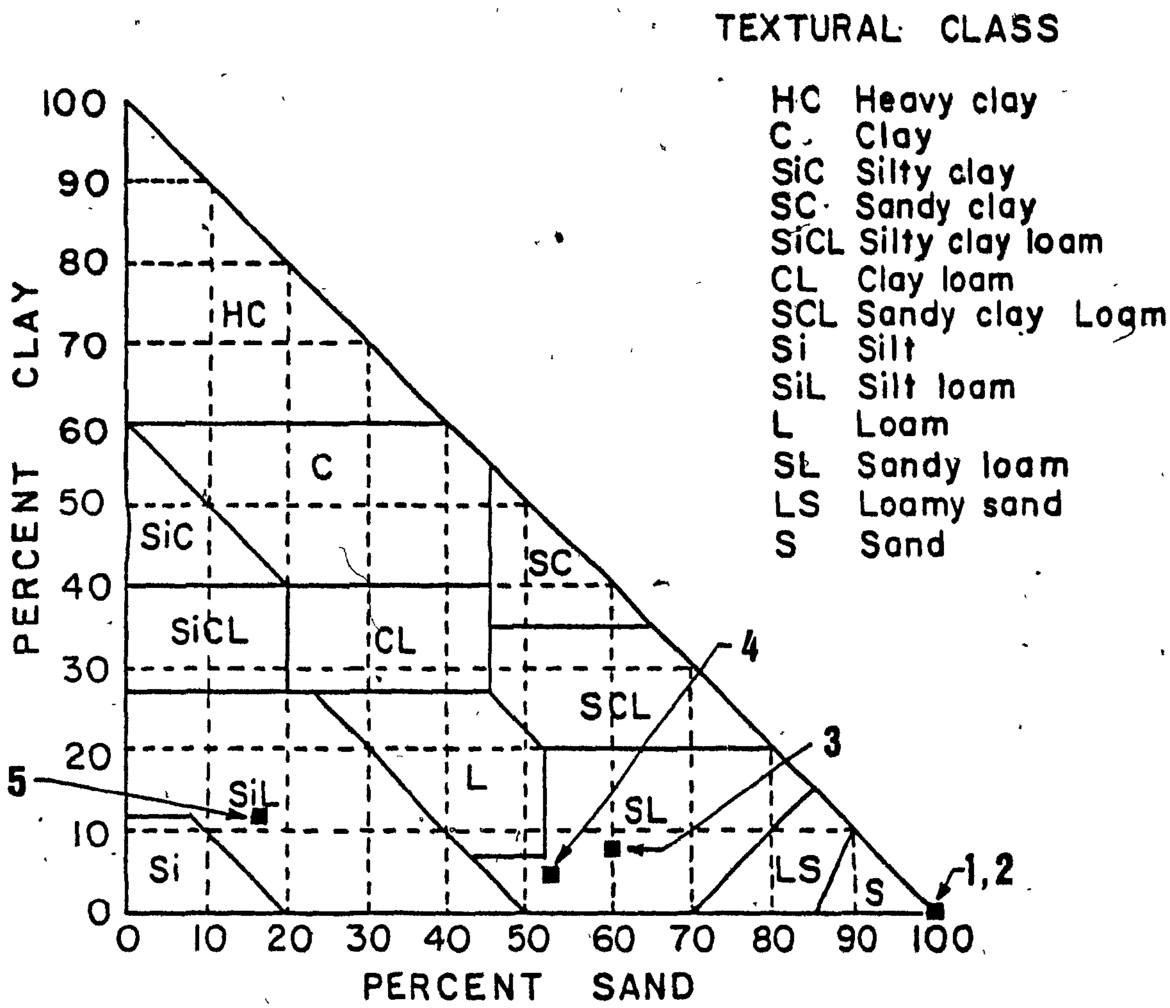


Figure 4.2. Particle size distribution of soils used.



	(%)	S	Si	C
1. Ste. Barbe,	Medium sand	100		
2. Ste. Sophie,	Fine sand	100		
3. Soulanges,	Fine sandy loam	60	32	8
4. Bainsville,	Very fine sandy loam	54	41	5
5. Ormstown,	Silt loam	17	71	12

Figure 4.3. Classification of soils used according to the Binary Textural Triangle.

small slots.

4.3 Soil and Water Test Tanks

Three tanks 120 cm wide by 240 cm long and 76 cm deep (4 x 8 x 2.5 ft) were built as indicated by Figures 4.4 and 4.5 and Figures B1 to B4 in Appendix B. Permeable dividers were provided between each of the four sections in each tank so that the water supply to the drain tube placed in each soil chamber was identical. In this way, no tube had an adverse effect on any other tube. All four tubes were tested at once in one type of soil under the same head and drainage conditions.

A 12.7 mm thick clear pexiglass window was installed in the front end of each cell (soil chamber). The windows were bolted onto the tank wall and sealed with a thick layer of silicone around their perimeter to avoid any leakage. The windows permitted observation of the settling of the soil around the drain.

Start-up water and make-up water was supplied from the College chlorinated water supply. The water was distributed through a perforated pipe into the crushed stone at the base of the tank and between the expanded metal sheets which separate the soil chambers within the tank. A mirafi filter fabric was draped over the permeable dividers between the soil chambers to keep the soil separated from the crushed stone. Water flowed easily through the crushed stone to give the same energy head all around each soil chamber within a tank. The head was kept constant for any one test run by allowing a small continuous overflow at the head selected for the test run. A collection pipe, tank, pump and

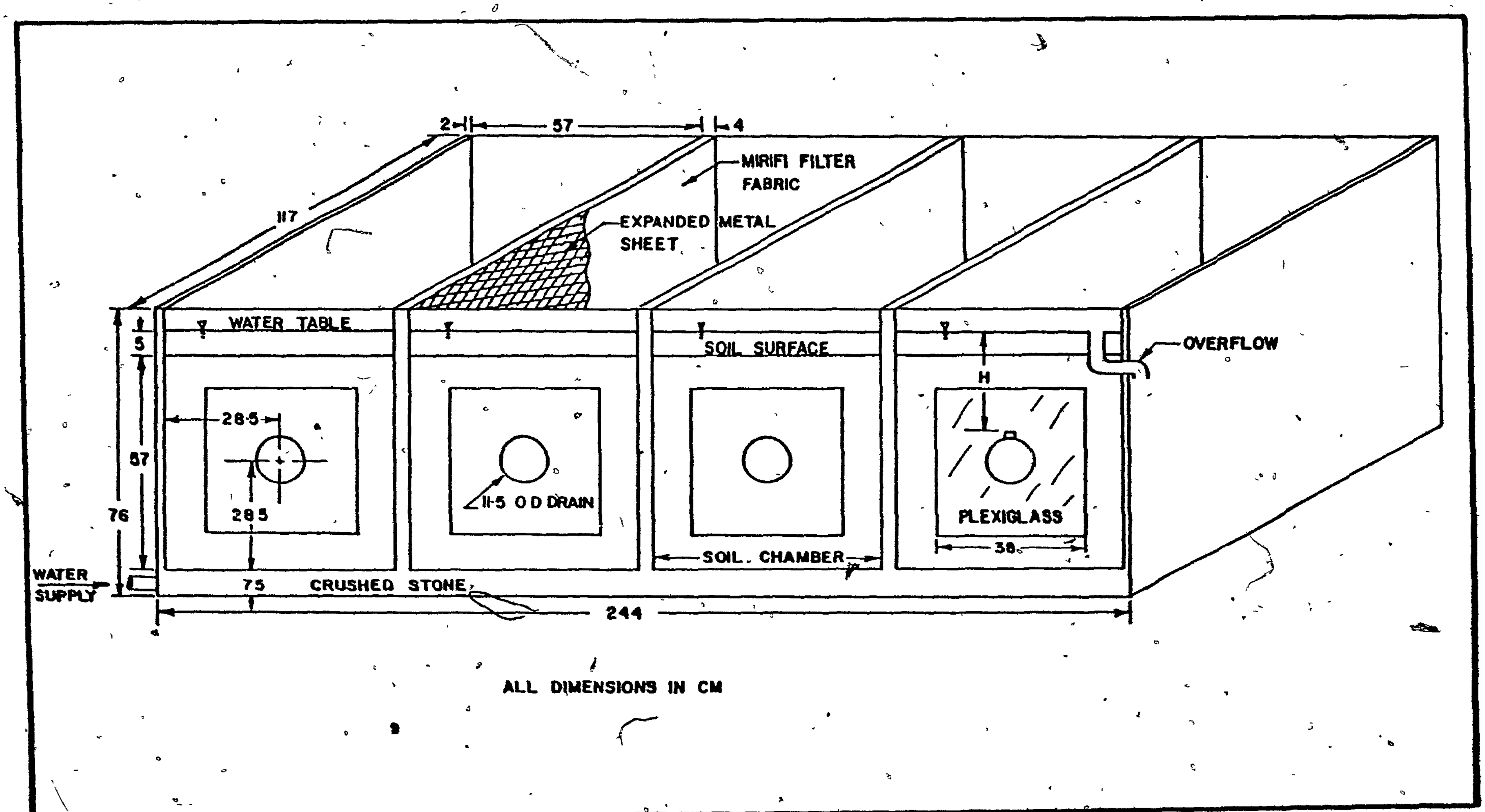


Figure 4.4. Soil and water tank for drain tube tests.

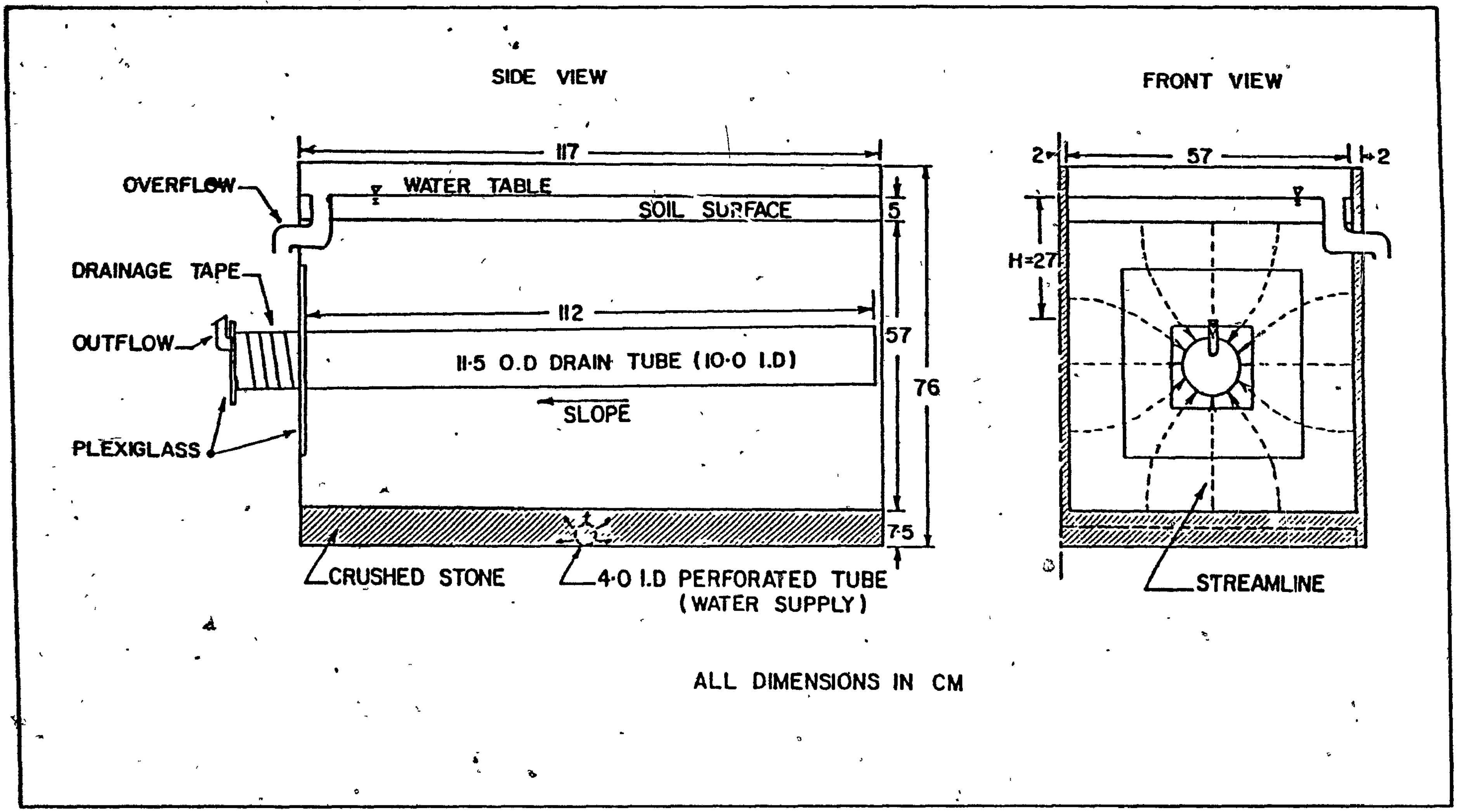


Figure 4.5. Details of one tank cell.

head tank was incorporated to recycle the drainage water. This recycling kept the test water at room temperature and avoided the use of cold high-pressure supply water with air in solution.

As can be seen from the photographs in Appendix B, the outflows from each drain tube passed through a conical filter so that any sand and coarse silt flowing out with the drainage water could be trapped. Most of the clay particles flowing out of the drain will pass through the conical filter unless a fair amount of sediments deposit at the bottom of the filter, thus sealing it.

The test tank dimensions were chosen to give:

1. A reasonable length of tubing to give representative inflow conditions with a minimum of uncertain boundary effects.
2. A width of soil sufficient to give nearly radial streamlines approaching the drains, as could be expected in the field when drainage occurs. The width of 57 cm used for each cell is nearly five times the tube diameter. This is about equal to the trench width created by wheel trenchers currently being used for installing drain tubes. It is also a width sufficient to give reasonable space for working around the drain tubes, placing drains and soil.

4.4 Procedure

Before placing it into the tank, the soil was air-dried to a moisture content suitable for soil manipulation. The soil was sieved through a 4 mm square grid screen mesh to control the maximum size of aggregates for a more uniform compaction. The tanks were filled to drain level with soil by repeatedly placing a 50 mm layer of soil into the tank, lightly tamping the soil with a 15 kg concrete block and scratching the soil surface with a rake. At drain level, a groove was made with a 11.5 cm outside diameter smooth PVC pipe. This was almost the same as the corrugated drain tubes which were 11.6 cm O.D. The tubing was then installed with a 1.0 percent slope towards the outlet and soil was packed around it. Care was taken to fill up all voids between the drain and the surrounding soil. An end cap was taped onto the extremity of the tubing inside the soil chamber. In this way, only the perforations around the drain would participate in the drainage process.

The junction between the drain and the plexiglass wall was sealed with a layer of silicone applied all around the drain. The silicone was allowed to dry for 24 hours. The drain extended 10 to 15 cm from the window. The extension was covered with drainage tape, thus preventing water from flowing through the perforations (see Figure 4.5).

The tank was filled with soil to within 11.5 cm of the top. Water was slowly introduced via the lower inlet. This allowed the soil air to escape upward to the atmosphere as the soil became saturated. During test runs, a constant ponding depth of 5 cm was kept above the soil surface via the overflow. This overflow level was set to provide a hydraulic gradient condition near the drain which would be close to that which occurs in the field after a rainy spell, which brings the water table in the soil about 30 cm above the drain level near the drains.

The three tanks were used simultaneously and the Ste. Barbe, Ste. Sophie and Bainsville soils were first used. The first test run was made with the drain outlet open so there was air above the water in the drain tubes. Since the tubes were only receiving water along a 112 cm length, they would not be flowing full as field drains 500 m long might be. It was then decided to operate the remaining runs with the drain tubes full of water outflowing at a level just above the top of the tube at the outlet end. This gave a reproducable condition of full tube flow, no air in the tubes and radial seepage through the soil to the drain tubes.

This condition occurs in the field at times of maximum drainage rate when the drains are surcharged and water is entering the tubes all around their circumference. To achieve full flow, square end caps made of 6.3 mm thick clear pexiglass, 16.5 cm on one side were glued to the outlet with silicone. A concrete block held the end caps in place from below until the silicone dried 24 hours later. A 2 cm inside diameter PVC elbow tube pointing upward from the end cap allowed outflow, as shown in Figure 4.5.

Outflow from the tube was measured once or twice a day for 9 to 39 days. Two cycles were run for most of the experiments. Between cycles and at the end of each test, the tank would be drained from the bottom outlet through the perforated pipe lying at the base of the tank. To avoid any loss of fine sediments through the mirafi fabric draping the dividers, the plug at the entrance of the bottom outlet was kept in place but open a little to allow slow drainage of the tank. At the same time, this reduced soil disturbance in the cells. A period of rest of one to three days was allowed between cycles.

After the soil had drained at the end of a run, it would be allowed to dry for a few days until adequate for sampling. A fan would be used to dry the top few inches of soil when testing with the finer soils. Three soil core samples per cell were then taken above and below drain tube level to measure the soil dry bulk density. Soil samples were also taken from each cell 3 to 5 cm below the soil surface and above the drain for particle size analysis. All samples, including the core samples were taken equally spaced along the drain length. The drain tubes were carefully removed from the tanks and allowed to dry at room temperature. Three samples of the soil immediately adjacent to the outside walls of the tubing were collected, dried and analyzed for particle size distribution as well as the soil that had collected inside the drain. Particle size analyses consisted of the sieving method, the hydrometer method or a combination of both as described in Lambe (1951). All the soil was then removed from the tanks and prepared, as described above, for the next test run.

A new set of tubings was used for each run when possible, otherwise the same tubing was used again after cleaning from the inside and outside with a brush and a jet of water. Care was taken not to damage the perforations. To make sure all perforations were not clogged, they were viewed through a light. Any remaining clogged openings were then cleaned until the tube was completely free of soil.

4.5 Piezometric Installations

To study the hydraulic head distribution in the soil around the tubings, piezometers were installed above, below and on each side of the drain, at radial distances of 1, 3, 6 and 10 cm away from the outside wall of the drain. In total, 16 piezometers were installed in each cell. The piezometers consisted of 6.3 mm outside diameter by 3.2 mm inside diameter copper tubings, 25 mm long. They were drilled inside the plexiglass window and installed flush with the inside wall. Epoxy was put around the copper tubes to hold them tight. A small piece of filter fabric was inserted into the copper tubings to prevent soil particle migration into the piezometers.

Two manometer boards were mounted for each pair of drains in the wall area available between the plexiglass windows. 6.3 mm I.D. tygon tubing was used to connect the bottom piezometers to these boards (see Figure B4). The zero reading was set at the bottom of the drain. A tygon tubing extending from the piezometers on each side and above the drain, was held upright by a clamping device installed on top of the tank. For the last three sets of piezometers, the hydraulic head was read from a board installed above the window. The board started reading at elevation 250 mm which coincides with a zero reading at the bottom of the drain. If the water level inside the tygon tubing was lower than the 250 mm mark, the difference was read with a ruler and substracted from 250 mm to obtain the hydraulic head.

Later on when time permitted, the manometer boards were redesigned by Mashallah (1987) so that all 32 piezometers from two cells were connected to one board only.

To avoid the formation of air bubbles inside the piezometers, the tygon tubes were filled with water from the top and water was allowed to flow in a reverse condition. This was done just after the water level in the tank ponded above the soil surface. Checks were often made while the test was running. Any entrapped air would be removed by either gently tapping the tygon tubing so as to move the bubble upward to the atmosphere or by unplugging it from the copper tubing and repeating the reversed flow described above. Readings were taken once a day and one day after a cycle had begun.

4.6 Experimental Design

The five soils used in this research were analysed separately as they present different characteristics and come from different fields under different boundary conditions. Thus, for each soil type, the experimental design would consist of a randomized complete block experiment with four levels of treatment for the four types of drain tubes studied. The number of runs for each soil type would determine the number of blocks. The different runs were not considered as simple replicates. Indeed, reusing the same soil from one experiment to the other and inflicting a rough treatment on the soil (i.e. shovelling, drying, sieving, etc...) might have an effect on the various levels of responses studied. If such an effect does exist, it might be sequential and thus, the runs were considered as representing the blocks with a gradient in the direction of the number of runs.

When samples are taken at different locations or the experiment consists of two cycles, the data are analyzed according to the split-plot model. A multivariate analysis of variance was used to determine if differences existed between the collected soil samples. The particle size distribution was divided in fractions used by the USDA classification with the exception that the silt fraction was divided into coarse (0.02 to 0.05 mm) and fine (0.002 to 0.02 mm); a combination of both the USDA and International classifications. Each fraction was treated as a variable. The variables so generated are not independent and thus the analysis is reduced to a multivariate problem. One of the fractions can, however, be computed by substracting the sum of all other fractions from the total. Therefore, the upper fraction of the particle size distribution which was not considered to be so critical, was not included in the multivariate analysis. That is, for the Ste. Sophie fine sand, the very coarse fraction was not included in the statistical analysis, whereas, for the Ormstown silt loam soil, the fine sand fraction was rejected.

Unless otherwise specified, only the runs with the tubes flowing full were considered for the statistical analysis as there was only one run with the tube outlets open.

V. RESULTS AND DISCUSSION

5.1 Some Clarifications

The number of runs and treatment applied to the four tubes tested are given for each soil type in Table 5.1. The number of runs was not the same for all five soils for several reasons.

There was only one test run with the Ste. Barbe medium sand (MS) as this soil produced very high flowrates and showed no sedimentation problem. Tests with the Ste. Barbe MS soil were then stopped and the tank was used to analyse other soil types. The decision to change the flow conditions from open drain tube outlets to submerged outlets to simulate full pipe flow occured during the second run with the Ste. Sophie fine sand (FS) and Bainsville very fine sandy loam soils (VFSL). Thus, end caps were installed at the extremity of each drain tube without stopping the experiment. The installation did not prove successfull and the second runs had to be ended a few days later.

The Ste. Sophie FS soil also produced very high flowrates and almost no sedimentation. However, beacuse this soil gave a lot more problems than the medium sand, more tests were carried out to confirm the drain performance.

A minimum of three runs with the tubes flowing full were to be carried out for the Ste. Sophie FS, Soulanges fine sandy loam (FSL), Bainsville VFSL and Ormstown silt loam (SiL) soils, depending on how much variations there was between runs. Six runs were carried out with

Table 5.1. Number of runs and treatment applied to the tubes tested in each type of soil.

Soil Type	Ste. Barbe Medium sand	Ste. Sophie Fine sand	Soulanges Fine sandy loam	Bainsville Very fine sandy loam	Ormstown Silt loam
Run No.	Flow conditions - Test days - cycles				
1	O - 19-2	O - 11-1	F - 39-2	O - 9-1	F - 36-2
2		O-F -	F - 8-2	O-F -	Fp- 30-2
3		Fp- 39-2	F - 17-2	F - 39-2	Fp- 19-2
4		Fp- 23-2	Fp- 23-2	F - 25-2	Fp- 10-2
5		Fp- 23-2	Fp- 27-2	F - 24-2	
6			Fp- 29-2		

O = open outlet
F = full flow with submerged outlet.
O-F = run 2 stopped and rejected due to change in treatment from open to full flow.
p = piezometer readings taken in that run.

the Soulanges FSL soil and four with the Ormstown SiL soil to bring up to three the test runs with piezometric observations. Only two out of the three tanks that were built, had piezometric installations. Therefore, no piezometric observations were taken for the Bainsville VFSL soil.

5.2 Drainage Rates

5.2.1 Some comments about the shape of drainage curves with time

The measured daily discharge rates are given in Figures 5.1 to 5.10 for all soils tested. The discharge rates are given in mL/s for the 1.12 m of perforated tubing in the tanks and in mm/d for drains placed 20 m apart. A spacing between drain laterals of 20 m and a drainage rate of 9 to 14 mm/d would be considered by many persons to be in the right range for a fine sandy loam soil used for growing corn or beans in eastern North America.

A glimpse at all these figures reveals that, except for the Ste. Sophie FS soil, the drainage starts, in general, at a high rate shortly after the flow begins and decreases gradually over a few days until a nearly constant rate is achieved. In the second cycle, the drainage starts off at rate slightly lower than at the end of the first cycle except for some cases when it would be higher.

The decrease in drainage rate may be due to some rearrangement of soil particles near the drain tubes as drainage progresses. If smaller particles were shifting a little to block spaces between larger particles, the flow rate would decrease, and the hydraulic gradient near

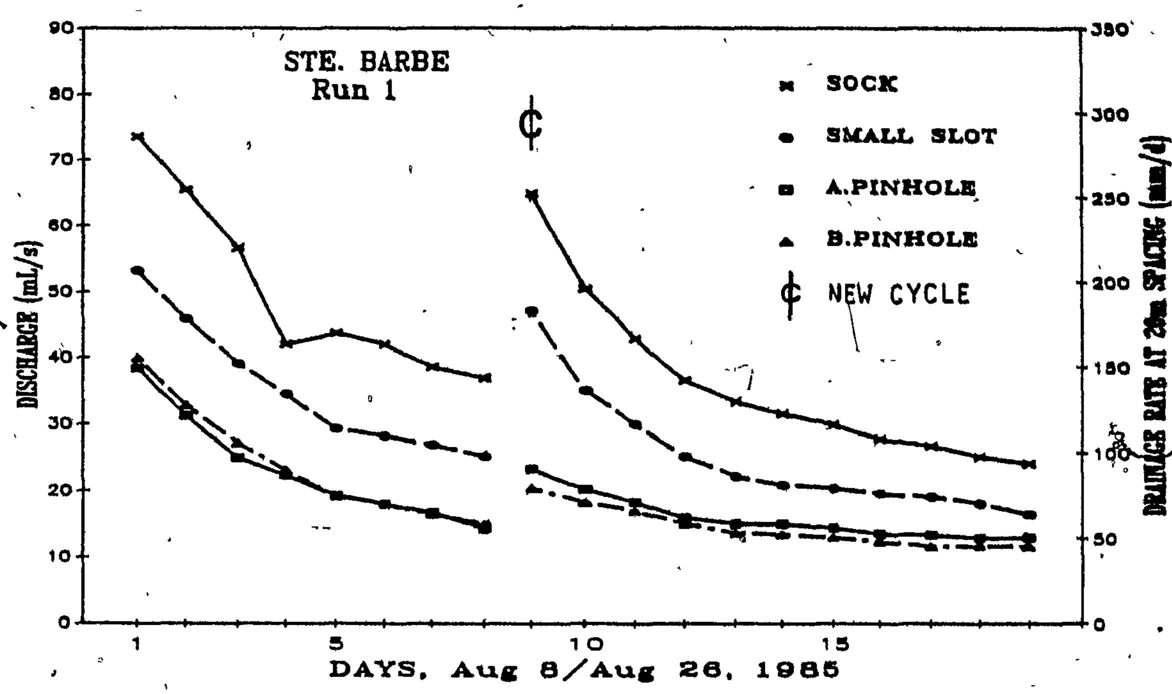
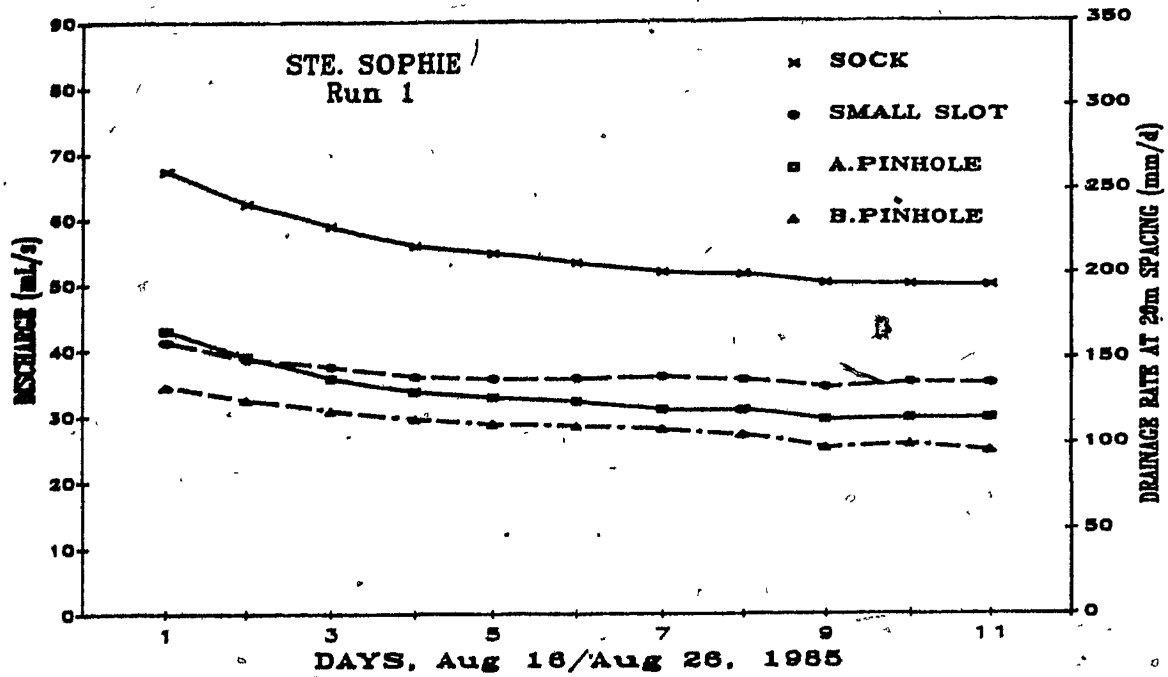
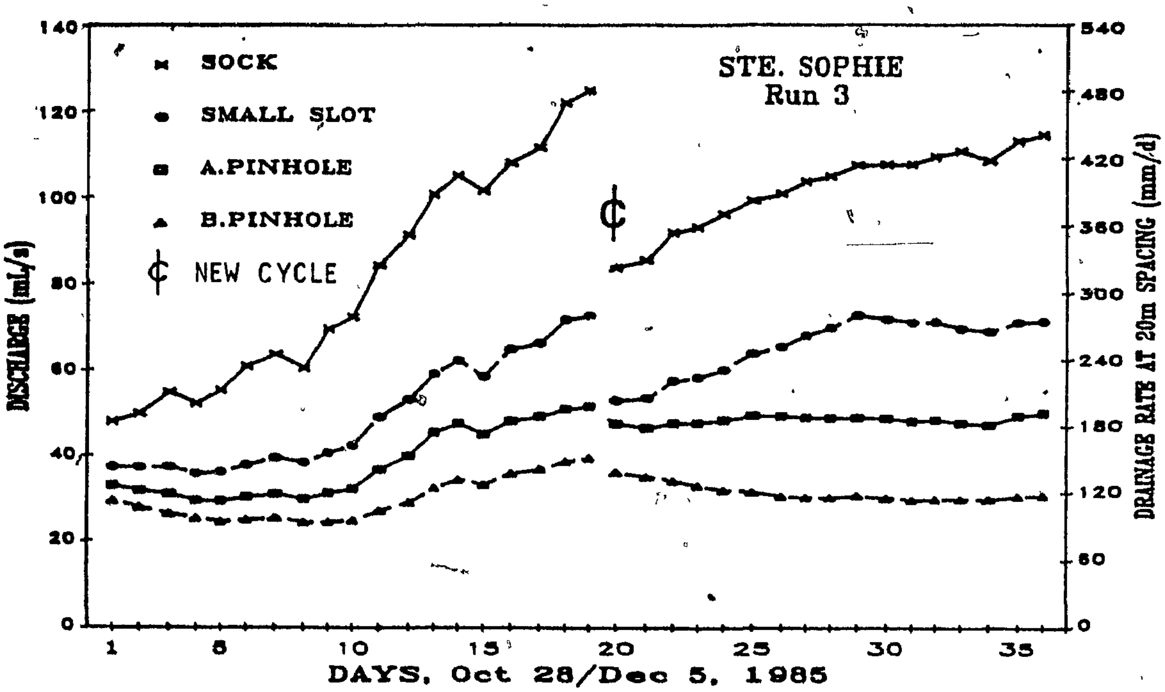


Figure 5.1. Discharge and drainage rate versus time in run 1 with the Ste. Barbe medium sand soil.

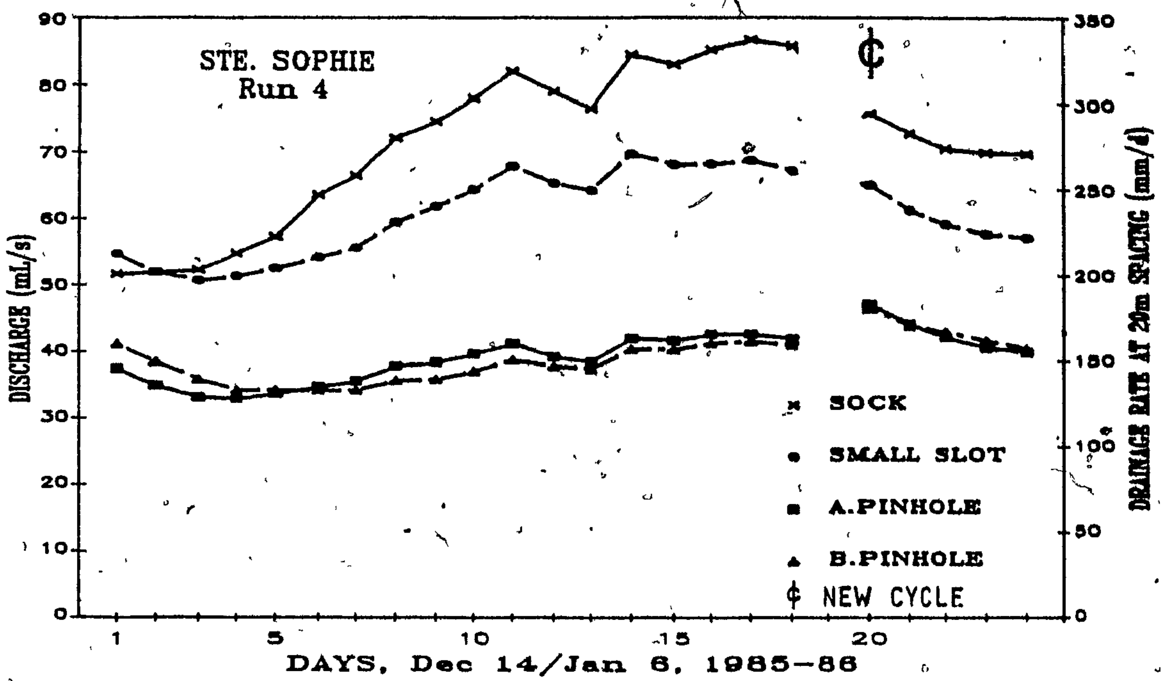


(a)

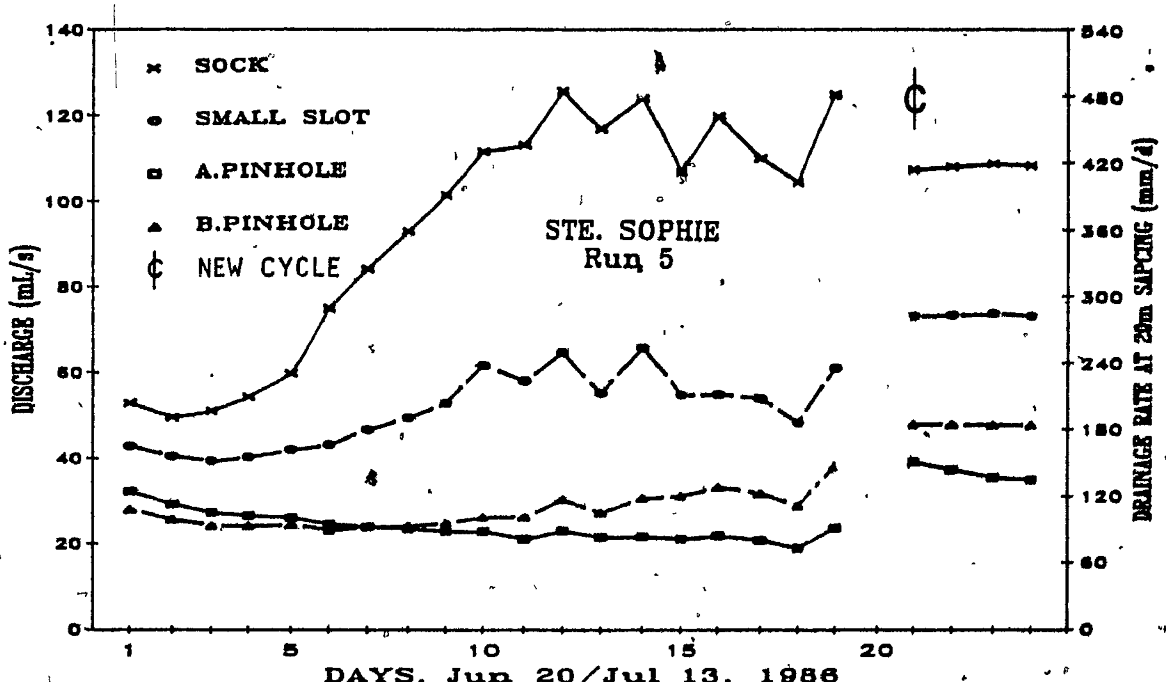


(b)

Figure 5.2. Discharge and drainage rate versus time in (a) run 1 and (b) run 3 with the Ste. Sophie fine sand soil.

