DRAIN ENVELOPE THICKNESS AND PERMEABILITY EFFECTS ON PRESSURE HEAD LOSS ACROSS THE ENVELOPE

BY

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Aliyu Abubakar Ramalan

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ABSTRACT

Drain Envelope Thickness and Permeability Effects on Pressure Head Loss Across the Envelope

by

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A properly designed envelope placed around drain pipe should continuously transmit water into the drain unimpeded at a comparatively low head loss. A low head loss across the envelope is therefore one of the measures of effectiveness by which a drain envelope performance can be evaluated. An inherent physical property on which porous envelope materials depend for their abilities to transmit water is permeability.

Tests were conducted on drain envelopes in a physical model to determine the effects of envelope thickness and permeability on pressure head loss across envelopes. Three synthetic and one natural envelope materials with one soil type were used for the research. The flow rate range used was typical of field situations. The desired data, piezometric heads, were measured at radial distances from drain center at predetermined locations in or across the envelope and soil.

Test results showed that magnitude of head loss across the envelope material is inversely proportional to the permeability of the material while thickness of granular envelope was found to be directly related to pressure head loss.

(102 pages)

INTRODUCTION

In subsurface drainage, drain tubes are used for draining excess water from the land. For the agricultural land drainage applications, such tubes are commonly installed at depths from four to six feet below ground surface. Excess water from the soil passes through perforations on the tube wall, or joints where ends of tile drains are butted together. The drain collects the water and disposes of it at a suitable outlet.

Drain installation in certain unstable soils, especially in irrigated areas, have water moving into the drains accompanied by significant amounts of sediments in the form of sand and silt particles. If the flow velocity is not sufficient to carry the particles along, they will settle and clog the drain tube. The inevitable result is that the effectiveness of the drainage system will be impaired and consequently the land will be less productive. One of the practical solutions to this problem which is an outgrowth of an early research by Terzaghi and currently used is to place some form of envelope material around the drain tube. Such a solution has proved quite adequate in dealing with the problem where careful design of the sand and gravel envelope was made with due consideration to the base soil material. In addition, permeability to water around the drain tube is improved; as is the bedding support for the tube itself.

With depleting supply of pit-run, naturally graded sand and gravel envelope materials and increasing haulage and overhead costs associated with the use of such materials, attention has been focused on synthetic envelope materials.

Synthetic envelope materials, like the granular sand and gravel envelopes, provide high permeability to water around the drain tubes, though the former is lacking in bedding support for the tube. With higher permeability, which is the desirable physical characteristic required of all envelopes, resistance to flow of water is minimal; thus minimizing head loss across it. This in effect means that the same amount of flow can be transmitted at lower hydraulic gradients. To enable better and more efficient systems to be designed and remain operative some studies of the physical capabilities of the envelopes vis-a-vis their permeabilities and head loss are necessary.

The aim of this research therefore is to investigate the influence of synthetic envelope material on the head loss in a drain-envelope-soil environment. In addition, to determine the relationship between envelope (granular) thickness and pressure head loss across the envelope.

LITERATURE REVIEW

Flow in Porous Media

Flow of fluid in porous media, e.g. soil, takes place in response to a hydraulic gradient. Darcy in 1856 pioneered work in his studies of flow of water through filter beds discharging at atmospheric pressure, using a simple apparatus. He enunciated the Darcy's Law of flow through porous media. The law has been extensively tested and its validity established for conditions normally encountered in drainage designs (22). Darcy's Law states that flow of water through porous material is directly proportional to the hydraulic gradient and to a factor of the porous media known as the hydraulic conductivity. Symbolically, Darcy's Law is:

$$Q = KiA \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where K is the porous media hydraulic conductivity; i is the hydraulic gradient, A is the cross sectional area of flow, and Q is the volume of flow per unit time.

The hydraulic gradient, i, is sometimes expressed in its full form as $i = \Delta h/L$ where Δh is the piezometric head difference over points a distance L apart, where the piezometric heads, h, are measured. The quantity i is dimensionless. The coefficient K, with dimension L/T (length/time), designated hydraulic conductivity, (11, 30), is related to intrinsic permeability k', with dimensions of length squared, (L^2) by

$$K = k'\rho g/\mu \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

where ρ and μ are the density and viscosity of the fluid respectively and g is the acceleration due to gravity, k' is referred to as the intrinsic permeability of the medium; its value is independent of the fluid type used. The lumped permeability constant, K had been adopted by the Soil Science Society of America and called "the hydraulic conductivity" of a specific porous medium.

Darcy's law is appropriate where excessive velocities of flow are not encountered. To define the range where the law is appropriate, a dimensionless quantity known as the Reynold's number, dVs/η is one of the criteria of velocity of flow in pore used. The quantity V is the true mean velocity of flow of fluid in pore channel of diameter, D. Substituting known values, Reynolds number should not exceed the value 0.1 to 1.0. The few exceptional circumstances where Darcy's Law do not hold occur in flows in sands and gravels, etc., where velocities are high and Reynolds number range in values from 0.150 to 18.10. Such flows are characteristically turbulent and seldom occur in agricultural drainage.

An empirical equation derived relating Reynold's number R with an average grain diameter given by Luthin (22) is expressed as:

$$R = dV\rho/\eta \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

where d is the diameter of pore; η is the viscosity of the fluid; ρ is the density of the fluid, and V is the true mean velocity of flow.

Fanchers, Lewis and Barnes (7) in their paper expressed Reynold's number in terms of the average grain diameter, given as:

$$d = \sqrt[3]{\frac{\Sigma n_s d_s{}^3}{\Sigma n_s}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where d_s is the arithmetic mean of the opening in any two consecutive sieves of the Tyler or U.S. standard sieves, and n_s is the number of grains of diameter, d_s, as determined from the sieve analysis.

At low velocities, Ward (39) showed that Reynolds number can be obtained from a relationship where the Reynolds number is directly proportional to the square-root of permeability of the medium. He emphasized use of permeability of the medium for the characterization of porous media rather than average grain diameter as in the formula above. For determining Reynolds number, Ward gave the following relationship:

$$R_k = \frac{k^{\frac{1}{2}} \rho v}{\mu} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where R_k is the Reynolds number for low velocity flow in porous medium, k is the permeability of the medium, ρ and μ are the mass density and absolute viscosity of the fluid, respectively, and v being flow velocity in the soil pores.

Experiments show that departure from laminar flow begins at R values between about 1 and 10, depending upon the range of grain sizes and shapes (22). In any natural drainage situation, R value of 0.01 is most unlikely to be exceeded and in practice it is usual to assume the validity of Darcy's Law without further discussion.

Flow of water towards a drainage well is a practical example of porous media flow, the principle of this flow has been used in certain convenient locations for lowering water table height.

Flow Toward a Confined Well

Drainage by wells has over the years drawn some attention. Unconfined wells are used for drainage. In certain suitable locations wells have served a dual role of providing irrigation water from the drainage water. Pumped wells offer the possibility in many instances of overcoming restriction of location and elevation imposed by natural outlets. They are most economical where the water pumped can be used for irrigation or some other useful purposes (28).

The foundation for analytical basis of groundwater theory, as related to seepage toward wells was laid during the period 1850 to 1950 by investigators working independently in Europe and United States. Out of this came a report by a French engineer Henry Darcy in 1856, which included among other things a statement of the basic equation of flow through porous media.

In 1863, Dupuit arrived at an equation similar to Darcy's by extending rationally de Pronny's equation for open channel flow (28). Dupuit made the assumption that hydraulic gradient is the same at all points in a vertical cross section and that this gradient is equal to the slope of the phreatic or piezometric surface. He obtained the equation:

$$Q = 2\pi k r y \frac{dy}{dr} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Integrating Equation 6 between r_1 and r_2 and replacing y_1 and y_2 with h_e and h_w; and r_1 and r_2 with r_e and r_w

$$Q = \pi k \left[\frac{h_e^2 - h_w^2}{\ln(r_e/r_w)} \right] \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where Q is the flow or discharge to the well; h_e is the depth of water at a radius r_e; h_w is the depth of water in the well; and r_w is the radius of the well.

The Dupuit equation has been widely used with water table wells. It does have the apparent weakness in that it does not take into account the curvilinear nature of flow in the radial plane. Where the radius of influence is sufficiently great so that curvilinearity is negligible, results are reasonably accurate, and the equation can be useful in predicting the drawdown curve outside the vicinity of a well. The other shortcoming of the Dupuit equation is that it fails to take into account the fact that the water level inside the well always stands lower than that outside the well--a phenomenon known as a seepage face.

For an artesian or confined well, Peterson (23)indicated that the thickness of the water bearing layer does not decrease as the well is approached. Starting with an equation similar to Equation 6 above written thus:

$$Q = 2\pi r m k \frac{dv}{dr} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Integrating, yields

$$Q = 2\pi km \left[\frac{y_2 - y_1}{\ln(r_2/r_1)} \right] \quad . \; . \; . \; . \; . \; . \; . \; . \qquad (9)$$

where if r_1 and r_2 are the radius of influence and radius of the well, *respectively, and* $y_2 - y_1$ *equal to the drawdown D at the* well, then

$$Q = \left[\frac{2\pi kmD}{\ln(r_e/r_w)} \right] \quad . \; . \; . \; . \; . \; . \; . \; . \qquad (10)$$

From Equation 10, if k, m and D are known, we may be able to predict the decrease in piezometric head at any value of r_e.

Despite the apparent advantages in use of wells for drainage not many installations have exploited the opportunity. Much of the drainage water in many lands even where wells are feasible is removed by drain pipes laid beneath the groundsurface.

Drain Pipes

In subsurface drainage practice, drain tubes or pipes are used extensively for the removal of excess ground water in order to lower the water position. The drain pipe may be located at or above the impermeable layer. The soil above the impermeable layer may be uniform or stratified. The drainage analysis problem of uniform soil is much simpler than that of stratified: and there may be a single tube or a number of them installed (17).

In an investigation using flow nets and sand tank experiments, Kirkham (17) showed that about 40 percent of the water that entered the drain tube was from the underside. The experiment showed that good practice requires the bottom of the drain tube be unsealed. Flow into a drain tube is significantly reduced where the tube is either partially or completely embedded in subsoil layers where the permeability of that material is much lower than the overlying material. Having the drain pipe placed in a more permeable soil layer or surrounded by it improves water entry into the tube.

The effect of drain diameter on flow into drain pipes has been investigated. In an experiment, Kirkham (14) showed that when drain pipe diameters were doubled and quadrupled from two inches diameter there was in each case a corresponding increase in inflow to the drain in the order of 15 and 34 percent, respectively. In contrast, Luthin and Haigh (21) obtained a 30 to 60 percent increase, depending on water-table height, when drain diameter was doubled. Increasing the drain diameter 3.9 times, they reported a 90 to 130 percent inflow increase, depending on water table height.

Increased outflow from drains and rate of falling water table is significantly affected by drain size. Besides increasing effective physical dimensions of the drain the placement of envelope material around drain pipe helps to reduce sediment entry into the pipe and increases permeability to water in the immediate surrounding of the pipe.

Envelope Materials

Closed, subsurface drain pipes or conduits, ranging from clay and concrete tiles to modern-day corrugated plastics have faced one major setback in usage since the idea of using pipes for subsurface drainage was first discovered. The major setback is that of clogging and silt accumulation within the drainpipe. The washed-through materials which clog drainpipes are mainly made up of small soil particles carried in suspension with the inflowing water. As the material settles in the drainpipe, the effective diameter and discharge capacity is inevitably reduced causing the efficiency of the drainage system to decrease.

Sisson (34) in his review reported that in 1859 H. F. French indicated that most drain failures were largely due to clogging by soil particles from the base material. Some of the solutions advanced prior to detailed investigation of hydraulics of particle transport and sedimentation included use of sand and gravel envelope around drain pipes to remedy the problem (9).

Later, in 1922, Terzaghi developed a soil mechanics-based theory on the piping and seepage forces that develop beneath hydraulic structures (29). Terzaghi enunciated the term "reverse filter," the concept which he later used to control seepage under an Austrian dam built on pervious foundation (41). The embodiment of this concept is that, the filter material made up of sand and gravels--several times more pervious than the soil base material in which it is installed--will retain the soil particles which are finer, and prevent them from entering the drain pipe. This early work by Terzaghi though basically conceived for controlling seepage and piping under hydraulic structures, developed to form the basis for work in the design of envelope materials used in agricultural subsurface land drainage works today.

Using the Stokes Law equation, Willardson, et al. (40) theorized a criterion based on flow entrance velocity to limit or prevent entrance of sediment into drains. The idea is to control both the velocity and direction of flow of water upward through a channel so that as it approaches and enters the drain, the velocity of flow is nearly zero--thus making the velocity energy practically insignificant. To achieve this, a large cross-sectional area of the channel is required, seemingly impractical as pointed out in a later publication (41).

Prieto (28) pointed out that there is a critical gradient at which soil particles begin to move. He used fine sand, and found that the critical gradient is a function of porosity of the envelope and its initial void ratio.

Envelope Material Types

There are quite a wide variety of types of envelope materials currently marketed. They can, however, be broadly classified into three main categories: organic material; sand and gravel; and synthetic envelope materials. They have all been used in various localities with varying degrees of success.

Organic Material.

--The most common organic material types used are straw and sawdust; others include peat litter, corn cobs, wood chips, reeds, heather, and grass sod (12). Reports of drain installations in Tulelake Basin in northeastern California using 15 cm of wheat straw (Triticum spp) as envelope material by Baghott and Houston, reviewed by Willardson (41) indicated that after six years the drains were still controlling the water table effectively. The major drawback with some organic material envelopes after some years of use is decay.

Brownscombe (4) inspected field installations where straw and wood chips had been used as envelopes. He reported that the straw was effective in excluding sediment and showed a moderate decay after 11 years. The wood chips decayed slightly after nine years. There is therefore, the need to investigate and establish the wide range of conditions under which organic material envelopes can be used.

Sand and Gravel.--The most common and widely used envelope materials are the naturally graded coarse sand and fine gravels. Such materials are widely available. Envelope materials used are primarily pit-run sand with a minimum of fines (41). Experiments by Lembke and Bucks (19) and the American Society of Agricultural Engineers (1) have shown that a graded fine gravel or sand envelope placed around a subsurface drain helps protect it from sediment and improves its performance.

Synthetic.--Synthetic envelope materials from manufacturing processes have greatly alleviated the problems of depleting sources of natural sand and gravel envelope materials. It has, to a large extent, cut down installation and handling costs associated with other material types. The synthetic material that has received the most attention is fiberglass. Fiberglass made of lime-borosilicate glass is recommended because the glass does not dissolve in soil.