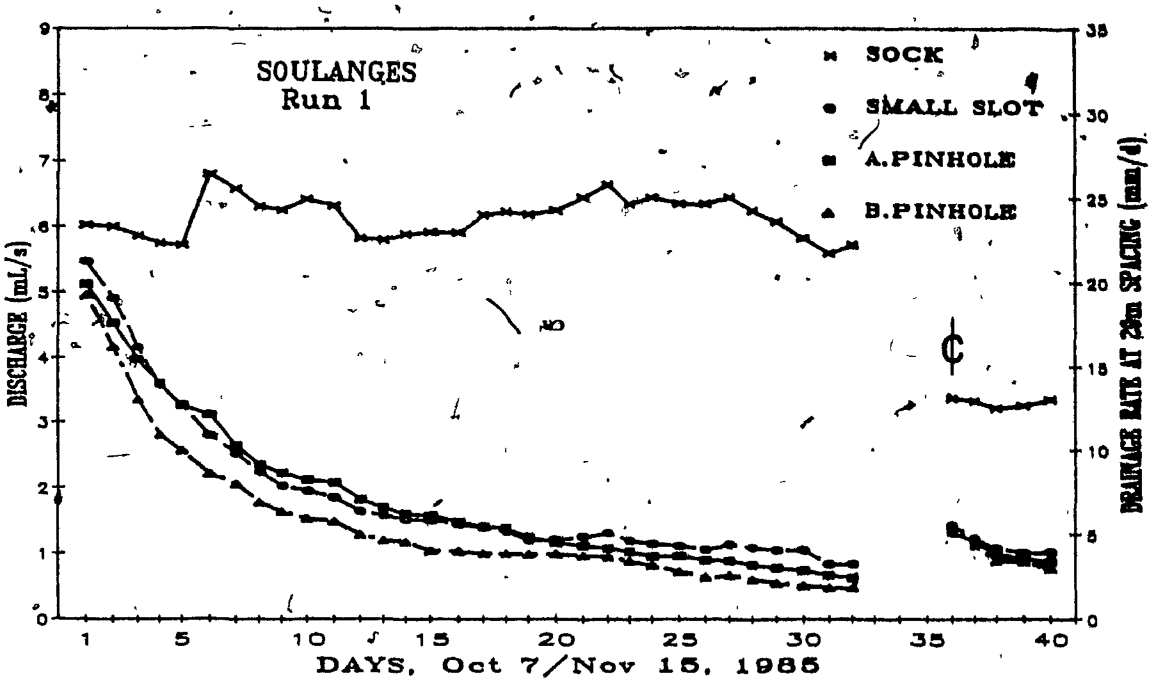


(a)

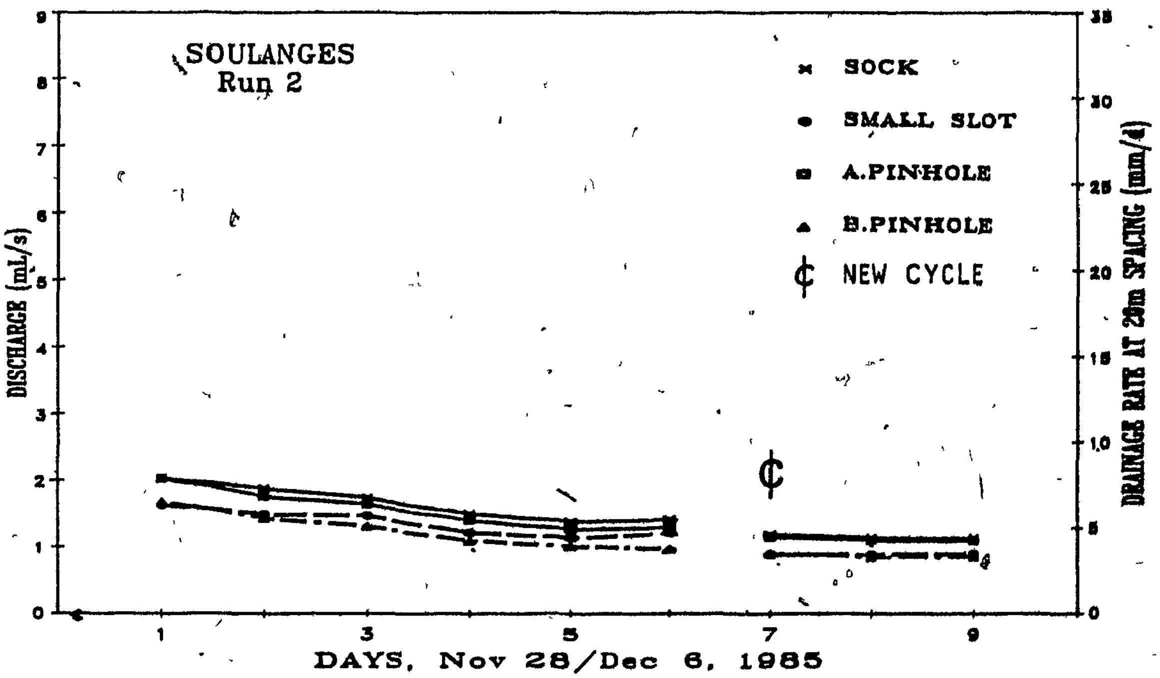


(b)

Figure 5.3. Discharge and drainage rate versus time in (a) run 4 and (b) run 5 with the Ste. Sophie fine sand soil.

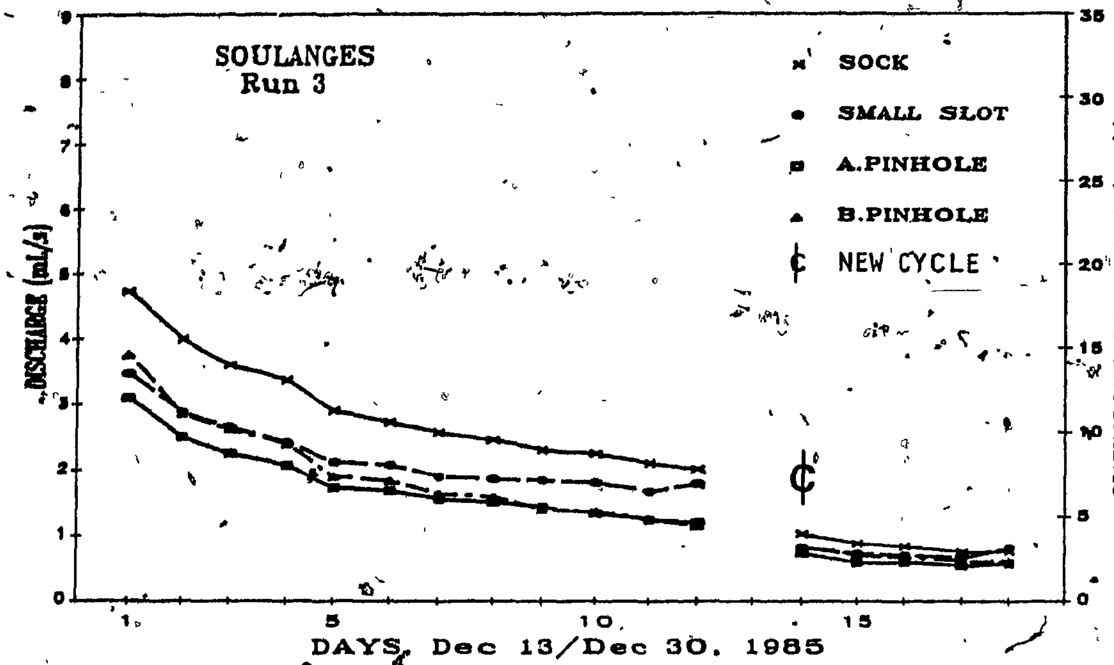


(a)

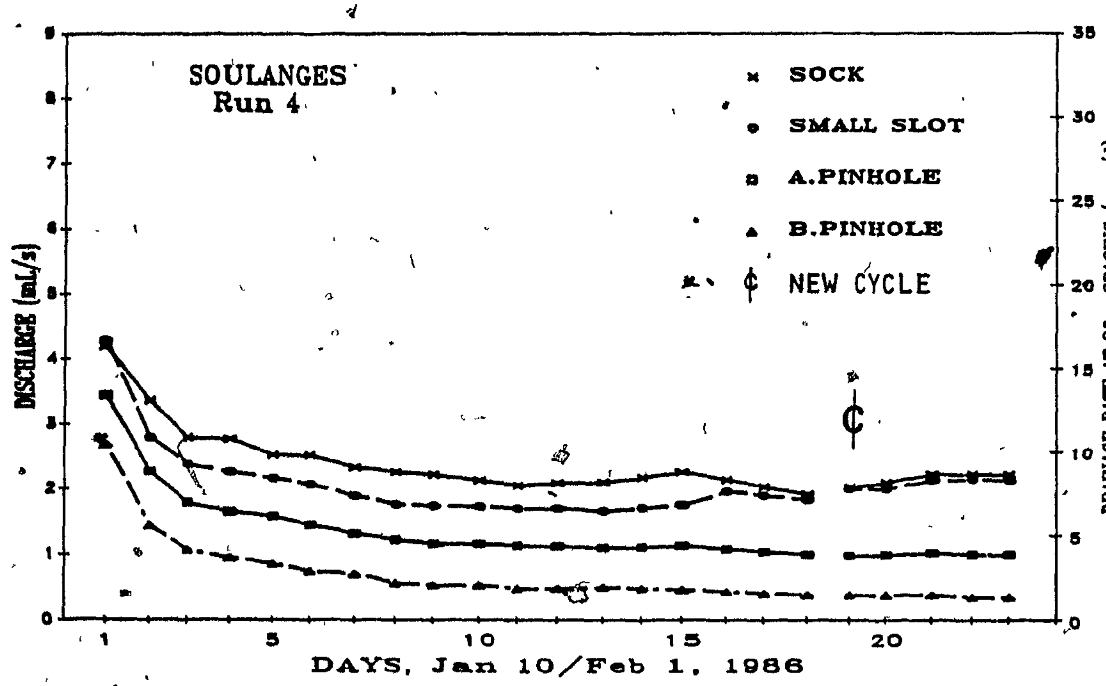


(b)

Figure 5.4. Discharge and drainage rate versus time in (a) run 1 and (b) run 2 with the Soulanges fine sandy loam soil.

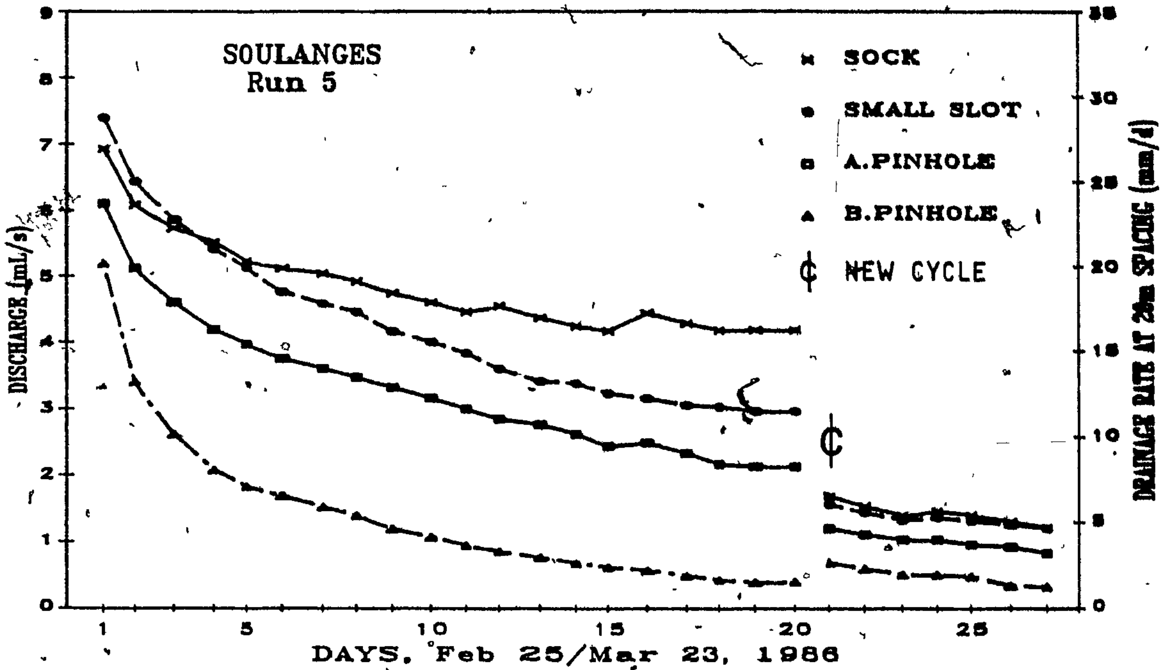


(a)

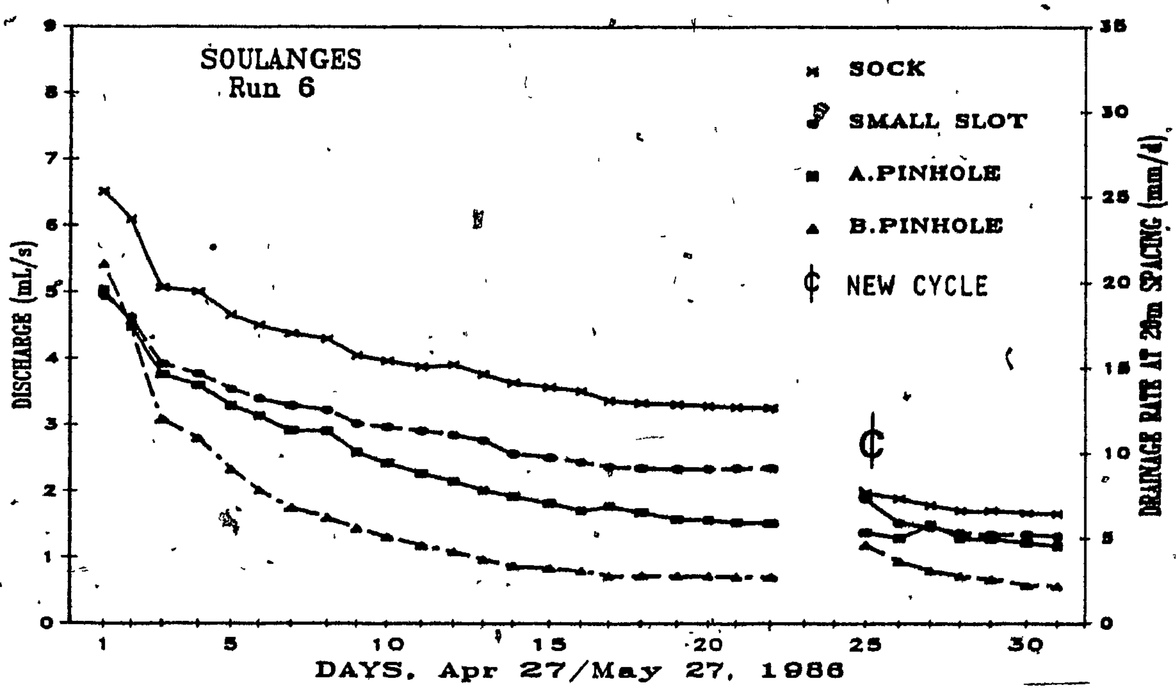


(b)

Figure 5.5. Discharge and drainage rate versus time in (a) run 3 and (b) run 4 with the Soulanges fine sandy loam soil.

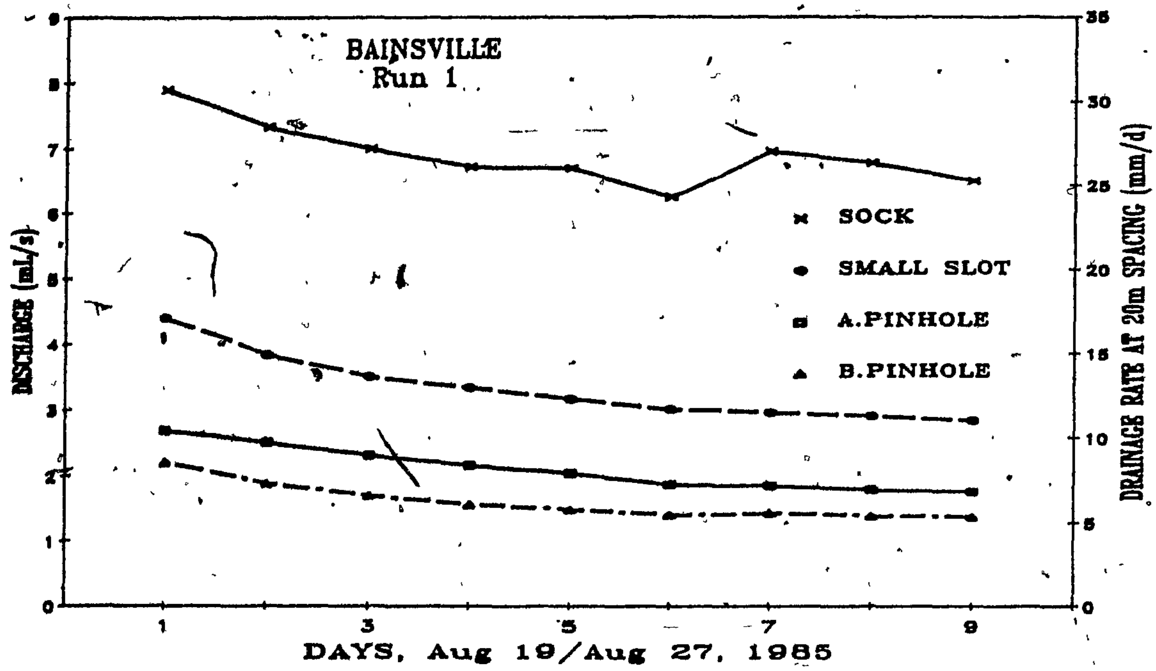


(a)

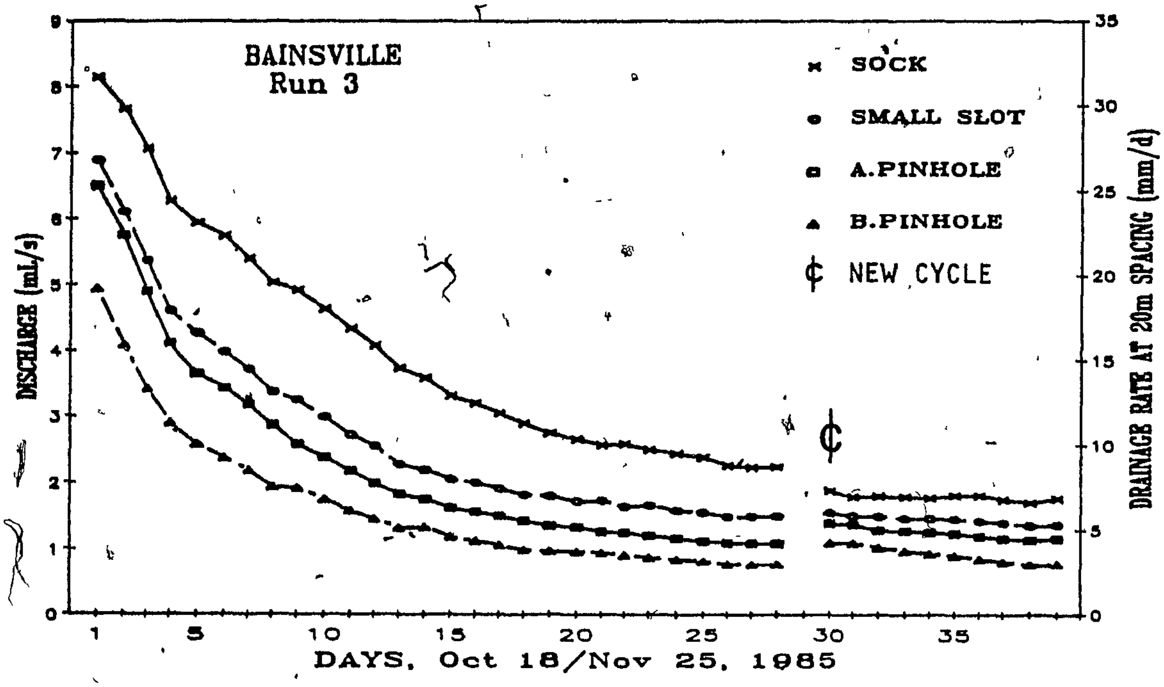


(b)

Figure 5.6. Discharge and drainage rate versus time in (a) run 5 and (b) run 6 with the Soulanges fine sandy loam soil.

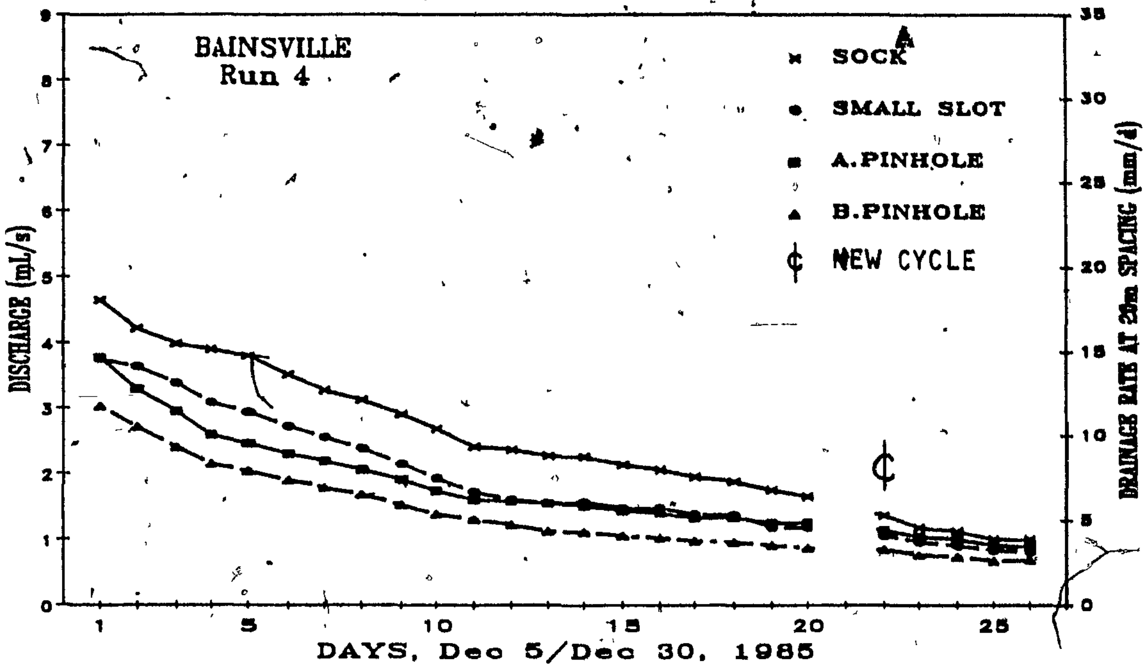


(a)

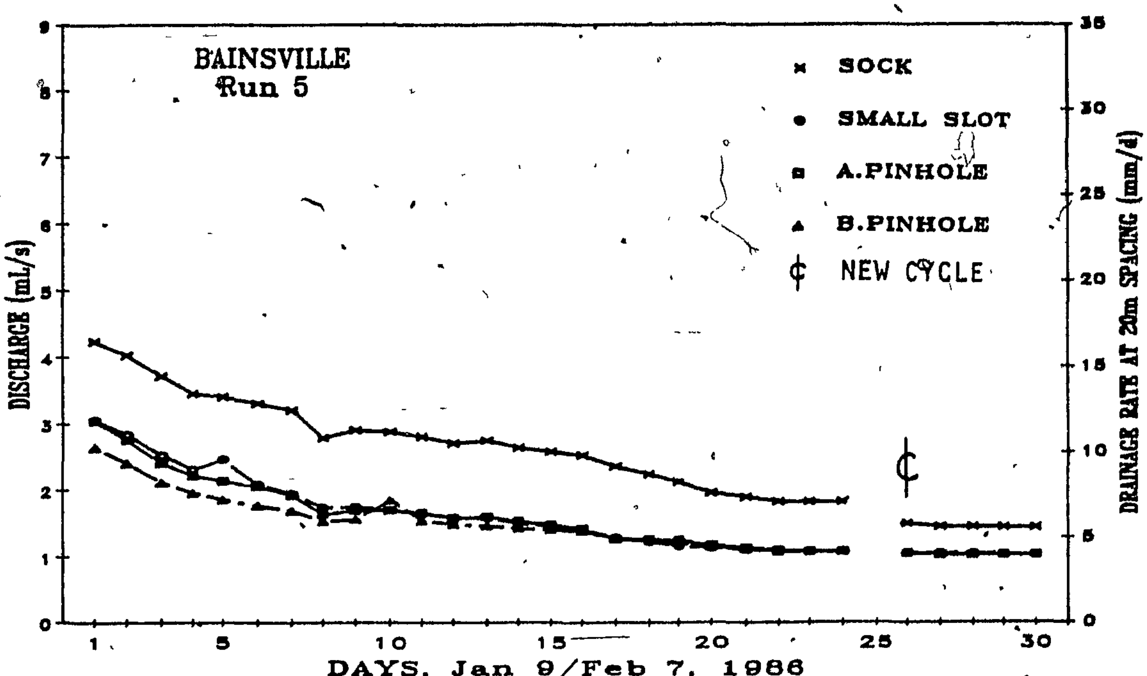


(b)

Figure 5.7. Discharge and drainage rate versus time in (a) run 1 and (b) run 3 with the Bainsville very fine sandy loam soil.

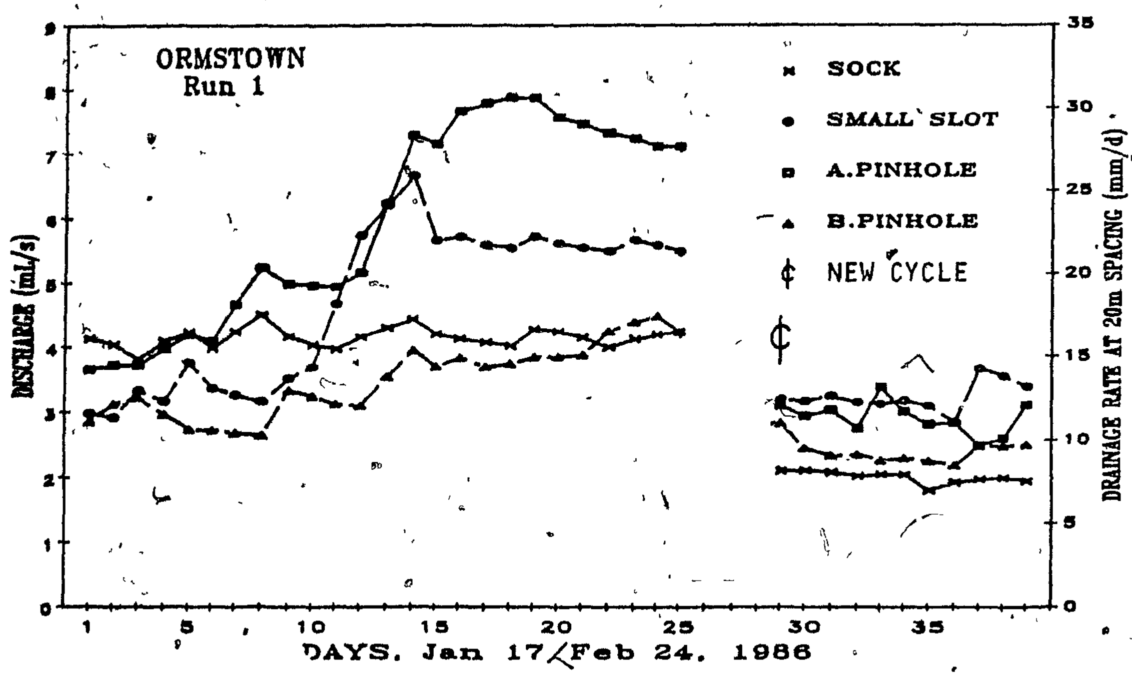


(a)

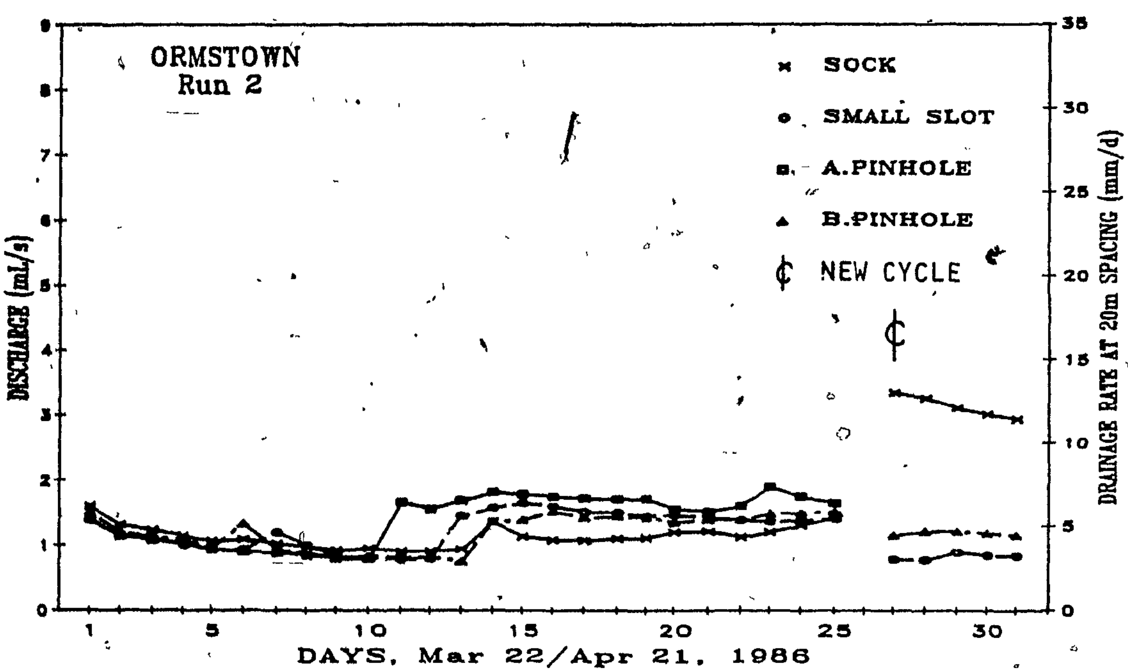


(b)

Figure 5.8. Discharge and drainage rate versus time in (a) run 4 and (b) run 5 with the Bainsville very fine sandy loam soil.

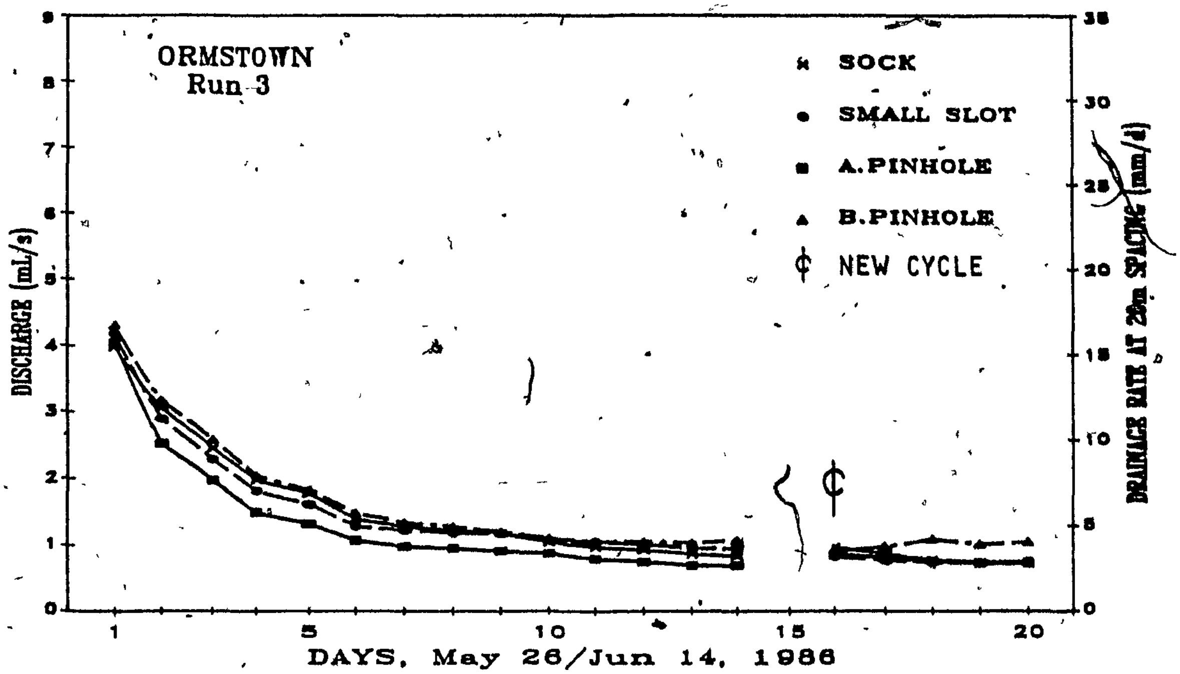


(a)

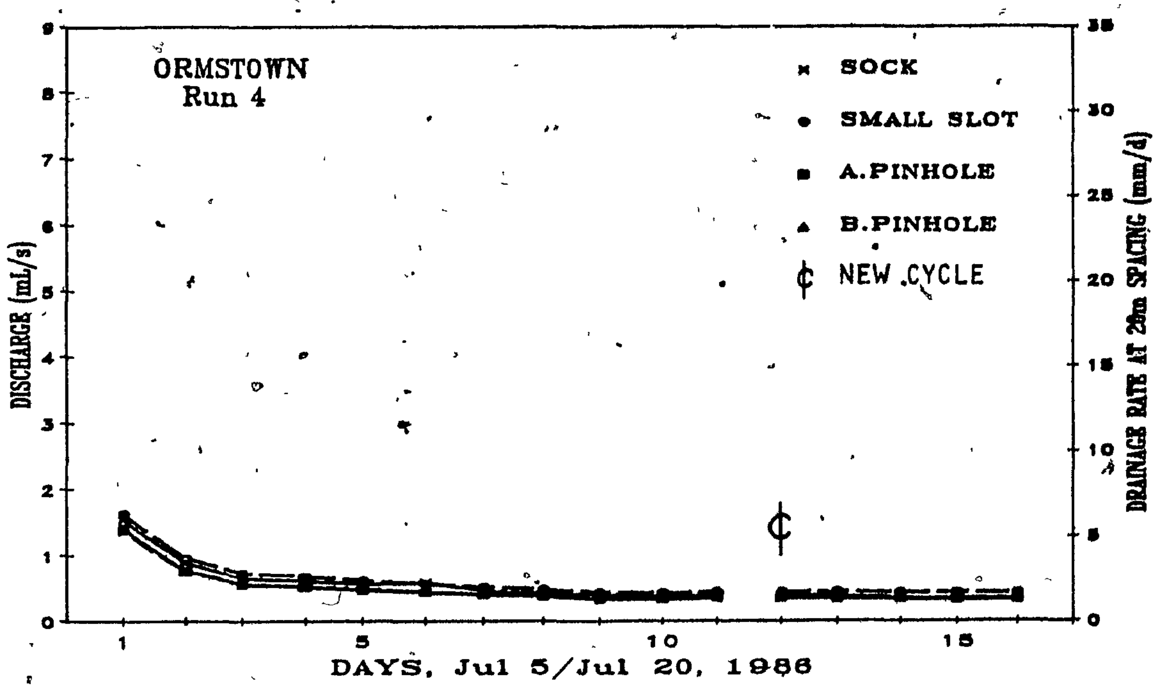


(b)

Figure 5.9. Discharge and drainage rate versus time in (a) run 1 and (b) run 2 with the Ormstown silt loam soil.



(a)



(b)

Figure 5.10. Discharge and drainage rate versus time in (a) run 3 and (b) run 4 with the Ormstown silt loam soil.

the drain tube would increase tending to pack the soil particles even tighter, and further reduce the flowrate. An increase in flowrate would indicate that the critical hydraulic gradient was surpassed and that some of the particles bridging on top of the opening would have passed through the opening or moved away from the opening.

There was no evidence of microbial growths near the drains causing blockage and reducing flow rates. Also, using the recycled drainage water, no air bubbles were found to develop in the soil mass. Therefore, it is not thought that the soil permeability was being reduced by air coming out of the supply water.

It can be seen from Figure 5.1 that the first cycle with the Ste. Barbe MS was ended only eight days after the start of the test even though steady-state was not reached yet. Actually, the discharge stopped due to an interruption in the laboratory water supply. When flow was re-established the day after, drainage started at a rate higher than the previous day and gradually decreased and stabilized. Overall, the drainage rates remained higher than needed for farm drainage.

Interestingly, the Ste. Sophie FS soil behaved differently from the other soils. The drainage rate decreased slightly with time in the first run (Figure 5.2a). But, as can be seen in Figures 5.2b and 5.3 for runs 3, 4 and 5, the flow generally decreased in the first five days and increased with time till the end of the first cycle. With a limited rate of water supply to the tank, the first cycle was ended the number of days indicated on the graphs. In the second flow period though, the flow decreased or stabilized very rapidly.

It could be that in the first few days of the flow period, a flow restricting layer of soil (filter cake) develops as explained above. However, some of the finer particles would be washed out of the soil into the drain, disrupting the particle-bridges forming on top of the openings and thus, increasing the permeability of the filter cake. A small amount of sediment did enter the tubes but not enough to cause a sedimentation problem. With less than 2% of the soil particles being smaller than 0.074 mm (Figure 4.2), only a few particles would find their way through the tortuous voids towards the drain openings. Hence, most of the collapsed bridges would take a long time to re-establish.

Nevertheless, even though the results obtained were quite peculiar, it is seen from Figures 5.2 and 5.3 that all four tubes tested gave adequate drainage rates. Evidently, drain tubes could be placed at spacings much larger than 20 m in fine and medium sandy soils similar to the Ste. Sophie FS and Ste. Barbe MS soils.

Referring to Figures 5.4 to 5.10, the discharges are decreasing with time as could be expected. The decrease in flowrate might be due to some rearrangement of soil particles. In these cases, even if some particle-bridges collapse due to hydraulic gradients greater than the critical gradient, the percentage of fine particles present in these soils is so high that the empty spaces are quickly refilled. The distribution of these particles ranging from fine sand to silt is such that they help in establishing a dense and gradually less permeable cake around the drain. The tubes are draining at a much slower rate than with the coarser sands as the soils are less permeable. The drainage rates in all tests for the Soulanges FSL (Figures 5.4, 5.5 and 5.6) and Bainsville VFSL (Figures 5.7 and 5.8) start out at 10 to 25 mm/d but decrease with time till they level off at 3 to 10 mm/d in the first cycle, for the tubes with pinhole and small slots. The tube with the knitted polyester envelope gave drainage rates approximately twice those provided by the pinhole pipes. The enrobed tube did not produce decreasing flowrates in the first run with the Soulanges FSL (Figure 5.4a) soil but stabilized around the 24 mm/d mark. In this case, the fabric retained most of the sediments from the start and allowed only a small fraction to pass through.

The first run with the Ormstown SiL (Figure 5.9a) gave a drainage curve similar to the one observed with the Ste. Sophie FS soil. A nearly steady state was not achieved until 15 days after drainage had started. The batch of soil used for this experiment was collected from the field in October 1985 and it was not until January 1986 that the first run was started. At that time, the soil presented some structure with small aggregates and many loose silt particles. The free silt fraction combined with the small aggregates, would require some time to establish a stable cake around the drain. When drainage initially starts, many of the loose silts would pass through the drain openings and increase the permeability of the soil layer around the drain. Flowing water will bring in more sediments to fill up the voids. However, with virtually no free sand particles to stabilize the filter cake in a short time, the silts will be washed out making the cake even more permeable. With time, the travelling particles will join small aggregates and bridge over the openings. The discharge would then reach a plateau as shown in Figure 5.9a.

The normal slotted tube with the sock envelope in the Ormstown SiL did not allow much sediments to pass through and the soil layer around the drain had a nearly constant hydraulic conductivity. The drainage rates in the subsequent runs decreased with time (Figures 5.9b and 5.10). The preparation of the soil before each test run affected the soil structure to give larger temporary aggegates and less loose particles, as was qualitatively assessed. In compacting the soil in the tank, the larger aggregates were destroyed to give a massive type of structure. In this way, the permeability of the soil was decreased. This process prevented most of the soil particles from being washed out. Indeed, the sediments found in the drains were approximately 10 times less than obtained in the first run. Also, the difference in flowrates obtained between all four tubes in runs 2, 3, and 4 was very small and almost negligible in both cycles.

Broughton et al. (1974) tested several filter envelope materials for corrugated plastic drain tubes using horizontal cylindrical containers. The authors reported observing an increase in flowrate for up to 20 days for some of their products, but this increase was followed by a decrease in flow till the end of the runs. They also found that the flowrates in the early days of the second flow period were always higher than in the first one. This was not always the case in the present work. This increase in flowrate in the second cycle will not always occur as the destruction of the filter cake around the drain between cycles is aleatory and takes place at random places along the length of the drain.

It would certainly help to know that such a recovery occurs after every period of no flow. However, the reverse would not indicate an unacceptable product. Indeed, we are dealing in this case, with envelope-free tubings which have already been used commercially with some degree of success. Thus, for a conclusive statement to be made in this respect, field tests should be carried out. Furthermore, the sock envelope which had failed, in most cases, to show such a recovery in this research, is widely used in subsurface drainage systems with great success. When this fabric envelope would fail in the field, it is most of the time due to the fabric being damaged, or to installation in soils finer than the fabric was designed for (Papineau, 1985).

5.2.2 Statistical results on steady-state drainage rates

The mean steady-state drainage rates obtained in all tests are presented in Table 5.2 for each cycle. A minimum of 3 consecutive readings towards the end of each cycle were taken from the curves of Figures 5.1 to 5.10 that flattened out towards the end of the cycle. These observations were averaged to give the tabulated steady-state values. For runs 3, 4 and 5 of the Ste. Sophie FS soil (Figures 5.2b and 5.3), all observations within a cycle were used to find the average drainage rate since it was difficult to achieve steady-state. For runs 1 and 2 with the Ormstown SiL, all readings after the 16th day of drainage were used to compute the mean steady-state values.

Table 5.2. Weighted means of steady-state drainage rates obtained with an assumed field spacing of 20 m between laterals, (mm/d)

SOIL TYPE		STE. BARBE	STE. SOPHIE				SOULANGES						BAINSVILLE				ORMSTOWN			
	RUN	1	1	3	4	5	1	2	3	4	5	6	1	3	4	5	1	2	3	4
TUBING	CYCLE																			
SOCK	1	146.8	212.1	218.1	328.0	424.9	23.86	6.40	8.34	8.10	16.40	12.70	26.15	9.50	7.69	7.56	16.01	4.54	3.56	1.59
	2	95.9	**	423.9	270.0	416.4	12.75	4.46	3.02	8.34	5.18	6.51	**	6.89	4.37	5.62	7.72	11.31	2.89	1.41
	Mean	121.3	212.1	321.0	306.2	421.3	21.08	5.76	6.06	8.19	11.41	9.95	26.15	8.19	6.42	6.75	13.48	6.66	3.31	1.49
SMALL SLOTS	1	103.0	140.5	146.2	263.7	204.0	4.18	5.24	5.99	6.83	11.69	9.04	12.81	6.23	5.39	4.33	21.61	5.69	3.87	1.80
	2	70.3	**	274.2	223.6	283.5	4.45	3.46	2.88	8.03	4.94	5.20	**	5.57	3.52	4.00	12.49	3.17	2.84	1.70
	Mean	86.7	140.5	210.2	248.7	238.1	4.26	4.65	4.69	7.26	8.69	7.33	12.81	5.90	4.67	4.19	16.83	4.95	3.49	1.75
PINHOLE A	1	62.7	128.7	119.9	162.8	80.9	3.40	6.04	5.19	4.23	8.68	5.98	8.13	4.59	5.32	4.45	28.98	6.59	2.92	1.38
	2	50.8	**	187.4	157.7	144.0	4.08	4.31	2.35	3.85	3.61	4.78	**	4.79	3.84	4.00	11.24	*	1.41	1.30
	Mean	56.8	128.7	153.6	160.9	102.0	3.60	5.46	3.77	4.09	6.42	5.38	8.13	4.69	4.75	4.26	19.69	6.59	2.35	1.34
PINHOLE B	1	63.1	110.5	101.2	157.8	116.7	2.67	4.82	5.21	1.78	1.76	2.75	6.19	3.32	3.86	4.38	15.53	5.55	4.10	1.44
	2	45.5	**	116.3	160.8	182.9	3.93	3.37	2.63	1.42	1.60	2.45	**	3.54	2.86	3.99	9.26	5.24	4.05	1.36
	Mean	54.3	110.5	107.7	158.9	138.7	3.04	4.33	3.92	1.65	1.69	2.63	6.19	3.43	3.48	4.21	12.25	5.24	4.08	1.39

Sock represents normal slotted pipe wrapped with polyester stocking.
* Large void below pipe in second cycle produced very high flowrates.
** Only one cycle for this run.

A statistical analysis was carried out on all observations used to determine the weighted means shown in Table 5.2. The analysis of variance (AOV) tables are presented in Tables D1 to D4 for each soil type. A summary of the F-tests shown in these tables is indexed in Table 5.3 along with the results obtained for sediment weight. Also, results of Duncan's new multiple range tests are given in Table 5.4 for variables that showed some differences among blocks or treatments.

The effect of "run" (i.e. the reworking of the soil from one test run to the next) on drainage rate appears not to be significant for the first three soils, namely, the Ste. Sophie FS, Soulanges FSL and Bainsville VFSL soils (Table 5.3). This was to be expected for the Ste. Sophie FS as this soil has no structure whatsoever. The same statement can be made for the Ste. Barbe MS even though no analysis was carried out. Furthermore, the 8% and 5% clay content found in the Soulanges FSL and Bainsville VFSL soils, respectively, explains in part their relatively weak structure (Figure 4.3). The structure of these soils was altered by drying, sieving and compacting the soil between runs, especially between the first and second run. This alteration, however, was not severe enough to significantly affect the drainage rate at the 0.05 level. The Ormstown SiL on the other hand, with its 12% clay content had more structure initially. The rough treatment inflicted to the soil, changed its structure substantially and significantly decreased the permeability of the soil between the first and second run (Table 5.4).

Table 5.3 also indicates that "tubing" type had a significant effecton the first three soils at the 0.05 and 0.01 levels.Hence,it is

Table 5.3. Summary of F-tests obtained in the analysis of variance of steady-state drainage rates and sediment weight. (see AOV tables in Appendices D and E).

Source	Ste. Sophie Fine sand	Soulanges Fine sandy loam	Bainsville Very fine sandy loam	Ormstown Silt loam
DRAINAGE RATES				
Mainplots				
Run	n.s.	n.s.	n.s.	**
Tubing	**	*	**	n.s.
Subplots				
Cycle	n.s.	**	**	n.s.
Tubing*Cycle	n.s.	n.s.	n.s.	n.s.
SEDIMENT WEIGHT				
Run	n.s.	**	n.s.	**
Tubing	**	**	**	n.s.

n.s. not significant at the 0.05 level
* significant at the 0.05 level
** significant at the 0.01 level

Table 5.4. Summary of Duncan's multiple range tests for the steady-state drainage rate and sediment weight variables.

Source	Ste. Barbe Medium sand	Ste. Sophie Fine sand	Soulanges Fine sandy loam	Bainsville Very fine sandy loam	Ormstown Silt loam
DRAINAGE RATE (mm/d)					
Run No.					
1	n.a.	n.s.	n.s.	n.s.	a 13.6
2					b 5.2
3					b 3.0
4					b 1.4
Tubing Type					
Sock	121	a 303	a 10.8	a 6.5	
Small slot	87	b 202	b 5.3	b 4.6	n.s.
Pinhole A	57	c 126	b 4.0	b 4.1	
Pinhole B	54	c 115	b 2.5	b 3.3	
SEDIMENT WEIGHT (grams)					
Run No.					
1			a 304.0		a 55.6
2			b 139.0		b 7.7
3	n.a.	n.s.	b 96.4	n.s.	b 6.5
4			b 76.1		b 3.5
5			b 60.7		
6			b 59.6		
Tubing Type					
Small slot	52.3	a 217.6	a 237.9	a 1209.3	
Pinhole A	24.2	b 90.9	ab 159.6	b 566.1	n.s.
Pinhole B	8.5	c 13.0	bc 88.4	b 292.1	
Sock	3.1	c 4.5	c 4.5	c 15.2	

Means with the same letter are not significantly different at the 0.05 level.

n.a. not applicable; not analyzed statistically since only one run carried out

n.s. not significant at the 0.05 level

Sock represents tube with normal slots enrobed with polyester envelope.

likely that the design of the openings and the total opening area per unit length of drain have a significant effect on drainage rate. Table 5.4 shows some difference between the various tubes in the Ste. Sophie FS soil. All the pipes, however, gave adequate drainage in both the medium and fine sandy soils since the lowest mean drainage rate obtained was 54 mm/d, which is more than enough for agricultural applications.

For the fine and very fine sandy loam soils, the drainage rates were significantly higher with the tubing with knitted polyester stocking envelope than for the tubes with pinholes or small slots (Table 5.4). It appears that these tubes might need to be placed at spacings less than 20 m in fine and very fine sandy loam soils in order to achieve a design drainage rate of 9 mm/d as used in earstern North America.

Table 5.4 shows the drainage rate to decrease in the Ormstown SiL soil among runs but that only the first run was significantly different from the others. With flowrates up to 20 times the ones obtained in subsequent runs, any differences between runs 2, 3 and 4 were overshadowed by the first run. Rejecting the data from the first run, the drainage rate in run 2 was different from that obtained in the last two runs.

"Tubing" type did not seem to affect drainage rate in the Ormstown SiL soil (Table 5.3). It is thought that in these soil types with very low permeability, it is the hydraulic conductivity of the soil and not the drain opening area or the opening characteristics that controls the rate at which tiles will be draining. Thus, as long as the openings are such that they prevent most of the soil particles to pass through, a tube with pinholes or small slots would most likely drain equally to a tube with a fabric envelope similar to the one tested.

Table 5.3 indicates that "cycling" had an effect on the Soulanges FSL and Bainsville VFSL soils and that no interaction was found to exist between "cycle" and "tubing" in any of the soils. The lower drainage rates obtained in the second flow period were partly due to the settling of the soil in the chambers during the first flow period and when draining the tank between cycles.

5.3 Soil Movement into the Drain Tubes

The majority of the soil which entered the tubes stayed in the tubes as sediments until it was removed at the end of each test. The amount of sediment moving out with the drainage water, was negligible for all cases except run 1 with the Bainsville VFSL. There was qualitative evidence that most of the sediment enters the drains within the first few days of drainage each time drainage starts, but especially in the first cycle.

The dry weights of sediment found in the drain tubes are given in Table 5.5. These data have been presented in bar charts in Figures 5.11 to 5.13. The analyses of variance of sediment weight are tabulated in Appendix E for all soils but the Ste. Barbe MS soil. Also, Tables 5.3 and 5.4 summarize the results shown in Appendix E for the F-tests and Duncan's multiple range tests obtained for sediment weight, repectively.

Table 5.5. Dry weights of sediments deposited inside drain tubes (grams).

Soil Type	Run	Sock[a]	Tubing type: Small slots	Pinhole A	Pinhole B	Test days
STE. BARBE Medium sand	1	3.1	52.3	24.2	8.5	19
STE. SOPHIE Fine sand	1	3.6	129.2	61.0	22.1	11
	3	2.7	228.5	110.0	11.7	39
	4	7.8	245.0	85.3	13.1	23
	5	3.0	179.3	77.3	14.0	23
SOULANGES Fine sandy loam	1	14.2	538.2	424.4	239.1	39
	2	5.7	99.4	78.8	58.8	8
	3	1.5	124.2	72.1	40.5	17
	4	3.4	180.4	74.5	46.2	23
	5	1.2	320.6	153.9	80.2	27
	6	1.1	164.8	153.9	65.7	29
BAINSVILLE Very fine sandy loam	1	36.9	211.5	196.6	141.5	9
	3	17.3	1672.4	647.1	329.5	39
	4	6.7	985.9	597.8	308.1	25
	5	21.5	969.6	453.4	240.2	24
ORMSTWON Silt loam	1	13.2	84.5	72.9	51.3	36
	2	0.5	6.4	173.7[b]	3.7	30
	3	0.2	10.0	9.3	11.3	19
	4	0.4	9.0	8.8	8.1	10

[a] Sock represents tube with normal slots enrobed with polyester envelope
[b] Large void below drain in second cyle produced high sedimentation. Not considered for statistical analysis.

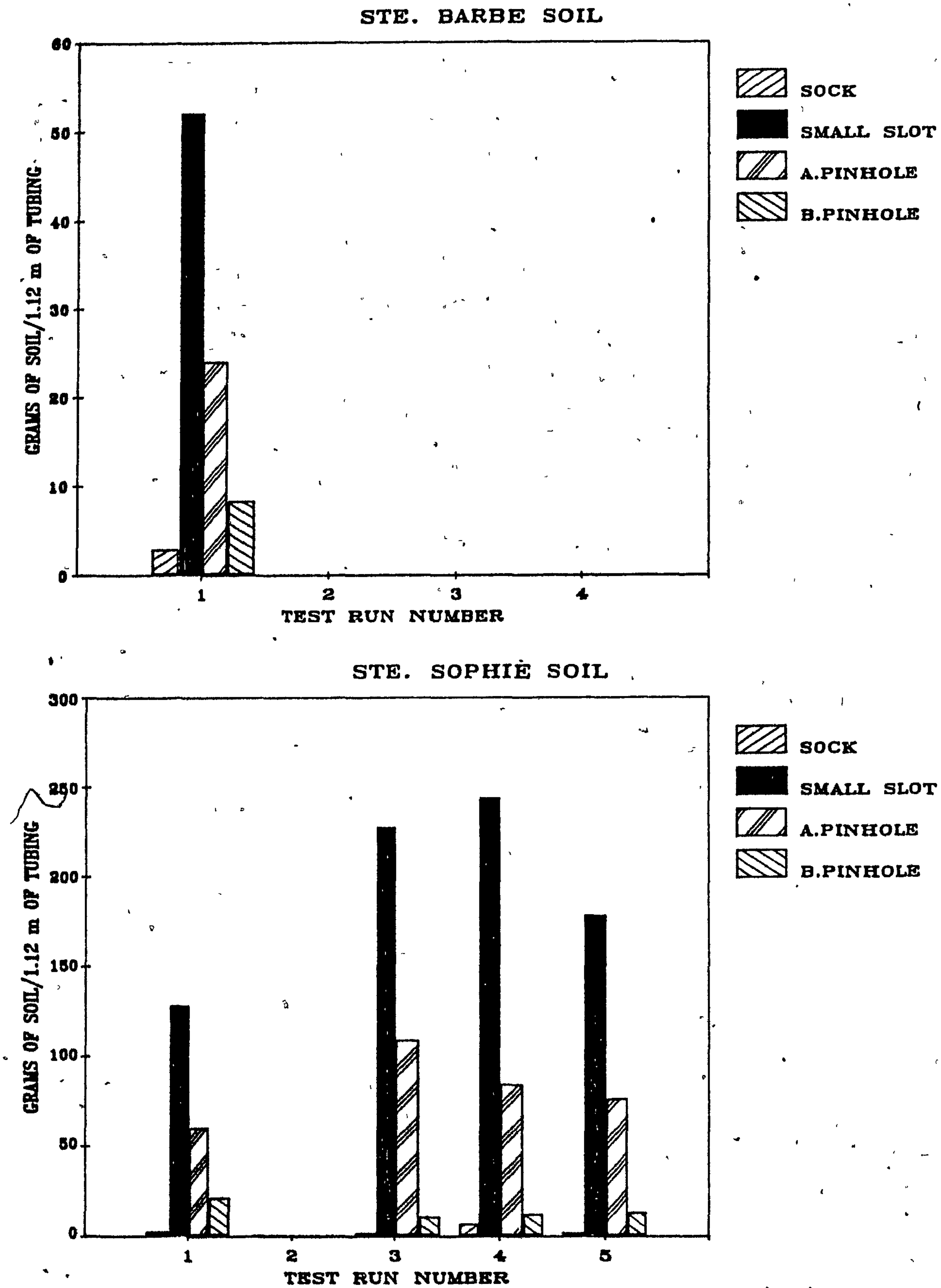


Figure 5.11. Sedimentation with the Ste. Barbe medium and (top) and Ste. Sophie fine sand soils (bottom).

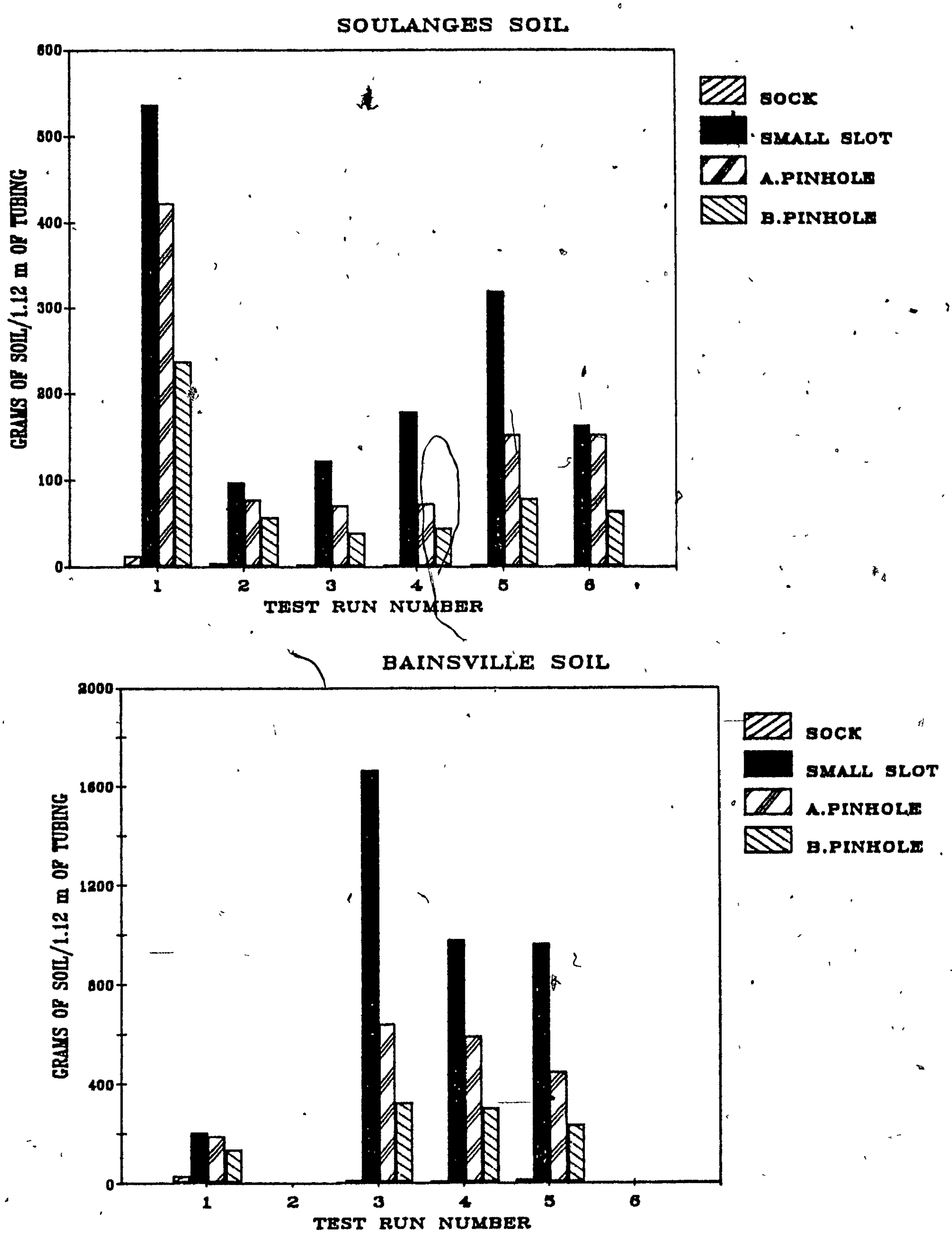


Figure 5.12. Sedimentation with the Soulanges fine sandy loam (top) and Bainsville very fine sandy loam soils (bottom).

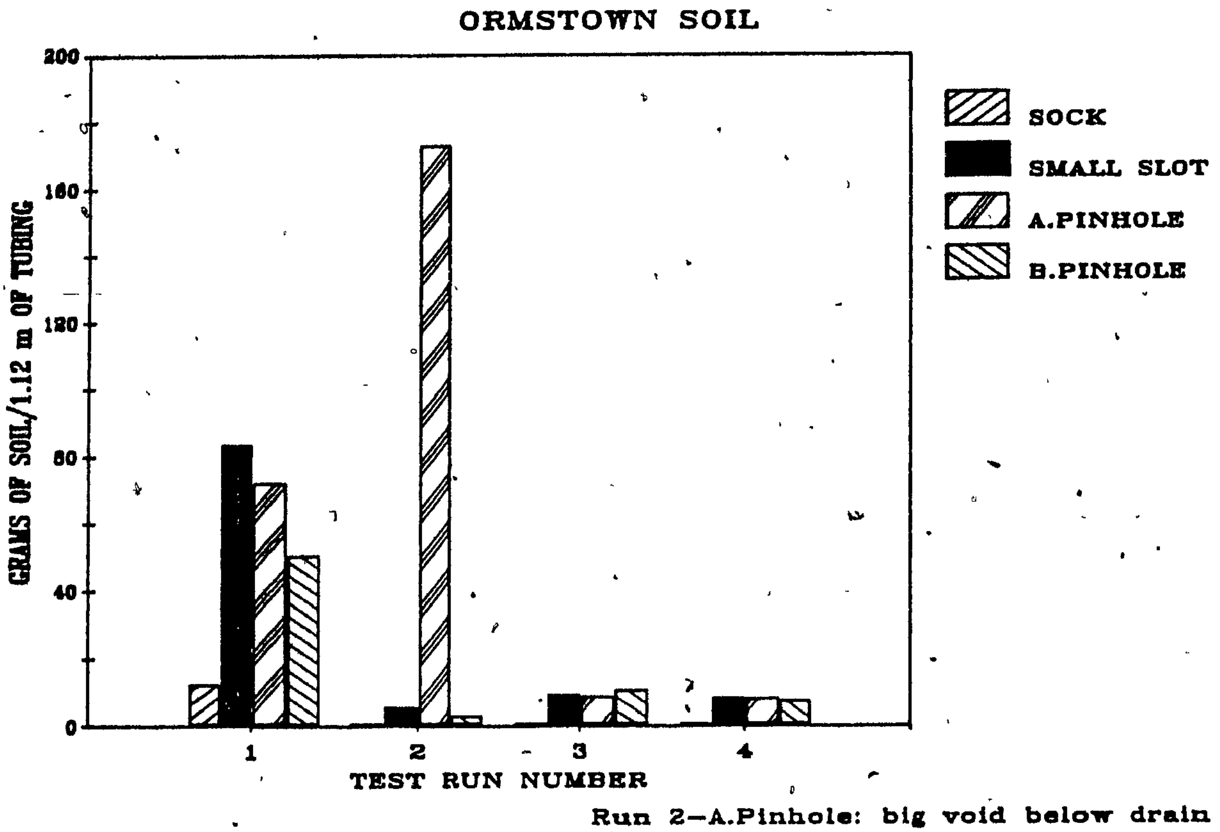


Figure 5.13. Sedimentation with the Ormstown silt loam soil.

It appears from Table 5.3 that "run" had an effect on sediment entry into the drain tubes for the Soulanges FSL and Ormstown SiL. Table 5.4 indicates that this effect is mainly due to the first run. At the time the first runs were started, the soils were coming fresh from the field. The soil structure prior to the first test was largely composed of very small aggregates with many of the fine sediments being loose. By the time the soil was prepared for the second run, the structure was altered to give larger aggregates and less of the loose particles. Therefore, less sediments entered the drains. This alteration of the soil structure was not severe enough to significantly reduce the drainage rate for the Soulanges FSL soil. It did however, reduce the drainage rate for the Ormstown SiL soil as more of the soil particles aggregated temporarily due to a higher clay content and gave a more massive structure upon compacting the soil.

The same kind of alteration occured with the Bainsville VFSL soil. The statistics do not show an effect of run on sediment weight because run 1 was not included in the analsysis. In addition to the dry weights shown in Table 5.5 for run 1, the amount of sediments washed out from the drain tubes with the drainage water totalled around 500 g for the tube with small slots and 100 g for the pinhole tubes. It is likely that more sediments would have deposited in the drains provided they were flowing full and the outlets were submerged.

It is seen from Tables 5.3, 5.4 and 5.5 that the type of tubing will definitely have an effect on the amount of sediment entering the drains in all soils but the silt loam. Sediment entry was always higher for the tube with small slots and lowest for the enrobed tube. As expected, the tubing with the fabric envelope is performing well. The Bainsville VFSL gave the highest amount of sediment.

Table 5.5 shows that sediment entry was low for the Ormstown SiL. It is likely that the aggregates blocking the openings or forming a stable arch over the openings withstood the erosive process taking place in the formation of the filter cake around the drain. However, Table 5.5 and Figure 5.13 indicate a high sediment deposition inside pinhole tube A in the second run. When draining the tank prior to starting the second cycle, a large void about 10 cm wide by 10 cm deep was created below the drain on the side of the plexiglass window. When drainage was initiated once more, the flowrates were 10 times higher than in the first cycle and sediments were entering the drain at this particular location at a fast rate. Before ending the first flow period, sedimentation inside the drain tube was very low. As seen with this case, the importance of placing soil around drain pipes installed in the field so as to reduce the presence of voids, is demonstrated.

In order to give some magnitudes for comparison of the amount of sediment in the drain tubes, the sediment weight from Table 5.5 has been presented in Table 5.6 as the approximate number of years of drainage, Ys, until the tubes could be half full of sediment.

The Ys data in this table are derived by taking the equivalent number of years of field drainage, Y, represented by each run,

Table 5.6. Estimated number of years for the drain tubes to become half full of sediments, Ys.

Soil Type	Run	Sock	Small slots	Pinhole A	Pinhole B
		Tubing Type			
STE. BARBE Medium sand	1	16450	680	960	2600
STE. SOPHIE Fine sand	1	10806	199	387	919
	3	82500	616	976	6517
	4	13558	367	681	4397
	5	46967	450	493	3225
	Mean 1	38458	408	634	3765
	Mean 2	47675	478	716	4714
SOULANGES Fine sandy loam	1	937	8	10	14
	2	140	7	10	10
	3	1667	16	22	43
	4	1029	17	27	22
	5	5750	19	30	26
	6	6000	30	27	41
	Mean	2587	16	21	26
BAINSVILLE Very fine sandy loam	1	108	9	6	7
	3	503	4	8	11
	4	597	3	5	7
	5	198	3	6	9
	Mean 1	351	5	6	9
	Mean 2	432	3	7	9
ORMSTWON Silt loam	1	614	117	160	142
	2	5500	352	33	622
	3	8750	170	145	164
	4	1000	50	40	43
	Mean	3966	172	94	243

Notes: - Mean 1 : mean of all runs
- Mean 2 : mean of runs with pipes flowing full (runs 3, 4, 5)
- Sock represents tube with normal slots enrobed with polyester envelope.

multiplying that by 5000 g (the approximate weight of dry soil required to half fill a 100 mm nominal diameter drain tube 1.12 m long) and dividing the number obtained by the total dry weight of sediment removed from the drain tubes after each run. The values of Ys thus obtained, are averaged over the number of runs.

Based on an assumed average annual subsurface drainage in eastern North America, of 300 mm of water depth from the field area drained, and an assumed spacing of 20 m between drain laterals, Y is equal to:

$$Y = \left(\sum \text{daily drainage rate (mm/d)} \times \text{No. of test days} \right) / (300 \text{ mm/year}) \quad (5.1)$$

The functional life of a subsurface drain tube could be considered to be over when the sediment depth averages half a diameter over the tube length. When this is the case, the tube will probably be full at a location where it dips half a diameter below the grade line. Some specifications allow depressions up to one half inside diameter as an installation tolerance (Darbyshire, 1985).

Considering the medium and fine sandy soils, it would take many years of drainage to half fill any of the tubes tested, as shown in Table 5.6. It can be stated that all of these drain tubes are a considerable improvement over bare drain tubes with normal 1.8 mm wide slots which have been found filled with each of these types of soils in field situations, within one year of installation.

A minimum working life expectancy of 30 years for a drain tube would be considered satisfactory. Thus, it appears from Table 5.6 that there is definitely a problem of too much sediment entering the tubes without an envelope when they are used in fine and very fine sandy loams. The tubes can be expected to become blocked in 3 to 9 years in the Bainsville VFSL and in 16 to 26 years in the Soulanges FSL. They would then need to be flushed out or replaced.

5.4 Sediment Inside Tubes versus Background Soil

The multivariate analyses of the particle size distributions of the soil samples collected above, on and inside the drain tubes are presented in Tables F1 to F4. The results from these tables have been summarized in Table 5.7 and the average distribution curves from all samples within a group, illustrated in Figures 5.14, 5.15 and 5.16.

It appears from Table 5.7 that in all soils, neither "run" nor "tubing" type had an effect on the different fractions analyzed. That is, the reworking of the soil and the shape and dimensions of the tube openings did not seem to significantly change the distribution of the soil particles. "Location", however, influenced the particle size distribution of the samples. Statistical tests on the means showed the sediments inside the drains to have soil fractions significantly different from the soil on (in vicinity) and away from the drains. The samples from the last two locations showed no difference at the 0.05 level of significance. No interaction was found to exist between "tubing" type and "location". Furthermore, samples collected in run 1 with the Ste. Sophie FS and Bainsville VFSL soils, for which the pipes were not flowing full, produced almost identical curves as in

Table 5.7. Summary of results obtained in the multivariate analysis of variance of particle size fractions of samples collected above, on and inside drain tubes. (see AOV tables in Appendix F).

Source	Ste. Sophie Fine sand	Soulanges Fine sandy loam	Bainsville Very fine sandy loam	Ormstown Silt loam
Fractions used	2 to 5	3 to 8	4 to 8	5 to 8
Mainplots				
Run	n.s.	n.s.	n.s.	n.s.
Tubing	n.s.	n.s.	n.s.	n.s.
Subplots				
Location	**	**	**	**
Tubing*Location	n.s.	n.s.	n.s.	n.s.

n.s.: not significant at the 0.05 level
** : significant at the 0.01 level

Fractions used :

1 = v. coarse sand (2 to 1 mm) ; 5 = v. fine sand , (0.1 to 0.05 mm)
2 = coarse sand (1 to 0.5 mm) ; 6 = coarse silt (0.05 to 0.02 mm)
3 = medium sand (0.5 to 0.25 mm) ; 7 = fine silt (0.02 to 0.002 mm)
4 = fine sand (0.25 to 0.1 mm) ; 8 = clay (less than 0.002 mm)

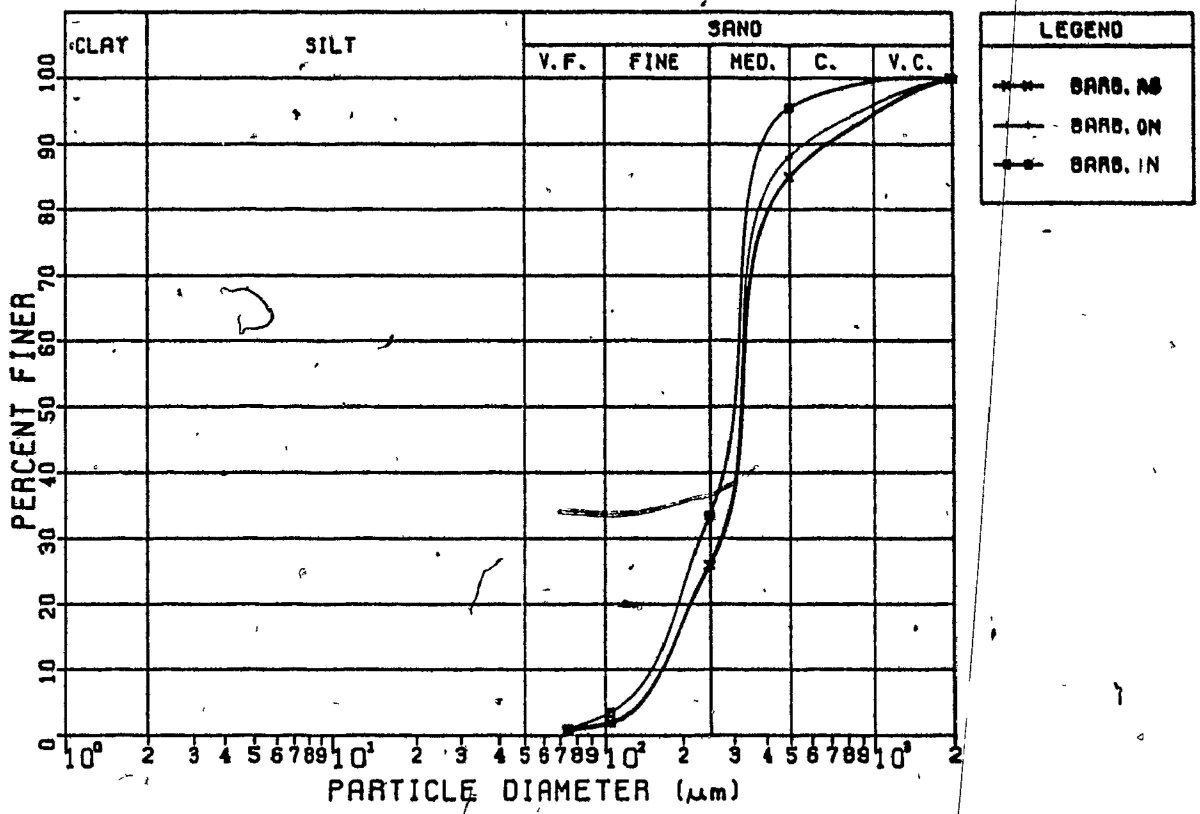
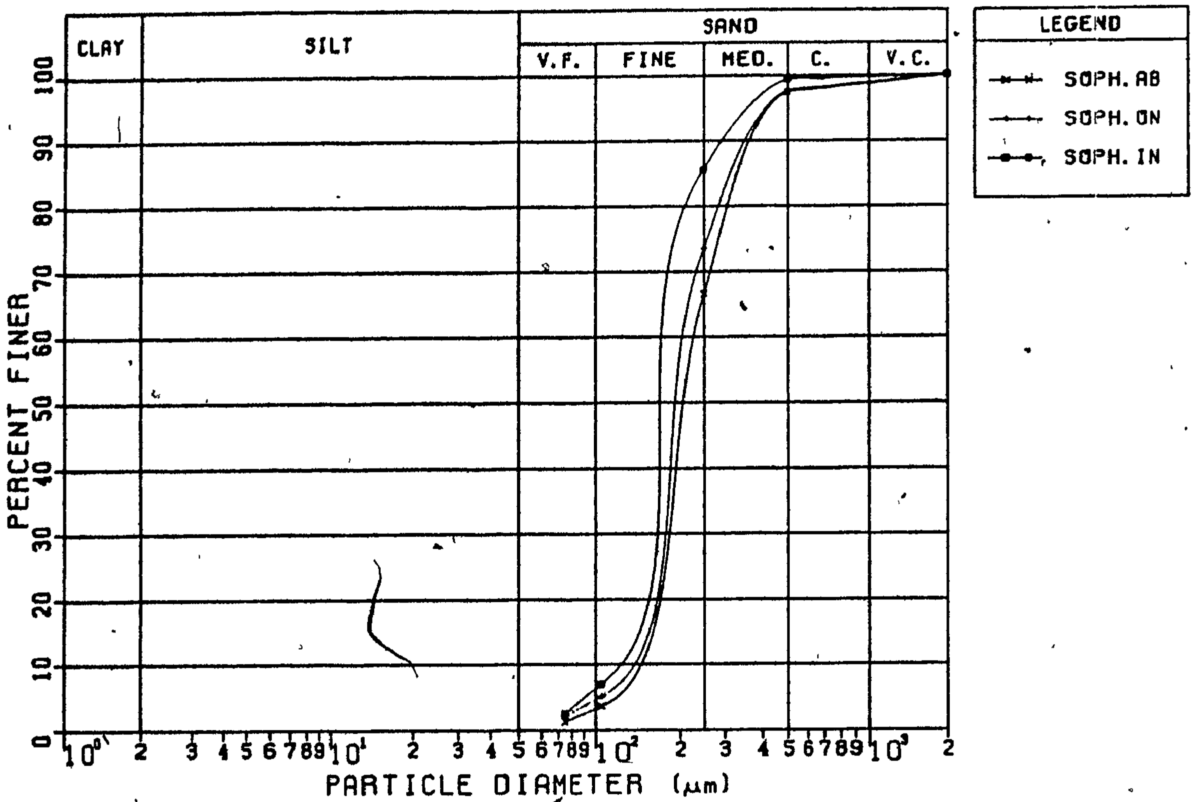


Figure 5.14. Mean particle size distribution curves of samples collected above (AB), ON and inside (IN) the drains with the Ste. Barbe medium sand soil.