In a sand tank experiment, Overholt (27) reported that drains protected with fiberglass over 75 percent of their circumference had a flow rate 1.7 times that of the unprotected lines; with complete wrap, the water was essentially silt-free and discharge rate was 2.26 times the unprotected.

Synthetic Envelope

Use.--Synthetic envelopes are increasingly gaining use because of the additional advantage over the conventional sand and gravel of handling and manufacturing. In the construction industry where these materials are referred to as filters they have been found to render three basic functions, namely: separation, filtering, and reinforcements (31). Some of these envelope materials have already found acceptance in the agricultural land drainage applications.

Whether synthetic envelope materials will be a more economic solution compared to sand and gravel depends upon the life and cost of the former, and availability and costs, including haulage within the proximity of the site of the latter. Seemel (31) indicated costs of filter fabrics as ranging from \$0.10 to \$1.10 per ft^2 (\$1.08 to \$11.80 per m^2) and installation costs from \$0.02 to \$0.25 per ft^2 (\$0.22 to \$2.70 per m^2) depending on site conditions.

Nelson (25) reports that the cost of using fiberglass as an envelope ranged from 10 to 20 percent of the cost of using a sand and gravel envelope.

Current Knowledge.--The most common materials used in the manufacture of synthetic envelope materials are: (a) nylon, (b) polyproplene, (c) polyvinylchloride, (d) polyethylene, (e) nylon/polypropelene combination and (f) polyester fibers. Manufacturing processes used include: (a) weaving--producing a window screen type of material, (b) knitting--resulting in an elastic sock like material and (c) bonded random filter--the density and opening size being controlled by fiber diameter and number of layers (38).

Seemel (31) reported a manufacturing process where the fiber is mechanically bonded by "needle-punching."

Availability of synthetic envelope material augmented interest in seepage control by subsurface drainage systems. The U.S. Army Corps of Engineers, through the Waterways Experiment Station, conducted an investigation to develop design criteria and acceptance specifications for fabric filter materials (5). Filtration tests and clogging tests were conducted to determine head losses across the fabric during filtration and soil loss through the fabric. A clogging ratio based on the hydraulic gradients measured across the fabric and across the system was used as a basis of comparison of performance.

The Corps of Engineers developed a design criteria for synthetic envelope materials for use with soils which have no less than 15 percent of soil particles larger than 0.075 mm (38).

Rosen and Marks (42) in their study of behavior of a nonwoven fabric filter--Mirafi 140--in subdrainage applications concluded that permeability and hydraulic gradient are directly related to the formation of an internal soil/fabric filtration system.

In hydraulic resistance measurements without soil-envelope interface Ogink (25), Hermsmeier (10) and Broughton, et al. (3) all showed that the resistance to water flow through the fabric was not significant compared to the other head losses in the subsurface drainage system. Hermsmeier (10) further reported that field installations using synthetic envelope materials had flow rates of about 50 to 67 percent of the flow rates from the systems using gravel envelopes.

Designs of Sand and Gravel Envelope

In order to achieve the desired objectives for which an envelope is required in drainage installations it must be properly designed. With the designs of envelopes, as opposed to filters, it is expected that some fine materials will be carried in suspension with the water through drain openings; it is not desired that the drained water will be sediment-free.

The general design procedure is first to make a particle size analysis of both the soil and the proposed envelope material. The two distribution curves from the analysis are compared, and by some predetermined set of criteria a decision is made as to the adequacy of the envelope material. One such criterion was that proposed by Terzaghi which pertained to his earlier work with filters.

In their investigations of envelope requirements for underdrains, the U.S. Corps of Engineers (37) arrived at similar conclusions to those of Terzaghi. The criteria is as summarized in Table 1. In addition to size specification, (41) it is desirable that the grain size curves for both filter and base material be approximately parallel in order to minimize washing of the fine base material particles into the drain.

Juusela (12) reported that in Finland the specification for graded envelope material requires that the 15 percent size of the envelope to be at least four times the 15 percent size of the soil material to ensure adequate permeability. To prevent movement of fines into the drains, the specification further requires that the 15 percent size of the envelope materials be no more than three times the 85 percent size of the base materials.

Bertram (2) using natural and crushed sand and quartz materials determined the critical ratios of the 15, 85, and 50 percent sizes of envelope to base materials as 6 for 15 percent size of envelope to the 85 percent size of the base material; 26 for 15 percent size of the envelope materials to the 15 percent size of the base material.

Design criteria for protective filters for hydraulic structures used by United States Bureau of Reclamation (13) is summarized in Table 1. The criteria requires, in addition, that gradation for the filter and base material be approximately parallel in the range of finer sizes in order to achieve stability and proper functioning of the filter. It also requires that the filter material adjacent to drainpipe be sufficiently coarse

TABLE 1.--Summary of the Design Criteria Used by the U.S. Army Corps of Engineers, the USBR and the SCS for the Design of Sand and Gravel Envelopes

Grading Requirements (1)		Other Requirements (2)
U.S. Army Corps of Engineers (Terzaghi)		
Graded env.	$\frac{D_{15}\text{ envelope}}{D_{15}\text{ soil}} \geq 4$	
Graded env.	$\frac{D_{15}\text{ envelope}}{D_{85}\text{ soil}} \leq 4$	
USBR		
Uniform env. (natural)	$\frac{D_{50}\text{ envelope}}{D_{50}\text{ soil}} = 5\text{ to }10$	10.16 mm minimum envelope thickness
Graded env. (natural)	$\frac{D_{50}\text{ envelope}}{D_{50}\text{ soil}} = 12\text{ to }50$	fines less than 0.07 mm should not exceed 5 percent.
Graded env. (crushed rock)	$\frac{D_{50}\text{ envelope}}{D_{50}\text{ soil}} = 9\text{ to }30$	
"	$\frac{D_{15}\text{ envelope}}{D_{15}\text{ soil}} = 6\text{ to }18$	
SCS		
Uniform env.	$\frac{D_{15}\text{ envelope}}{D_{85}\text{ soil}} < 5$	D_{85} envelope should not be less than half the drain opening.
Graded env.	$\frac{D_{50}\text{ envelope}}{D_{50}\text{ soil}} = 12\text{ to }58$	7.62 mm minimum envelope thickness.
Graded env.	$\frac{D_{15}\text{ envelope}}{D_{15}\text{ soil}} = 12\text{ to }40$	no more than 10 percent of the envelope smaller than 0.25 mm

to prevent movement of the finer filter material into the drain openings.

Kruse (18) reported on gravel pack designs for wells where the criteria used were based on pack-aquifer ratio of the 50 percent sizes; depending on uniformity of the aquifer, the permissible pack-aquifer ratio range from 9.5 to 17.5.

The Soil Conservation Service (34, p. 4.93ff) specification for evaluating pit-run and artificially graded granular materials as drain envelope sets an upper and lower limit curve for determining drain envelope suitability. The criteria sets the suitable 50 percent size limits for envelope material as 12 and 58 times the 50 percent size of the base materials. Similarly, the 15 percent size of envelope material limits are set at 12 and 40 times the 15 percent size of base material. Where both base and envelope materials are uniformly graded, an envelope stability ratio of less than 5 is given, see Table 1. For envelope material to be placed around drain pipes, its 85 percent size should be no smaller than one-half the perforation diameter.

Permeability and Hydraulic Gradient

The second most important function of a drain envelope is to improve the hydraulic conductivity, i.e., permeability, of the system in the immediate vicinity of the drainpipe. This is achieved by wrapping or placing around the drain pipe an envelope material which is several times more permeable than the base material. By virtue of this physical advantage, the envelope material is able to conduct the same amount of flow but with less head loss. Hence, the hydraulic gradient across the envelope remains comparatively lower than the base material.

In a sand tank study, Luthin and Haigh (21), drain pipes completely wrapped with fiberglass and drainpipes encased completely in gravel envelope were investigated. In both cases the relative envelope permeability to that of the base material was much greater. The drainpipe was thought to be completely permeable, and flow rate increased about 234 percent.

Kirkham (15) in a theoretical treatment of flow into drain tubes indicated a 180 percent increase in flow with a one-foot pipe segment embedded in gravel envelope.

As flow converges in the vicinity of the drain, considerable energy is lost, with a significant loss occurring at the soil-envelope interface. If the high gradient associated with high head loss becomes excessive, soil particles are susceptible to being washed into the drainpipe. Fine sands and silts are most likely to be washed into the drainpipe because they are noncohesive and sufficiently small to pass through the drain openings. Also where the cohesive force is not large enough to keep the soil particles aggregated, colloidal size particles, silts and fine sands are carried into the drain even when the soil at the drain entry is subjected to low exit gradients (40). Most of the silt and fine sand particles settle in the drain pipe while the colloid size particles are carried away in suspension. In contrast,soils high in clay and organic matter content have sufficient cohesiveness to resist dispersion of individual particles (20).

The use of envelope material around drainpipe not only increases the effective radius of the drain but decreases the hydraulic gradient at the soil/drain interface and sediment entry into the drain is curtailed. With properly designed envelopes, low hydraulic gradient assures a low exit velocity which helps keep sediments out.

MATERIALS AND METHODS

The aim of the experiment is to determine magnitudes of relative pressure head loss across different envelope materials; and to identify the relationship that exists between permeability and pressure head loss across the envelopes. Tests were therefore made on four envelope material types. Three of these materials were synthetic and the other was graded sand and gravel, i.e., a natural envelope material. Deaerated tap water at room temperature at the typical flow rates encountered in the field was used.

Description of the Physical Model

The model used consists essentially of a wooden open-topped box with 1.27 cm thick transparent plastic front panel held by screws. The main external dimensions of the box, which is made of 1.27 cm thick treated plywood, are 76.20 cm long, 33.02 cm wide, and 50.80 cm high. Two split "V" oriented wood panels are set inside the box at an angle of 75 degrees to each other, i.e. 37.5 degrees to the vertical for each panel. Sectors of pipe sizes 5.08, 10.16, and 20.32 cm in diameter cut at an angle of 75° to their centers fit snugly in between the two v-panels. The system models two-dimensional radial flow to a drain through a 75 degree sector.

Piezometers in three batteries are distributed radially in the soil and envelope at selected locations. A plastic piezometer block is used to hold all the piezometers together and to maintain constant their individual lengths above the pipe sector. The tight fit of the piezometers to the block ensures that no leakage of water occurs. Fig. 1 shows location of piezometers in the model before the soil is placed in position.

The lower ends of the piezometers are linked to manometers made of 0.24 cm ID nylon tubing by 6.0 cm long flexible vinyl tubing 0.32 cm ID. Height of water rise in the manometers gives pressure head distribution at the locations of the piezometers. Fig. 2 shows the dimensions and distribution of the piezometers on the block. Table 2 shows the piezometer heights above the block.

TABLE 2.--Piezometer Heights Above Block to the Nearest 0.05cm.

Piezometer Number* (1)	Length of Piezometer (cm) (2)
1, 7, 13	2.10
2, 8, 14	5.85
3, 9, 15	9.70
4, 10, 16	12.25
5, 11, 17	16.10
6, 12, 18	19.90

* Counting left to right in Fig. 2.

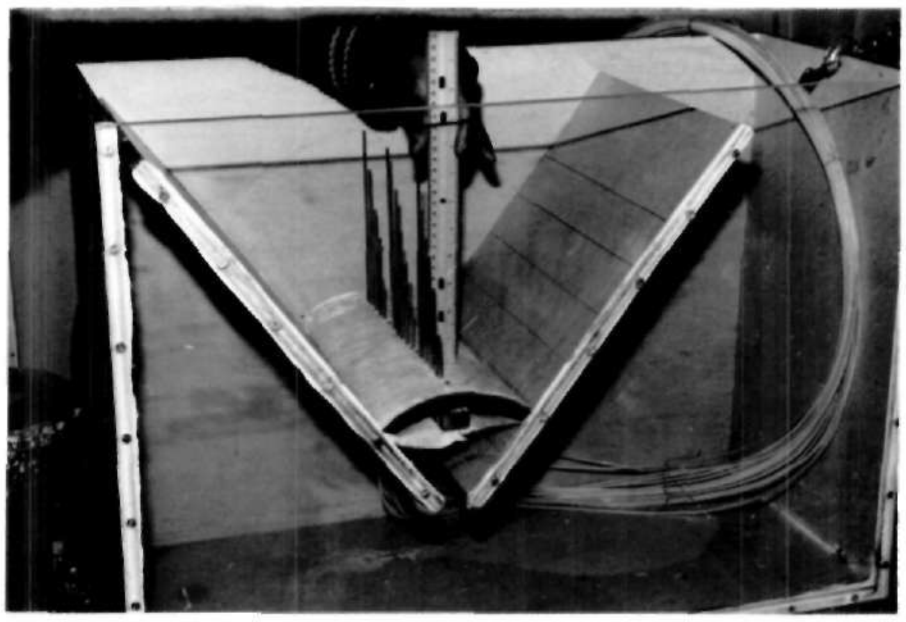

FIG. 1.--The Model Components

FIG. 2.--Relative Dimensions and Distribution of Piezometers

Description of Synthetic Envelope Materials

Three different types of synthetic envelope materials were used in the experiment. All three materials are nonwoven; their fibers are randomly bonded together to the desired thickness with no definite pattern. The materials are commercially available in varying dimensions, and cover the normal range of maximum opening sizes. The physical properties of these materials are summarized in Table 3; a pictorial view of all the envelope materials used is shown in Fig. 3. Permeability tests were conducted on the envelopes and are included in Appendix II. Unit weights of syntheti

TABLE 3.--Physical Properties of the Synthetic Envelope Materials Used in the Experiment

Envelope Material (1)	Fiber Type[a] (2)	Maximum Opening (mm) (3)	Thickness (mm) (4)	Unit Weight (gm/cm^2) (5)
Drainguard	N	0.30	0.08	0.016
Mirafi 140	PP, N/PP	0.15	0.51	0.054
Typar	PP	--	0.36	0.060

[a] PP--Polypropylene; N--nylon; N/PP--nylon sheath over polypropylene core

envelope materials are included in Table 3 for comparison purposes, this is because to a large extent, handling cost is a function of the unit weight of the material.

Physical Properties of the Sand and Gravel Envelope

The sand and gravel envelope material used was a naturally developed material obtained from a Logan gravel pit. It was analyzed for particle size distribution using dry sieving technique in the laboratory; results are shown in Table 4. The gradation curve from these tabulated values is shown in Fig. 4 with that of the soil. From the curve, coefficients of uniformity and gradation were determined at 4.71 and 0.60 for the envelope, respectively. The latter is lower than the SCS recommended value of 1.0 to 3.0.

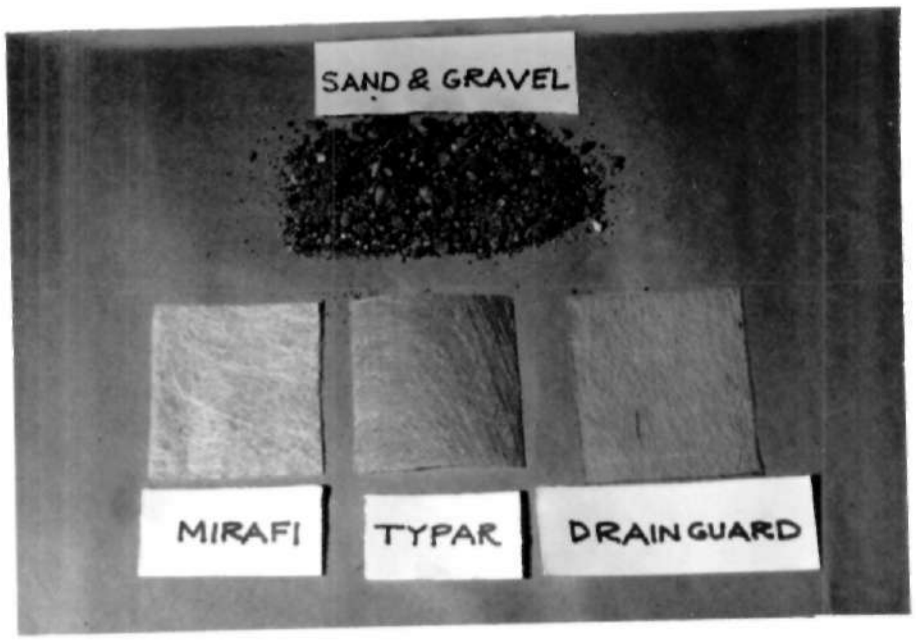

FIG. 3.--Envelope Material Types Used in the Experiment

TABLE 4.--Coarse Sieve Analysis for Sand and Gravel Envelope

Sieve Number (1)	Sieve Opening (mm) (2)	Mass Retained (gm) (3)	Cumulative Mass Retained (gm) (4)	Weight Passing (gm) (5)	Percent Finer (6)
8	2.36	82.80	82.80	416.34	83.4
10	2.00	16.95	99.75	399.39	80.0
16	1.18	51.08	150.83	348.31	69.8
30	0.60	77.12	227.95	271.19	54.3
50	0.30	118.28	346.23	152.91	30.6
100	0.149	125.54	471.77	27.37	5.5
200	0.075	23.61	495.38	3.76	0.8
pan	--	3.76	499.14		

Note: Total mass of sample in analysis = 500 gm
Test method: dry sieving
Sample description: sand and gravel (pit-run)
Location of sample: Gravel pits, Logan, Utah

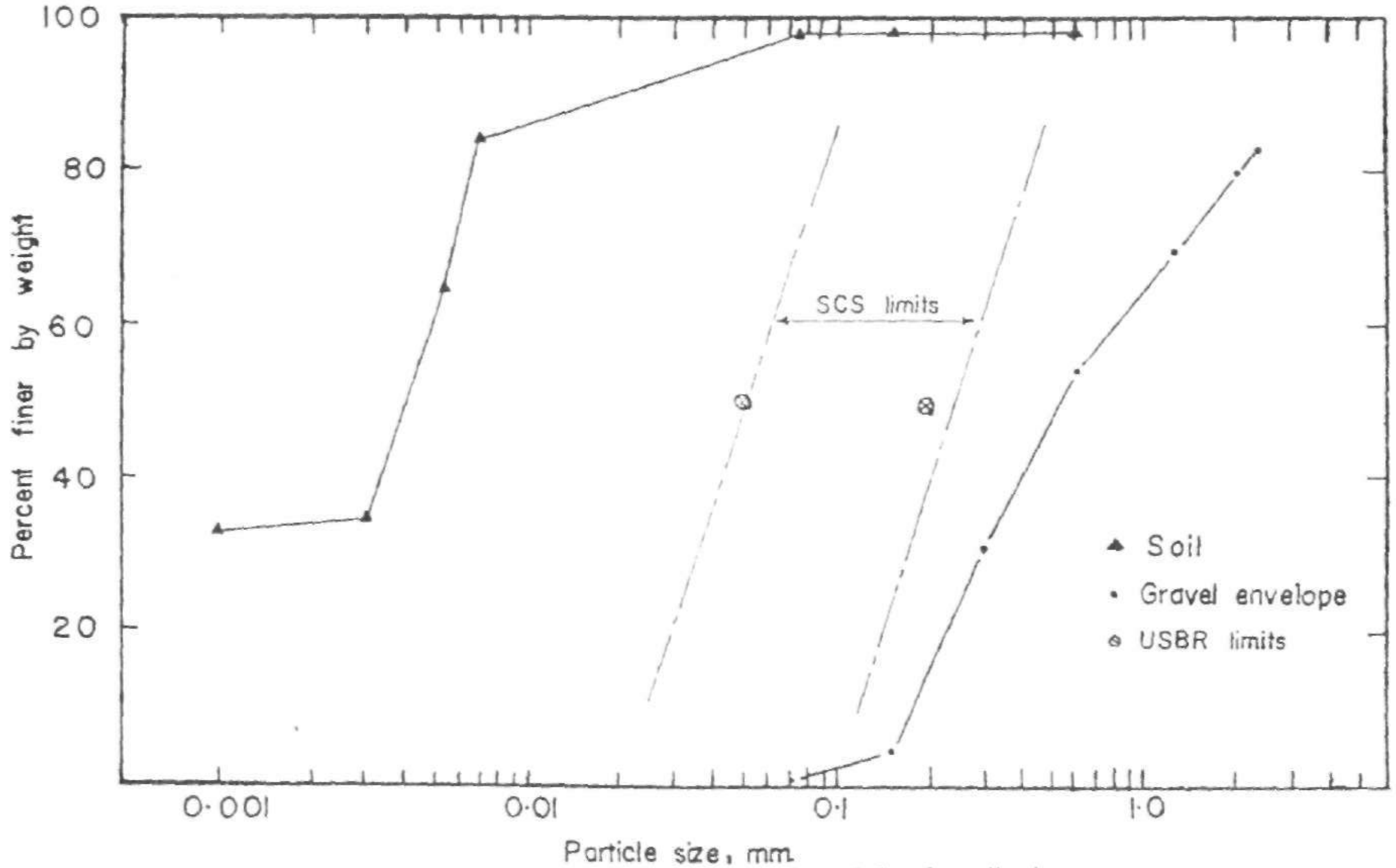

FIG. 4.--Particle Size Distribution for the Soil and Gravel Envelope Used

Description of the Base Material--Soil

One soil type was used in the experiment. The sample of the soil was obtained from Benson, in the Cache Valley, Utah. The soil, identified as Kidman fine sandy loam was collected at a depth 150 cm below ground surface. Tables 5 and 6 give details of particle size analysis for the soil. These values are shown plotted as gradation curve in Fig. 4.

The soil particle sizes are so fine that the envelope material used in the test did not come within the limits set by the design criteria of USBR, SCS, or Corps of Engineers.

The following steps were followed in the preparation of the soil before placement in the model:

a. The soil was air-dried.

b. The air dried soil was then crushed from its aggregated form.

c. Using a sieve with 4.75 mm openings, the soil was screened to remove clods for further crushing and any rocks that were present in the soil.

d. The screened soil was stored in covered plastic buckets at greater than air-dry moisture content.

e. After use, soil removed from the model was in wet condition, hence it had to be air-dried, crushed, screened, and stored away moist before reuse.

TABLE 5.--Wet Sieve Analysis for the Soil

Sieve Number (1)	Sieve Opening (mm) (2)	Mass Retained (gm) (3)	Cumulative Mass Retained (gm) (4)	Weight Passing (gm) (5)	Percent Finer (6)
30	0.60	0.11	0.11	74.89	99.85
50	0.30	0.09	0.20	74.80	99.73
100	0.149	0.22	0.42	74.58	99.44
200	0.075	0.50	0.92	74.08	98.77
Pan	--	74.08	75.00		

Note: Total mass of soil in the analysis = 75.0 gpm
Test method: wet sieving
Soil type and location: Kidman fine sandy loam, Benson, Utah

TABLE 6.--Hydrometer Analysis for the Soil Material

Time (1)	Elapsed Time (minutes) (2)	Temper-ature (°C) (3)	Hydrometer Reading Original (4)	Hydrometer Reading Corrected (5)	% Finer (6)	L (cm) (7)	K (8)	$D=K\sqrt{L/T}$ (mm) (9)	% finer in total sample (10)
10:25am	--								
10:27am	2	22.5	-	-					
10:30am	5	22.5	-	-					
10:40am	15	22.5	-	-					
10:55am	30	22.5	1.0520	1.0305	74.31	8.14	0.0132	0.0069	84.55
11:25am	60	23.0	1.0450	1.0235	57.25	10.02	0.0131	0.0054	65.14
14:35pm	250	23.0	1.0340	1.0125	30.45	12.97	0.0131	0.0030	34.64
10:25am	1440	23.0	1.0335	1.0120	29.24	13.10	0.0131	0.0012	33.27

Note: Hydrometer Correction is 0.0215 (hydrometer type: 151H HCL 270B)
Weight of oven-dried soil sample used ≈ 65.92 gm
Hygroscopic Correction = 12.1%

Drain Size Selection

Typically, field drain sizes range from 5.08 cm diameter to about 20.32 cm or more diameter. The latter being the size is more commonly used as lateral or collector drains. The drains selected for this research were of 5.08, 10.16, and 20.32 cm diameter. extruded corrugated plastic pipes. The pipes have slot perforations measuring about 20 mm by 1.5 mm circumferentially, with perforations spaced every other groove.

A sector forming an angle 75° to the center was cut from each of the three sizes of drain to a length of 80 cm. Holes 3.5 mm diameter were drilled through the pipe sectors to provide passage for piezometers.

Apparatus

Piezometers and Manometers.--The piezometers used are made from 2.5 mm ID and 3.5 mm OD stainless steel tubing. The length of each of the piezometers varied according to the radial distance from the drain center to the point in the soil or envelope at which the pressure head was measured.

For the convenience of location and the numbering system followed, the piezometers are all mounted on a block as shown in Fig. 2. The block is made of plastic, measuring 30 cm x 2.5 cm x 1.3 cm. The piezometers extend about 12.0 mm below the block to make room for the connection of manometers to the piezometers.

Piezometric heads monitored in the soil and envelope were read directly from a manometer panel as shown in Fig. 5. To

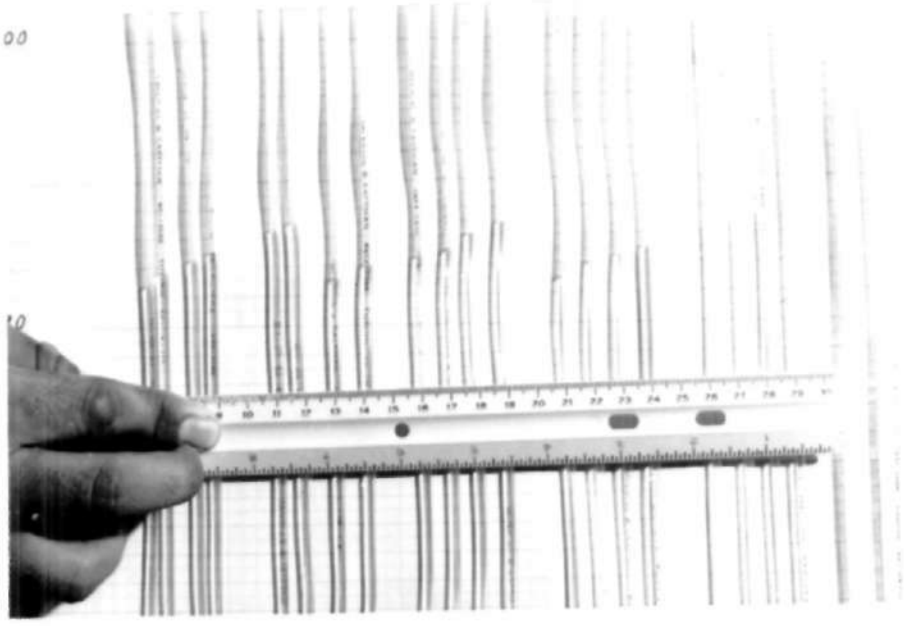

FIG. 5.--Piezometric Heads in Soil and Envelope as Registered on a Manometer Panel.

eliminate differing amounts of capillary rise due to variations in manometer diameters, approximately 20 cm of water with a mild liquid detergent (Kodak photoflow) was placed on top of each water column. The effectiveness of this practice was verified by checking the manometer readings at zero flow; which showed all readings at equal level. Under this condition of no flow, the pressure heads at all locations are equal.

Pump and Ancillary Equipment for Water Supply.--Water at room temperature, averaging 22°C, was used for the entire test. Continuous supply was maintained through the use of a reservoir, pump and other ancillary components. The relative positions of these are shown in the schematic diagram, Fig. 6. The system components are:

a. Reservoir.--It is made from half cut oil drum, with a capacity of 75 liters. It is placed at floor level and operates with sufficient freeboard to allow for discharge of the water in other components in case of emergency.

b. Deaerator.--Water is drawn through the deaerator to the pump with the former placed about 3.70 meters above floor level. Its chief function is to remove air contained in the water. It is connected to the suction side of the pump.

c. Pump.--The pump is a centrifugal pump with a rated discharge of 20 liters per minute driven by a 1/12 BHP electric motor at 3000 rpm.