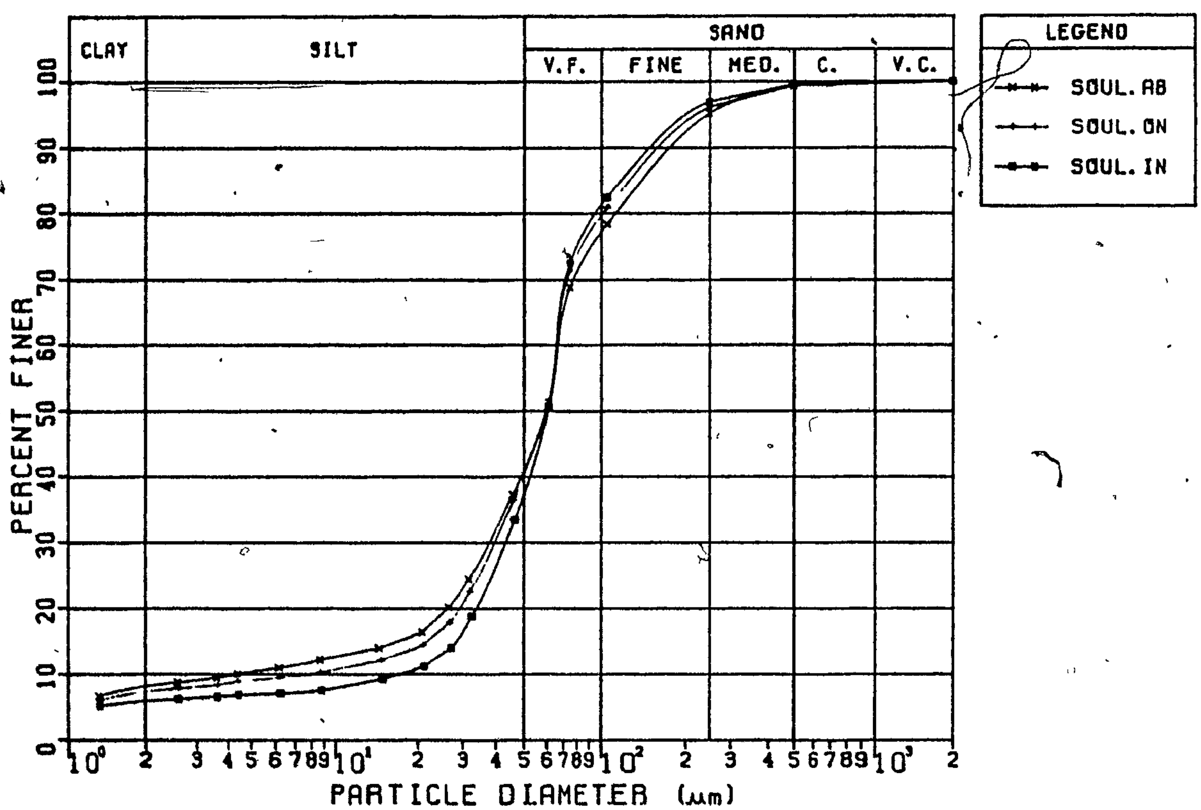
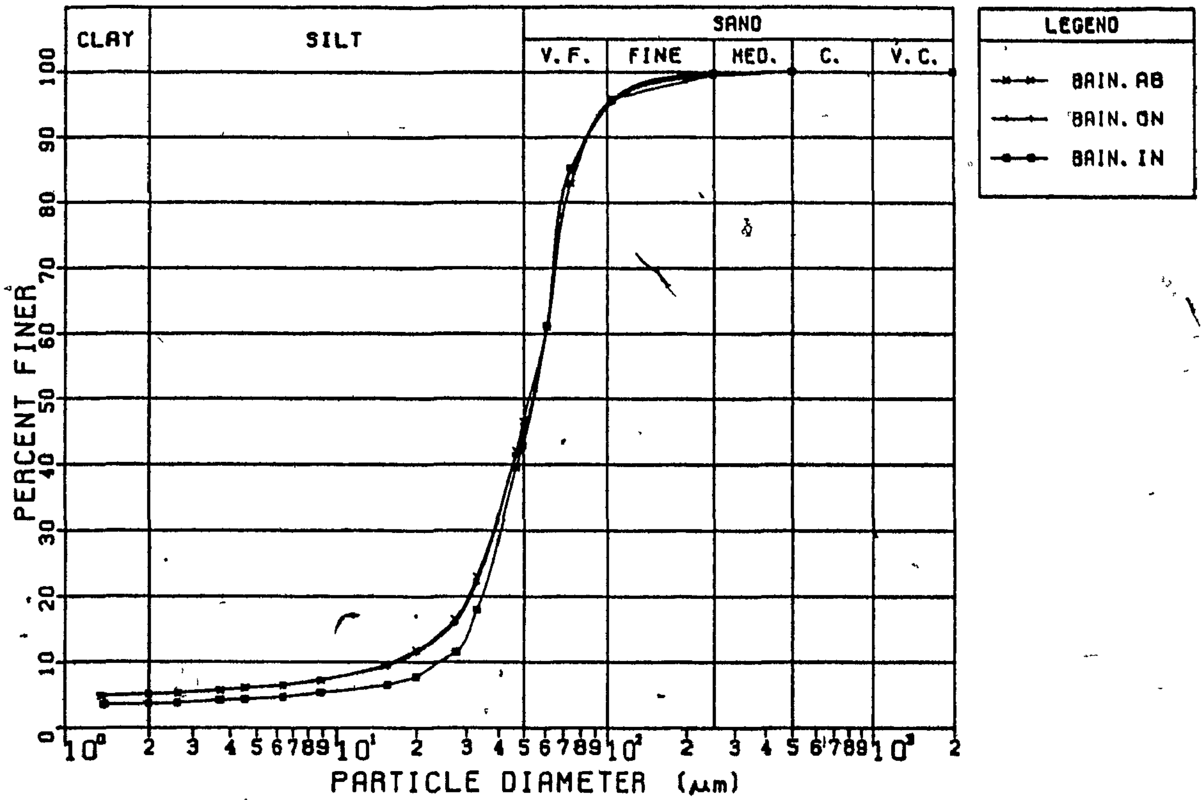


Figure 5.15. Mean particle size distribution curves of samples collected above (AB), ON and inside (IN) the drains with the Ste.Sophie fine sand (top) and Soulanges fine sandy loam soils (bottom).



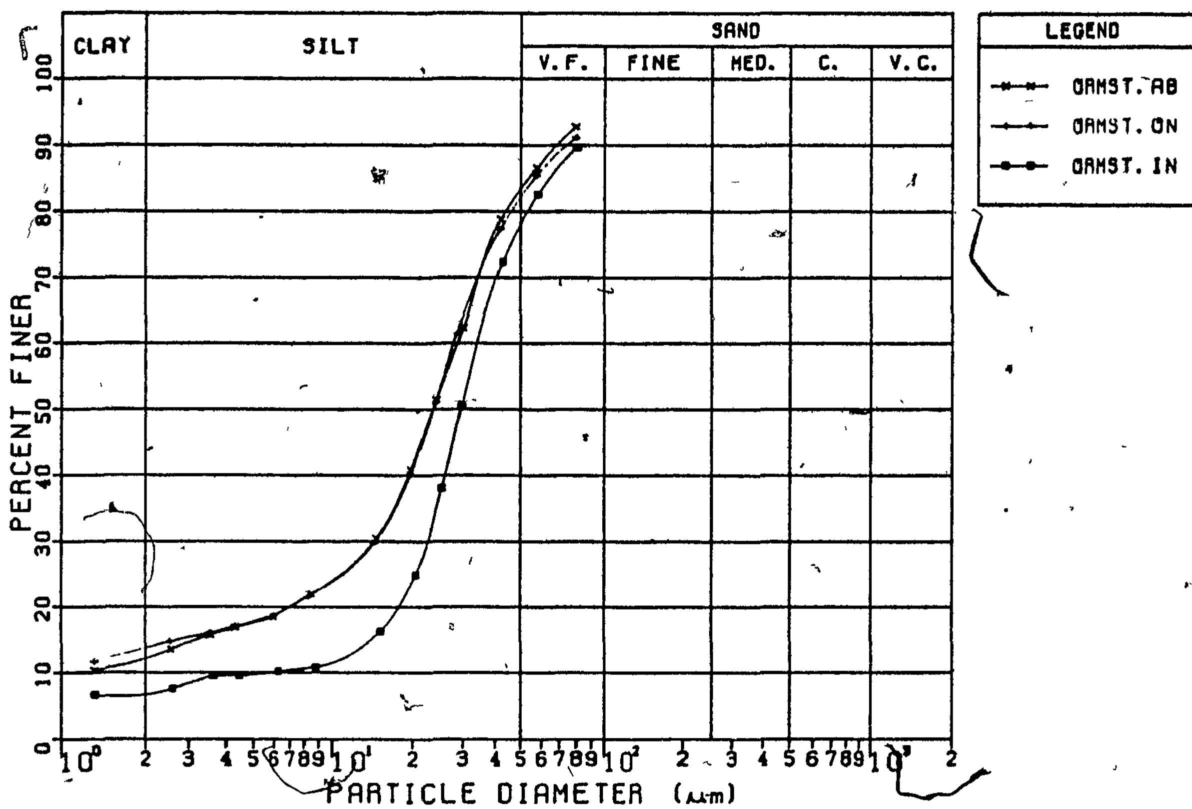


Figure 5.16. Mean particle size distribution curves of samples collected above (AB), ON and inside (IN) the drains with the Bainsville very fine sandy loam (top) and Ormstown silt loam soils (bottom).

subsequent runs.

Care was exercised in not losing much of the soil while preparing it between test runs. Also, the particles washed out into drains are negligible compared to the total volume of soil used in a tank (1.33 m^3). Thus, if an effect is expected due to the preparation of the soil, it shall be on soil structure rather than the distribution of the particles.

Before drainage started, the soil in vicinity of the drain (i.e. on the drain) was initially the same as the bulk soil. While drainage took place, the filter cake established itself by washing out some of the particles which would be replaced later by other particles travelling along the streamlines. This process would tend to keep the same distribution for particles around and away from the drain, independently of the type of openings on the tubes tested.

The maximum size of particles depositing inside the drains is restricted by the smaller of the size of openings or the soil itself. It appears from Table 4.2 that soil particles larger than 1 mm would not enter the pinhole tubes while particles larger than 0.71 mm would be retained by the tube with small slots. Despite this difference in maximum opening size, the particle size distribution was almost identical for the sediments collected inside the bare tubes. Indeed, particles larger than 0.71 mm accounted for only 2% of the Ste. Barbe sediments (Figure 5.14), 0.4% of the Ste. Sophie sediments and 0.2% of the Soulanges sediments (Figure 5.15). The type of opening did not affect the distribution of sediments in the Bainsville and Ormstown soils since the openings were not the restricting factor (Figure 5.16).

The normal slotted tube with the fabric envelope could produce sediments significantly different from the ones collected inside the bare tubes since the maximum fabric opening size was 0.45 mm (Figure 4.1). Time and budget limitations did not allow the use of the pipette method to analyze the distribution of the sediments on the few cases when enough sediments collected inside the tube. However, in all cases, all sediments passed the No. 35 sieve (0.5 mm opening size).

The effective particle diameters, coefficients of uniformity and curvature for the soils used are given in Table 5.8 for all three locations: above, on and inside the drain.

5.5 Opening Dimensions versus Soil Particle Considerations

Table 5.9 presents the maximum slot widths and hole diameters of drain openings to suit soils in accordance with some suggested criteria. This table has been prepared from the soils data of Table 5.8 and based on the Broadhead (1981), Thériault et al. (1982), US Corps of Engineers (Kovacs, 1981) and Willardson (1979) criteria for acceptable slot widths. These specifications are summarized in the table footnote.

Referring to Table 4.2, we see that the tubes with small slots and pinholes were: satisfactory for the Ste. Barbe MS, on the border line for the Ste. Sophie FS and too large for the finer soils. This border line shifts down to the Soulanges fine sandy loam for Willardson

Table 5.8. Effective diameters and coefficients of uniformity and curvature for the samples collected above (AB), ON and inside (IN) the drain (derived from the mean curves in Figures 5.14 to 5.16).

Soil Type	Location	D10	D15	D30	D50	D60	D85	Cc[b]	Cu[c]
		Effective particle diameters, (microns)[a]							
STE. BARBE	AB	161	186	270	320	330	500	1.37	2.05
Medium sand	ON	161	186	266	316	324	422	1.37	2.01
	IN	145	168	230	299	312	350	1.17	2.15
STE. SOPHIE	AB	145	159	184	207	227	335	1.03	1.57
Fine sand	ON	137	153	175	192	206	316	1.09	1.50
	IN	122	140	164	168	171	241	1.29	1.40
SOULANGES	AB	4.5	17	38	60	67	135	4.79	14.89
Fine sandy	ON	8	22	40	60	66	122	3.03	8.25
loam	IN	17	29	44	60	66	122	1.69	3.79
BAINSVILLE	AB	16.6	26	38	54	61	78	1.43	3.67
Very fine	ON	17	26	40	54	61	74	1.54	3.59
sandy loam	IN	25	31	42	54	61	74	1.16	2.44
ORMSTOWN	AB	1.2	3.2	14.5	24	28	54	6.04	24.17
Silt loam	ON	1.0	2.7	14.5	24	29	54	7.51	28.00
	IN	1.2	13.5	23	30	34	63	12.97	28.33

[a] 1 mm = 1000 microns
[b] Coefficient of uniformity, Cu = D60/D10
[c] Coefficient of curvature, Cc = $(D30)^2/(D60)(D10)$

Table 5.9. Maximum slot widths or hole diameters to suit soils in accordance with some suggested criteria (mm).

Soil Type	Location[a]	Particle size D60	Particle size D85	Broadhead[b] Slot width W	Broadhead[b] Hole dia. 1.3 W	Broadhead[b] Hole dia. 3.0 W	Thériault[c] Slot width W	Thériault[c] Hole dia. 1.3 W	Thériault[c] Hole dia. 3.0 W
STE. BARBE	AB	.300	.500	.72	.94	2.16	1.00	1.30	3.00
Medium sand	ON	.300	.450	.70	.96	2.10	.90	1.10	2.70
STE. SOPHIE	AB	.227	.335	.54	.70	1.62	.67	.87	2.01
Fine sand	ON	.206	.316	.49	.64	1.48	.63	.82	1.90
SOULANGES	AB	.067	.135	.16	.21	.48	.27	.35	.81
Fine sandy loam	ON	.066	.122	.16	.21	.47	.24	.32	.73
BAINSVILLE	AB	.061	.078	.15	.19	.44	.16	.20	.47
Very fine sandy loam	ON	.061	.074	.15	.19	.44	.15	.19	.44
ORMSTOWN	AB	.028	.054	.07	.09	.20	.11	.14	.32
Silt loam	ON	.028	.057	.07	.09	.20	.11	.15	.34

[a]Sample location: AB = above drain; ON = on drain
[b]By Broadhead's criteria, slot width W ≤ 2.4 D60 and hole dia. ≤ 1.4 W
[c]By Thériault's criterion, slot width W ≤ 2 D85

The diameter of an acceptable circular hole has been taken as 1.3 times the width of an acceptable slot for the purposes of the calculations for this table. 1.3 is halfway between the 1.4 obtained from the diagonal of a square but more than the 1.2 ratio used by the U.S. Corps of Engineers. It was also determined as 3.0 times the slot width as suggested by Willardson criterion when used in conjunction with Thériault's recommendations.

According to all these criteria, the dimensions of the openings in the tubes with small slots and pinholes, as seen in Table 4.2, meet the requirements shown in Table 5.9, for installation in the Ste. Barbe MS. Therefore, no sedimentation problem should be expected in that soil. This was confirmed by the laboratory tests carried out. The Broadhead criteria indicates that there should be a sedimentation problem in the Ste. Sophie FS, with the tube with small slots, since the slot width averaged 0.65 mm with a maximum of 0.71 mm (Table.4.2). This is a dimension greater than the maximum 0.54 mm allowed (Table 5.9). On the other hand, the Broadhead criteria used in conjunction with the Modified US Corps of Engineers (USCE) specifications for circular perforations, shows that both pinhole tubes were unsatisfactory for the Ste. Sophie FS. However, the data in both Tables 5.6 and 5.7 show that all tubes performed well in the fine sand. The combined criteria Broadhead - Willardson shows the pinhole tubes to be satisfactory for the Ste. Sophie FS, since the maximum measured opening diameter of 1.02 mm (Table 4.3) is smaller than the maximum allowed diameter of 1.48 mm (Table 5.9).

Thériault's criteria for rectangular slots shows the tube with small slots to be at the limit of being acceptable for installation in the Ste, Sophie FS, since 95% of the slots were smaller than 0.65 mm (Figure 4.1). This is halfway between the maximum allowable of 0.63 mm and 0.67 mm derived for samples located on and above the drain, respectively. Furthermore, both pinhole tubes met the specifications for this soil under both the combined criteria of Thériault - Modified USCE and Thériault- Willardson. Indeed, even though the measured maximum diameters were close to 1.0 mm (Table 4.2), the O_{95} of both pinhole tubes A and B were less than the maximum allowed of 0.82 mm for the combined Thériault - Modified USCE criteria and less than the maximum permissible diameter of 1.90 mm under the Thériault - Willardson criteria (Table 5.9). This was true for openings on both valleys and ridges, except for the openings on the valleys of corrugations of pinhole tubeA, for which 95% of the holes were smaller than 0.98 mm (Figure 4.1).

On the other hand, these criteria suggest that problems could be expected to occur in all of the three finer loamy soils as the maximum allowable dimensions are 2 to 12 times smaller than actually measured for the drain tubes. Table 7 confirms this expectation with the Soulanges fine and Bainsville very fine sandy loams. The Ormstown silt loam soil, however, presented no problem of sediment blockage.

Also, Figure 1 shows that the apparent opening size of the knitted polyester stocking is 360 microns (0.36 mm). This is large enough that considerable quantities of the fine and very fine sandy loam, and silt loam should have gone through, but they did not.

All this suggests that more than a single characteristic, such as the D60 or D85 of a soil, is required to define a potential sediment problem. In conjunction with the D60 or D85 citeria, use should be made of Cu and/or the aggregates present in the soil and whether these aggregates are stable or not. The discriminant method based on both particle and aggregate size distributions to predict drain silting and developed by Lagacé and Skaggs (1982) is promising but might need some further refinement.

5.6 Dry Bulk Density

The means of density measurements for each location and within each cell are given in Table 5.10 for all experiments. The analyses of variance tables are indexed in Appendix G and summarized in Table 5.11.

The results show that soil density did not vary significantly from one run to the next for the Ste. Sophie FS and Bainsville VFSL soils. This is an indication that the compaction procedure and the initial moisture content of the soil prior to testing were repeatedly consistent. The significant difference seen for the Soulanges FSL and Ormstown SiL soils is mainly due to the first run as seen from Table 5.10 and confirmed by Duncan's test. The higher densities obtained in the first run with the fine sandy loam partially explains the slightly lower drainage rates recorded for the bare tubes while lower densities account for the high flow rates observed for all pipes in the first run with the silt loam soil.

Similarly, the compaction was uniformly applied to all cells (soil chambers) within a tank and no significant difference in density was found among "cells" (Table 5.11). However, samples located below drains, in general, exhibited higher bulk densities than samples collected above

Table 5.10. Means of dry bulk density measurements from core samples collected above and below drains, (Mg/ m³).

SOIL TYPE		STE. BARBE	STE. SOPHIE				SOULANGES						BAINSVILLE				ORMSTOWN			
	RUN	1	1	3	4	5	1	2	3	4	5	6	1	3	4	5	1	2	3	4
CELL	LOCATION																			
1	Above	1.510	1.411	1.460	1.439	1.430	1.507	1.463	1.460	1.421	1.423	1.441	1.483	1.472	1.389	1.424	1.374	1.421	1.427	1.429
	Below	1.583	1.576	1.463	1.465	1.483	1.530	*	*	1.567	1.479	1.441	*	1.504	1.471	1.438	1.416	1.450	1.456	1.448
	Mean	1.547	1.493	1.462	1.452	1.457	1.519	1.463	1.460	1.494	1.451	1.441	1.483	1.488	1.430	1.431	1.395	1.435	1.441	1.438
2	Above	1.447	1.402	1.452	1.483	1.422	1.506	1.456	1.419	1.441	1.466	1.443	1.496	1.443	1.403	1.443	1.382	1.439	1.441	1.433
	Below	1.607	1.602	1.451	1.502	1.499	1.534	*	*	1.494	1.483	1.488	*	1.479	1.528	1.463	1.455	1.455	1.451	1.445
	Mean	1.527	1.502	1.452	1.493	1.461	1.520	1.456	1.419	1.467	1.475	1.466	1.496	1.461	1.465	1.453	1.418	1.447	1.446	1.439
3	Above	1.467	1.432	1.442	1.472	1.426	1.442	1.449	1.530	1.400	1.444	1.444	1.442	1.453	1.421	1.483	1.342	1.466	1.438	1.437
	Below	1.620	1.610	1.483	1.494	1.493	1.507	*	*	1.475	1.472	1.468	*	1.473	1.571	1.453	1.483	1.450	1.474	1.453
	Mean	1.543	1.521	1.463	1.483	1.460	1.474	1.449	1.530	1.437	1.458	1.456	1.442	1.463	1.496	1.468	1.412	1.458	1.456	1.445
4	Above	1.503	1.462	1.451	1.427	1.426	1.522	1.420	1.482	1.454	1.448	1.441	1.416	1.406	1.417	1.412	1.407	1.448	1.415	1.429
	Below	1.620	1.586	1.475	1.467	1.491	1.517	*	*	1.535	1.470	1.471	*	1.456	1.518	1.445	1.451	1.433	1.467	1.457
	Mean	1.562	1.524	1.463	1.447	1.459	1.519	1.420	1.482	1.495	1.459	1.456	1.416	1.431	1.467	1.429	1.429	1.441	1.441	1.443

* Soil not adequate for sampling

Density values shown are averages from three measurements - coefficient of variability never exceeded 7%.

Table 5.11. Summary of F-Tests results in the analysis of variance of dry bulk density. (see AOV tables in Appendix G).

Source	Ste. Sophie Fine sand	Soulanges Fine sandy loam	Bainsville Very fine sandy loam	Ormstown Silt loam
Mainplots				
Run	n.s.	*	n.s.	**
Cell	n.s.	n.s.	n.s.	n.s.
Subplots				
Location	**	**	*	**
Cell*Location	n.s.	n.s.	n.s.	n.s.

n.s. Not significant at the 0.05 level
* Significant at the 0.05 level
** Significant at the 0.01 level

them. The dead weight of the soil on top of the drains added to the settling of the soil during drainage might have contributed to pack the soil below the drain even more. A look at Table 5.10 reveals that similar conclusions can be made for the Ste. Barbe MS soil and run 1 of the Ste. Sophie FS soil, so far as sample location is concerned. The soil had to be shovelled out and the drain removed in order to collect the core samples below the drain. This could have compacted the soil slightly more, even though care was taken to reduce that effect.

Some measurements of settling of the trench surfaces were made. Soil settling or consolidation, occured very rapidly as the wetting front rose during saturation and slowed down within 24 hours of drainage. It varied from almost one centimeter for the medium and fine sand to six centimeters for the silt loam. Out of a total depth of soil of 57 cm, this would represent a settling of about 2 to 10%, respectively. Visualization of the process was made possible by the plexiglass windows.

Draining the tanks between cycles and starting the second flow period did not add significantly to the settling of the soil. Also, this phenomenon did not just occur in the top few centimeters of soil. It was integrated over the depth of the soil chamber as observed through the transparent end caps where the drains curved down a little while settling took place. This important consolidation process could explain the lower drainage rates recorded, in general, in the second cycle of most experiments.

While the densities measured did not reflect the initial compaction of the soil because of the settling phenomenon, it was observed that this settling occured uniformly across all soil chambers in the tank and from one run to the next. Therefore, any discrepancy between cells or runs would be mainly due to differences in the initial compaction of the soil. With this in mind, the conclusions made above are still valid.

5.7 Sediment Weight versus Drain Opening Hydraulic Radius

A first attempt was made to correlate the accumulation of sediments with the slot width (or opening diameter) and the hydraulic radius of the perforations by using the models developed by Lagacé (1983):

$$SEDW = \epsilon_0 \, e^{(\epsilon_1 \, WIDTH)} \tag{5.2}$$

$$SEDW = \beta_0 \, e^{(\beta_1 \, HR)} \tag{5.3}$$

where, SEDW = sediment weight, g

WIDTH = slot width or hole diameter, mm

HR = hydraulic radius of drain opening, mm

$\epsilon_0, \epsilon_1, \beta_0, \beta_1$ = regression parameters

It was found that, as determined by Lagacé (1983), the hydraulic radius gave a slightly better regression than the slot width when correlated with SEDW. Also, higher R^2 values than the maximum 0.66 reported by Lagacé (1983), were obtained for all soils but the Ormstown SiL soil, as indicated in Table 5.12. The Student t-test showed however, that the parameter β_0 was not significant at the 0.50 level. Therefore β_0 could be neglected, being close to unity. This was true for all cases

Table 5.12. Comparison of models for predicting sediment weight, SEDW.

Soil Type	Model I $SEDW = \beta_o e^{(\beta_1 HR)}$	Model II $SEDW = e^{(\beta_1 HR)} - 1$				Runs considered
	R^2	R^2	1	S.E.	C.V. (%)	
Ste. Barbe Medium sand	0.872	0.984	15.22	0.96	13.3	1
Ste. Sophie Fine sand	0.872	0.978	20.19	0.87	14.0	3,4,5
	0.922	0.989	19.23	1.04	20.0	1
Soulanges Fine sandy loam	0.703	0.958	22.32	0.96	22.0	all
Bainsville Very fine Sandy loam	0.853	0.973	29.85	1.45	17.3	3,4,5
	0.949	0.894	24.75	4.21	22.0	1
Ormstown Silt loam	0.336	0.812	12.49	1.53	49.9	all

Notes: - In all cases, the data fitted the model at the 0.01 level of significance
- S.E. = standard error of β_1
- C.V. = coefficient of variability

except with the Bainsville VFSL soil for which β_0 was significant at the 0.05 level.

Equation (5.3) was then improved by removing the parameter β_0 and substracting a value of unity from the exponentional term to account for a nil hydraulic radius or non-perforated drain in which no sedimentation is possible. The model becomes:

$$SEDW = e^{(\beta_1 HR)} - 1 \qquad (5.4)$$

With equation (5.4), the R^2 value* for the Ormstown SiL soil improved from 0.34 to 0.81 eventhough the variability was still very high (model II in Table 5.12). The high coefficient of variability is mainly due to the first run which produced much higher sediments than subsequent runs. Considering each run separately, the variability was less than 30% while the R^2 value ranged from 0.91 to 0.97. It was also found that both models I and II apply independently of drain flow. Using the data from Lagacé (1983), R^2 increased from 0.57 to 0.90.

Polynomial equations of the second and fourth order in HR were tried for the expression of the exponent. There was not much improvement and in most cases the second, third and fourth order regression coefficients were not even significant at the 0.50 level. Furthermore, it would be more difficult to characterize the variation in the regression coefficients when more than one parameter is considered.

*All R^2 values reported in this thesis have been adjusted for the degrees of freedom.

Figure 5.17 illustrates the relationship between sediment weight and hydraulic radius for the drains installed in the Soulanges FSL soil.

A close look at Table 5.12 indicates that β_1 increased in magnitude with the first four soils and dropped with the Ormstown soil. This parameter, which is part of the logarithmic expression of the sedimentation process, can be correlated with soil characteristics such as the D_{60} of the soil, coefficients of uniformity (C_u) and curvature (C_c), and/or the aggregate size distribution. This feature has been illustrated in Figure 5.18 with different approximation curves. Starting with highly clayey soils, and for a given drain opening type, the accumulation of sediment would increase with decreasing clay content and aggregate stability, and increasing D_{60} size until it reaches a maximum. It would then decrease as the soil becomes coarser and loses its structure. The range of problem soils for the particular drain under consideration would be determined by a lower limit (β_{1crit}) for which sedimentation is not critical. Under saline conditions, siltation is a problem in clay soils, and therefore, the rising limb of the curve would be more gradual, thus widening the range of problem soils.

With the soils used in this study, it was difficult to correlate β_1 with more than one soil characteristic. Therefore, only the D_{60} size was considered. Several models were tried and produced in Table 5.13 along with the corresponding R^2 values for the first four coarser soils. At this stage, only a straight line was regressed over the Ormstown SiL and Bainsville WFSL soils since almost any model can be fitted to two points. Also, the estimate of β_1 for the Ormstown SiL soil is not very

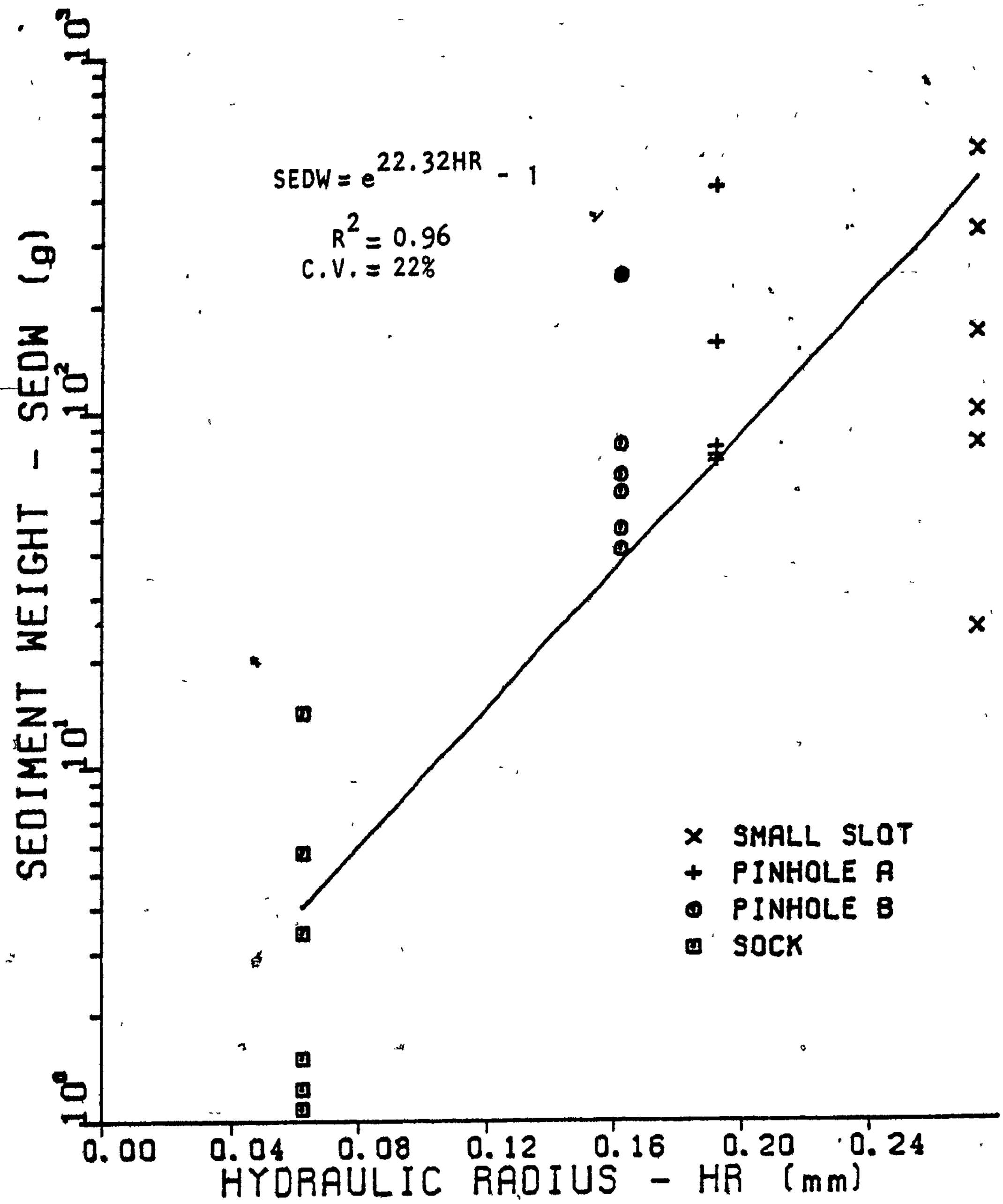


Figure 5.17. Sediment weight versus drain opening hydraulic radius with the Soulanges fine sandy loam soil.

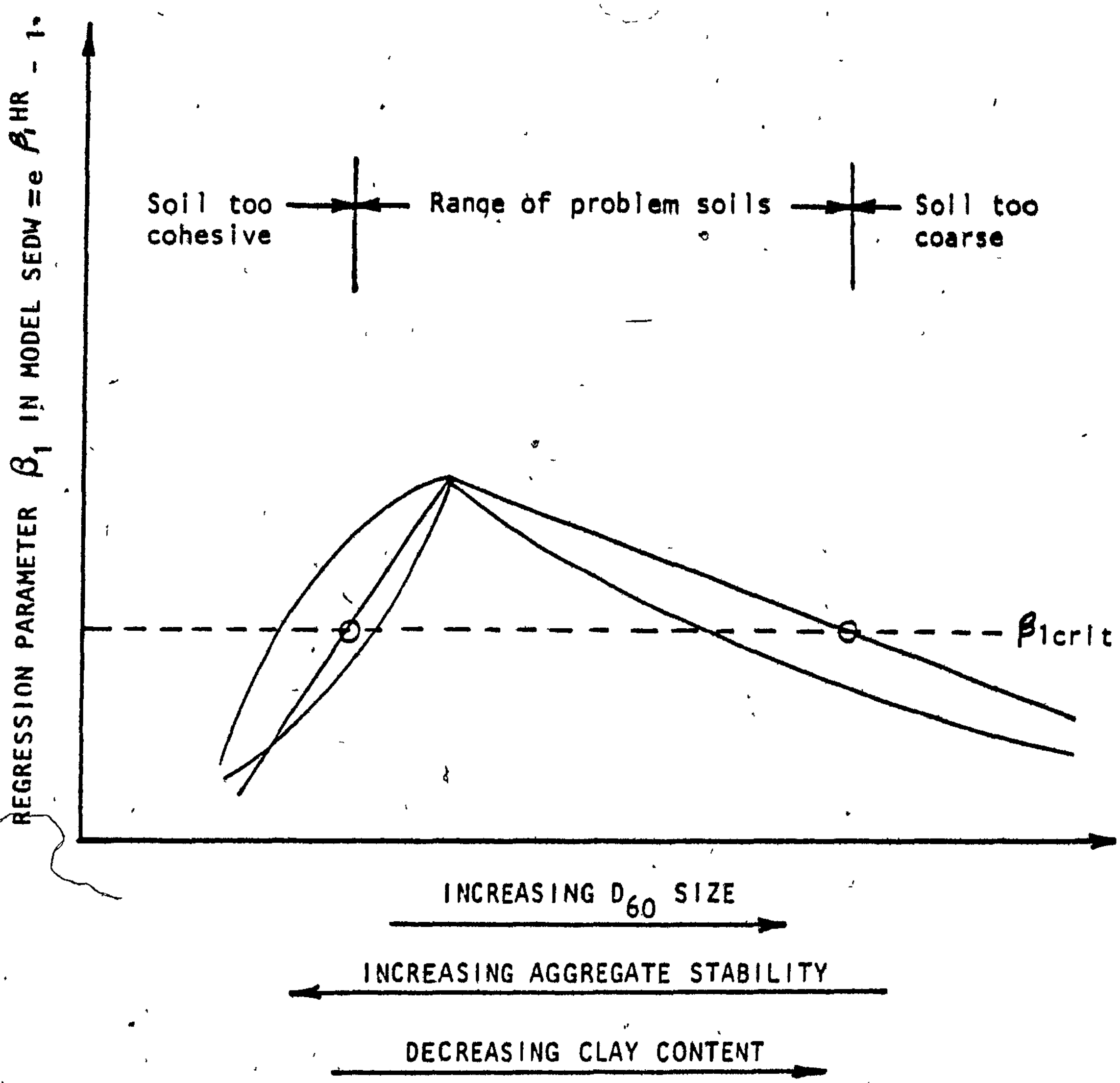


Figure 5.18. Theoretical variation of parameter β_1 in equation (5.4) with the soil D60 size.