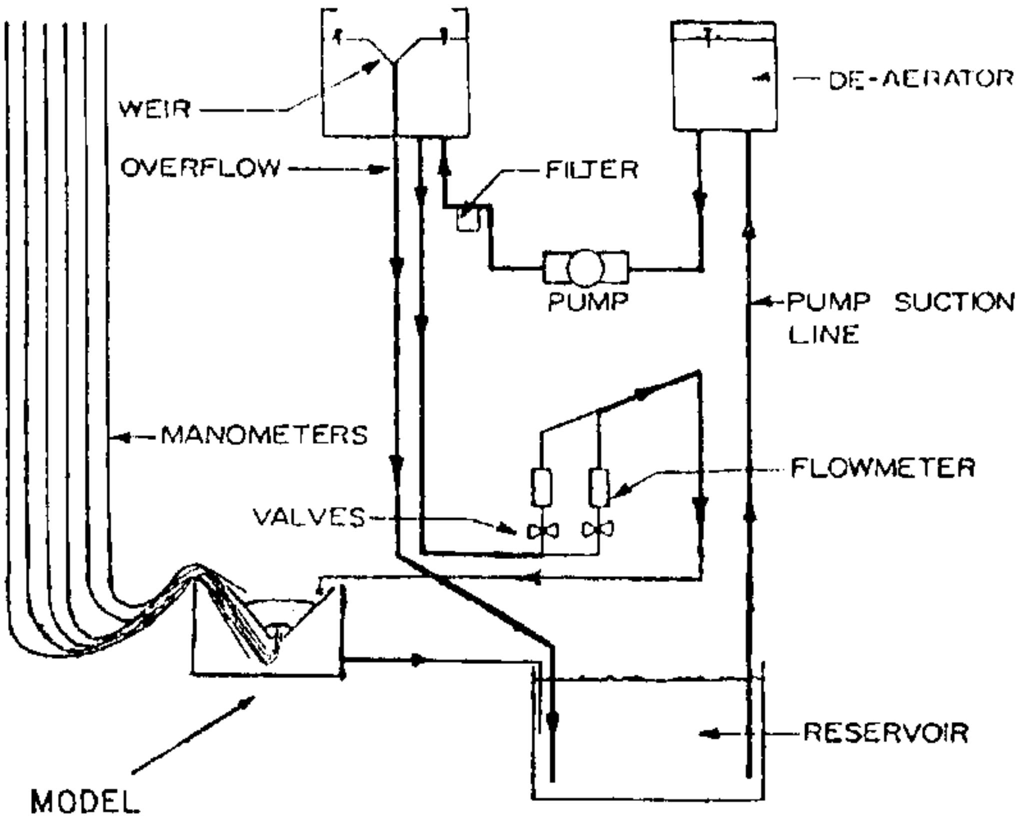

FIG. 6.--Schematic Diagram of Pump and Ancillary Equipment for Water Supply.

d. Filter.--Deaerated water is pumped through an in-line filter, with replaceable cartridge, capable of removing particles of size 0.03 mm from the water.

e. Overflow weir.--This is a circular weir about 19 cm diameter to maintain a constant head of water on the flow control valve. Any excess flow which might result in higher head flows over the weir and is bypassed to the reservoir.

f. Modified needle valves.--Two brass modified needle valves are used to set the desired flow rate for the system. Each of the valves serves a flowmeter.

g. Flowmeters.--Two parallel flowmeters are placed in line to monitor the flowrates in the system. With both flowmeters discharge in the range 0.01 to 1000.87 ml per minute can be measured.

h. Pipelines.--A network of plastic and copper pipeline is used to convey water from one component to the other. Water is delivered to and from the model by short lengths of flexible vinyl hose.

Test Set-up Procedure

The preliminary steps followed in the setting up of equipment for data collection include:

a. Piezometers are securely fixed onto the piezometer block and pipe sector. The three-inch long jumper leads for manometer connections to the piezometers are connected at its ends; noting the numbering system adopted.

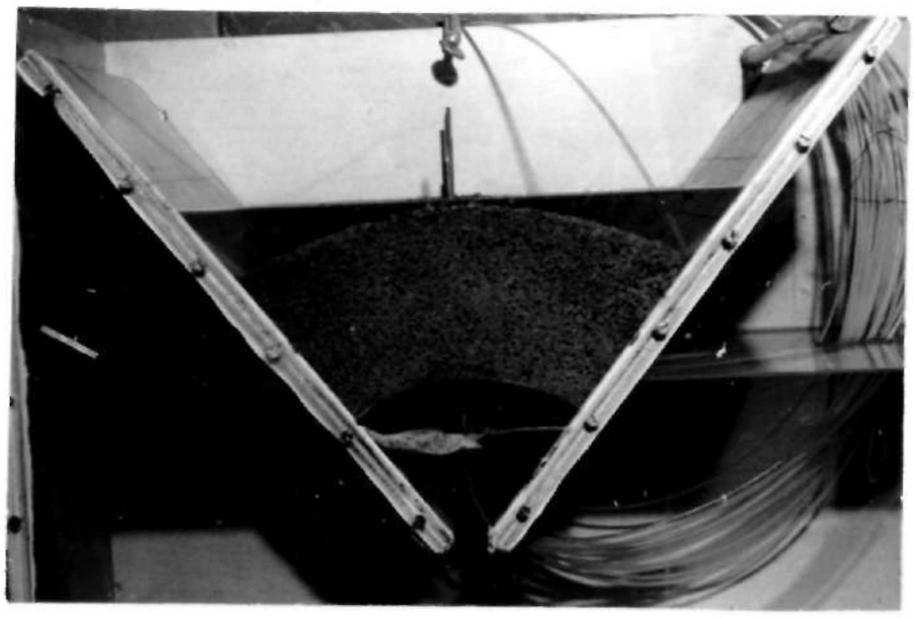

FIG. 7.--Synthetic Envelope Material Test in the Model

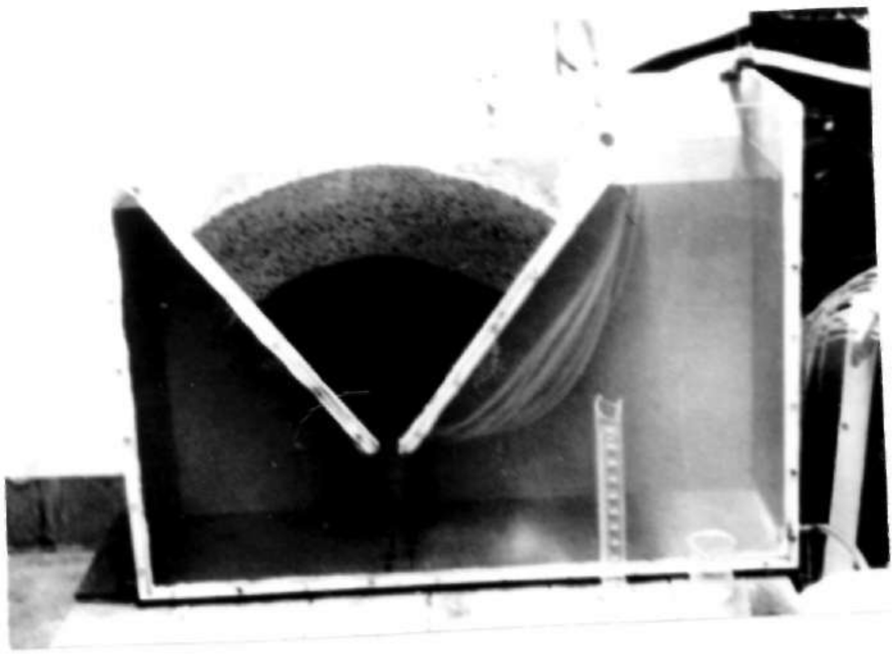

FIG. 8.--Sand and Gravel Envelope Material Test in the Model

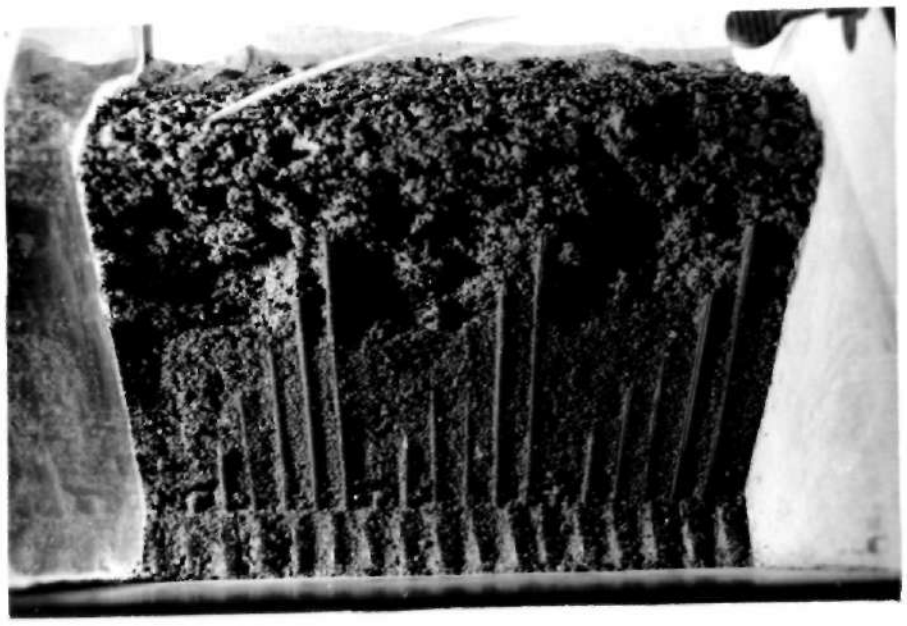

FIG. 9.--Typical Profile Through Sand and Gravel Envelope and Soil Showing Locations of Piezometers

b. Where a synthetic envelope material is to be used, the required size is cut and wrapped around the pipe size sector to be used with it. The edges of the envelope are firmly secured by sewing them with needle and thread. This prevents the overlapping edges from being an obstruction.

c. The "T" junctions with clamps are then fit on the manometer line, these facilities provide means by which both the manometers and piezometers can be flushed of any blockage. In addition, they provide means of putting water in the manometer for pressure measurements.

d. Some glue is slightly smeared along the sitting edge of the envelope before putting it between the "V" panel to prevent leakage of water along the edge, thereby concentrating all the flow across the envelope. A nonpermanent set glue (tub and tile caulk) was used for ease of removal of the envelope at the end of each test.

e. Piezometer openings are stuffed with fiberglass to prevent entry of small soil particles which could cause clogging and malfunctioning of the device.

f. The prepared soil is then carefully placed on top of the envelope-wrapped pipe sector to the desired thickness through a large stem diameter plastic funnel. The use of the funnel reduces soil particle separation. Compactness of the soil material is achieved with this practice. It also enhances the attainment of equal permeability of the soil at every point.

g. Water is pushed through the piezometers with a syringe to displace the air contained therein. Detergent mixed with water is also used to displace the air in the manometers up to a column about 90 cm above the centerline of pipe sector.

h. Warm water is then introduced into the model from below so that as it rises it displaces entrapped air in the soil and envelope. After the soil is totally wetted, the water on the discharge side is then lowered to a desired head difference and deaerated water is pumped through the flowmeter from above the soil surface for the test.

i. Return flow discharge from the model to the reservoir is set at about equilibrium inflow and outflow, using the screw clamp on the discharge hose.

PROCEDURE

Data Collection Procedure

The necessary data required from the experiment are: piezometric heads, flow rate in the system and water temperature. Water through the flowmeter is continuously applied on the soil surface, which then passes through the soil, the envelope, the pipe perforations, into the pipe and finally out at the discharge.

The initial total head, Δh, causing flow to occur across the whole system is recorded. At regular intervals of 30 to 60 minutes readings are monitored; final readings are taken when the equilibrium conditions are established. Under such condition, the flow is said to be at steady-state; no additional storage occurs in the soil or reservoir, and whatever flow is entering the system is also coming out, hence no change occurs in the head established. At this state, piezometric heads in the system are recorded to show energy decadence in the system. In addition, the flow rate and water temperature are also recorded. The latter is recorded because any significant fluctuation in its normal value affects permeability of the soil.

The flow is then adjusted to a new setting, higher or lower flow rate, and the head allowed to vary until it reaches an equilibrium head when new set of recordings are made. The usual elapsed time for this process where the variation is small is about 8 to 10 hours; during this interval the total Δh is regularly monitored. The variation in flow settings adopted in this experiment is from 0-40 ml/minute in steps of 5ml/minute. Recordings were made at both incrementing and decrementing flow settings, as shown in data sheet in Appendix IV.

Analysis of Data

The data obtained for the four different envelope materials are included in the appendix. Drain center axis was referenced to as the datum for the experiment and all pressure head readings have been transformed in such a way as to give a pressure head equal to zero inside the pipe. The merits of such a transformation is that calculations become easier since all the figures involved are small. By this transformation, all the available energy is used up in the soil and envelope; resulting in zero relative energy in the pipe, since no head is lost at pipe perforations, see Appendix III. The drawdown obtained for a Mirafi 140 test using a transformed data is shown plotted in Fig. 10. This figure is representative of the rest of the data, showing the same trend of energy decay for flow toward the pipe.

To determine head loss across the envelope, the data at each of the flow settings was fitted to a natural log curve using the measured pressure heads, P/γ and the radial distances, r_e from the drain pipe center at which the heads were measured. The best-fit curve was of the form: $y = a + b.\ln x$; where a and b are the intercept and the slope of the curve respectively. When the data were fitted to this relationship, R^2 values ranging from 0.72 to

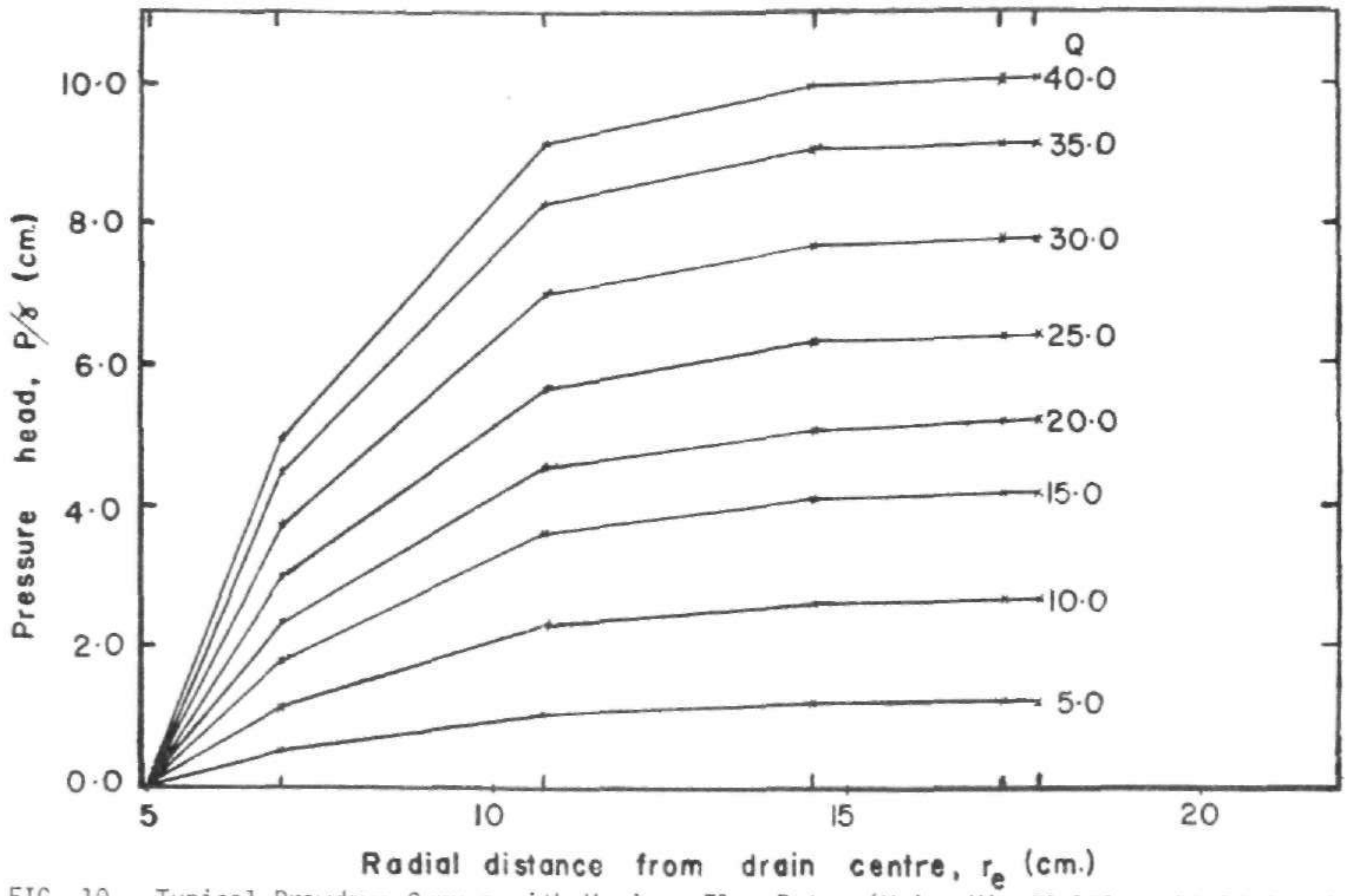

FIG. 10.--Typical Drawdown Curves with Various Flow Rates (Using Mirafi 140 on 10.14 ID pipe) Incrementing Head.

1.00 were obtained with 0.90 being the most frequent. An R^2 usually referred to as "correlation coefficient" is a statistical function used to indicate how close a fit sets of data are to a least square line generated from the data. The closer to unity (1.00) the R^2 value is, the better the fit of the data to the relationship. The high R^2 obtained with these data is indicative of the log relationship that exists between pressure head and radius of measurement. For all envelopes therefore, their data were fitted to the log relationship and then by interpolation pressure heads at envelope radii evaluated. An envelope radius is made up of the sum of half the drain outside diameter, OD, and the envelope thickness.

Another parameter of interest which was also evaluated is the permeability of the envelope and the soil. Permeability of a material is largely a function of the structural arrangement of particles or fibers in the material. The confined well equation which can be used to define a well drawdown, provides a relationship in terms of head and permeability and radii; from which the permeability of either the soil or envelope may be calculated. Expanding Equation (10), already discussed, Flow Q is expressed as:

$$Q = \frac{2\pi km(h_e - h_w)}{\ln (r_e/r_w)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Rearranging,

$$h_e = h_w + \frac{Q}{2\pi km} \cdot \ln (r_e/r_w) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

This equation is of the same form as the best-fit curve obtained for the experimental data. The two equations when combined give a relationship for permeability, K thus:

$$K = \frac{2\pi mb}{Q} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

all terms as previously defined.

Alternatively, since head loss across the material, soil or envelope, is known or can be determined from the best-fit curve, that value can be substituted into the confined well equation together with the other known parameters to determine K as:

$$K = \left(\frac{360}{75} \right) c.Q \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where

$$c = \frac{\ln(r_e/r_w)}{2\pi m\Delta(P/\gamma)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

c is permeability constant having the dimension of $1/L^2$.

The latter relationship was used for determining K values shown in Tables 12A to 15D in Appendix IV. Some slight discrepancies exist for K values determined using the two relationships which in the case of the former are largely due to the slight imperfections of the fit of the data points to a best-fit line while for the latter due to inherent inadequacy of the formula to account for high convergence losses close to the drain. For this reason, K values of envelopes may be subject to error, especially with the thin envelope materials. Table 7 shows sample data obtained for Mirafi 140 on a 10.16 cm ID pipe. The pressure head loss across the envelope and K values were determined from the collected data using the analysis procedure outlined above. Table 8 gives a summary of

TABLE 7.--Pressure Head Determination in the Soil/Envelope System

Envelope type: Mirafi 140
Pipe ID = 10.16 cm

			Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability (cm/min)				
Flow Rate Q (ml/min) (1)	Water Temperature (°C) (2)	Total Head Loss, Δh (cm) (3)	r_d 5.08 (4)	r_{e1} 7.00 (5)	r_{e2} 10.75 (6)	r_{e3} 14.55 (7)	r_{e4} 17.25 (8)	r_{e5} (9)	r_{e6} (10)	r_s 17.75 (11)	K_{env} (12)	K_s (13)	K_{env}/K_s Ratio (14)	Head loss Across Envelope (cm) (15)	$*R^2$ (16)
5.0	20.5	0.50	0.00	0.34	0.47	0.49	0.50			0.50	0.1167	0.4150	0.2811	0.17	0.80
10.0	21.5	1.38	0.00	0.70	1.26	1.33	1.37			1.38	0.1044	0.2739	0.3811	0.38	0.89
15.0	21.0	2.22	0.00	1.09	2.00	2.18	2.21			2.22	0.0992	0.2536	0.3910	0.60	0.90
20.0	20.0	3.32	0.00	1.60	3.00	3.27	3.30			3.32	0.0891	0.2254	0.3954	0.89	0.90
25.0	20.0	4.05	0.00	2.02	3.68	3.97	4.02			4.05	0.0893	0.2329	0.3835	1.11	0.89
30.0	20.0	5.30	0.00	2.67	4.82	5.24	5.30			5.30	0.0809	0.2145	0.3773	1.47	0.89
35.0	20.5	8.90	0.00	4.32	8.02	8.72	8.88			8.90	0.0581	0.1473	0.3944	2.39	0.90
40.0	20.5	10.07	0.00	4.91	9.11	9.94	10.05			10.07	0.0583	0.1491	0.3913	2.72	0.90
35.0	20.5	9.12	0.00	4.46	8.24	9.02	9.12			9.12	0.0562	0.1448	0.3899	2.47	0.90
30.0	20.5	7.75	0.00	3.70	6.97	7.67	7.75			7.75	0.0578	0.1444	0.4000	2.06	0.90
25.0	22.0	6.40	0.00	2.97	5.62	6.30	6.38			6.40	0.0605	0.1439	0.4203	1.64	0.92
20.0	22.0	5.20	0.00	2.31	4.51	5.13	5.20			5.20	0.0615	0.1401	0.4389	1.29	0.93
15.0	21.5	4.15	0.00	1.77	3.57	4.07	4.15			4.15	0.0601	0.1300	0.4622	0.99	0.93
10.0	21.5	2.65	0.00	1.10	2.25	2.58	2.65			2.65	0.0640	0.1349	0.4741	0.62	0.94
5.0	21.0	1.20	0.00	0.50	1.01	1.15	1.20			1.20	0.0708	0.1489	0.4758	0.28	0.94

Note:
Envelope thickness = 0.051 cm
Soil thickness = 12.30 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe O.D. = 11.80 cm
Envelope radius = 5.951 cm

TABLE 8.--Summary of Pressure Head Loss Across Envelope Materials at Varying Flow Rates with Four Inch ID Plastic Pipe

Flow Rate, Q (ml/min)	Envelope Materials							
	Mirafi 140		Typar		Drainguard		Sand and Gravel	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
5	0.17	0.28	0.75	0.78	0.24	0.71	0.19	0.21
10	0.38	0.62	0.85	1.66	0.39	1.22	0.46	0.40
15	0.60	0.99	1.26	2.23	0.69	1.87	0.77	0.58
20	0.89	1.29	1.72	2.39	1.06	2.15	1.00	0.78
25	1.11	1.64	2.21	3.52	1.59	2.40	1.15	0.97
30	1.47	2.06	4.84	5.27	2.41	2.95	1.32	1.13
35	2.39	2.47	5.84	6.43	3.09	3.49	1.52	1.33
40	2.72		7.08		4.41		1.85	1.57

Note: Readings in the first and second column were taken at incrementing and decrementing heads respectively the pressure head loss for the four envelope materials at various flow rates.

Similar analyses were used for the second part of the experiment which investigated envelope thickness influence on pressure head loss for granular sand and gravel envelopes. For ease of interpretation of the results, permeabilities of envelopes were adjusted from their estimated values to an average value to determine an equivalent head loss if that average permeability value envelope were used. The adjusted K values were obtained from an arithmetic average of the K_{env} values for the same Q at different envelope thicknesses.

RESULTS AND DISCUSSION

The piezometric head readings at selected radial distances in the soil and envelope are contained in Tables 12A to 15D in the appendix IV. The holes are arranged in the order the tests were conducted for each of the drain pipe sizes used. The data in the tables show the range of flow rates used and water temperature at the time of the tests. The total head required to cause a given flow rate to occur across the soil and envelope are estimated from difference between the equilibrium static head readings of the inflow and outflow piezometers. Head loss across pipe perforation is very small, hence is neglected in the analysis. The total head loss is the entire driving force for water through the soil and envelope around the drain. Piezometers located in the soil and envelope measure the pressure heads at those locations. A plot of such values gives the typical drawdown shown in Fig. 10; Mirafi 140 synthetic envelope was used on a 10.16 cm ID pipe for this test. The results show that very little, usually less than 10 percent of the total head loss, occurred between the soil surface and about three-quarters way down the soil profile. Indeed, about 80 percent of the total head loss occurred just a little above the pipe in between piezometer locations r_{e1} and r_{e2}. The trend is similar in other tests.

High head loss near the drain pipe is largely caused by the excess convergence losses in the vicinity of the drain and is the power source for the drag of small and unstable soil particles that enter and clog drains. The presence of the 0.051 cm thick permeable synthetic envelope material around the drain pipe improves this permeability so much as to cause a considerable decay of the energy of the flowing water before it entered into the drain. Pressure heads measured about 0.5 cm in the soil above the envelope showed little difference from that measured in the soil next to the envelope which in effect means that the effective radius of the drain had been increased by the presence of the relatively thin synthetic envelope. This effect is more dramatic with the sand and gravel envelope; the plot in Fig. 11 shows the comparatively low head loss in the envelope relative to the amount of head loss in the soil. In this instance, the effective radius of the drain has been enlarged due to the additional radius of permeable material offered by the thickness of the envelope.

Permeability Effects

Piezometer readings were taken and drawdown to the pipe obtained, the latter was used to estimate the proportion of the total head that was lost in the envelope. Under all situations, it was found that the pressure head loss across the envelope per se varied with the flow rate in the system. There appears to be a linear relationship between head loss across envelope and the established flow rate. Table 8 is a summary of the results of head loss with varying flow, Q, for the materials that were tested. These values are also plotted in Fig. 12. The results showed that at low flow rates and up to about 25 ml/min, there are no significant differences

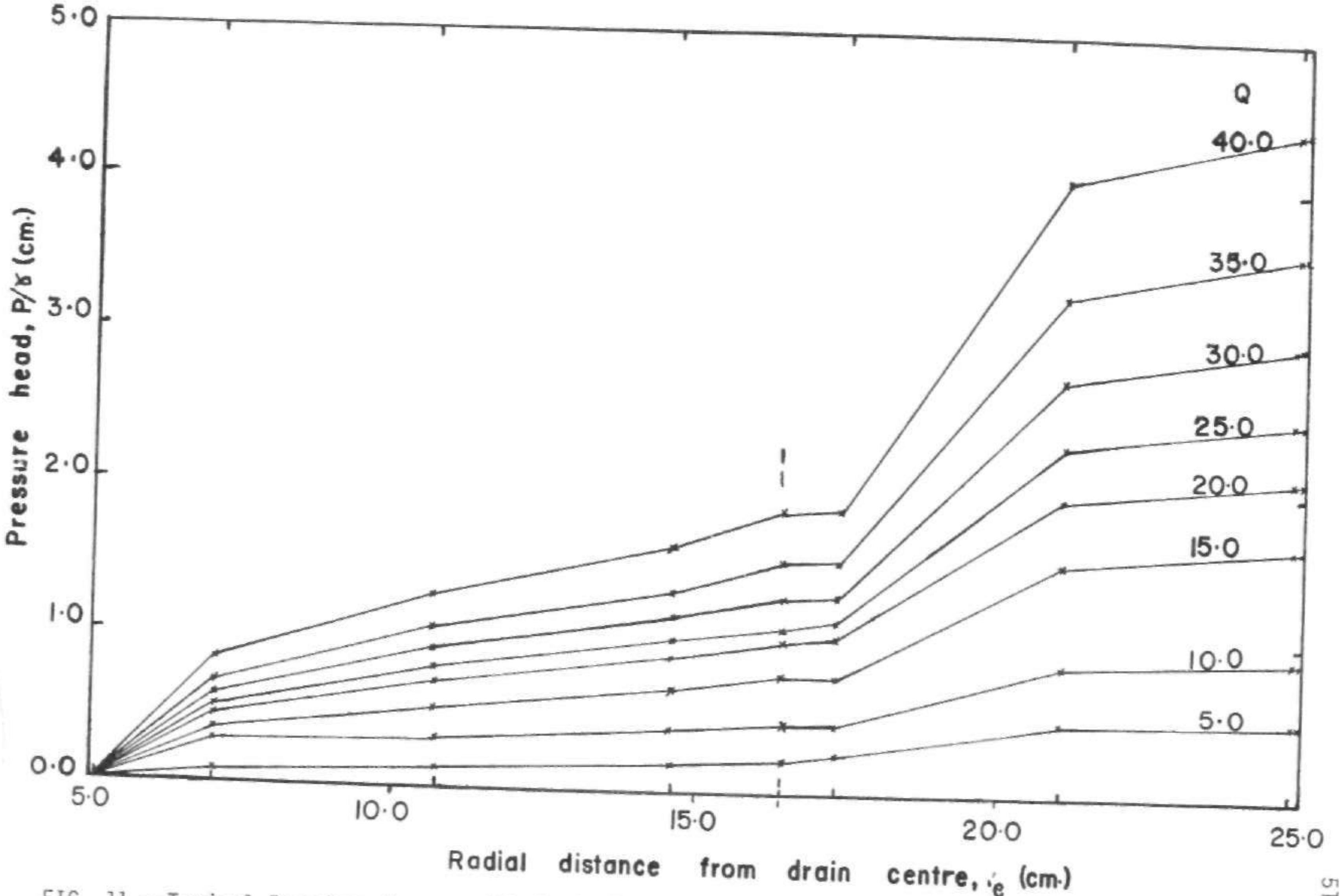

FIG. 11.--Typical Drawdown Curves with Variable Flow Rates (Using Sand and Gravel on 10.16 cm ID Pipe).Incrementing Head.