Table 5.13. Regression models of parameter $_1$ in equation (5.4) over the soil D_{60} size for the Ste. Barbe medium sand, Ste. Sophie fine sand, Soulanges fine sandy loam and Bainsville very fine sandy loam soils.

Model	R^2	C.V. (%)
1. $a_0 + a_1/D_{60}$	0.44	14.8
2. $a_0 + a_1 (D_{60})^{-1/2}$	0.43	14.8
3. $a_0 + a_1 \ln(D_{60})$	0.42	15.0
4. $a_0 (D_{60})^{a1}$	0.47	4.6
5. $a_0 \exp(a_1/\ln(D_{60}))$	0.47	4.5
6. $\exp(a_1/\ln(D_{60}))$	0.99	9.5

In all cases the data fitted the model at the 0.01 level of significance good due to the high variability observed. The regression and the curve represented by model 6 have been plotted in Figure 5.19.

Despite the R^2 of 0.99 and C.V. of 9.5% obtained with model 6, it is seen that the predicted value of β_1 for both the Ste. Barbe MS and Ste. Sophie FS soils is well below the experimental value. With models 4 and 5, R^2=0.47 and C.V.=4.5%. Even if only one run was carried out with the Ste. Barbe MS soil, it is very likely that under either full or open pipe flow, sediments accumulated in subsequent runs would not differ by much from the first run as this soil was already coarse enough for the size of the openings in the drain types used. It is rather, the closeness of the D_{60} size of the Soulanges FSL soil to the Bainsville VFSL that influenced the type of regression model. Rejecting the Soulanges data set, model 4 gave the best prediction with R^2=0.88 and a coefficient of variability of only 2.5%. The predicted value of β_1 for the Soulanges FSL was close to the one obtained in run 1 but over estimated the other runs (Figure 5.19). Nevertheless, it is safer for design purposes to overestimate the accumulation of sediment to account for unknown factors.

This suggests that more soils falling between the Bainsville VFSL and Ste. Sophie FS should be tested to complement the present analysis. This also applies for soils finer than the Bainsville VFSL. It is probable that the maximum value of β_1 would increase if soils finer than the Bainsville VFSL soil but with less than 10% clay content were tested. An Ormstown SiL with less than 5% clay or a silt from the Lac St-Jean area in Northern Québec would most likely give a higher

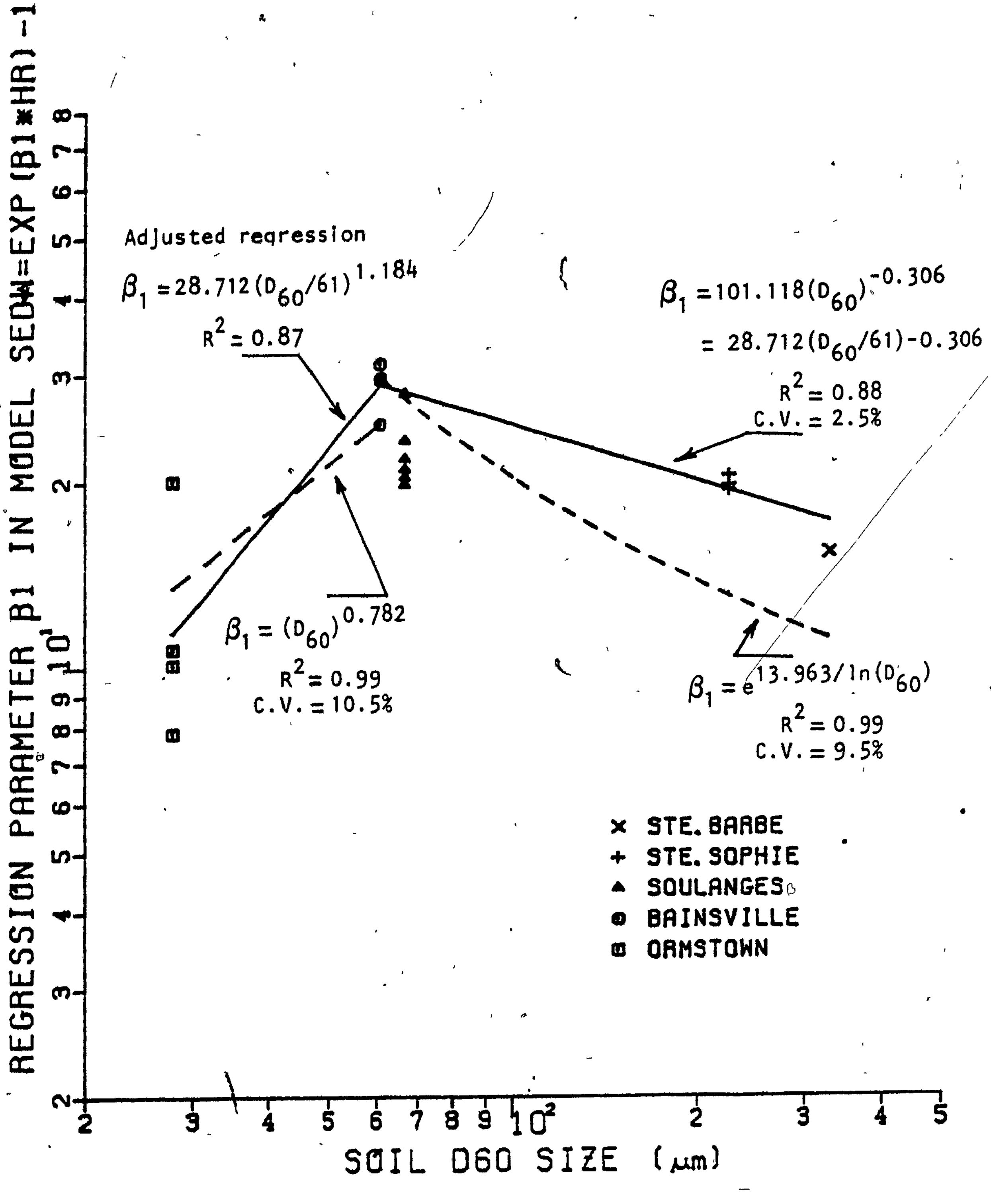


Figure 5.19. Experimental regressions of parameter β_1 in equation (5.4) over the soil D_{60} size for all soils tested.

sedimentation than occured with the Bainsville soil. Papineau (1985) reported the Lac St-Jean silt to fill up drains completely after only 24 hours of operation.

Nevertheless, only two parameters such as the hydraulic radius of the drain openings and the D_{60} of the soil served to explain most of the sediment weight inside drains. Pooling the data from all runs with the Ste. Barbe MS, Ste. Sophie FS, Soulanges FSL and Bainsville VFSL soils, an R^2=0.95 is obtained with a regression coefficient close to unity (0.92) which is an indication of the accuracy of the expression of β_1. With the present data, the final expression of SEDW becomes:

$$SEDW = e^{(\alpha_0 \cdot (D_{60})^{\alpha_1} HR)} - 1 \qquad (5.5)$$

Sediment depth was not measured in this study, but it can easily be correlated to sediment weight and an equation determined for predicting sediment depth, for a given type of drain opening. Usually sediments would form hillocks spread over the tube length or would pile up at the downstream end of the lateral or collector. An average sediment bulk density of 1.0 g/cm^3 over the entire length of the drain is not unreasonable as was determined from Lagacé's (1983) data. Such a density was used to estimate the number of years to half fill a drain (Table 5.6).

Assuming a maximum allowable sediment depth of one quarter tube diameter, the sediments would total approximately 1750 g. Substituting this value of SEDW in equation (5.4) results in β_1=27.3 for a tube with small slots. It is seen from Figure 5.19 that the range of problem soils for such a drain type, includes both the Soulanges FSL and Bainsville VFSL soils. Considering pinhole tube A, results in β_1=39.0, a value of β_1 for which none of the soils tested becomes critical. However, Table 5.6, indicates that this tube could be half full of sediment after only six years of drainage in the Bainsville VFSL soil. The need exists to include other factors. A correlation between sedimentation rate and the rate of decrease in drainage rate and/or the effect of several wetting and drying cycles could be determined and combined with the above model to estimate sediment weight or sediment depth. The present study does not allow a good modelling of the process described above.

Predicting drain silting under almost any field and drain conditions is not an easy task nor will it be easy to design an experiment to fulfill that objective. However that need exists if fabric envelopes are to be avoided to reduce installation costs. The challenge would be to develop a way to produce porous pipes rather than to cut holes in the pipe after it is produced.

5.8 Drainage Rate versus Drain Opening Area

It was seen in Figures 5.1 to 5.10 that, in general, the larger the opening area, the higher the discharge or drainage rate. Several models were regressed from which two were retained. These are of the form:

$$q = \gamma_1 \ln(A+1) \quad (5.6)$$

and

$$q = \gamma_2 A/(A+1) \quad (5.7)$$

where, q = discharge rate, m^3/d/m length or mm/d

A = total drain opening area per unit length, cm^2/m

γ_1, γ_2 = regression parameters

The coarser the soil, the greater the influence of the drain opening area on discharge rate. Therefore, equation (5.6) applied to the sandy and sandy loam soils. The drainage rate in the Ormstown SiL soil, however, was not greatly affected by the opening area. Therefore, equation (5.7) proved to be the best regression as q slowly increases with large increases in A. Table 5.14 presents R^2 values and coefficients of variability of the above models for some of the cases considered in each type of soil. The R^2 ranged from 0.94 to 0.99 with 9 to 30% variabilty. In general, the data fitted the models whether it be on a daily basis from the beginning to the end of each cycle or by taking the average of the steady-state values. The table shows a lower R^2 and very high variability for the end of the first cycle in run 1 with the Soulanges FSL soil. While drainage decreased with the tubes with small slots and pinholes, it stayed fairly constant with the normal tube with the fabric envelope.

Mohammad and Skaggs (1982) used mortar sand to measure the effect of drain tube openings on transient drainage. Using equation (5.6), it was found that perforation area (cm^2/m) was correlated at 99% with the 24-hr drainage volume (cm). Reeve (1982) illustrated relative flow as a function of inlet area for bare drains and drains covered with different fabric envelopes, over the range from 12 to 3600 cm^2/m for a completely

Table 5.14. Regression analysis of discharge rate, q, versus drain opening area per unit length, A.

Soil type	Run	Cycle	$q = \gamma_1 \ln(A+1)$ R^2	C.V.(%)	$q = \gamma_2 A/(A+1)$ R^2	C.V.(%)
Ste. Barbe Medium sand	1	1	.99/.98	12/14		
		2	.96/.99	22/ 9		
Ste. Sophie Fine sand	1	1	.98/.98	12/13		
	3	1	.97/.99	17/11		
		2	.99/.98	9/16		
Soulanges Fine sandy loam	1	1	.93/.69	25/85		
		2	.97/.91	20/30		
	3	1	.93/.95	26/22		
		2	.94/.92	20/22		
Bainsville Very fine sandy loam	1	1	.97/.94	18/30		
	3	1	.95/.99	22/12		
		2	.95/.97	23/18		
Ormstown Silt loam	1	1			.97/.93	16/23
		2			.97/.94	18/22
	2	1			.996/.99	6/ 8
	3	1			.997/.97	5/16
		2			.95/.96	22/20
	4	1			.996/.99	6/11
		2			.99/.998	9/ 4

Beginning/End of cycle
C.V. = coefficient of variability
In all cases the data fitted the models at the 0.01 level of significance

porous drain. Relative flow is defined in this case as the ratio of the actual discharge to the flow obtained with a completely porous pipe. This relationship followed the one expressed by equation (5.6) with a correlation of 99.8% with 5.3% variability.

The radial flow theory expressed by equations (3.1) or (3.4) shows that the flowrate is proportional to the inverse of the natural log of the drain radius. Since it is analytically impossible to relate drain radius to drain opening area when considering a real drain, the influence of total opening area has been broken down into the individual perforations with the corresponding circumferential and longitudinal spacings, as derived by Kirkham (1949, 1950) and others. The complex analytical solutions developed by the latter authors led to the concept of "equivalent drain size" or "effective radius". Effective drain radius is correlated to drain opening area and follows Kirkham's equations, as found by Mohammad and Skaggs (1982). Equation (5.6) is of interest since it expresses drainage rate as a function of the drain opening area. An added feature to equation (5.6) besides simplicity, is the direct application to field situations when expressed in a "dimensionless" form. Note that both models are not dimensionally consistent in terms of the opening area. We have:

$$\delta = q/q_0 = \nu_1 \ln(A_0 \alpha + 1)/(\ln(A_0+1) \qquad (5.8)$$

where, δ = relative flow, dimensionless

$\alpha = A/A_0$ = relative opening area, dimensionless

q, q_0 = discharge or drainage rate corresponding to a drain opening area of A or A_0, repectively.

The parameter A_0 was taken as 1427.5 cm^2/m for the normal tube with the polyester envelope. The regression parameter, ν_1, can be considered equal to unity. Due partly to experimental error, it varied from 0.97 to 1.14 for the sandy soils and from 0.85 to 1.25 for the sandy loam soils. A value of ν_1 equal to one, intrisically assumes that the hydraulic conductivity of the filter cake is independent of the type of drain used.

When designing a new type of drain or replacing an old subsurface drainage system, the relative flow can be predicted using equation (5.8), provided all other factors are kept constant. This flow is used to determine if a given total opening area would be adequate in comparison with a drain opening area for which the discharge or drainage rate is known. If the new drain opening area is satisfactory, it can be broken down into the shape and dimension of the perforations and their respective spacings in both circumferential and longitudinal axes. The entry resistance factor can then be calculated to predict head loss by using, for example, the formulae developed by Dierickx (1982a). Also, using equation (5.5), the hydraulic radius can be computed and sediment weight or depth predicted for the given situation.However, one must keep in mind the limitations of equations (5.5) and (5.6). The latter being derived for drains of equal nominal diameters.

The discharge is proportional to the square of the drain diameter and the velocity of flow. Therefore, for drains of different diameters, equation (5.8) becomes:

$$\delta = \nu_1 \; (V/V_0) \; (d/d_0)^2 \; \ln(A_0 \alpha + 1)/\ln(A_0+1) \qquad (5.9)$$

where V is the velocity and d the drain diameter, the subscripts corresponding to the early definition.

Similarly, equation (5.7) can be rewritten as:

$$\delta = \nu_2 \; \alpha (A_0+1)/(A_0 \alpha + 1) \qquad (5.10)$$

or

$$\delta = \nu_2 \; (V/V_0) \; (d/d_0)^2 \; \alpha \; (A_0+1)/(A_0 \alpha + 1) \qquad (5.11)$$

Figure 5.20 depicts the relationship between discharge rate and drain opening area at the end of the first cycle for run 3 with the Ste. Sophie FS and Bainsville VFSL soils.

The variations of flowrate with time in Figures 5.1 to 5.10 can also be modelled. The models do not have any practical applications at this point but help to describe the trends of flow. Rejecting the unstable curves, each drainage curve represented for every tube followed the simple linear regression or the exponentional decay. The data of all four drain tubes within a test run can be pooled together to include either of equations (5.6) and (5.7) in the models.

Table 5.15 presents a summary of the best regression models for almost every case studied. In runs 3, 4 and 5 with the Ste. Sophie FS soil (Figures 5.2b and 5.3), the discharge increased linearly with time while it decreased in the same manner in the first run as well as in all

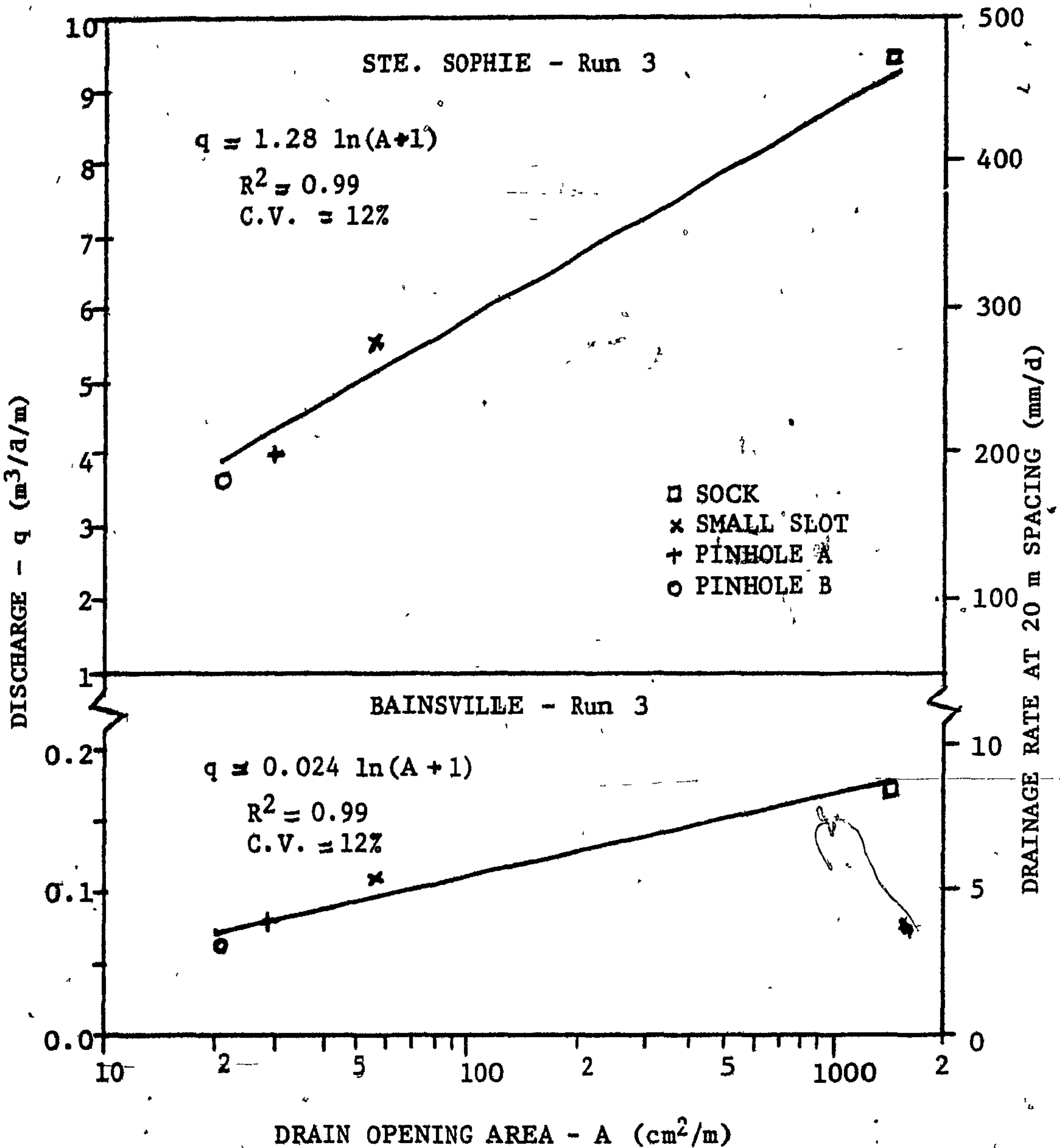


Figure 5.20. Discharge rate versus drain opening area per unit length at the end of the first cycle for run 3 with the Ste. Sophie fine sand and Bainsville very fine sandy loam soils.

Table 5.15. Regression analysis of discharge rate, q, versus time, t, and drain opening area per unit length, A.

Soil type	Run	Model	R^2 range	C.V.(%)
Ste. Barbe Medium sand	1	$a(1-e^{-1/t})\ \ln(A+1)$	0.90	20
Ste. Sophie Fine sand	1	$(a-bt)\ \ln(A+1)$	0.99	12
	3,4,5	$(a+bt)\ \ln(A+1)$	0.93-0.97	19-25
Soulanges[1] Fine sandy loam	all	$(a-bt)\ \ln(A+1)$	0.90-0.96	20-30
Bainsville Very fine sandy loam	all	$(a-bt)\ \ln(A+1)$	0.95-0.98	16-27
Ormstown[2] Silt loam	3,4	$a(1-e^{-1/t})\ A/(A+1)$	0.95-0.97	19-22

t, time in days

a,b regression parameters with different numerical values for each model

[1] Tube with fabric envelope not considered in first run.

[2] Runs 1 and 2 not considered.

runs with the Soulanges FSL (Figure 5.4a) and the Bainsville VFSL soils (Figures 5.7 and 5.8). The only exponentional decays with time were observed with the Ste. Barbe MS and Ormstown SiL soils. Looking at Figures 5.4 to 5.8, it can be argued that the flowrate decreases linearly as drainage progresses. Actually, the best regression is a combination of the models described above. A complete drainage curve can be explained by an exponentional decay in the first few days of drainage, followed by a linear decrease and a constant flow after the filter cake had been well established.

5.9 Equipotential Lines

One of the objectives of this research was to study the influence of the type of drain on the pressure distribution and its consequences on drain performance. The piezometer readings collected on the tanks furnished information from which equipotential lines could be plotted. Figures 5.21 to 5.24 illustrate the average equipotential pattern for all four tubes tested in the Ste. Sophie FS soil. The sets of piezometers on each side of the drain have been identified by a ,b, c, and d , going away from the drain as shown in Figure 5.21. The average piezometer readings were used because some of the piezometers had a slow response and were prone to error. Furthermore, since measurements were taken at one point along the drain axis, the changes observed might not necessarily occur in the soil chamber and thus, only conclusions on general trends can be made. Figures H1 to H8 represent the equipotential lines of all drains in the Soulanges FSL and Ormstown SiL soils. Because the piezometers did not function properly in run 4 with the Soulanges FSL soil, the data were averaged over the last two runs only.

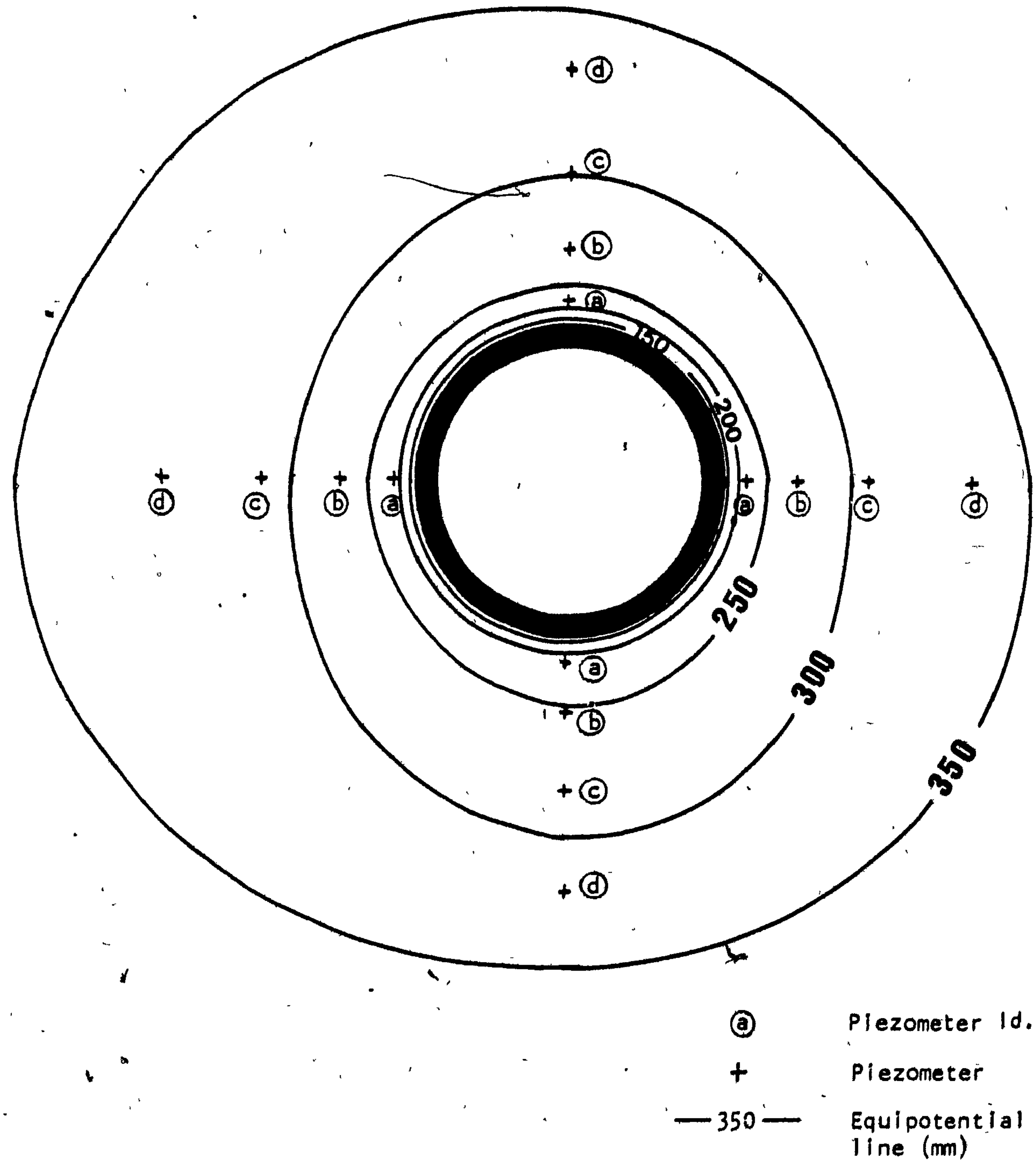


Figure 5.21. Average equipotential lines observed around the normal slotted tube with the fabric envelope in the Ste. Sophie fine sandy soil.

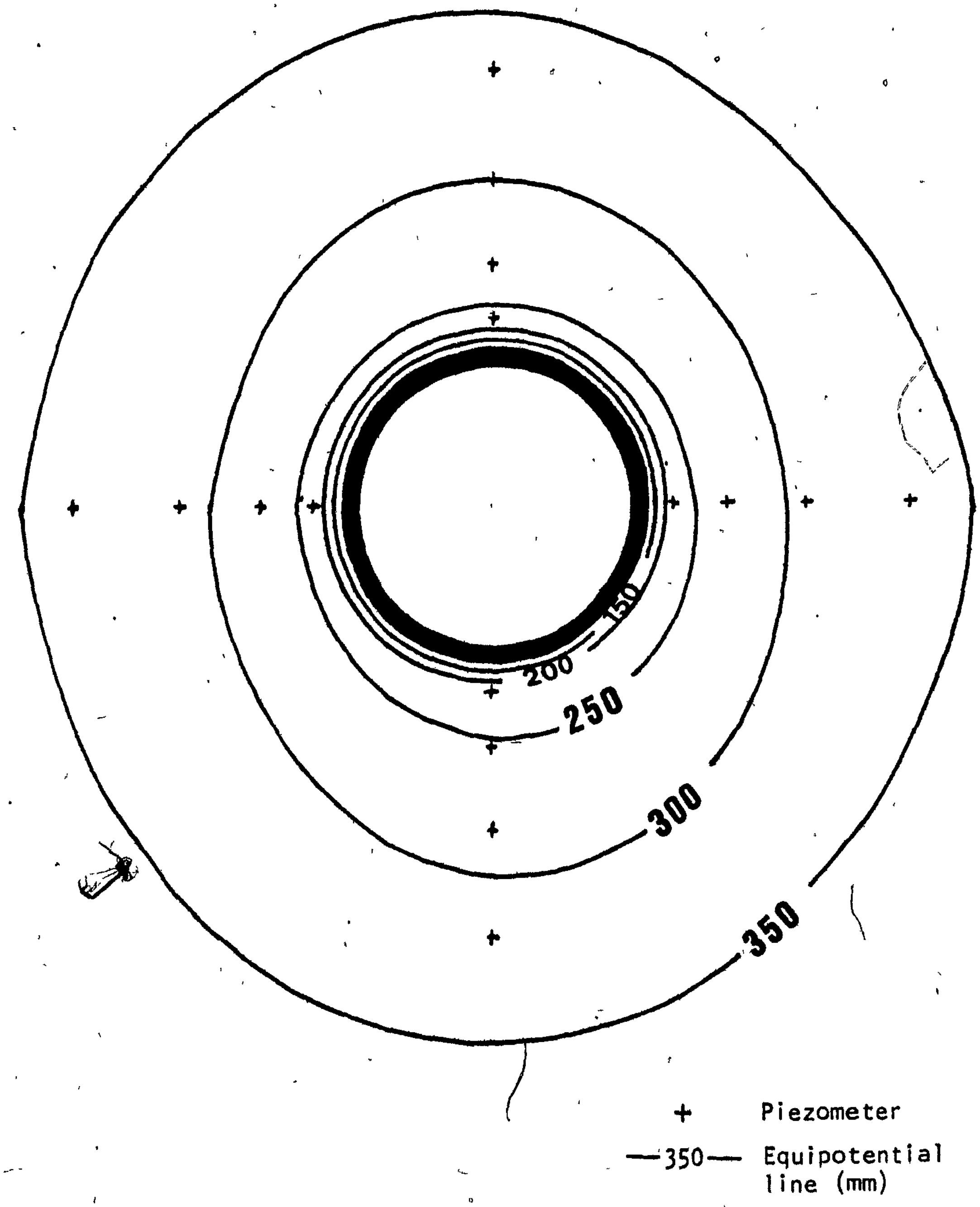


Figure 5.22. Average equipotential lines observed around the tube with small slots in the Ste. Sophie fine sandy soil.

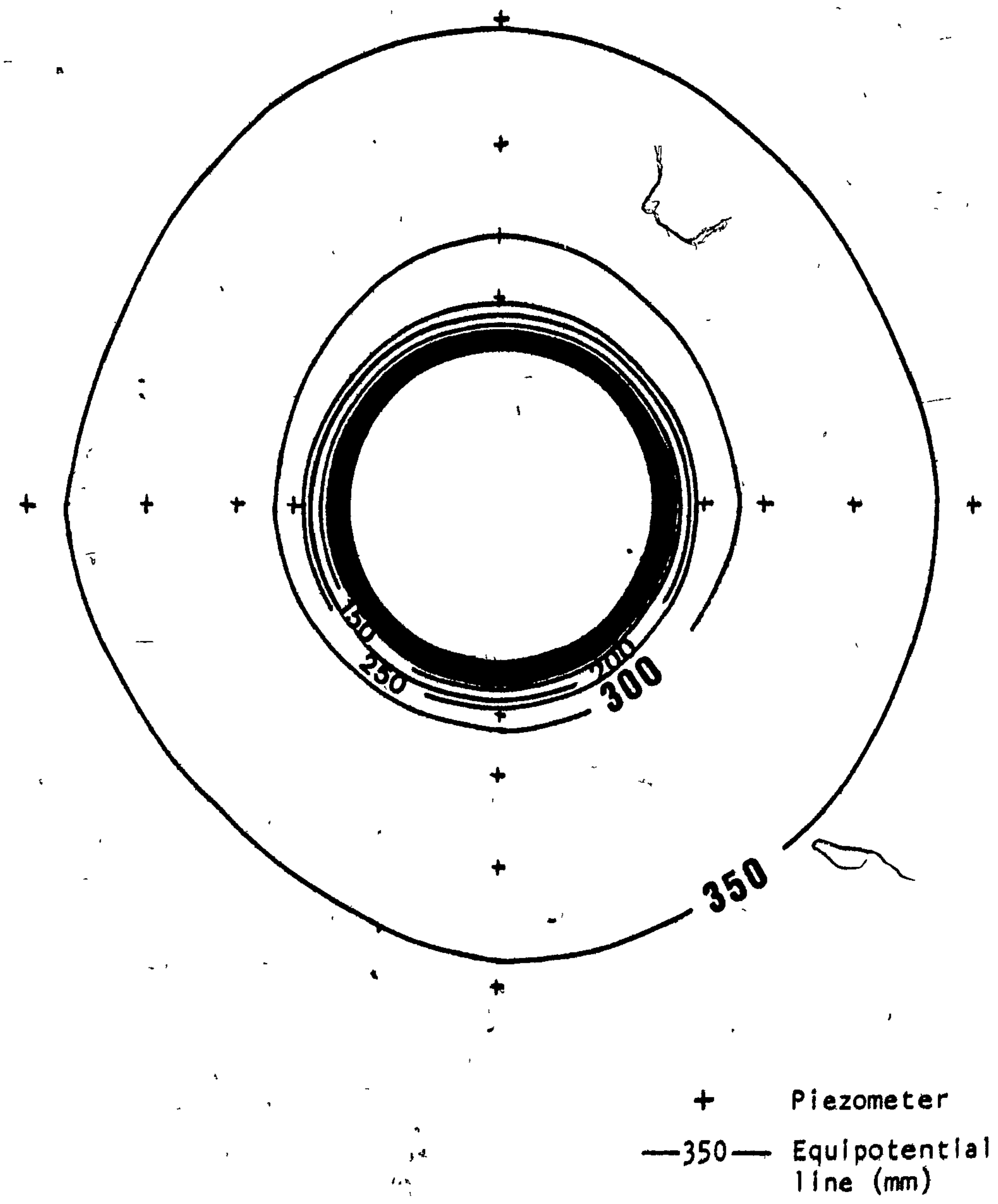


Figure 5.23. Average equipotential lines observed around pinhole tube A in the Ste. Sophie fine sandy soil.

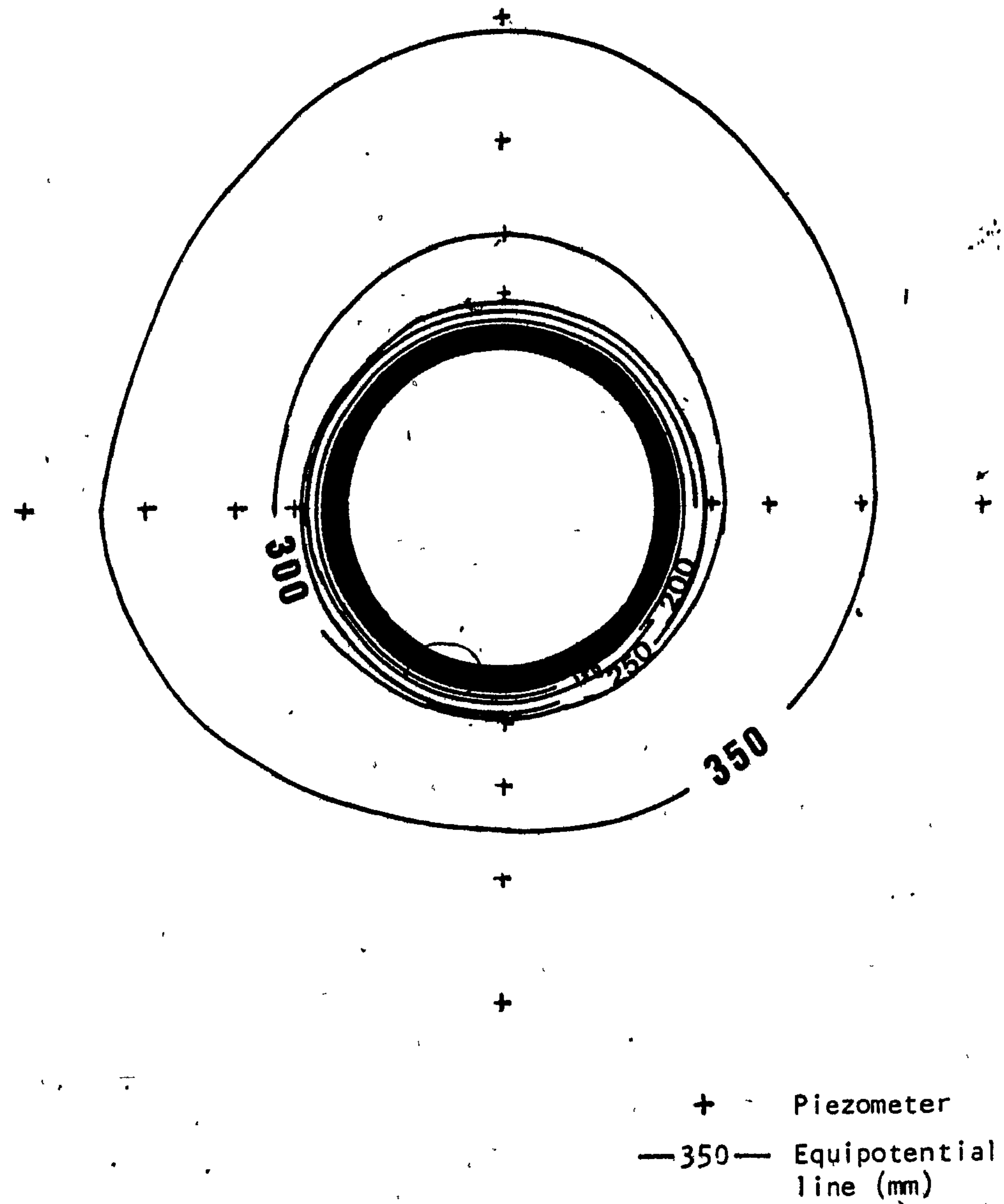


Figure 5.24. Average equipotential lines observed around pinhole tube B in the Ste. Sophie fine sandy soil.