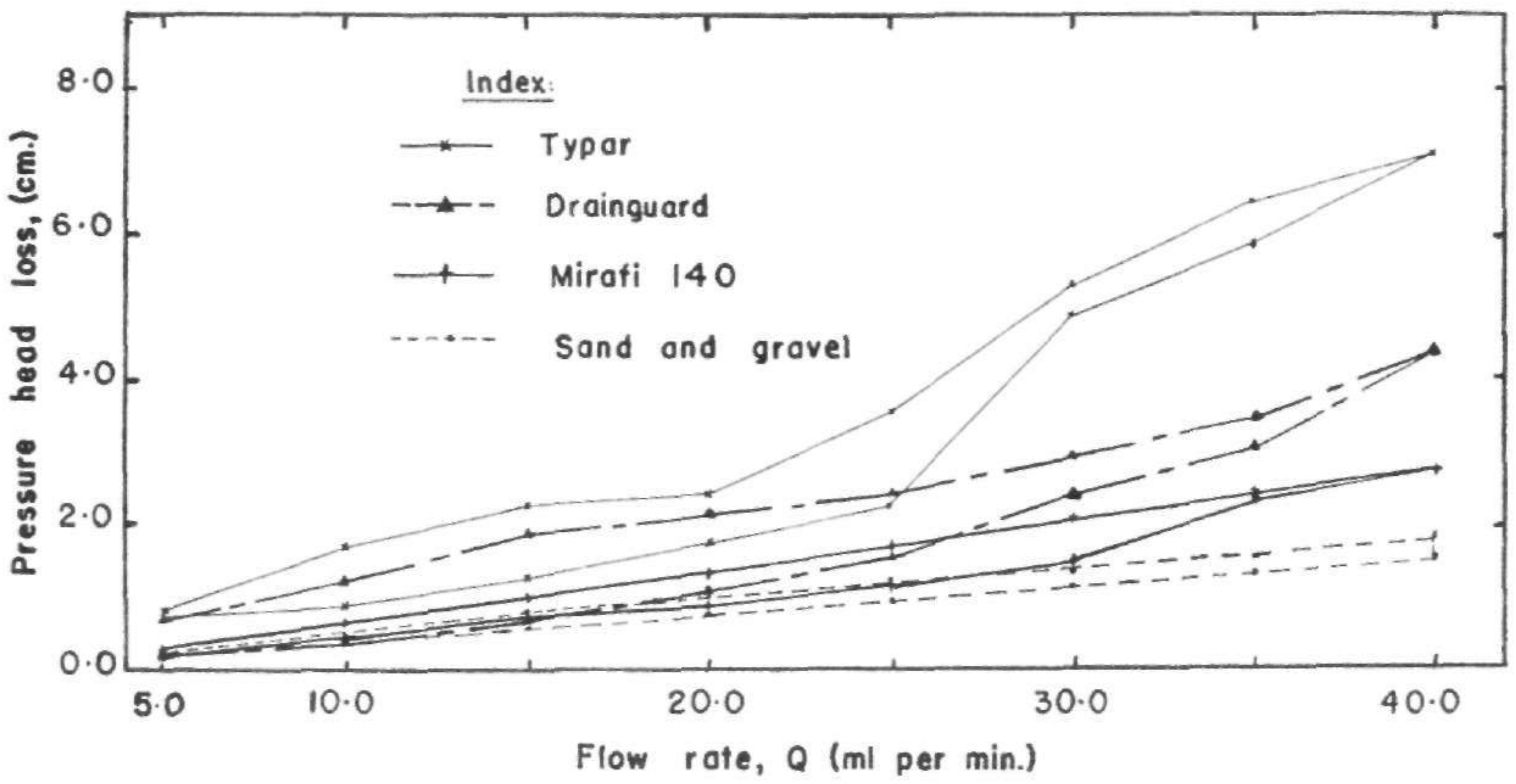

FIG. 12.--Pressure Head Loss Across Four Envelope Materials.

between head loss in the different synthetic materials; beyond this threshold flow rate, the differences in the magnitudes became more apparent. Higher head losses occurred in Typar with much less in sand and gravel. Drainguard and Mirafi 140 had values in between the other two. Between flow rates 25 and 40 ml/min, the head loss in Typar at nearly all flow rates is about twice that which occurred in the other materials. This result is consistent with what is expected considering that Typar is the least permeable of the four materials, see appendix II for preliminary test of permeability of materials. Typar being less permeable offered the highest resistance to flow, thus causing high head loss across it compared to the other materials with the same flow.

When the same tests were repeated with decrementing heads, estimates of the head loss across the envelopes differed with values previously obtained. In most cases there was an increase in the head loss. With both sets of data plotted in Fig. 12, the curve for each material formed a loop similar to "hysterisis curve" encountered with wetting and drying curves in soils. Two possible explanations to this may be: at higher heads small soil particles might have been dragged into the envelope pores causing it to plug which then requires additional head to pass the same flow; where there was decrease, this may be due to continued release of air bubbles trapped in the materials. Air bubbles cause additional head loss to occur.

Though there are measurable differences in head losses among the materials tested, these are not as significant as the difference between the total head loss and the amount that occurred in the envelope. For all tests it was found that at any one flow rate, the percent of the total head loss that occurred in the envelopes is less than 25 percent. Unless some serious plugging of the envelope occurs with time, the materials can be expected to function well. These findings of low head losses in the materials tested support an earlier finding by Benz et al. reported by Walker (38) which showed that synthetic envelope materials have comparable performance to the granular sand and gravel envelope materials under the conditions for which they were all tested.

Envelope Thickness

Granular sand and gravel envelope thicknesses were investigated to determine its effect on pressure head loss. Four thicknesses 5.5, 8.30, 10.50 and 14.60 cm of gravel on drain pie 10.16 cm ID were tested. A summary of the data collected given in Table 15A-D are given in Table 9 with the results plotted in Fig. 13. The results essentially show that there is an accompanying increase in head loss in the envelope as it is made thicker; however the rate of increase is small as evidenced by slope of the curves. It is interesting to note that as the ratio of permeabilities of the gravel envelope to the overlying soil material K_{env}/K_s increases, the steepness of the curves increase showing that even though a more permeable envelope is used, any additional thickness of the material will result in a slightly higher head loss. Despite the additional head loss, the use of thick envelope material around the drain pipe offers a technically feasible method of increasing drain effective radius not to mention improvement of permeability and curtailment

TABLE 9.--Summary of Data on the Effect of Granular Envelope Thickness on Pressure Head Loss

	R_{en}/R_d				Regression Line		
	2.24	2.80	3.23	4.04	$*R^2$	a	b
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Estimated	0.53	0.63	0.46	0.70			
Adjusted for a (K_e/K_s = 4.5)	0.42	0.54	0.61	0.73	0.99	0.05	0.17
Estimated	1.10	0.99	1.00	1.42			
Adjusted for a (K_e/K_s = 5.5)	0.82	1.05	1.19	1.42	0.99	0.11	0.33
Estimated	1.41	1.25	1.32	1.98			
Adjusted for a (K_e/K_s = 6.2)	1.08	1.05	1.57	1.87	0.99	0.14	0.43
Estimated	1.80	1.49	1.85	2.30			
Adjusted for a (K_e/K_s = 7.5)	1.36	1.73	1.97	2.25	0.97	0.31	0.49

*Correlation factor

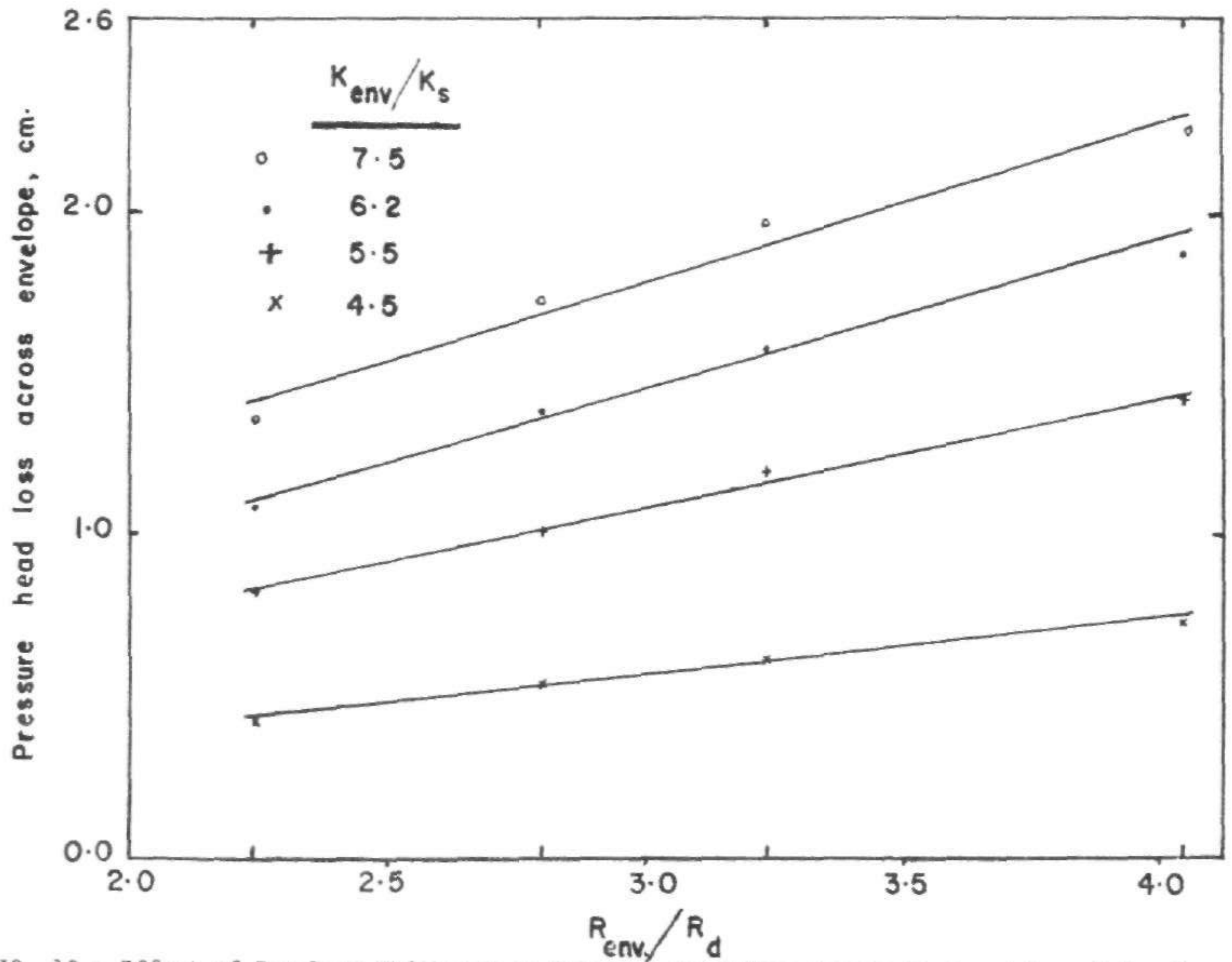

FIG. 13.--Effect of Envelope Thickness on Pressure Head Loss Across Sand and Gravel Envelope

of sediment entry into the pipe. However, increasing effective radius per se by additional thicker gravel envelope is not generally economic. The practical limitation to increasing gravel envelope thickness is the associated costs involved. Increased thickness increases volumetric requirement of the material and its costs, and costs associated with haulage and placement of the material.

The curves in Fig. 13 have been expanded and included in Appendix V as Fig. 14 with an illustration of how it can be used to determine an optimum size sand and gravel envelope for placement around drain considering both the permeabilities of the soil and envelope and permissible head loss in the envelope itself.

SUMMARY AND CONCLUSIONS

Summary

The main objectives of this research are twofold. The first is to determine quantitatively the magnitude of pressure head loss across four drain envelope materials. Three of these materials are synthetic, the fourth is a naturally graded pit run sand and gravel envelope. The second objective is to determine envelope thickness relationship to head loss on granular envelope material.

To achieve these objectives, a physical model illustrated in Fig. 1 was used for the investigation and collection of the necessary data, including piezometric head readings. Flow of water used in the model were in the laminar range and rates were varied from 5 to 40 ml/min. The same soil type was used throughout the entire tests; its preparation and placement in the model was maintained uniform to minimize variability in the soil permeability.

Within the limitations of this investigation the following findings were made from the data obtained:

1. Pressure head loss across envelopes responded linearly to increase in flow through them.

2. The magnitude of head loss is inversely proportional to the permeability of the envelope material.

3. For the same permeability, the thicker a gravel envelope is, the higher the possible head loss across it.

4. Pressure head loss occurs at soil/envelope interface.

5. The exact nature of drawdown at soil/envelope interface is unclear.

Conclusions

Envelope materials tested showed that they could perform their functions quite satisfactorily with low energy loss. Head loss across all the materials, except perhaps Typar, are relatively low compared to the total head loss.

The main limitation to use of very thick granular envelope materials around drain is economic. The additional head losses resulting from use of thicker materials are not generally excessive.

RECOMMENDATIONS

As a result of this research it is recommended for future study that some investigations be made into behavior of flow at the soil/envelope interface with a view to clearly delineating drawdown at that location. It is presumed that the head loss that occurs at the interface is due to sudden change of materials at the interface; this needs to be investigated further.

Research should also be continued on gravel envelope thickness so as to expand and update sources of information as suggested in the use of chart in Fig. 14 in Appendix V to determine optimum thickness of granular envelope for placement around drain pipe.

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APPENDICES

Appendix I.--Calculations for Model Size Determination

In order to come up with an appropriate size model, the drainage coefficient for agricultural drains in Cache Valley was used since the soil used in the experiment was collected locally. The value used for most subsurface drainage installations is 0.0051 m/day (0.20 in/day). The SCS (34) in its studies of yields of drains in arid and semi-arid irrigated areas indicated average flow from areas above one square mile to be in the range of 2 to 4 cfs per square mile (0.15 to 0.30 in/day or 0.0038 to 0.0076 m/day). The actual value depends on individual farm situation, since such a value is a function of the size of watershed, type of crop grown, soil type, land slope, leaching requirement, surface runoff, etc.

With a 0.0051 m/day drainage coefficient, a 30.48 cm length of pipe, 10.16 cm maximum well radius, radius of influence equal to 30.48 cm maximum, and a predetermined composite K value of 0.18 m/day, the available drawdown was estimated using the equation:

$$Q = \frac{2\pi kmD}{\ln(r_e/r_w)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (16)$$

where Q is equal to the discharge which equals drainage coefficient spacing, assuming a drain spacing of 20 m, or $Q = 0.1016\ m^3/day$; K is equal to 0.18 m/day; r_w equals 0.1016 m (4 in); r_e equals 0.3048 m (12 in); m equals length of pipe, 0.3048 m and D equals drawdown or maximum available head.

Rearranging the equation and substituting known values,

$$D = \frac{Q \ln(r_e/r_w)}{2\pi km}$$

$$= \frac{0.1016 \times \ln(0.3048/0.1016)}{2 \times \pi \times 0.18 \times 0.3048}$$

$$= 0.3238 \text{ m}$$

i.e.,

$$D = 32.38 \text{ cm}$$

The 32 cm drawdown or total available head obtained above will satisfy all conditions of head requirement for the tests. The split V panels have however, been made 35 cm deep.

The other critical dimension is that of angling of the split "V" panels. They have been set at an angle of 75 degrees to each other so that the tangent angle to the soil and the horizontal does not exceed angle of repose of dry soil. The tangent angle is about 37.5 degrees. At this angle, soil particles do not roll down during placement, thereby permitting maintenance of the curvature on the surface throughout the entire tests. The rest of the dimensions are secondary and not as critical and are made to provide sufficient room for working convenience, see Fig. 1.

Appendix II.--Preliminary Tests of Permeability, K

Envelopes.--All four envelope material types, three synthetic and one sand and gravel were tested for permeability. Though the actual value is not expected to remain constant, the values obtained served as indicators of the typical values in real test situation. The test value also provided data for the model design.

The tests were conducted in constant-head permeameters. The sand and gravel envelope was tested in the conventional glass type constant head permeameter. The synthetic envelopes were tested in a constant head 10 cm diameter plastic permeameter. Flow rates ranging from 151.90 to 956.71 ml/min were used for the investigation. Piezometric heads were measured on both sides of the envelopes, representing inflow and outflow heads; the resultant difference being head loss across the material. Each of the synthetic materials was tested single layered, then the test was repeated for double and triple layers. Under each of the conditions, relevant data were collected. Six tests were conducted on each material.

Using Darcy's equation for flow in porous media, the average permeability, K, of the materials were evaluated from the data obtained. The average K values are as summarized in the table below.

TABLE 10.--Preliminary Test Values for Permeability of Envelope Materials

Envelope Material (1)	Average Permeability, K (cm/min) (2)
Mirafi 140	1.69
Typar	0.08
Drainguard	1.09
Sand and Gravel	0.98

Soil.--The soil sample used in the entire tests was also tested for permeability using the conventional glass type constant head permeameter. Varying lengths of columns of soil were used for the six different tests made. Salty water at specific gravity 1.003 at room temperature of 20°C was also used to check for presence of salts in the soil which could affect its permeability. No salt presence was evident.

Average permeability of the soil was found to be 8.93 cm/day, i.e., 0.0062 cm/min. At the end of the tests in the model, the soil was retested for permeability. A K-value of 0.0070 cm/min was obtained from an average of eight readings. Compared to the sand and gravel envelope, the sand and gravel envelope is about 158 times more permeable than the soil used. Except for Typar, similar comparisons with the other envelope material types showed that the envelopes are significantly much more permeable than the soil. This is a desirable characteristic, as far as drainage is concerned.

Appendix III.--Velocity Head Loss at the Perforations

As water passes from the soil, across the envelope, then through the pipe perforations, some head loss due to velocity occurs at such a constriction. The magnitude of such a head loss is a function of the flow velocity, v; where v = Q/A.

Treating the perforations as rectangular orifices, the system can be analyzed using discharge through rectangular orifice relationship given below as:

$$Q = 0.61A(2gh)^{1/2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

where Q equals the discharge through the perforations in ml/s (cc/s); A equals the cross-sectional area of flow in cm^2; g is the acceleration due to gravity, 981 cm/sec^2; and h equals the velocity head loss in cm of water rise. For a 10.16 cm diameter corrugated plastic pipe:

Total cross-sectional area of perforations per foot length of the pipe (8 perforations per foot) = 8 x 20 mm x 1.5 mm = 2.4 cm^2. Discharge through the perforations per foot length are given in the table below:

Rearranging the formula above:

$$h = \left(\frac{Q}{0.61 \times 60 \times A} \right)^{1/2} \times 1/2g \text{ cm} \quad . \quad . \quad . \quad (18)$$

Estimated velocity head loss at the orifice for various discharges are tabulated below. From the table, it can be seen that even at high discharges the velocity head loss, less than 0.01, is insignificant. Therefore, for all practical purposes, it can be neglected. Similar determinations for the 5.08 and 20.32 cm diameter

TABLE 11.--Velocity Head Loss Across the Perforations Per Foot Length at Various Discharges.

Discharge Q(ml/m) (1)	Velocity Head Loss, h (10^{-6} cm) (2)
5.0	1.65
10.0	6.61
15.0	14.86
20.0	26.42
25.0	41.29
30.0	59.45
35.0	80.92
40.0	105.69

showed that the component is much too small compared to pressure and elevation components.

Appendix IV

TABLE 12A.--Pressure Head Determination in the Soil/Envelope System

Envelope Type: Mirafi 140
Pipe I.D.: 5.08 cm

Flow Rate Q (ml/min)	Water Temper- ature (°C)	Total Head Loss, Δh (cm)	Pressure Head at Various Radial Distances From The Drain Center (cm)								Permeability (cm/min)		K_{env}/K_s Ratio	Head Loss Across Envelope (cm)	$*R^2$
			r_d 2.54	r_{e1} 4.35	r_{e2} 8.10	r_{e3} 11.92	r_{e4} 14.48	r_{e5}	r_{e6}	r_s 15.05	K_{env}	K_s			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
5.0	21.5	1.00	0.00	0.30	0.52	0.88	0.98			1.00	0.2871	0.2174	1.3209	0.08	0.98
10.0	21.0	2.05	0.00	0.65	1.22	1.80	2.00			2.05	0.2188	0.2174	1.0064	0.21	1.00
15.0	21.0	3.15	0.00	1.00	2.00	2.87	3.10			3.15	0.2027	0.2135	0.9493	0.34	1.00
20.0	21.5	4.05	0.00	1.22	2.57	3.67	3.98			4.05	0.2241	0.2198	1.0197	0.41	1.00
25.0	22.0	5.10	0.00	1.57	3.27	4.67	5.03			5.10	0.2167	0.2188	0.9904	0.53	1.00
30.0	22.0	6.00	0.00	1.83	3.82	5.48	5.87			6.00	0.2260	0.2226	1.0149	0.61	1.00
35.0	21.5	6.75	0.00	2.08	4.52	6.17	6.58			6.75	0.2203	0.2326	0.9472	0.73	1.00
40.0	21.0	7.85	0.00	2.23	4.50	6.17	6.67			7.85	0.2588	0.2241	1.1551	0.71	0.99
151.9	22.0	33.60	0.00	18.40	26.52	31.63	33.17			33.60	0.0952	0.2313	0.4116	7.33	0.94
35.0	21.5	6.05	0.00	2.05	3.98	5.43	5.90			6.05	0.2233	0.2627	0.8503	0.72	1.00
30.0	21.5	4.35	0.00	1.48	2.85	3.90	4.26			4.35	0.2703	0.3125	0.8648	0.51	1.00
25.0	21.5	3.70	0.00	1.38	2.52	3.43	3.67			3.70	0.2297	0.3125	0.7351	0.50	0.99
20.0	22.5	2.80	0.00	1.05	1.92	2.60	2.78			2.80	0.2418	0.3306	0.7315	0.38	0.99
15.0	22.5	2.05	0.00	0.75	1.40	1.88	2.03			2.05	0.2552	0.3371	0.7572	0.27	1.00
10.0	23.0	1.25	0.00	0.48	0.87	1.13	1.23			1.25	0.2552	0.3738	0.6828	0.18	0.99
5.0	22.0	0.50	0.00	0.25	0.42	0.47	0.50			0.50	0.2297	0.5000	0.4594	0.10	0.95

Note:
Envelope Thickness = 0.051 cm
Soil thickness = 12.00 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 6.0 cm
Envelope radius = 3.051 cm

TABLE 12B.--Pressure Head Determination in the Soil/Envelope System   Envelope Type: Typar
Pipe I.D.: 5.08 cm

Flow Rate Q (ml/min)	Water Temper-ature (°C)	Total Head Loss, Δh (cm)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability			Head Loss Across	
			r_d 2.54	r_{e1} 4.24	r_{e2} 8.04	r_{e3} 11.94	r_{e4} 14.49	r_{e5}	r_{e6}	r_s 17.04	K_{env} (cm/min)	K_s (cm/min)	K_{env}/K_s Ratio	Envelope (cm)	$*R^2$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
5.0	22.5	1.60	0.00	1.07	1.45	1.53	1.60			1.60	0.0476	0.1913	0.2486	0.47	0.83
10.0	22.0	3.25	0.00	2.30	2.97	3.13	3.20			3.25	0.0438	0.1939	0.2261	1.02	0.80
15.0	22.0	4.95	0.00	3.52	4.58	4.80	4.90			4.95	0.0427	0.1919	0.2226	1.57	0.80
20.0	22.5	6.45	0.00	4.65	5.92	6.27	6.40			6.45	0.0438	0.1970	0.2204	2.06	0.80
25.0	22.0	9.20	0.00	6.93	8.50	9.00	9.20			9.20	0.0365	0.1760	0.2075	3.06	0.77
30.0	22.0	10.70	0.00	8.12	9.95	10.48	10.65			10.70	0.0374	0.1824	0.2048	3.59	0.77
35.0	22.0	12.90	0.00	10.25	12.10	12.67	12.88			12.90	0.0345	0.1808	0.1911	4.53	0.74
40.0	22.0	14.70	0.00	11.72	13.85	14.47	14.70			14.70	0.0345	0.1817	0.1900	5.18	0.74
35.0	21.5	14.50	0.00	12.12	13.83	14.35	14.50			14.50	0.0292	0.1656	0.1763	5.36	0.70
30.0	22.0	11.05	0.00	9.22	10.50	10.92	11.03			11.05	0.0330	0.1858	0.1773	4.07	0.71
25.0	22.0	9.35	0.00	7.68	8.72	9.22	9.35			9.35	0.0332	0.1808	0.1835	3.37	0.72
20.0	22.0	7.00	0.00	5.48	6.58	6.88	6.98			7.00	0.0368	0.1892	0.1945	2.43	0.75
15.0	21.5	5.30	0.00	4.27	4.98	5.22	5.30			5.30	0.0357	0.1896	0.1881	1.88	0.73
10.0	22.0	3.60	0.00	2.87	3.37	3.52	3.58			3.60	0.0352	0.1856	0.1897	1.27	0.74
5.0	22.0	1.65	0.00	1.32	1.55	1.63	1.65			1.65	0.0385	0.2020	0.1908	0.58	0.74

Note: Envelope thickness = 0.036 cm
Soil thickness = 14.00 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads.
Pipe OD = 6.00 cm
Envelope radius = 3.036 cm

TABLE 12C.--Pressure Head Determination in the Soil/Envelope System

Envelope type: Drainguard
Pipe I.D.: 5.08 cm

Flow Rate Q (ml/min) (1)	Water Temperature (°C) (2)	Total Head Loss, Δh (cm) (3)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability (cm/min)		K_{env}/K_s Ratio (14)	Head Loss Across Envelope (cm) (15)	$*R^2$ (16)
			r_d 2.54 (4)	r_{e1} 4.29 (5)	r_{e2} 8.09 (6)	r_{e3} 11.86 (7)	r_{e4} 14.46 (8)	r_{e5} (9)	r_{e6} (10)	r_s 17.01 (11)	K_{env} (12)	K_s (13)			
5.0	21.5	0.70	0.00	0.25	0.63	0.67	0.70			0.70	0.1766	0.3743	0.4718	0.12	0.94
10.0	22.0	1.30	0.00	0.47	1.15	1.25	1.28			1.30	0.1927	0.4021	0.4792	0.22	0.94
15.0	21.5	2.05	0.00	0.78	1.83	1.90	2.01			2.05	0.1766	0.3854	0.4582	0.36	0.94
20.0	22.0	2.85	0.00	1.05	2.57	2.72	2.78			2.85	0.1730	0.3680	0.4701	0.49	0.93
25.0	22.5	3.55	0.00	1.30	3.17	3.32	3.40			3.55	0.1737	0.3692	0.4704	0.61	0.93
30.0	21.5	4.25	0.00	1.55	3.77	4.00	4.15			4.25	0.1766	0.3690	0.4786	0.72	0.94
35.0	21.5	4.80	0.00	1.90	4.30	4.53	4.70			4.80	0.1686	0.3877	0.4348	0.88	0.93
40.0	22.0	5.35	0.00	2.05	4.80	5.07	5.23			5.35	0.1785	0.3948	0.4521	0.95	0.93
35.0	23.0	4.65	0.00	1.85	4.17	4.43	4.60			4.65	0.1745	0.4000	0.4364	0.85	0.93
30.0	23.5	4.05	0.00	1.60	3.62	3.83	3.98			4.05	0.1718	0.3936	0.4366	0.74	0.93
25.0	23.5	3.15	0.00	1.22	2.78	2.98	3.10			3.15	0.1892	0.4191	0.4514	0.56	0.94
20.0	23.5	2.50	0.00	0.98	2.18	2.30	2.38			2.50	0.1927	0.4216	0.4570	0.44	0.94
15.0	23.5	1.85	0.00	0.73	1.67	1.75	1.81			1.85	0.1870	0.4314	0.4335	0.34	0.93
10.0	23.0	1.25	0.00	0.48	1.10	1.18	1.23			1.25	0.1927	0.4216	0.4570	0.22	0.94
5.0	22.0	0.45	0.00	0.24	0.36	0.39	0.42			0.45	0.2119	0.6203	0.3416	0.10	0.92

Note:
Envelope thickness = 0.008 cm
Soil thickness = 14.00 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 6.00 cm
Envelope radius = 3.008 cm

TABLE 12D.--Pressure Head Determination in the Soil/Envelope System Envelope type: Sand and Gravel
Pipe I.D.: 5.08 cm