It is seen in Figures 5.21 to 5.24 that, in general, the equipotential lines are circular in the vicinity of the drain but have a slightly elliptical shape away from the drain between the inner and most outer piezometer. A circular equipotential would indicate a uniform hydraulic conductivity of the soil in that region. It seems that the hydraulic conductivity of the bulk soil was not exactly uniform on each side of the drain. However, that discrepancy is not exagerated, which is an indication of the close-to-uniform compaction procedure.

The graphs also show a higher concentration of equipotentials at the first piezometer with the pinhole tubes. This reflects on the concentration of the streamlines in that region and therefore, on the high velocities and hydraulic gradients. Even though there were 48 holes per ring on those tubes, their small size contributed to offering a high resistance to the flow of water. The tube with small slots had opening widths approximately the same size as the pinholes but offered less resistance. This is mostly due to the higher hydraulic radius and opening area. The numerous small openings in the fabric envelope helped to spread the streamlines all around the drain and reduce the impedance. These observations explain the fact that, due to an increase in head loss near the drain, the discharge is reduced when the opening area is decreased.

Similar remarks can be made for the tubes in the Soulanges FSL (Figures H1 to H4). In this case, however, the equipotential lines are closer to the drain and are more concentrated on top of the drain than below. The proximity of the equipotential lines to the drain is a reflection of the higher resistance the soil is offering because of its finer structure and lower permeabilty. Soil settling in the soil chamber and resulting in a higher density above the drain, is probably the explanation to the higher concentration of streamlines above and close to the drain.

Table 5.11 showed the bulk density of the soil to be higher below the drain than above. It could be that the effect of shovelling out the soil to collect the samples tamped the soil below the drain to a density higher than it actually was while the test was running. Therefore, the situation would be of a higher density above the drain than below it during drainage. This means that the density values below the drain in Table 5.10 are not necessarily indicative of the situation prevailing during the test run. This, however, does not affect the conclusion made earlier for the effect of run and cell compaction on density.

The Ormstwon SiL (Figures H5 to H8) behaved in the same manner as the Soulanges soil but with a more accentuated proximity of equipotentials and contraction on top of the drain. This is due respectively, to a lower permeability of the soil and a greater settling of the soil in the trench. Note that the difference in the flow pattern among all four tubes is not as pronounced as in the two other soils. This emphasizes the fact that in fine soils with low permeability, the controlling drainage factor is the soil permeability rather than the drain opening area.

5.10 Radial Flow

Radial flow theory indicates that the hydraulic head should be proportional to the log of the distance from the drain center. When this is true, a plot of h, the hydraulic head, versus ln(r), r radial distance, should form a straight line with a slope $s=Q/(2\pi LK)$. For all three soils considered, the regression of h versus ln(r) for piezometer readings taken for each drain quarter, gave R^2 values ranging from 0.95 to 0.999 with a very low coefficient of variability, whether it be on a daily basis or by taking the average of all readings. This was done for all four piezometer readings on each side of the drain. Thus, the flow was radial outside the first piezometer, when considering each drain quarter separately.

The concentration of streamlines occured mostly between the drain and the first piezometer, as seen in Figures 5.21 to 5.24 and H1 to H8. According to Zaslavsky (1979), the streamlines would conglomerate over a distance approximately equal to the distance between perforations. The circumferential spacing was in the order of the millimeter for the tube with the fabric envelope, 8 mm for the tube with small slots, and 7 mm for pinhole tubes A and B. The axial spacing remained basically the same for the fabric envelope, was 12 mm for the second tube, 8 mm for pinhole tube A and 9 mm for pinhole tube B. Actually, the pitch was twice as much for the pinhole tubes, but because both valleys and ridges were perforated, the influenced distance of the streamline contraction was reduced to the distance between valleys and ridges. Therefore, it can be assumed that the piezometer readings were relatively free of the convergence effect of streamlines.

Figure 5.25 gives a plot of h versus ln(r) for each quarter of pinhole tube A in the first cycle of run 5 with the Soulanges FSL soil.

5.11 Hydraulic Conductivity

Having shown that the flow was radial outside the first piezometer when considering each drain quarter separately, the hydraulic conductivity can be computed by the slope of the line represented by Figure 5.25. The four slopes for each quarter can be averaged and the mean hydraulic conductivity of the soil be determined. This would, however, require a lot of computer work. A faster approach which produces the same results is to rewrite equation (3.4) as follows:

$$q_t = Q_t/L = 2\pi K\ (h_a - h_d)/\ln(r_a/r_d) \qquad (5.12)$$

where, q_t = total discharge per unit length, $m^3/d/m$

Q_t = total discharge over drain length, m^3/d

h_a = hydraulic head at the inner piezometer a, m

h_d = hydraulic head at the outer most piezometer d, m

r_a, r_d = radial distance to the corresponding piezometer, m

Considering each quarter of the drain,

$$q_t = \sum_{i=1}^{4} q_i \qquad (5.13)$$

where, q_i is the contribution of flow from one quarter of the drain and is equal to:

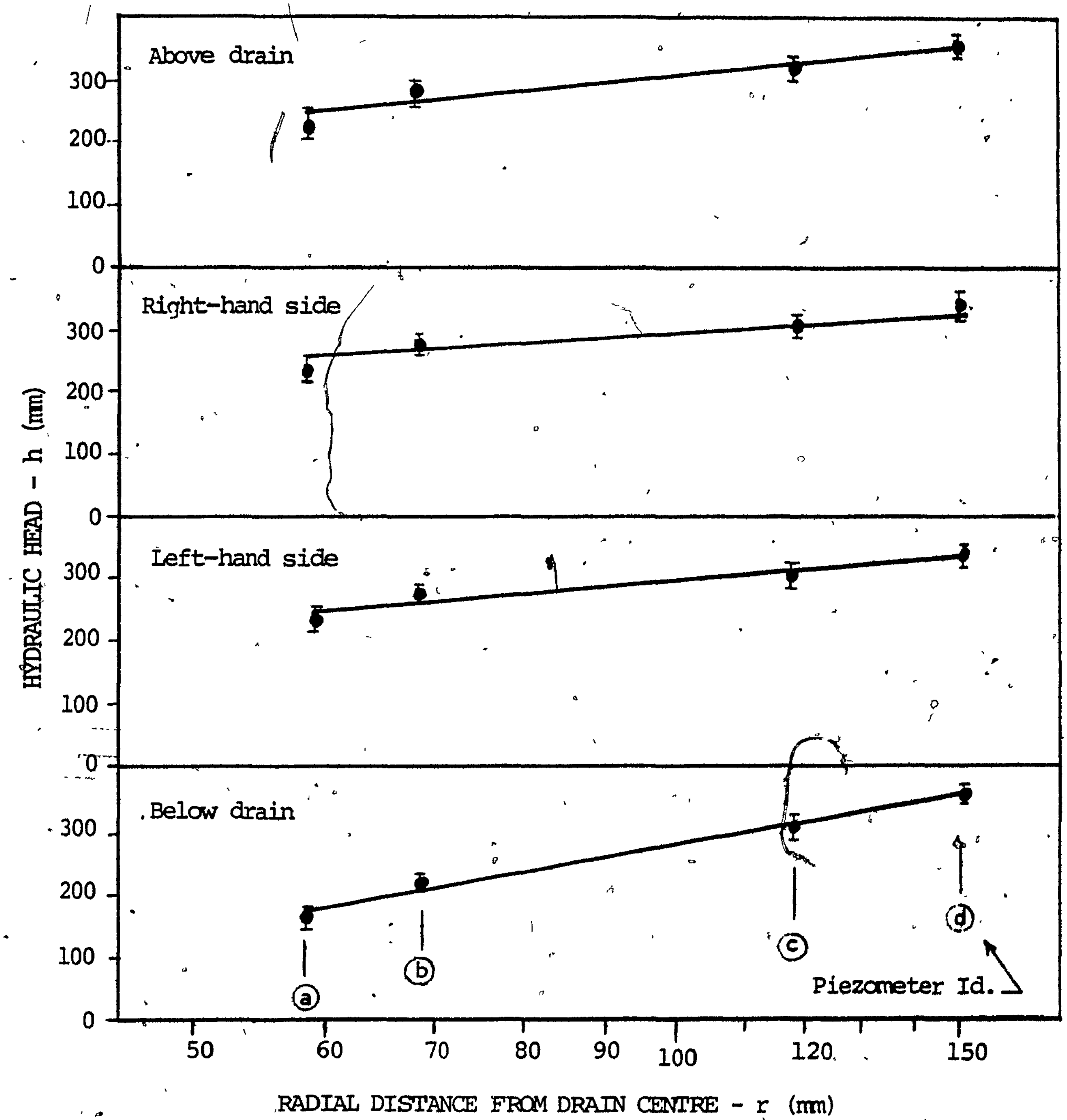


Figure 5.25. Plot of hydraulic head, h, versus the radial distance, r, from the drain center for each set of piezometers around the drain in the first cycle of run 5 with the Soulanges fine sandy loam soil.

$$q_i = 1/4 \; (K_i \; LNH_i) \tag{5.14}$$

$$LNH_i = 2 \pi \, (h_a - h_d)_i / \ln(r_d / r_a)_i \tag{5.15}$$

Considering the average hydraulic conductivity, K, of the soil around the drain,

$$q_t = K \; LNH_t \tag{5.16}$$

with $LNH_t = \sum_{i=1}^{4} LNH_i / 4$ (5.17)

or $K = q_t / LNH_t$ (5.18)

The average hydraulic conductivity can be computed using equation (5.18) but the best estimate is given by equation (5.16) where q_t is regressed over LNH_t. The regression method provides the least square estimate. To see if any difference exists between the hydraulic conductivity in each quarter of the soil chamber, equation (5.14) can be substitued in equation (5.13) and an estimate of each K_i be regressed over LNH_i. Estimates of the hydraulic conductivity on each quadrant were thus obtained. However, with four parameters to estimate, the regression gave some negative numbers. The negative hydraulic conductivities cannot be used but might give an indication of the drainage contribution of each quarter. Yet, it was not possible to isolate this effect because of the variabilty and the inconsistency of the estimated conductivities. A second regression was then tried where the bottom of the drain was compared to the three other locations. Here again, this method was not successful. The best estimate proved to be the average hydraulic conductivity as determined by the regression equation (5.16). The results are presented in Table 5.16, while a summary of the analysis of variance appears in Table 5.17. The detailed AOV tables are indexed in

Table 5.16. Weighted averages for the computed hydraulic conductivity, K (m/d).

SOIL TYPE	RUN	CYCLE	N	SOCK[a]	SMALL SLOTS	PINHOLE A	PINHOLE B
STE. SOPHIE Fine sand	3	1	28	8.34	6.35	6.06	5.06
		2	48	8.56	7.15	7.07	4.28
		Mean	76	8.48	6.85	6.70	4.57
	4	1	28	6.68	7.07	4.86	7.36
		2	12	6.00	6.24	4.95	8.52
		Mean	40	6.46	6.79	4.89	7.74
	5	1	36	6.53	4.99	6.38	3.94
		2	8	9.10	9.01	9.82	7.82
		Mean	44	7.00	5.72	7.00	4.65
SOULANGES Fine sandy loam	5	1	24	.250	.304	.209	.146
		2	8	.082	.110	.096	.061
		Mean	32	.208	.256	.181	.125
	6	1	40	.268	.284	.127	.120
		2	20	.098	.110	.085	.079
		Mean	60	.212	.226	.113	.106
ORMSTOWN Silt loam	2	1	40	.086	.123	.137	.111
		2	16	.181	.068	*	.084
		Mean	56	.113	.107	.137	.105
	3	1	20	.052	.051	.043	.056
		2	16	.044	.048	.039	.053
		Mean	36	.049	.049	.041	.055
	4[b]	1	20	.053	.046	.038	.072

[a] Sock represents tube with normal slots enrobed with fabric envelope.
[b] No readings taken in second cycle.
N Number of observations.
* Large void below pipe produced very high flowrates.

Table 5.17. Summary of the F-test results in the analysis of variance of the hydraulic conductivity computed by regression. (see the AOV tables in Appendix I).

Source	Ste. Sophie Fine sand	Soulanges Fine sandy loam	Ormstown Silt loam
Mainplots			
Run	n.s.	n.s.	**
Cell	n.s.	n.s.	n.s.
Subplots			
Cycle	n.s.	**	n.s.
Cell*Cycle	n.s.	n.s.	n.s.

n.s. not significant at the 0.05 level
** significant at the 0.01 level

Appendix I.

It appears from Table 5.17 that the hydraulic conductivity of the soil in the area covered between the first and fourth piezometers did not vary significantly among test runs for the Ste. Sophie FS and Soulanges FSL soils. This points out, once again, on the repeatability of the compaction procedure. Run 2 with the Ormstown SiL soil gave higher permeabilities than the last two runs (Table 5.16). These remarks agree with the results reported in Table 5.3 which indicated no effect of "run" on drainage rate with the fine sand and fine sandy loam. They also agree for the silt loam for which the second run gave higher drainage rates than the last two, when the overshadowing effect of run 1 was removed.

Table 5.17 also indicates a uniform hydraulic conductivity among cells in all three soils. From this observation, it can be stated that any difference in flowrates, among drain tubings, would result from differences in the total opening area of the drains and the hydraulic conductivity in the vicinity of the drain before the first piezometer. Once more, the inferences made on the effect of cycle and interaction between tubing and cycle corroborate the results of Table 5.3. The wetting and drying cycle did not disturb much of the soil in the chambers with the fine sand and silt loam. In the former soil, the settling being negligible while in the latter one, most of the settling took place in the first cycle. It seems that the fine and very fine sandy loam soils were most sensitive to a wetting and drying cycle.

5.12 RPZ Ratio

Figures 5.21 to 5.24 and H1 to H8 showed almost circular equipotential lines in the vicinity of the drain, illustrating a possible uniform hydraulic conductivity around the drain in that region. It was not possible to point this out by the regression method. However, using the RPZ ratio concept by Lagacé (1983), it is theoritically possible to isolate the effect of each drain quarter. Using equation (3.19), the RPZ ratios were calculated and the averages presented in Table 5.18. The entry resistance, α_t was calculated as shown in Appendix L. The analysis of variance tables appear in Appendix J with a summary of the results in Table 5.19. In all three soils, the accumulation of sediment never exceeded 20 mm. Therefore, it can be assumed that the RPZ ratios are free of the resistance through the sediment.

Looking at the "overall mean" in Table 5.18, for each tubing and among all runs, we see that the tube with small slots in the Ste. Sophie FS soil gave RPZ ratios lower than with the other tubes. Table 5.19 shows, however, that this discrepancy was not significant at the 0.05 level. The RPZ values greater than one indicate that the hydraulic conductivity of the soil in vicinity of the drain was smaller that in the outer region (away from the first piezometer). The tendency would be that the filter cake is denser than the bulk soil. However, it appeared that very fine sediment particles were being washed out of this soil, resulting in increasing flowrates with time (section 5.2). The explanation given was that the hydraulic conductivity of the filter cake was also increasing with time due to the washing out of the soil

Table 5.18. Weighted averages for the computed RPZ ratio.

SOIL TYPE	RUN	CYCLE	N	SOCK[a] Bot	SOCK[a] Left	SOCK[a] Right	SOCK[a] Top	SMALL SLOTS Bot	SMALL SLOTS Left	SMALL SLOTS Right	SMALL SLOTS Top	PINHOLE A Bot	PINHOLE A Left	PINHOLE A Right	PINHOLE A Top	PINHOLE B Bot	PINHOLE B Left	PINHOLE B Right	PINHOLE B Top
STE. SOPHIE	3	1	7	0.88	1.07	1.34	0.95	0.75	0.87	0.78	0.83	1.18	1.14	1.12	1.03	1.30	1.01	1.16	0.93
		2	12	0.78	0.96	0.96	0.79	**	0.97	0.97	0.76	1.31	1.17	1.18	0.89	1.34	1.01	1.19	0.77
		Mean	19	0.82	1.00	1.10	0.90	0.75	0.90	0.84	0.79	1.26	1.16	1.16	0.96	1.33	1.01	1.18	0.83
	4	1	7	1.66	1.70	0.99	1.23	1.05	0.93	0.74	0.98	1.24	1.11	0.93	0.91	1.38	1.11	1.26	1.10
		2	3	1.68	1.44	0.95	0.74	1.08	0.78	0.70	0.85	1.16	1.02	0.85	0.82	1.36	0.97	1.18	0.97
		Mean	10	1.67	1.61	0.98	1.08	1.06	0.88	0.73	0.94	1.22	1.08	0.90	0.88	1.38	1.07	1.24	1.06
	5	1	9	1.42	1.34	1.44	1.94	0.67	0.90	0.78	0.96	1.32	1.46	1.51	1.53	1.39	1.22	0.89	1.02
		2	2	0.69	1.40	1.51	1.74	0.66	1.03	0.93	0.99	1.40	1.45	1.56	1.61	1.41	1.71	0.90	1.21
		Mean	11	1.29	1.35	1.45	1.90	0.66	0.92	0.81	0.97	1.33	1.46	1.52	1.54	1.40	1.21	0.89	1.06
	Overall Mean		40	1.16	1.24	1.17	1.30	0.83	0.90	0.80	0.87	1.27	1.23	1.20	1.13	1.36	1.08	1.12	0.95
SOULANGES	5	1	6	0.39	0.65	0.87	0.27	0.99	0.66	0.73	0.40	**	0.43	0.70	0.71	1.21	1.24	1.15	1.25
		2	2	0.29	0.51	2.16	0.22	0.83	0.50	0.79	0.43	1.03	0.91	1.00	0.67	1.11	1.22	1.01	1.09
		Mean	8	0.36	0.62	1.19	0.26	0.95	0.62	0.74	0.41	1.03	0.49	0.77	0.70	1.18	1.23	1.11	1.21
	6	1	10	0.84	2.13	1.55	1.42	0.92	1.32	0.30	1.33	0.38	0.37	0.72	0.85	1.10	1.17	0.97	1.15
		2	5	0.70	0.48	0.87	0.92	0.75	0.77	0.56	0.80	0.15	0.28	0.36	0.52	0.86	1.08	0.95	1.03
		Mean	15	0.79	1.54	1.33	1.25	0.86	1.14	0.39	1.15	0.30	0.34	0.59	0.74	1.02	1.14	0.96	1.11
	Overall mean		23	0.64	1.21	1.29	0.91	0.89	0.96	0.51	0.89	0.39	0.39	0.66	0.73	1.08	1.17	1.02	1.15
ORMSTOWN	2	1	10	2.19	1.82	1.48	1.90	0.89	0.79	0.52	0.87	0.73	0.71	0.99	0.66	0.83	0.77	0.49	0.62
		2	4	0.51	1.14	0.18	0.51	0.59	0.43	0.35	0.73	*	*	*	*	0.03	0.63	0.41	0.52
		Mean	14	1.71	1.63	1.11	1.50	0.81	0.68	0.47	0.83	0.73	0.71	0.99	0.66	0.65	0.74	0.47	0.59
	3	1	5	0.15	0.86	0.20	2.23	0.06	0.27	0.10	0.67	0.32	0.40	0.72	0.36	0.05	0.09	0.62	0.67
		2	4	0.07	0.38	0.14	1.76	0.06	0.45	0.52	0.79	0.18	0.21	0.60	0.21	0.11	0.10	0.40	0.68
		Mean	9	0.12	0.65	0.17	2.02	0.06	0.35	0.29	0.72	0.26	0.31	0.66	0.29	0.08	0.10	0.52	0.67
	4[b]	1	5	1.65	2.72	2.53	2.54	0.66	0.86	0.98	0.97	0.23	0.97	1.04	1.39	1.29	1.33	1.02	1.25
	Overall mean		28	1.19	1.51	1.06	1.86	0.58	0.61	0.50	0.82	0.45	0.61	0.88	0.67	0.60	0.66	0.59	0.74

[a] Sock represents tube with normal slots enrobed with fabric envelope.
[b] No readings taken in second cycle.
N Number of observations.
* Large void below pipe produced very high flowrates.
** Piezometer did not function properly

Table 5.19. Summary of F-test results in the analysis of variance of the computed RPZ ratios (see AOV tables in Appendix J).

Source	Ste. Sophie Fine sand	Soulanges Fine sandy loam	Ormstown Silt loam
Mainplots			
Run	n.s.	n.s.	**
Tubing	n.s.	n.s.	n.s.
Subplots			
Cycle	n.s.	**	n.s.
Loc(ation)	n.s.	n.s.	*
Cycle*Loc	n.s.	n.s.	*
Tubing*Cycle	n.s.	n.s.	n.s.
Tubing*Loc	n.s.	n.s.	n.s.
Tubing*Cycle*Loc	n.s.	n.s.	n.s.

n.s. not significant at the 0.05 level
* significant at the 0.05 level
** significant at the 0.01 level

particles. This could very well be the case and still have a conductivity lower than the bulk soil, since the Ste. Sophie FS soil is quite permeable. Therefore, the RPZ values obtained do not necessarily contradict the comments made earlier.

In the Ormstown SiL soil, the "overall mean" RPZ ratios (Table 5.18) were higher than one for the tube with the fabric envelope and less than one with the other tubes. An RPZ value smaller than one means that the soil in vicinity of the corrugations is more permeable than the bulk soil in the envelope-free tubes. Although the soil was compacted and settled by about 6 cm in the trench as drainage progressed, the soil inside the corrugations was not compacted as much and was more conductive to the flow. However, the tube with the fabric envelope, presenting no corrugations, the compaction procedure and settling helped to pack the soil even tighter. This is probably why there was an effect due to tubing type in that soil (Table 5.19). Duncan's test showed the enrobed tube to be the reason of this effect.

It appears from Table 5.19 that "run" had an influence on the RPZ ratio with the Ormstown SiL soil. With flowrates decreasing from run 2 to run 4, the order of influence should be reversed for the RPZ analysis. Duncan's test showed the order to be 4-2-3. It could be, for run 3, that the soil close to the plexiglass window was not as compacted as the soil in the trench, therefore giving low ratios. One needs to remember that readings were taken at only one point and that the observations might not always represent the situation in the trench.

Nevertheless, the general tendency for the RPZ ratios was to be higher on top of the drain than below the drain with fluctuating values on each side of it. The difference became, however, only significant with the Ormstown SiL soil. This means that the hydraulic conductivity was, statistically speaking, almost uniform all around the drain in the inner region, so far as the Ste. Sophie FS and Soulanges FSL soils are concerned.

5.13 Hydraulic Gradient

The hydraulic gradient at the drain opening can be used to explain drain failure by silting. Substituting equation (3.18) into equation (3.21), the hydraulic gradient at the opening, I, becomes:

$$I = (h_a - h_o)/(A\,\alpha_{ta}) \qquad (5.19)$$

As given in equation (5.19), the gradient is only dependent on the head loss, the total flow resistance and the drain opening area, provided the hydraulic conductivity of the soil between the drain and the first piezometer is uniform all around the drain. This was the case for the Ste. Sophie FS and Soulanges FSL soils but not the Ormstown SiL soil. Still, the analysis was done for all three soils because the RPZ means did not vary by large amounts in the silt loam. Table 5.20 gives the average computed gradient per cycle, tubing and run while Table 5.21 summarizes the statistical analysis shown in Appendix K. For the total drain opening area, a multiplicative factor of $\pi/2$ was used to account for arch boundaries on top of the openings.

Table 5.20. Weighted averages for the computed hydraulic gradient, I.

SOIL TYPE	RUN	CYCLE	N	SOCK[a] Bot	SOCK[a] Left	SOCK[a] Right	SOCK[a] Top	SMALL SLOTS Bot	SMALL SLOTS Left	SMALL SLOTS Right	SMALL SLOTS Top	PINHOLE A Bot	PINHOLE A Left	PINHOLE A Right	PINHOLE A Top	PINHOLE B Bot	PINHOLE B Left	PINHOLE B Right	PINHOLE B Top
STE. SOPHIE	3	1	7	3	5	6	5	49	56	50	58	172	170	165	155	250	201	231	180
		2	12	3	4	5	4	**	65	55	53	192	172	175	134	255	199	241	150
		Mean	19	3	4	5	4	49	59	53	55	185	172	171	144	253	200	238	161
	4	1	7	7	8	5	6	76	68	56	71	186	165	140	131	279	216	253	205
		2	3	7	6	4	4	76	53	50	59	169	142	123	112	265	178	225	173
		Mean	10	7	7	5	5	76	64	54	67	180	157	134	125	275	204	245	195
	5	1	9	7	7	7	10	45	62	53	56	209	240	238	233	275	233	170	181
		2	2	3	6	6	8	38	60	51	51	216	243	238	246	265	216	165	198
		Mean	11	6	6	7	10	44	62	52	55	210	241	238	235	274	231	169	185
	Overall Mean		40	5	5	6	7	57	62	53	58	191	188	182	168	264	210	221	176
SOULANGES	5	1	6	2	3	4	2	70	45	48	30	**	60	99	111	242	249	229	260
		2	2	1	2	11	1	53	32	47	30	126	108	133	95	206	232	180	218
		Mean	8	2	3	6	2	66	41	48	30	126	72	108	107	232	245	219	249
	6	1	10	4	12	9	8	67	98	22	103	51	56	114	134	211	236	191	231
		2	5	3	3	4	5	47	55	38	62	18	41	46	77	156	215	178	206
		Mean	15	4	9	7	7	61	84	28	89	40	51	89	115	193	229	187	223
	Overall mean		23	3	7	7	5	62	69	35	69	50	58	96	112	206	234	198	232
ORMSTOWN	2	1	10	14	12	9	12	62	64	38	73	114	109	148	113	150	145	98	129
		2	4	2	6	1	4	25	27	22	58	*	*	*	*	44	104	71	108
		Mean	14	11	10	7	10	51	53	34	68	114	109	148	113	116	136	92	125
	3	1	5	1	6	1	16	5	22	9	62	51	62	113	66	10	20	141	162
		2	4	1	2	1	13	4	34	41	72	23	28	81	38	16	19	81	165
		Mean	9	1	4	1	15	4	28	23	66	38	47	99	53	13	20	114	163
	4[b]	1	5	10	16	14	15	56	64	74	85	33	151	168	241	265	279	214	284
	Overall mean		28	7		6	12	40	47	38	71	69	95	133	117	113	128	122	169

[a] Sock represents tube with normal slots enrobed with fabric envelope.
[b] No readings taken in second cycle.
N Number of observations.
* Large void below pipe produced very high flowrates.
** Piezometer did not function properly

Table 5.21. Summary of F-test results in the analysis of variance of the computed hydraulic gradient.(see AOV tables in Appendix K).

Source	Ste. Sophie Fine sand	Soulanges Fine sandy loam	Ormstown Silt loam
Mainplots			
Run	n.s.	n.s.	n.s.
Tubing	**	**	**
Subplots			
Cycle	n.s.	**	n.s.
Loc(ation)	**	n.s.	**
Cycle*Loc	n.s.	n.s.	n.s.
Tubing*Cycle	n.s.	n.s.	n.s.
Tubing*Loc	**	n.s.	n.s.
Tubing*Cycle*Loc	n.s.	n.s.	n.s.

n.s. not significant at the 0.05 level
** significant at the 0.01 level

Table 5.21 shows that the type of drain opening has a definite effect on the hydraulic gradient. It also depicts a significant difference among locations in both the Ste. Sophie FS and Ormstown SiL soils. The gradients were lowest for the normal tube with the filter stocking and highest for pinhole tube B, increasing as the opening area decreased. Also, the gradients , which ranged from 1 to 284, were in general, higher on top of the drain than below with intermediate values for the sides.

With the values obtained with the small slotted tube and pinhole tubes, one must expect failure to occur and high sedimentation to take place. This is what actually happened as sediments were collected in these drains. However, the sediments represented only a small amount in the Ste. Sophie fine sand and Ormstown silt loam. Using the model developed by Samani and Willardson (1981) - equation 3.20 - and assuming a plasticity index of 2, 5 and 15 for the fine sand, fine sandy loam and silt loam soils, the hydraulic failure gradient for these soils, reached 3,7,and 25 respectively. Even when assuming a high plasticity index of 25 for all soils (range for highly clayey soils), the failure gradient would only be 15, 27 and 34. This is still much lower than the experimental values.

Such high gradients were also reported by Lagacé (1983) and in his case too, the model by Samani and Willardson underestimated the hydraulic failure gradient. With these high gradients one would expect a very high sedimentation rate. This was not the case. It therefore, seems that other factors than just the plasticity index and the hydraulic conductivity, used in the model by Samani and Willardson (1981), play an important role in preventing siltation. Further investigation would be needed to determine the nature of these factors.

VI. SUMMARY AND CONCLUSIONS

6.1 Summary

The main objectives of this research were to measure the drainage and sedimentation performance of two pinhole tubes A and B and a tube with small slots in comparison with a normal slotted tube enrobed with a knitted polyester envelope 152 g/m^2 of unit weight. It was hoped that tubing with pinholes and small slots would not require a fabric envelope as has been required for normal slotted tubing in soils known to cause sedimentation problems in subsurface drainage systems.

The perforations in pinhole tubes A and B averaged a diameter of 0.77 mm and 0.68 mm for both valleys and ridges and for a total opening area of 29.7 and 21.0 cm^2/m, repectively. The tube with small slots had perforations in the valleys of corrugations averaging 0.65 mm in width and 3.56 mm in length for a total opening area of 56.9 cm^2/m. The normal slotted tube with the fabric envelope had an opening area of 1427.5 cm^2/m with 95% of the fabric openings being less than 0.36 mm. The tubes were tested in five different soils taken from fields where a normal slotted tube without an envelope had become filled with soil. The soils used were a Ste. Barbe medium sand, a Ste. Sophie fine sand, a Soulanges fine sandy loam, a Bainsville very fine sandy loam and an Ormstown silt loam.

Three tanks 120 cm wide by 240 cm long and 76 cm deep were built for that purpose. Each tank was divided in four equal compartments with permeable dividers between each of the four cells so that the water supply to the drain tubes placed in each soil chamber was identical. Piezometers were installed on top, below and each side of the drain at the outlet end to study the pressure distribution around each drain. Pressure distribution was studied on the Ste. Sophie fine sand, Soulanges fine sandy loam and Ormstown silt loam soils. All four drains were tested at once under the same head and drainage conditions. Ponded case was simulated and, except for the first run with the Ste. Barbe, Ste. Sophie and Bainsville soils in which the drains were not flowing full, full pipe flow was simulated by means of an end cap installed at the outlets. The five soils were analysed separately as they present different characteristics. Thus for each soil, the experimental design consited of a randomized complete block design with four levels of treatment for the four types of drain tubes tested. The number of runs for each soil type determined the number of blocks.

Drainage rate and piezometer readings were measured on a daily basis, and at the end of each test run, drains were removed and sediments collected. Other measurements included core samples for dry bulk density, particle size analysis of samples collected away from the drain, on the drain and of the sediments inside the drain. Each test run consisted of two distinct flow periods (cycles) to simulate a wetting and drying cycle. Each test run lasted from 9 to 39 days. When samples are taken at different locations or the experiment consists of two cycles, the data are analyzed according to a split-plot model. A multivariate analysis was used to determine if differences existed between the collected soil samples.

For comparison, a field spacing between drain laterals of 20 m was used to determine the drainage rate. If the rate obtained was in vicinity of the design drainage rate of 9 mm/d, currently used in Eastern North America, the drain was considered satisfactory. The number of years to half fill the drain of sediments was calculated based on the time it took to collect the measured sediments.

Although not directly part of the objectives, two models were developed. The first model related sediment weight to the drain opening hydraulic radius and the soil D_{60} size. The model proposed is an improvement of the original model by Lagacé (1983). The second model related discharge rate to the total drain opening area per unit length. The validity of the second model was checked by using data from other researchers. Also, the assumption of a uniform hydraulic conductivity around the drain was checked using the radial flow theory and the entry resistance factor (RPZ ratio developed by Lagacé, 1983). The hydraulic gradient was also determined to explain drain failure by sedimentation.

6.2 Conclusions

Based on the results of this study, the following practical conclusions can be drawn:

1. All of the drain tubes tested provided plentiful drainage and adequate soil retention with the Ste. Barbe medium sand and Ste. Sophie fine sand. Therefore, any of the tubes with pinholes and small slots can be used without restriction in a soil with a particle size distribution very similar to the distribution of the above two soils.

2. The normal slotted tube wrapped with a knitted polyester envelope had significantly higher drainage rates than the tubes with pinholes or small slots when used in the Soulanges fine and Bainsville very fine sandy loam soils. It is likely that the greater entry area provided by the fabric envelope is responsible for the higher flowrates than obtained with the tubes with pinholes or small slots.

3. It appears that in soils with very low permeability, it is the hydraulic conductivity of the soil rather than the drain opening area that controls the drainage rate, provided the drain tubes retain the soil adequately. Hence, a normal slotted tube with a knitted polyester envelope could be replaced by any of the tubes with pinholes and small slots and still drain equally. This was the case with the Ormstown silt loam soil.

4. All drain tubes tested might need to be placed at spacings less than 20 m in the Soulanges fine sandy loam, Bainsville very fine sandy loam and Ormstown silt loam soils, in order to achieve a drainage rate of 9 to 14 mm/d. However, this would still need to be verified in the field as the rates obtained in the laboratory might not necessarily represent field values. This does not apply to the medium and ~~fine~~ sand for which the minimum drainage rate was 54 mm/d.

5. The quantity of sediments entering the drain might be considered excessive for tubes with pinholes and small slots placed in the Bainsville very fine sandy loam and the Soulanges fine sandy loam soils.

In the former soil, the number of years to half fill the drain with sediments ranged from 3 to 9 years while it varied from 16 to 26 years in the latter soil. Sediment entry was not a problem in the medium and fine sand, and silt loam soils.

6. The majority of the soil which entered the tubes settled in as sediments. The amount of sediments moving out with the drainage water was negligible in all cases except in the first run with the Bainsville very fine sandy loam. In the latter case, the pipes were not flowing full and the depth of flow was only approximately 1.5 times the depth of sediments. The sediments washed out represented approximately half the weight of particles settled in the pinhole tubes, and 2.5 times the sediments settled in the tube with small slots. This indicates that when sediments are not flushed out from a subsurface drainage system, drainage could be seriously reduced by sediments moving with the drainage water and accumulating at a downstream location along the length of the lateral.

7. The Soulanges fine sandy loam and Bainsville very fine sandy loam soils were most sensitive to the effect of a wetting and drying cycle. The lower drainage rates obtained in the second flow period were not solely due the cycling effect. Soil settling in the trench (or chamber) also had some influence. However, when this situation happens in the field, some sedimentation might be induced at the start of a new flow period after a dry spell. Therefore, the life expectancy of all envelope-free tubes tested would be shortened.

8. The sediments collected inside the drains presented a particle size distribution significantly different (finer) than the bulk soil and the soil in vicinity of the drain. The soil from the last two locations was basically the same. The type of drain opening (i.e. tubing type) did not seem to affect the distribution of the sediment particles inside the drain.

9. From the comparison made of opening dimensions and soil particle considerations with some suggested criteria, it appears that additional research is needed to establish a dependable relationship for determining the maximum hole size in tubes and envelopes to be used for soils having most particles between 0.02 and 0.30 mm.

10. Two parameters, namely, the drain opening hydraulic radius and the soil D_{60} size, served to explain most of the sediment weight inside the tubes. It was found that sediment weight varies as an exponentional function of the product of the drain opening hydraulic radius and a power function of the soil D_{60}. Using that model, one is able to determine the range of problem soils for a given drain opening type. It was found however, that other factors would need to be included to improve on the model.

11. Drainage rate was found to vary as the logarithm of the total drain opening area per unit length, in all soils except the Ormstown silt loam. This was true whether the tubes were flowing full or not. In the latter soil where the controlling drainage factor appeared to be the soil hydraulic conductivity, the drainage rate slowly increased with

large increases in the opening area. Therefore, the drainage rate was found to be proportional to the ratio of the opening area to the opening area plus one. A dimensionless form of the models could be used to predict the drainage performance of a new type of drain with a given opening area, in comparison with an actual drainage system for which the drainage rate is known.

12. The study of the entry resistance factor showed the soil in vicinity of the drain to have a different hydraulic conductivity than the bulk soil. Therefore, the assumption of a uniform hydraulic conductivity around the drain at any radius does not always apply. This agrees with the findings of Lagacé (1983).

13. There was a general tendency for the entry resistance factor to be higher on top of the drain than below the drain, but this difference became only significant with the Ormstown soil. This indicates that higher flowrates can be expected to occur below the drain.

14. The type of drain used has a definite effect on the hydraulic gradient at the opening. The gradient was lower for the tube with the fabric envelope and highest for pinhole tube B, increasing with decreasing drain opening area.

15. Existing models (Samani and Willardson, 1981) could not explain drain failure by siltation in all cases. The gradients obtained in the Ste. Sophie fine sand and Ormstown silt loam were considerably higher than the predicted hydraulic failure gradient and yet, the accumulation

of sediments was negligible. There seem to be factors other than just the plasticity index and the hydraulic conductivity that play an important role in the sedimentation process and the soil stability around drain openings.

VII. RECOMMANDATIONS FOR FURTHER RELATED WORK

As a result of this study, and in addition to the recommendations made in the previous chapter, the following topics are deemed important for further investigation:

1. In this research, the reworking of the soil from one test run to the next had an effect on drainage rate in the Ormstown silt loam and on the sedimentation process in the Soulanges fine sandy loam, the Bainsville very fine sandy loam and the Ormstown soil. If the same batch of soil is used more than once in laboratory tests of drain performance, it is likely that this repetitive use will have an effect on the variables analyzed unless this soil is structureless. It is recommended that this effect be taken into consideration in studies involving replications in time with the same batch of soil, or that it be avoided by making replicates with separate homogeneous batches of soil taken fresh from the same field.

2. Drain performance is significantly affected by the structure of the soil. This effect was only qualitatively assessed in the present study. It is suggested that the inclusion of the effect of that variable, by means of aggregate size analyses, be a rule in future works involving the study of drain performance.

3. The tanks built for this research could be used for many other investigations. At the present time, the tanks are provided with an external rising pipe on which holes were drilled at increment heights of

5 cm. This was done in prevision of studies involving the control of the water table depth on the performance of the various drains to be tested. The tanks can be enhanced by adding plexiglass windows at the upstream tank wall for a better visualisation of the sedimentation process.

4. The exit head loss at drain openings is less in drainage than in subirrigation (Piekutowsky, 1986). With this in mind and using the same tanks, it would be interesting to test the performance of tubes with pinholes and small slots under subirrigation at various levels of head control.

5. The tubes with pinholes and small slots were found to perform well in the Ormstown silt loam so far as sedimentation is concerned. Therefore, there should be no problem in clay soils. However, under saline conditions, dispersion of soil particles in silty and clayey soils are of a major concern. It would be of interest to investigate the performance of these tubes or similar tubes in saline soils.

6. The model developed for predicting sediment weight for a given tube opening hydraulic radius and a given soil should be further investigated. Using the present tanks or similar ones, a broader range of soils could be tested. The model can easily be transformed to predict sediment depth rather than sediment weight. It is suggested that it be improved by monitoring sedimentation rate (depth) and to see how it is correlated to a rate of decrease or increase in drainage rate and the time it took to reach that discharge. Also, other soil characteristics than just the D_{60} size, such as aggregate stability, coefficients of

uniformity and curvature could be included in the model. The sedimentation process might vary as the head varies. This feature can also be studied using the external pipes provided with the tanks.

7. Brouillette and Delisle (1982) reported of drains with very small slots (average width of 0.80 mm) to be clogged at 63% under soils presenting ochre problems. Kuntze (1979) recommends the opening to be larger than 1.2 mm in order to avoid the formation of bridges of ochre and soil particles. This would indicate that the small slotted tube and pinhole tubes tested in this research are not suitable for soils with a potential ochre problem. However, not much research has been done in that field with respect to drains with small slots and pinholes. Further consideration should be given in testing the performance of such drains in those types of soil.

8. Further research should be carried out to improve on the model by Samani and Willardson (1981) in predicting soil hydraulic failure gradient. Multiplicative correction factors could be determined for soils from areas other than the ones used by the authors but falling in the same range.

9. Since the drainage rates determined in the laboratory do not necessarily represent field values, field tests should be carried out. However, because the soils tested were taken from fields where subsurface drainage systems are installed, the drains tested in the laboratory do not need to be installed in the field. The drainage rate of the existing laterals can be monitored and the opening area of the

drains be determined. These values would be replaced in the dimensionless form of the model predicting drain discharge versus drain opening area. The new drainage rates for the tubes tested in this research could then be determined for the same spacing used in the field. This would avoid having to spend tremendous amounts of money for a field experiment.

10. However, field experiments might still be needed to confirm the estimated number of years to half fill the drains of sediments. Field studies would not be compulsory for the Ste. Barbe medium sand and Ste. Sophie fine sand. Nor would they be necessary for the Bainsville very fine sandy loam since performance in the laboratory indicates that failure would likely occur in the field. For the Soulanges fine sandy loam, the working life expectancy of the tubes with pinholes and small slots was, generally, unacceptable. However, with some of the cases presenting acceptable levels of siltation, a small field scale experiment might be necessary in this soil to confirm the results. The Ormstown silt loam tested had 12% clay content and presented no problem. In the field, however, the clay content varies and can go down to 5%, a critical level for the percentage of silt contained in the soil. Therefore, special care should be exercised when installing the tube with small slots or pinholes. A quick test can be carried out with the same tanks on a batch of soil with 5% clay, to confirm the above suspiscion.

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APPENDIX A

Figures showing histogram of measured drain openings for the small slotted tube and pinhole tubes A and B.

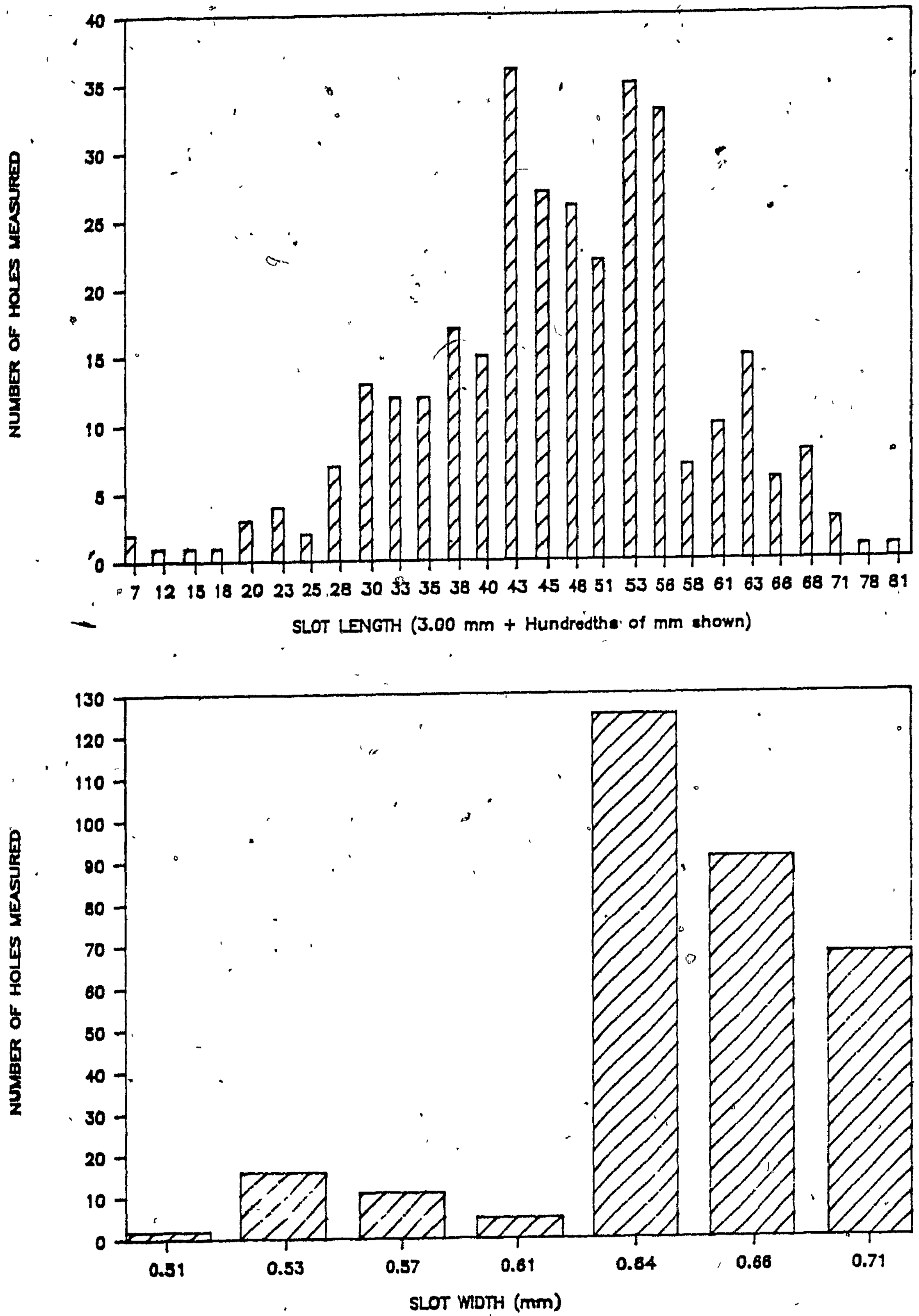
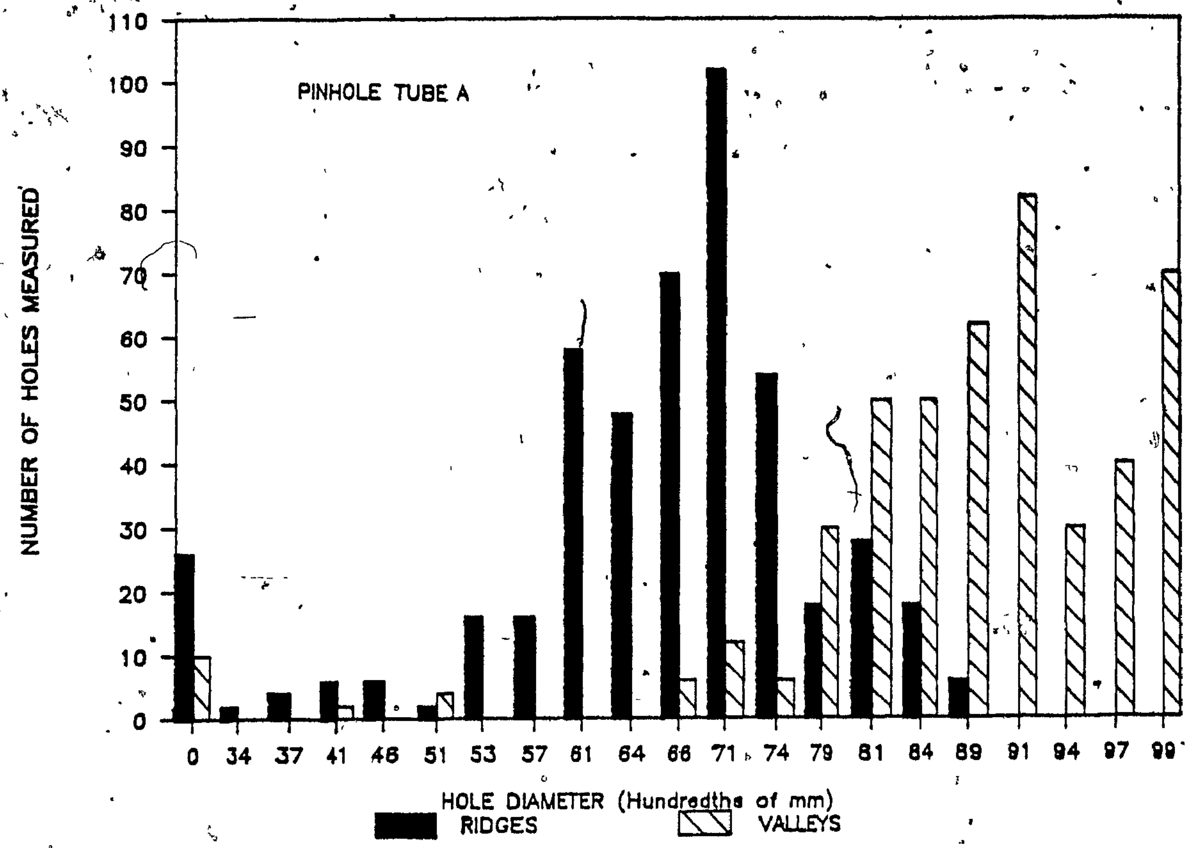


Figure A1. Histogram of measured drain openings for slot length (top) and slot width (bottom) for the tube with small slots.



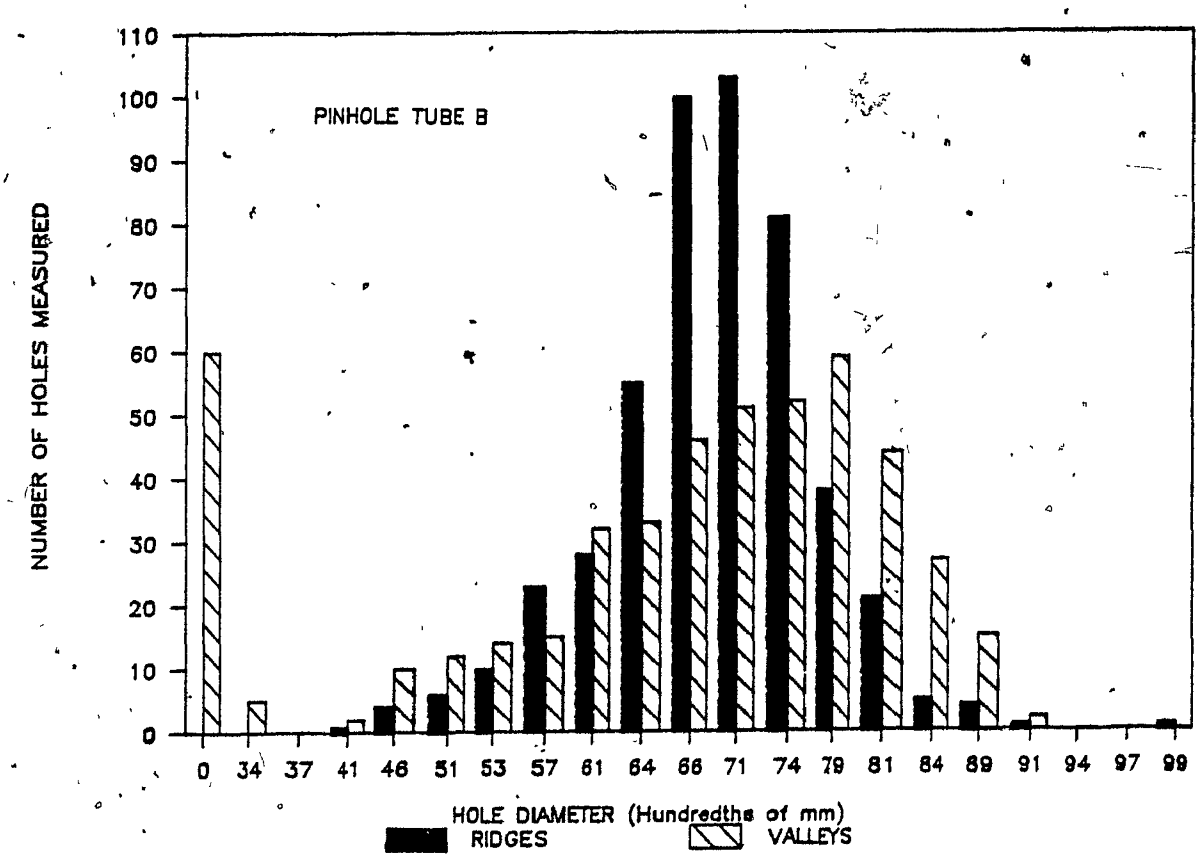


Figure A2, Histogram of measured drain openings in ridges and valleys of Pinhole tube A (top) and Pinhole tube B (bottom).

APPENDIX B

Photographs showing the soil and water test tanks built for this research.

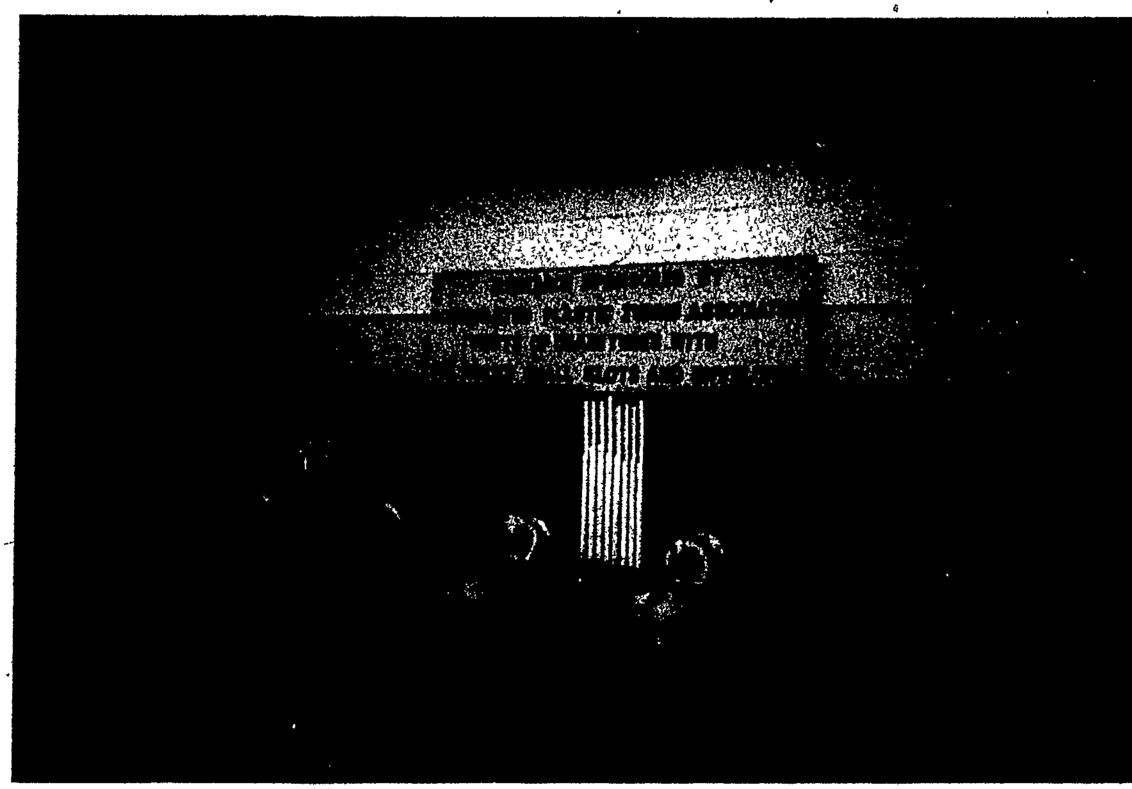


Figure B1. An over-view of test tank number 2 with four drain tubes functioning in the Ste. Sophie fine sand. Note the funnels used to collect water and sediment draining from the tubes.

Figure B2. A close-up view of the overflow device used to maintain a constant head of water above the soil surface. Note the aggregates visible on the soil surface (Bainsville very fine sandy loam).

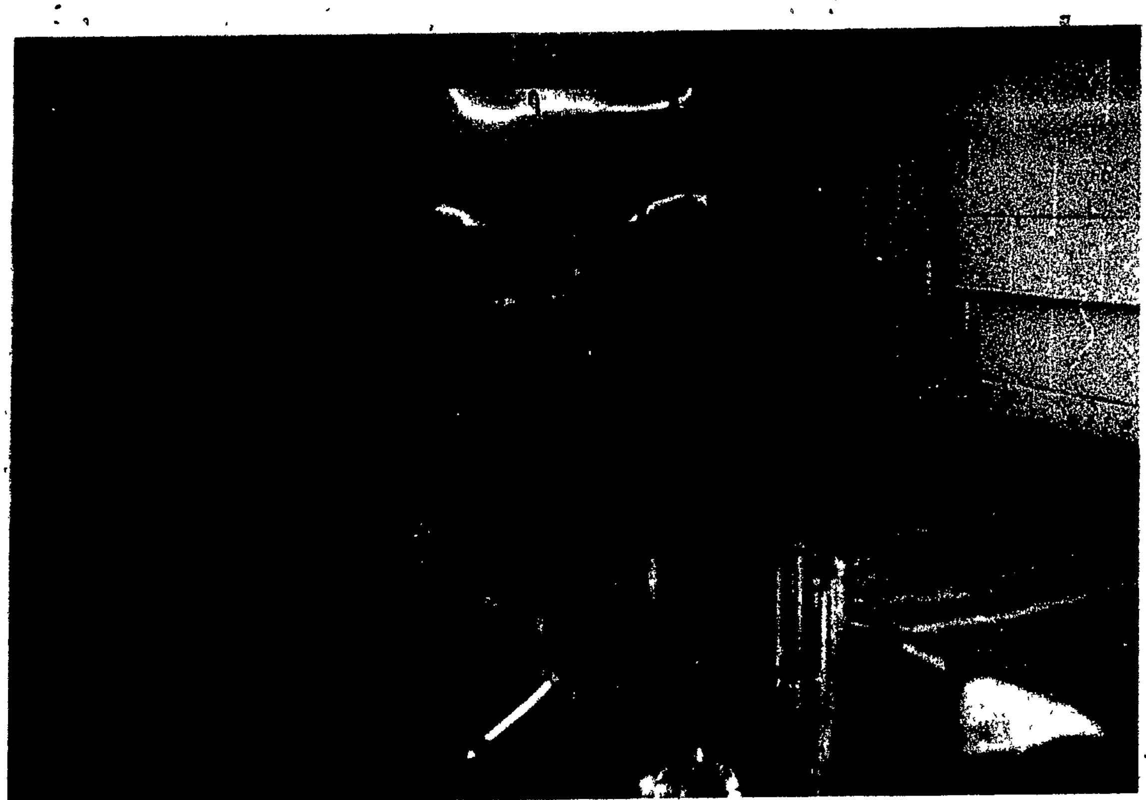


Figure B3. A soil and water test tank with four drain tubes installed. The drainage water is collected via the funnels and pumped up to the reservoir tank then gravity fed back into the bottom of the test tank.

Figure B4. A close-up view of one drain tube installed with a plexiglass end cap. Note the head control via the overflow device (upper right-hand corner), the piezometers through the plexiglass window and the manometer boards.

APPENDIX C

Calculation of Opening Area, A, for the Knitted Polyester Envelope

A) Envelope Porosity

The porosity of the stocking envelope was estimated using the following equation taken from Fayoux (1981):

$$\eta = 1 - \mu / (\rho T_e) \qquad (C1)$$

where η = porosity

μ = unit weight = 0.152 kg/m^2

ρ = density = 1.38 kg/m^3 (standard specific gravity for polyester fibres, as taken from drainage company catalogues)

T_e = thickness of fabric = 0.00089 m

With the above numbers, the porosity is equal to 87.6%.

B) The pipes were perforated in the valleys of the corrugations. The width of the valleys available for water entry was estimated at 0.712 cm. With 61 valleys/m length, this gives a total entry length of 43.44 cm.

C) With a tube outside diameter of 11.94 cm, the total opening area is

$$A = \pi \, d \, L \, \eta \qquad (C2)$$

$$= \pi \, (11.94) \, (43.44) \, 0.876$$

$$= 1427.5 \text{ cm}^2/\text{m}$$

APPENDIX D

Analysis of variance tables for the steady-state drainage rate

Note: Both the actual data and the log transformation of the data were used for the analysis of variance. The log transformation helps to normalize the error associated with the observation, when the error is proportional to the magnitude of the observation. Both types of analyses gave identical conclusions. However, the actual data were kept and the corresponding AOV tables shown in this appendix. This was done because the log transformation, while giving the same conclusions, did not improve the coefficient of variability (C.V.) for the Soulânges, Bainsville and Ormstown soils. In these soils, the C.V. passed from 7%-8% (actual) to 16%-86% (log). This is so because the error associated with the flowrate measurements was small since the flowrates were quite low. It took sometimes more than 30 min to collect 500 mL of water and the longer the collection time, the more accurate the measurement. With the Ste. Sophie soil, the error would be higher as the flowrates are much more important. But even in this case, the C.V. was only improved from 5% to 1.3%.

The data used had units of mm/d.

Table D1. Analysis of variance of drainage rate for the Ste. Sophie fine sandy soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	2	18653.80	9326.90	0.89	0.4580
Tubing	3	618350.39	206116.80	19.71	0.0016**
Error a (Run*Tubing)	6	62740.36	10456.73		
Subplots					
Cycle	1	40102.14	40102.14	2.53	0.1505
Tubing*Cycle	3	2170.44	723.48	0.05	0.9861
Error b (Run*Cycle(Tubing))	8	126931.25	15866.41		
Within Cycle	104	172515.06			
Corrected Total	127	1041463.45			

** Significant at the 0.01 level

Table D2. Analysis of variance of drainage rate for the Soulanges fine sandy loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	5	235.1970	47.0394	0.66	0.6624
Tubing	3	1148.1272	382.7091	5.33	0.0106*
Error a (Run*Tubing)	15	1076.7329	71.7826		
Subplots					
Cycle	1	332.9983	332.9983	16.46	0.0006**
Tubing*Cycle	3	181.8190	60.6063	3.00	0.0551
Error b (Run*Cycle(Tubing))	20	404.6500	20.2325		
Within Cycle	226	2524.0558			
Corrected Total	273	5903.5801			

* Significant at the 0.05 level
** Significant at the 0.01 level

Table D3. Analysis of variance of drainage rate for the Bainsville very fine sandy loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	2	26.2003	14.1001	2.31	0.1803
Tubing	3	192.8415	64.2805	11.34	0.0070**
Error a (Run*Tubing)	6	34.0257	5.6709		
Subplots					
Cycle	1	42.4774	42.4774	27.86	0.0007**
Tubing*Cycle	3	16.0124	5.3375	3.50	0.0748
Error b (Run*Cycle(Tubing))	8	12.1978	1.5247		
Within Cycle	156	87.6343			
Corrected Total	179	411.3894			

** Significant at the 0.01 level

Table D4. Analysis of variance of drainage rate for the Ormstown silt loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	3	5822.2017	1940.7339	23.86	0.0001**
Tubing	3	32.3877	10.7959	0.13	0.9399
Error a (Run*Tubing)	9	747.6696	83.0744		
Subplots					
Cycle	1	281.7076	281.7076	2.54	0.1395
Tubing*Cycle	3	134.0363	44.6788	0.40	0.7542
Error b (Run*Cycle(Tubing))	11	1221.6578	111.0598		
Within Cycle	197	885.1723			
Corrected Total	227	9124.8830			

** Significant at the 0.01 level

APPENDIX E

Analysis of variance tables for sediment weight (grams) inside drains

Table E1. Analysis of variance of sediment weight inside drains for the Ste. Sophie fine sandy soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Model	5	88750.76	17750.15	55.74	0.0001
Error	6	1910.77	318.46		
Corr. Tot.	11	90661.53		Mean =	81.48
				Std. Dev. =	17.85

Source	DF	Sum of Sq.	F Value	Pr > F
Run	2	1026.00	1.61	0.2750
Tubing	3	87724.66	91.82	0.0001**

** Significant at the 0.01 level

Table E2. Analysis of variance of sediment weight inside drains for the Soulanges fine sandy loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Model	8	353980.73	44247.59	8.05	0.0003
Error	5	82489.29	5499.29		
Corr. Tot.	23	436470.02		Mean =	122.62
				Std. Dev. =	74.16

Source	DF	Sum of Sq.	F Value	Pr > F
Run	5	175286.90	6.37	0.0023**
Tubing	3	178693.83	10.83	0.0005**

** Significant at the 0.01 level

Table E3. Analysis of variance of sediment weight inside drains for the Bainsville very fine sandy loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Model	5	2484704.43	496940.89	13.98	0.0030
Error	6	213325.92	35554.32		
Corr. Tot.	11	2698030.35		Mean =	520.79
				Std. Dev. =	188.56

Source	DF	Sum of Sq.	F Value	Pr > F
Run	2	133230.49	1.87	0.2330
Tubing	3	2351473.94	22.05	0.0012**

** Significant at the 0.01 level

Table E4. Analysis of variance of sediment weight inside drains for the Ormstown silt loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Model	6	8542.82	1423.80	6.61	0.0089
Error	8	1722.80	215.35		
Corr. Tot.	14	10265.62		Mean =	19.28
				Std. Dev. =	14.67

Source	DF	Sum of Sq.	F Value	Pr > F
Run	3	7169.92	11.10	0.0032**
Tubing	3	1372.90	2.13	0.1753

** Significant at the 0.01 level

APPENDIX F

Multivariate analysis of variance tables for particle size fractions derived from the particle size distribution curves

Fractions:

V. coarse sand	(2 to 1 mm) ;	V. fine sand	(0.1 to 0.05 mm)
Coarse sand	(1 to 0.5 mm) ;	coarse silt	(0.05 to 0.02 mm)
Medium sand	(0.5 to 0.25 mm) ;	fine silt	(0.02 to 0.002 mm)
Fine sand	(0.25 to 0.1 mm) ;	clay	(less than 0.002 mm)

Table F1. Multivariate analysis of the particle size fractions for the Ste. Sophie fine sandy soil.

Source	DF	Wilk's Lambda	RAO's F-Test		Prob > F
Mainplots					
Run	2	0.04315	F(8,6) =	2.86	0.1051
Tubing	3	0.16797	F(12,8) =	0.66	0.7515
Error a (Run*Tubing)	6				
Subplots					
Loc(ation)	2	0.02779	F(8,22) =	1375	0.0001**
Tubing*Loc	5	0.44858	F(20,37) =	0.51	0.9438
Error b (Run*Loc(Tubing))	14				
Within Location	33				
Total	66				

** Significant at the 0.01 level
Fractions used: Coarse sand; Medium sand; Fine sand; Very fine sand

Table F2. Multivariate analysis of the particle size fractions for the Soulanges fine sandy loam soil.

Source	DF	Wilk's Lambda	RAO's F-Test		Prob > F
Mainplots					
Run	5	0.05184	F(30,42) =	1.53	0.1000
Tubing	3	0.31221	F(18,29) =	0.81	0.6709
Error a (Run*Tubing)	15				
Subplots					
Loc(ation)	2	0.11205	F(12,40) =	6.62	0.0001**
Tubing*Loc	5	0.12511	F(36,91) =	1.52	0.0644
Error b (Run*Loc(Tubing))	25				
Within Location	12				
Total	68				

** Significant at the 0.01 level
Fractions used: Medium sand; Fine sand; Very fine sand; Coarse silt; Fine Silt; Clay

Table F3. Multivariate analysis of the particle size fractions for the Bainsville very fine sandy loam soil.

Source	DF	Wilk's Lambda	RAO's F-Test		Prob > F
Mainplots					
Run	2	0.01467	F(10,4) =	2.90	0.1580
Tubing	3	0.04404	F(15,6) =	0.83	0.6445
Error a (Run*Tubing)	6				
Subplots					
Loc(ation)	2	0.10365	F(10,20) =	4.21	0.0030**
Tubing*Loc	5	0.29808	F(25,39) =	0.60	0.9128
Error b (Run*Loc(Tubing))	14				
Within Location	11				
Total	43				

** Significant at the 0.01 level

Fractions used: Fine sand; Very fine sand; Coarse silt; Fine Silt; Clay

Table F4. Multivariate analysis of the particle size fractions for the Ormstown silt loam soil.

Source	DF	Wilk's Lambda	RAO's F-Test		Prob > F
Mainplots					
Run	3	0.14010	F(9,17) =	2.37	0.0592
Tubing	3	0.64328	F(9,17) =	0.38	0.9293
Error a (Run*Tubing)	9				
Subplots					
Loc(ation)	1	0.54209	F(3,10) =	2.82	0.0936
Tubing*Loc	3	0.45607	F(9,24) =	1.04	0.4408
Error b (Run*Loc(Tubing))	12				
Within Location	16				
Total	47				

Fractions used: Very fine sand; Coarse silt; Fine Silt; Clay

APPENDIX G

Analysis of variance tables for the measured dry bulk density, (kg/m^3)

Table G1. Analysis of variance of density measurements for the Ste. Sophie fine sandy soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	2	0.0011	0.0006	0.28	0.7673
Cell	3	0.0125	0.0042	2.10	0.2021
Error a (Run*Cell)	6	0.0119	0.0020		
Subplots					
Location	1	0.0284	0.0284	19.65	0.0022**
Cell*Location	3	0.0023	0.0008	0.53	0.6769
Error b (Run*Location(Cell)	8	0.0116	0.0014		
Within Location	48	0.0419			
Corrected Total	71	0.1097			

** Significant at the 0.01 level

Table G2. Analysis of variance of density measurements for the Soulanges fine sandy loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	5	0.0556	0.0111	3.13	0.0393*
Cell	3	0.0011	0.0004	0.10	0.9587
Error a (Run*Cell)	15	0.0533	0.0036		
Subplots					
Location	1	0.0554	0.0554	20.06	0.0008**
Cell*Location	3	0.0014	0.0005	0.17	0.9165
Error b (Run*Location(Cell)	12	0.0331	0.0028		
Within Location	80	0.0609			
Corrected Total	119	0.2608			

* Significant at the 0.05 level
** Significant at the 0.01 level

Table G3. Analysis of variance of density measurements for the Bainsville very fine sandy loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	2	0.0026	0.0013	0.41	0.6781
Cell	3	0.0083	0.0028	0.90	0.4923
Error a (Run*Cell)	6	0.0185	0.0031		
Subplots					
Location	1	0.0507	0.0507	8.58	0.0221*
Cell*Location	3	0.0023	0.0008	0.13	0.9382
Error b (Run*Location(Cell)	7	0.0413	0.0059		
Within Location	46	0.0607			
Corrected Total	68	0.1844			

* Significant at the 0.05 level

Table G4. Analysis of variance of density measurements for the Ormstown silt loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	3	0.0172	0.0057	14.98	0.0008**
Cell	3	0.0030	0.0010	2.62	0.1153
Error a (Run*Cell)	9	0.0034	0.0004		
Subplots					
Location	1	0.0249	0.0249	10.24	0.0076**
Cell*Location	3	0.0012	0.0004	0.16	0.9218
Error b (Run*Location(Cell)	12	0.0292	0.0024		
Within Location	64	0.0731			
Corrected Total	95	0.1520			

** Significant at the 0.05 level

APPENDIX H

Figures showing equipotential lines around the drain for the Soulanges very fine sandy loam and the Ormstown silt loam. Equipotential lines are the averages of all data among runs and cycles.

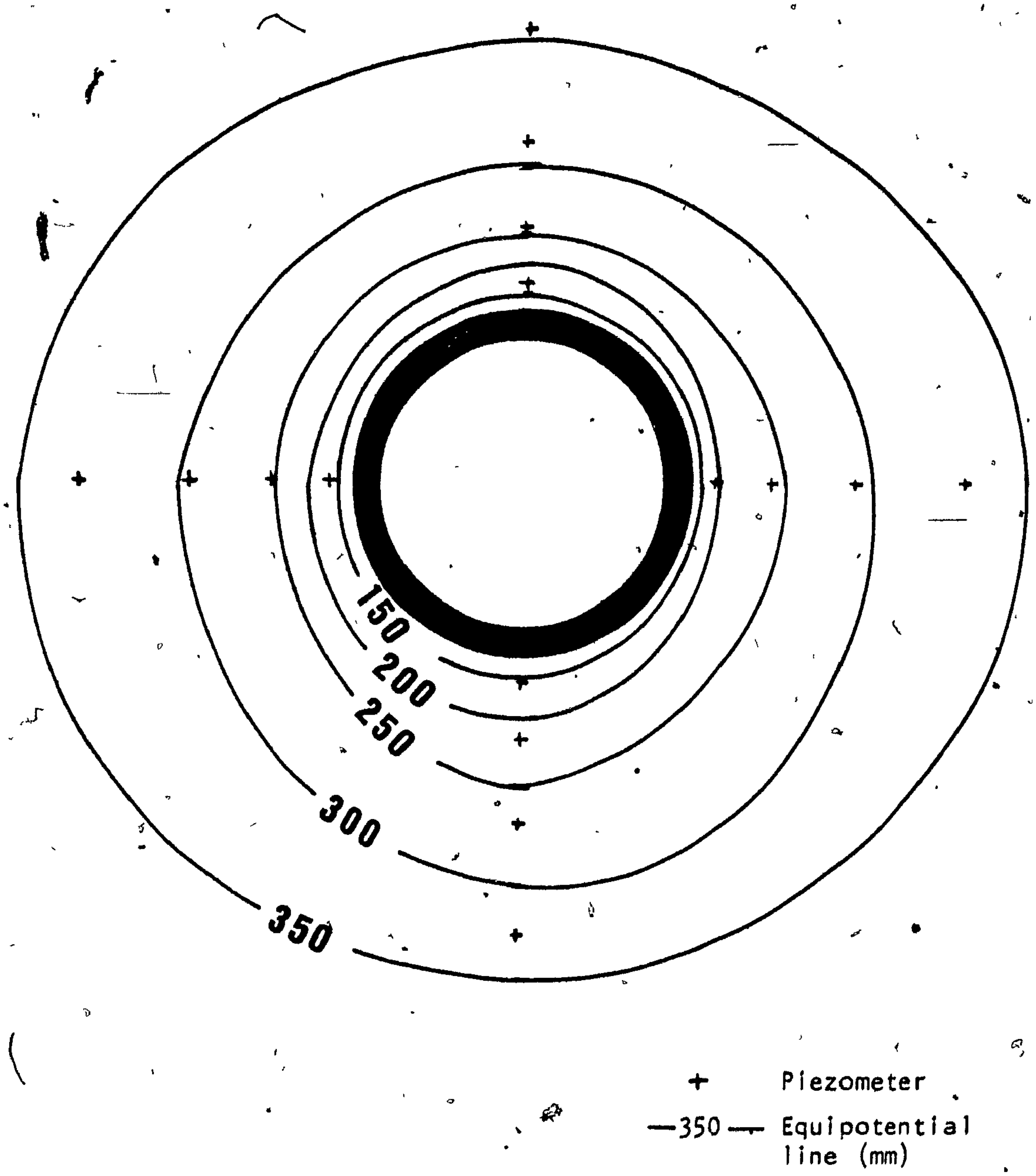


Figure H1. Average equipotential lines observed around the normal slotted tube with the fabric envelope in the Soulanges fine sandy loam soil.

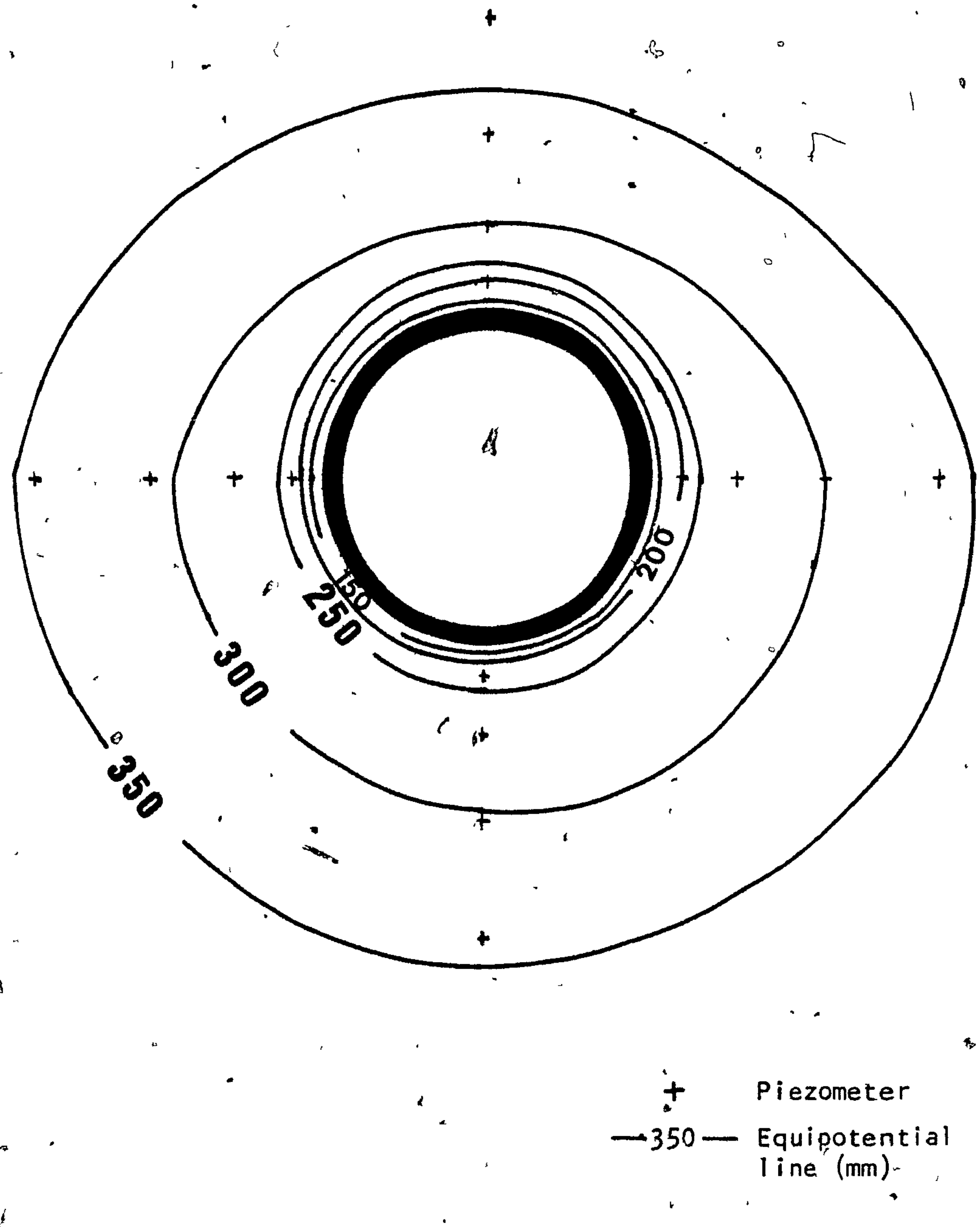


Figure H2. Average equipotential lines observed around the tube with small slots in the Soulanges fine sandy loam soil.

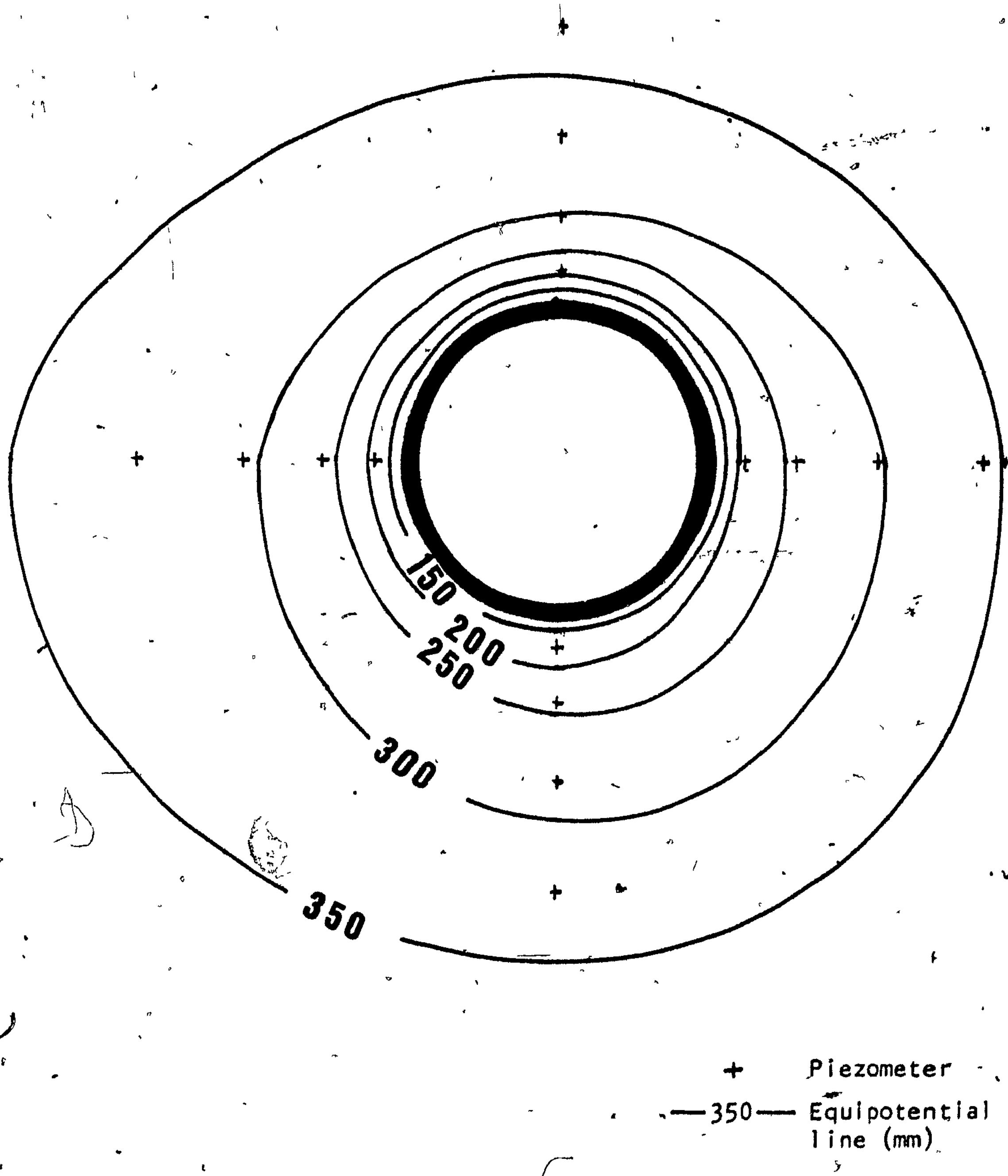
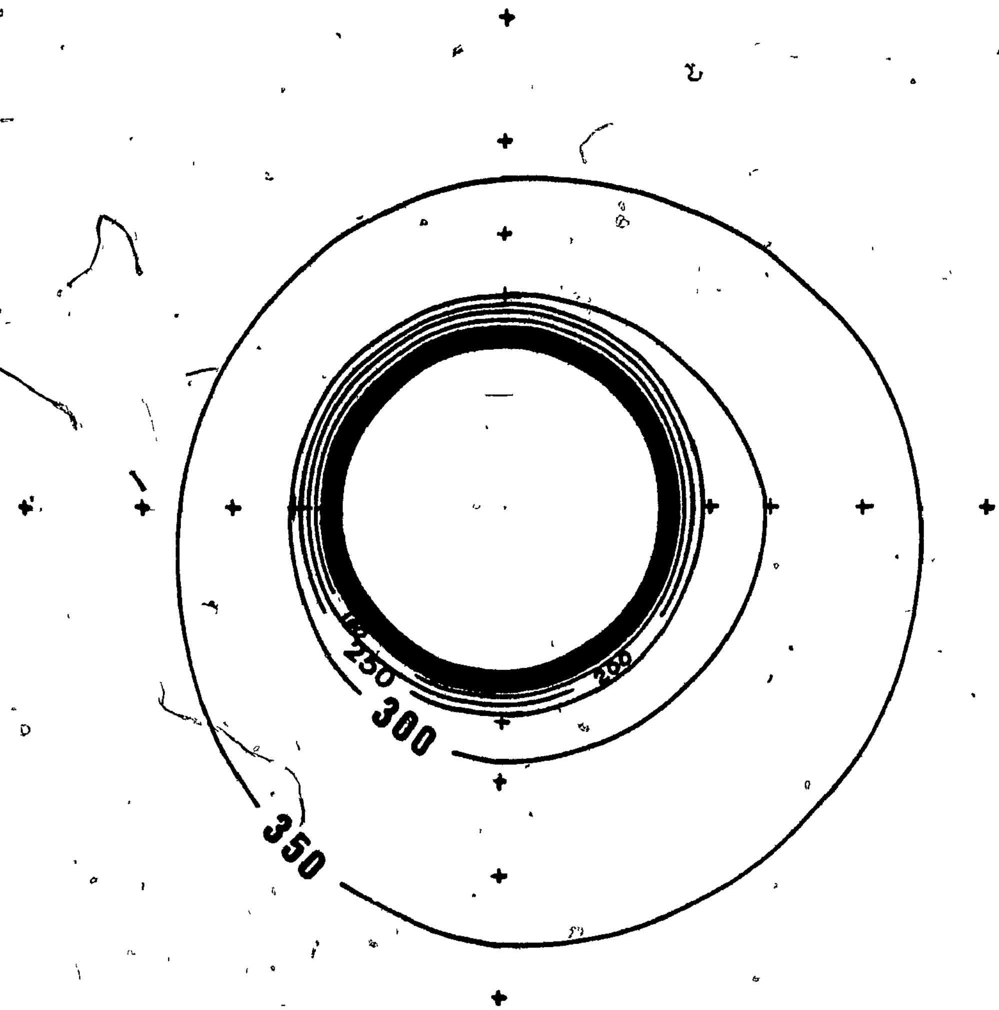


Figure H3. Average equipotential lines observed around pinhole tube A in the Soulanges fine sandy loam soil.



+ Piezometer

—350— Equipotential line (mm)

Figure H4. Average equipotential lines observed around pinhole tube B in the Soulanges fine sandy loam soil.

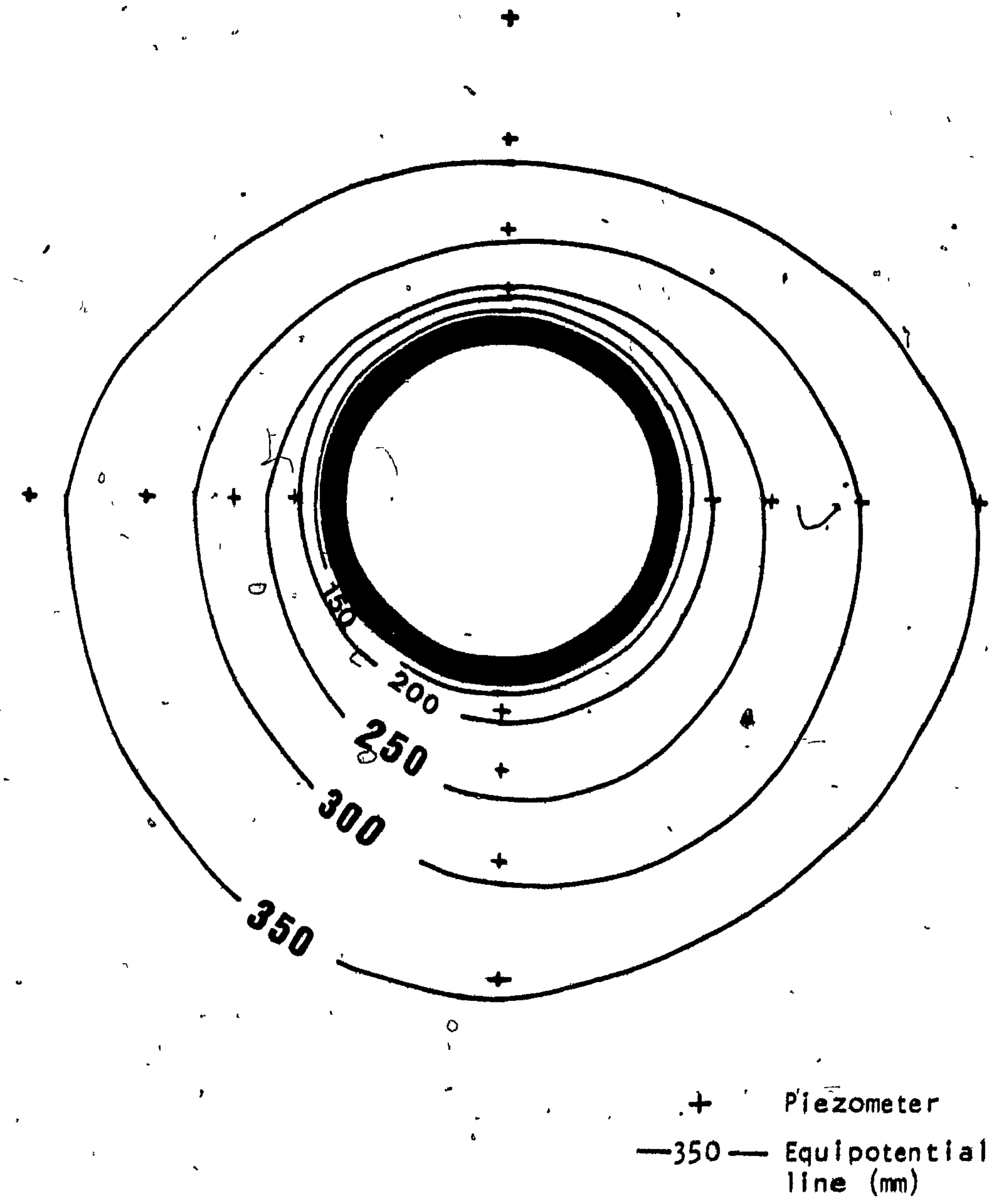


Figure H5. Average equipotential lines observed around the normal slotted tube with the fabric envelope in the Ormstown silt loam soil.

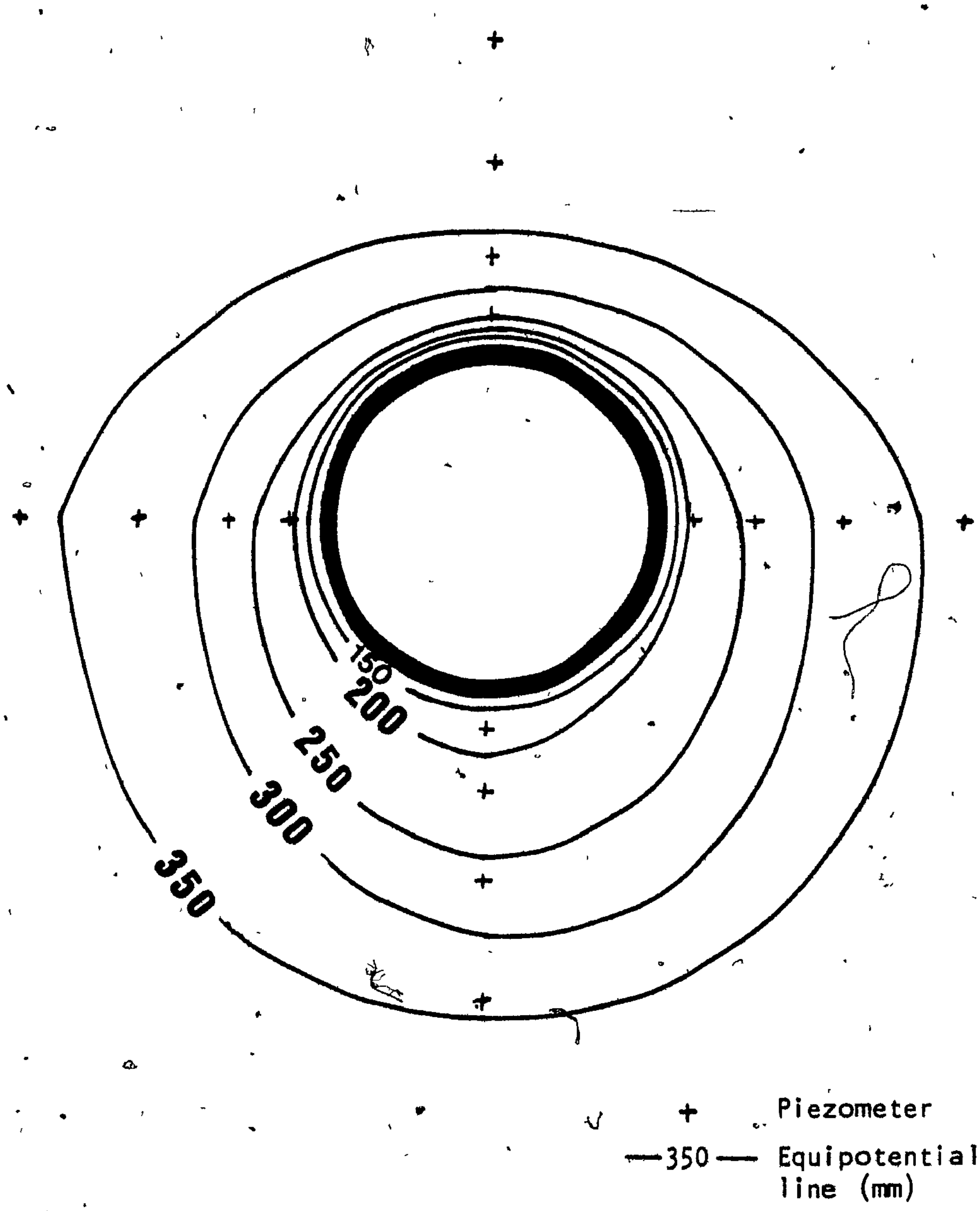


Figure H6. Average equipotential lines observed around the tube with small slots in the Ormstown silt loam soil.

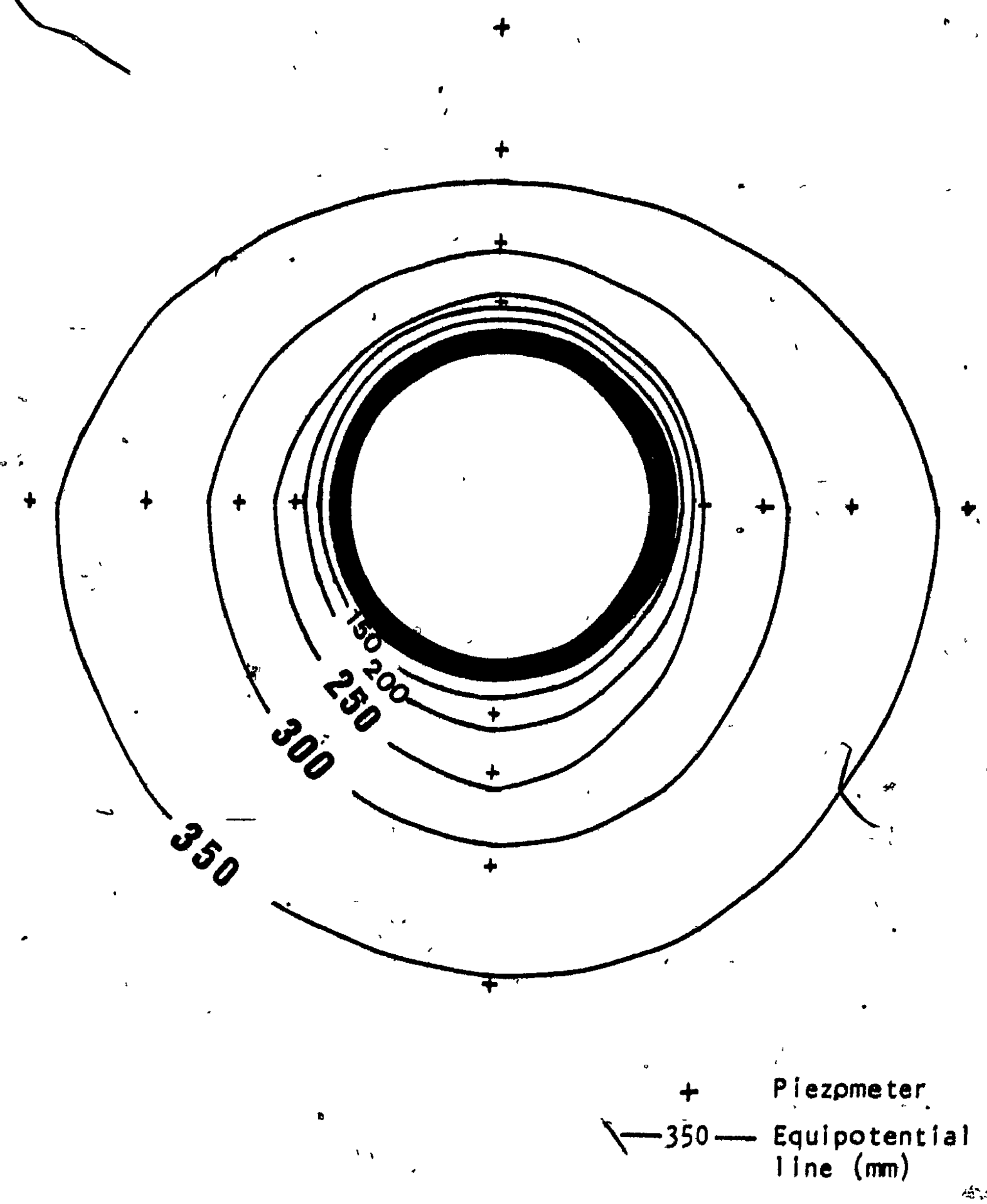


Figure H7. Average equipotential lines observed around pinhole tube A in the Ormstown silt loam soil.

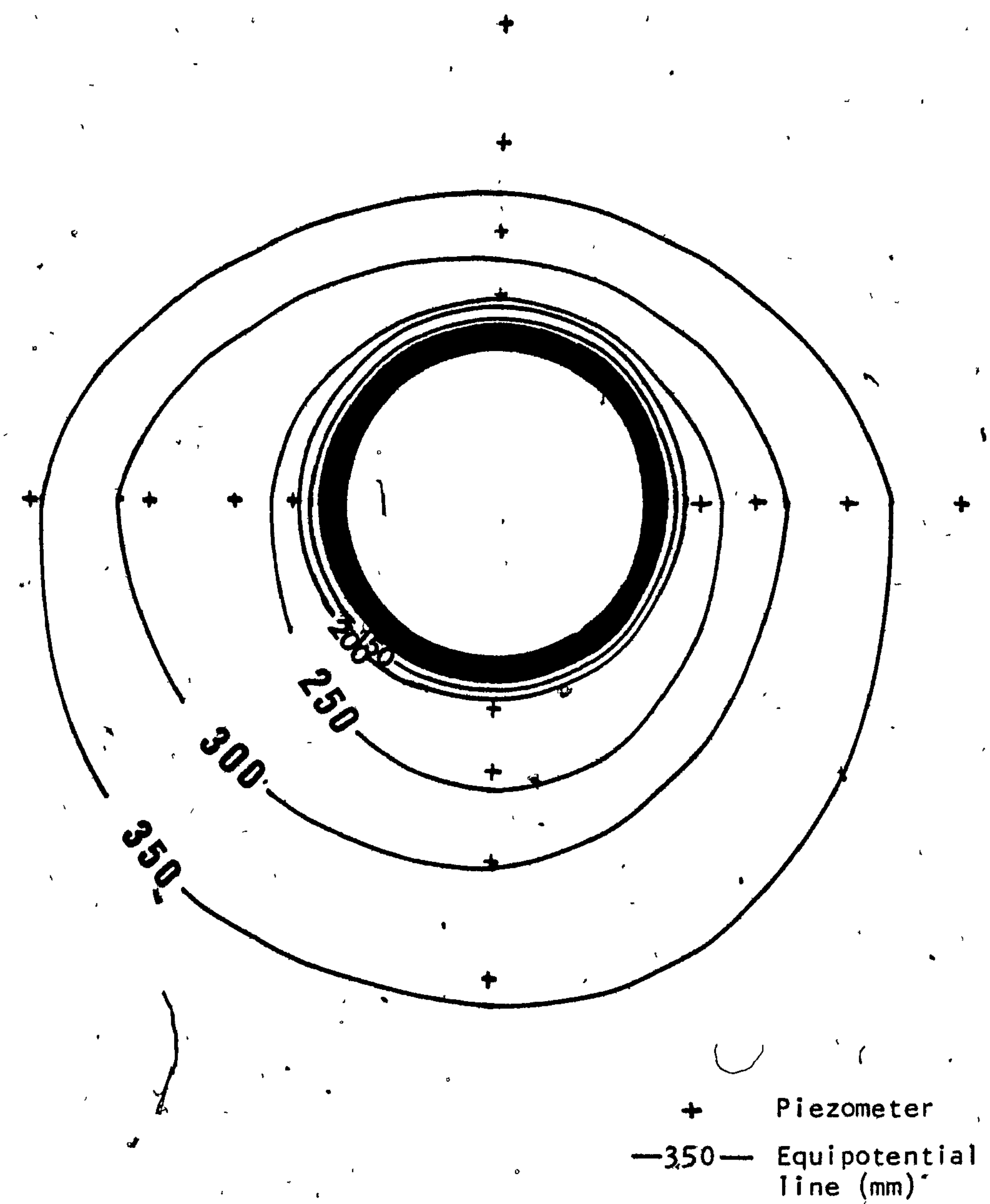


Figure H8. Average equipotential lines observed around pinhole tube B in the Ormstown silt loam soil.

APPENDIX I

Analysis of variance tables for the computed hydraulic conductivity, K.

Note: Because K is proportional to the drainage rate, Q and that the error associated with Q is proportional to the magnitude of the observation, the log transformation of the data was used. This was done to normalize the error. Using the actual data in the analysis of variance produced the same conclusions.

However, to be consistent with the AOV tables for drainage rate, the tables shown in this appendix are the results from using the actual data.

Table I1. Analysis of variance of the computed hydraulic conductivity for the Ste. Sophie fine sandy soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	2	8.9333	4.4667	0.24	0.7949
Tubing	3	27.3663	9.1221	0.49	0.7037
Error a (Run*Tubing)	6	112.3609	18.7268		
Subplots					
Cycle	1	41.5452	41.5452	4.78	0.0703
Tubing*Cycle	3	2.7000	0.9000	0.10	0.9557
Error b (Run*Cycle(Tubing))	8	65.5518	8.1940		
Within Cycle	132	267.4607			
Corrected Total	155	525.9182			

Table I2. Analysis of variance of the computed hydraulic conductivity for the Soulanges fine sandy loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	1	0.0019	0.0019	0.66	0.4752
Tubing	3	0.0652	0.0217	7.49	0.0730
Error a (Run*Tubing)	3	0.0087	0.0029		
Subplots					
Cycle	1	0.2520	0.2520	134.40	0.0003**
Tubing*Cycle	3	0.0252	0.0019	4.42	0.0952
Error b (Run*Cycle(Tubing))	4	0.0075	0.0019		
Within Cycle	76	0.2863			
Corrected Total	91	0.6468			

** Significant at the 0.01 level

Table I3. Analysis of variance of the computed hydraulic conductivity for the Ormstown silt loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value	Prob > F
Mainplots					
Run	2	0.1039	0.0520	17.88	0.0030*
Tubing	3	0.0030	0.0010	0.35	0.7941
Error a (Run*Tubing)	6	0.0174	0.0029		
Subplots					
Cycle	1	0.0003	0.0003	0.07	0.7988
Tubing*Cycle	3	0.0077	0.0026	0.72	0.5728
Error b (Run*Cycle(Tubing))	3	0.0252	0.0036		
Within Cycle	87	0.0243			
Corrected Total	105	0.1818			

* Significant at the 0.05 level

APPENDIX J

Analysis of variance tables for the computed RPZ ratio.

Table J1. Analysis of variance of the computed RPZ ratio for the Ste. Sophie fine sandy soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value
Mainplots				
Run	2	3.8033	1.9017	2.46
Tubing	3	8.6108	2.8703	3.71
Error a (Run*Tubing)	6	4.6370	0.7728	
Subplots				
Cycle	1	0.2780	0.2780	1.44
Loc(ation)	3	0.7070	0.2357	1.22
Cycle*Loc	3	0.1162	0.0387	0.20
Tubing*Cycle	3	0.6063	0.2354	1.22
Tubing*Loc	9	1.9680	0.2187	1.14
Tubing*Cycle*Loc	9	0.1759	0.0195	0.10
Error b (Run*(C L)(Tubing))	55	10.5836	0.1924	
Within Cycle	506	9.1839		
Corrected Total	600	40.7700		

Table J2. Analysis of variance of the computed RPZ ratio for the Soulanges fine sandy loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value
Mainplots				
Run	1	0.1553	0.1553	0.09
Tubing	3	8.0355	2.7850	1.63
Error a (Run*Tubing)	3	4.9289	1.6430	
Subplots				
Cycle	1	1.0037	1.0037	1.85
Loc(ation)	3	0.8410	0.2803	0.52
Cycle*Loc	3	1.2408	0.4136	0.76
Tubing*Cycle	3	0.3979	0.1326	0.24
Tubing*Loc	9	6.6553	0.7395	1.36
Tubing*Cycle*Loc	9	2.5395	0.2822	0.52
Error b (Run*(C L)(Tubing))	27	14.6404	0.5422	
Within Cycle	297	7.9114		
Corrected Total	359	47.7497		

APPENDIX K

Analysis of variance tables for the computed hydraulic gradient, I.

Table K1. Analysis of variance of the computed hydraulic gradient for the Ste. Sophie fine sandy soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value
Mainplots				
Run	2	21481.52	10740.76	0.63
Tubing	3	3201779.83	1067259.94	62.45**
Error a (Run*Tubing)	6	102541.98	17090.33	
Subplots				
Cycle	1	2654.68	2564.68	2.15
Loc(ation)	3	33221.88	11073.96	8.96**
Cycle*Loc	3	873.20	291.07	0.24
Tubing*Cycle	3	1883.03	627.68	0.51
Tubing*Loc	9	68964.21	7662.69	6.20**
Tubing*Cycle*Loc	9	645.18	71.69	0.06
Error b (Run*(C L)(Tubing))	55	67956.98	1235.58	
Within Cycle	506	76993.37		
Corrected Total	600	3578995.86		

** siginificant at the 0.01 level.

Table K2. Analysis of variance of the computed hydraulic gradient for the Soulanges fine sandy loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value
Mainplots				
Run	1	5937.83	5937.83	0.66
Tubing	3	1614276.59	538092.20	59.49**
Error a (Run*Tubing)	3	27135.35	9045.12	
Subplots				
Cycle	1	13920.45	13920.45	8.72**
Loc(ation)	3	8556.56	2852.19	1.79
Cycle*Loc	3	2231.43	743.81	0.47
Tubing*Cycle	3	7588.22	2529.41	1.58
Tubing*Loc	9	30562.55	3395.84	2.13
Tubing*Cycle*Loc	9	8721.85	969.09	0.61
Error b (Run*(C L)(Tubing))	27	43102.69	1596.40	
Within Cycle	298	66179.02		
Corrected Total	360	1828212.54		

** siginificant at the 0.01 level.

Table K3. Analysis of variance of the computed hydraulic gradient for the Ormstown silt loam soil.

Source	DF	Sum of Sq.	Mean Sq.	F Value
Mainplots				
Run	2	217862.29	108931.15	3.27
Tubing	3	711246.46	237082.15	7.13*
Error a (Run*Tubing)	6	199645.28	33274.21	
Subplots				
Cycle	1	22085.10	22085.10	3.82
Loc(ation)	3	86642.20	28880.73	4.99**
Cycle*Loc	3	3526.02	1175.34	0.20
Tubing*Cycle	3	12632.75	4210.92	0.73
Tubing*Loc	9	57149.97	6350.00	1.10
Tubing*Cycle*Loc	9	7579.98	842.22	0.15
Error b (Run*(C L)(Tubing))	36	208351.20	5787.53	
Within Cycle	348	64046.75		
Corrected Total	423	1590768.00		

* siginificant at the 0.05 level.
** siginificant at the 0.01 level.

APPENDIX L

Determination of the entry resistance factor at the opening, α_e and the total entry resistance factor, α_t.

A) Normal Slotted Tube with Fabric Envelope

Equation (3.16) was used to determine the entry resistance at the opening, α_e. It was assumed that the envelope had a block profile with valleys 2 mm deep and a circumferential opening 20% smaller than the valley width. It is reasoned that the weight of the soil around the drain would push against the fabric and deflect it by a small distance in the valleys of the corrugations, thus creating a sinusoidal profile. This was, however, simplified by assuming a block profile. Henceforward, a probably overestimated 2 mm deflection was used. Rather than estimating the spacing between individual fabric openings, a continuous circumferential gap with 20% width less than the valley width was considered as being adequate. This reduction in width accounted for the resistance to the flow created by the fibres. With these assumptions, α_e = 0.0141.

Asuming a circumferential opening width equal to the valley width, yields an entry resistance of 0.0134. The two numbers, differing by only 5%, the first one was used as it is more representative of the reality. A first attempt was to consider each fabric opening separately and estimate the spacing between individual perforations. Equation (3.14) was then used, This approach, however, did not prove reasonable as it gave an entry resistance of only 0.000161.

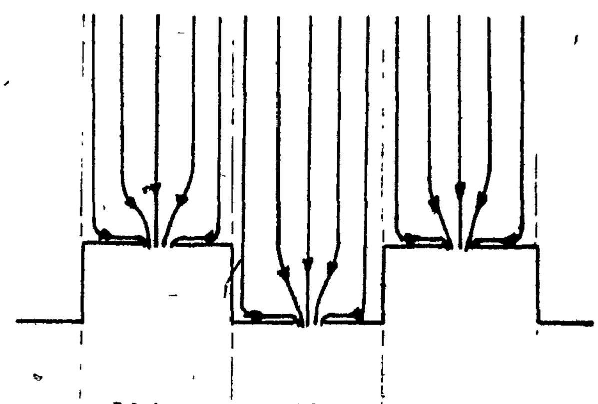
Table L1 gives the entry resistance of each drain along with the drain characteristics used to compute that number.

B) **Tube with Small Slots**

In this case, because the slots were of a much larger size and in the valleys of the corrugations, equation (3.17) was used.

C) **Pinhole tubes A and B**

Both pinhole tubes had perforations in valleys as well as ridges. The streamlines would most probably converge directly to the openings and no additional convergence would be experienced by the streamlines towards the corrugations, as shown in the figure below.



Therefore, it can be assumed that we have two smooth pipes with discontinuous perforations and radii r_o and r_o'. The entry resistance for the drain would be the average resistance created by the two pipes of different radii. Because no equations were developed for circular perforations, and that it is beyond the scope of this study to do so, the perforations were assumed to be square and equation (3.14) was used. Actually, the perforations, while being circular on the outside, were approximately either rectangular, square, elliptical or trapezoidal on the inside.

Table L1. Drain characteristics and entry resistance at openings as determined by using the equations in Chapter III.

Characteristic	Sock	Small slots	Pinhole A Valleys	Pinhole A Ridges	Pinhole B Valleys	Pinhole B Ridges
Equation	(3.16)	(3.17)	(3.14)		(3.14)	
r_o (mm)	59.754	58.103		58.496		58.966
r_o' (mm)	57.754	51.608	50.800		51.245	
δ_r (mm)	2.000	6.495				
N		32				
c	17.018	12.700	14.981	16.510	18.796	18.796
β_s (mm)	5.696	0.650	0.880	0.660	0.610	0.690
β_v (mm)	7.120	6.858				
λ_p (mm)		3.470	0.880	0.660	0.610	0.690
λ_c (mm)			7.093	7.657	6.708	7.719
γ			0.124	0.086	0.091	0.089
$F(\gamma,\epsilon)$			4.15	4.37	4.40	4.40
α_e	0.0141	0.1560	0.1104	0.1690	0.1984	0.1756
α_e average			0.1397		0.1870	
r_a	69.754	68.103	60.800	68.496	61.245	68.966
r_d	159.754	158.103	150.800	158.496	151.245	158.966
α_{ta}	0.0441	0.2001	0.1873	0.1648	0.2343	0.2119
α_{ta} average			0.1760		0.2231	
α_{td}	0.1760	0.3341	0.3208	0.2983	0.3670	0.3448
α_{td} average			0.3096		0.3559	

- α_{ta} and α_{td} computed using equation (3.9)
- Subscript "d" would correspond to subscript "b" in equation (3.9)