Flow Rate Q (ml/min) (1)	Water Temper-ature (°C) (2)	Total Head Loss, Δh (cm) (3)	Pressure Head at Various Radial Distances From the Drain Center (cm) r_d 2.54 (4)	r_{e1} 4.25 (5)	r_{e2} 8.05 (6)	r_{e3} 11.85 (7)	r_{e4} 14.45 (8)	r_{e5} 18.25 (9)	r_{e6} 22.10 (10)	r_s 26.00 (11)	Permeability K_{env} (cm/min) (12)	K_s (13)	K_{env}/K_s Ratio (14)	Head Loss Across Envelope (cm) (15)	$*R^2$ (16)
5.0	21.5	0.55	0.00	0.11	0.19	0.24	0.31	0.44	0.50	0.55	0.7418	0.2757	2.6905	0.30	0.98
10.0	22.0	1.10	0.00	0.31	0.47	0.60	0.67	0.92	1.02	1.10	0.6359	0.3447	1.8449	0.70	0.97
15.0	22.0	1.60	0.00	0.38	0.62	0.83	0.97	1.39	1.60	1.60	0.6883	0.3282	2.0969	0.97	0.99
20.0	22.0	1.90	0.00	0.59	0.88	1.08	1.20	1.63	1.78	1.90	0.7065	0.4308	1.6399	1.26	0.96
25.0	22.5	2.40	0.00	0.67	1.05	1.29	1.48	2.01	2.25	2.40	0.7273	0.3962	1.8359	1.53	0.97
30.0	22.0	2.95	0.00	0.79	1.26	1.58	1.82	2.50	2.78	2.95	0.7141	0.3830	1.8647	1.87	0.98
35.0	23.0	3.45	0.00	0.87	1.42	1.78	2.08	2.89	3.25	3.45	0.7348	0.3628	2.0255	2.12	0.98
40.0	22.5	4.10	0.00	1.00	1.63	2.08	2.42	3.41	3.85	4.10	0.7237	0.3362	2.1524	2.46	0.98
100.0	22.0	11.70	0.00	1.83	2.93	3.73	4.30	8.52	11.28	11.70	1.0139	0.1886	5.3761	4.39	0.98
300.0	22.0	33.70	0.00	4.18	7.53	9.92	11.58	30.05	32.42	33.70	1.1442	0.1877	6.0948	11.67	0.99
40.0	22.0	5.80	0.00	1.27	1.77	2.17	2.42	5.28	5.63	5.80	0.7010	0.1692	4.1438	2.54	0.95
35.0	21.5	5.30	0.00	1.27	1.73	2.07	2.35	4.88	5.18	5.30	0.6359	0.1693	3.7557	2.45	0.93
30.0	21.5	4.70	0.00	1.13	1.57	1.87	2.07	4.30	4.60	4.70	0.6097	0.1648	3.7004	2.19	0.93
25.0	21.0	3.90	0.00	1.12	1.47	1.75	1.90	3.57	3.83	3.90	0.5564	0.1814	3.0672	2.03	0.91
20.0	21.5	3.05	0.00	0.97	1.23	1.45	1.55	2.82	2.97	3.05	0.5299	0.2013	2.6329	1.68	0.89
15.0	21.0	2.00	0.00	0.72	0.85	1.00	1.07	1.85	1.95	2.00	0.5756	0.2462	2.3380	1.16	0.86
10.0	21.0	1.35	0.00	0.58	0.67	0.75	0.82	1.28	1.35	1.35	0.5001	0.2997	1.6687	0.89	0.83
5.0	21.0	0.90	0.00	0.33	0.43	0.50	0.58	0.87	0.90	0.90	0.3709	0.2298	1.6143	0.60	0.91

Note: Envelope thickness = 12.00 cm
Soil thickness = 11.0 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 6.0 cm
Envelope radius = 15.00 cm

TABLE 13A.--Pressure Head Determination in the Soil/Envelope System Envelope Type: Mirafi 140
Pipe I.D.: 20.32 cm

			Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability				
Flow Rate Q (ml/min) (1)	Water Temper-ature (°C) (2)	Total Head Loss, Δh (cm) (3)	r_d 10.16 (4)	r_{e1} 12.20 (5)	r_{e2} 16.00 (6)	r_{e3} 19.90 (7)	r_{e4} 22.40 (8)	r_{e5} (9)	r_{e6} (10)	r_s 23.28 (11)	K_{env} (cm/min) (12)	K_s (13)	K_{env}/K_s Ratio (14)	Head Loss Across Envelope (cm) (15)	$*R^2$ (16)
6.92	21.5	2.05	0.00	0.52	1.25	1.63	1.80			2.05	0.0621	0.0723	0.8590	0.43	0.99
12.24	22.0	4.10	0.00	0.82	2.83	3.60	3.97			4.10	0.0549	0.0639	0.8590	0.86	0.98
17.56	21.5	6.35	0.00	1.38	4.28	5.68	6.32			6.35	0.0502	0.0594	0.8445	1.35	0.99
22.88	22.0	7.50	0.00	1.53	5.37	6.55	7.33			7.50	0.0548	0.0657	0.8342	1.61	0.97
28.20	21.5	10.65	0.00	2.25	7.28	9.52	10.50			10.65	0.0481	0.0569	0.8465	2.26	0.98
33.52	21.5	12.55	0.00	2.93	8.58	10.58	11.42			12.55	0.0474	0.0578	0.8202	2.73	0.98
38.84	21.0	15.80	0.00	3.07	10.53	13.72	14.73			15.80	0.0468	0.0522	0.8978	3.20	0.98
44.16	21.5	16.15	0.00	2.03	12.52	14.97	16.05			16.15	0.0523	0.0580	0.9016	3.26	0.94
38.84	22.0	14.05	0.00	2.40	9.23	12.55	14.00			14.05	0.0551	0.0580	0.9498	2.72	0.98
33.52	22.0	12.10	0.00	2.20	7.98	10.87	12.07			12.10	0.0539	0.0585	0.9216	2.40	0.98
28.20	22.5	9.70	0.00	1.77	6.37	8.55	9.67			9.70	0.0570	0.0613	0.9300	1.91	0.99
22.88	22.0	7.05	0.00	1.38	4.62	6.13	6.95			7.05	0.0626	0.0687	0.9121	1.41	0.99
17.56	21.0	5.70	0.00	0.98	3.38	4.73	5.07			5.70	0.0658	0.0636	1.0338	1.03	0.99
12.24	21.0	4.60	0.00	0.92	3.02	4.05	4.53			4.60	0.0508	0.0564	0.8998	0.93	0.99
6.92	21.0	2.80	0.00	0.50	1.73	2.37	2.58			2.80	0.0513	0.0514	0.9998	0.52	0.99

Note:
Envelope thickness = 0.051 cm
Soil thickness = 11.430 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 23.60 cm
Envelope radius = 11.851 cm

TABLE 13B.--Pressure Head Determination in the Soil/Envelope System

Envelope type: Typar
Pipe I.D.: 20.32 cm

Flow Rate Q (ml/min)	Water Temper-ature (°C)	Total Head Loss, Δh (cm)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability (cm/min)		K_{env}/K_s Ratio	Head Loss Across Envelope (cm)	*R^2
			r_d 10.16	r_{e1} 12.26	r_{e2} 16.06	r_{e3} 19.91	r_{e4} 22.44	r_{e5}	r_{e6}	r_s 23.27	K_{env}	K_s			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
6.92	21.5	6.65	0.00	0.05	6.35	6.53	6.62			6.65	0.0188	0.0198	0.9476	1.28	0.84
12.24	21.5	11.95	0.00	0.08	11.63	11.87	11.92			11.95	0.0199	0.0216	0.9227	2.35	0.84
17.56	21.5	17.90	0.00	0.10	17.38	17.68	17.83			17.90	0.0192	0.0207	0.9293	3.50	0.84
22.88	21.0	24.70	0.00	0.20	23.67	24.37	24.63			24.70	0.0183	0.0195	0.9388	4.79	0.84
28.20	21.5	27.00	0.00	0.12	25.75	26.57	26.92			27.00	0.0208	0.0219	0.9514	5.18	0.85
33.52	21.0	29.35	0.00	0.17	28.17	28.93	29.28			29.35	0.0226	0.0240	0.9412	5.68	0.84
38.84	21.0	31.00	0.00	0.25	29.70	30.48	30.87			31.00	0.0247	0.0263	0.9392	6.01	0.84
44.16	21.5	31.00	0.00	0.40	29.73	30.52	30.88			31.00	0.0278	0.0300	0.9276	6.07	0.84
38.84	21.5	30.40	0.00	0.32	29.20	29.97	30.30			30.40	0.0251	0.0269	0.9320	5.93	0.84
33.52	22.0	30.20	0.00	0.30	28.87	29.68	30.07			30.20	0.0219	0.0233	0.9381	5.86	0.84
28.20	21.0	25.25	0.00	0.35	24.15	24.78	25.08			25.25	0.0219	0.0235	0.9309	4.93	0.85
22.88	22.0	21.65	0.00	0.27	20.72	21.28	21.52			21.65	0.0207	0.0222	0.9329	4.22	0.84
17.56	22.0	17.05	0.00	0.20	16.32	16.73	16.93			17.05	0.0202	0.0217	0.9341	3.32	0.84
12.24	21.0	11.95	0.00	0.20	11.40	11.70	11.87			11.95	0.0200	0.0216	0.9276	2.34	0.85
6.92	21.5	5.30	0.00	0.18	4.87	5.00	5.10			5.30	0.0257	0.0275	0.9363	1.03	0.86

Note:
Envelope thickness = 0.035 cm
Soil thickness = 11.430 cm
*R^2 obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 23.60 cm
Envelope radius = 11.836 cm

TABLE 13C.--Pressure Head Determination in the Soil/Envelope System

Envelope type: Drainguard
Pipe I.D.: 20.32 cm

Flow Rate Q (ml/min) (1)	Water Temper-ature (°C) (2)	Total Head Loss, Δh (cm) (3)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability (cm/min)		K_{env}/K_s Ratio (14)	Head Loss Across Envelope (cm) (15)	*R^2 (16)
			r_d 10.16 (4)	r_{e1} 12.26 (5)	r_{e2} 16.11 (6)	r_{e3} 19.96 (7)	r_{e4} 22.46 (8)	r_{e5} (9)	r_{e6} (10)	r_s 22.61 (11)	K_{env} (12)	K_s (13)			
5.0	20.5	5.55	0.00	0.10	5.08	5.10	5.53			5.55	0.0190	0.0179	1.0658	0.99	0.87
10.0	20.0	11.80	0.00	0.05	11.07	11.57	11.80			11.80	0.0177	0.0168	1.0505	2.13	0.86
15.0	21.0	20.20	0.00	0.12	19.15	19.90	20.18			20.20	0.0153	0.0148	1.0319	3.70	0.86
20.0	21.0	22.65	0.00	0.18	21.52	22.37	22.65			22.65	0.0180	0.0176	1.0225	4.18	0.86
25.0	21.5	23.90	0.00	0.57	22.90	23.60	23.88			23.90	0.0206	0.0211	0.9788	4.57	0.86
30.0	21.5	30.90	0.00	0.75	29.70	30.47	30.90			30.90	0.0191	0.0196	0.9744	5.93	0.86
33.5	21.5	32.95	0.00	0.67	31.65	32.13	32.95			32.95	0.0202	0.0204	0.9866	6.26	0.86
40.0															
30.0	22.0	30.25	0.00	0.23	29.12	29.52	30.25			30.25	0.0201	0.0198	1.0119	5.63	0.85
25.0	21.0	25.30	0.00	0.33	24.12	24.92	25.30			25.30	0.0200	0.0198	1.0089	4.72	0.86
20.0	21.5	19.55	0.00	0.60	18.55	19.10	19.65			19.65	0.0201	0.0206	0.9782	3.74	0.87
15.0	21.5	15.85	0.00	0.45	15.03	15.53	15.85			15.85	0.0187	0.0190	0.9831	3.02	0.86
10.0	21.0	11.45	0.00	0.37	10.77	11.07	11.45			11.45	0.0173	0.0175	0.9840	2.18	0.87
5.0	21.0	5.60	0.00	0.35	5.22	5.47	5.58			5.60	0.0168	0.0182	0.9256	1.12	0.88

Note:
Envelope thickness = 0.008 cm
Soil thickness = 10.80 cm
*R^2 obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 23.60 cm
Envelope radius = 11.808

TABLE 13D.--Pressure Head Determination in the Soil/Envelope System

Envelope type: Sand and Gravel
Pipe I.D.: 20.32 cm

Flow Rate Q (ml/min)	Water Temper-ature (°C)	Total Head Loss, Δh (cm)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability			Head Loss	
			r_d 10.16	r_{e1} 12.25	r_{e2} 16.10	r_{e3} 19.92	r_{e4} 22.50	r_{e5} 26.32	r_{e6} 29.50	r_s 32.80	K_{env} (cm/min)	K_s	K_{env}/K_s Ratio	Across Envelope (cm)	$*R^2$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
5.0	21.0	3.60	0.00	0.10	0.12	0.14	0.18	2.41	3.34	3.60	0.5628	0.0133	42.2301	0.18	0.87
10.0	21.0	6.55	0.00	0.16	0.20	0.23	0.27	6.26	6.37	6.55	0.7235	0.0145	49.7712	0.28	0.86
15.0	21.5	9.75	0.00	0.18	0.25	0.29	0.34	9.18	9.50	9.75	0.8441	0.0146	57.9738	0.36	0.90
20.0	21.5	11.90	0.00	0.27	0.30	0.35	0.43	11.15	11.85	11.90	0.9209	0.0159	57.8896	0.44	0.82
25.0	22.0	14.70	0.00	0.25	0.30	0.37	0.45	12.05	14.48	14.70	1.1010	0.0160	68.8051	0.46	0.88
30.0	20.5	18.00	0.00	0.25	0.30	0.35	0.48	16.40	17.73	18.00	1.2931	0.0156	82.8997	0.47	0.87
35.0	22.5	21.30	0.00	0.27	0.33	0.42	0.53	18.98	21.00	21.30	1.3379	0.0154	87.1022	0.53	0.91
40.0	22.0	24.40	0.00	0.38	0.55	0.67	0.77	21.40	24.08	24.40	1.0004	0.0155	64.7309	0.81	0.93
40.0	22.0	23.45	0.00	0.58	0.85	0.98	1.25	22.60	23.10	23.45	0.6431	0.0164	39.1431	1.26	0.93
35.0	22.0	20.45	0.00	0.53	0.67	0.91	1.12	19.87	20.15	20.45	0.6275	0.0165	38.0012	1.13	0.93
30.0	21.5	17.95	0.00	0.50	0.64	0.82	0.84	17.18	17.60	17.95	0.6535	0.0161	40.6767	0.93	0.87
25.0	22.0	14.70	0.00	0.45	0.52	0.65	0.83	14.24	14.59	14.70	0.6102	0.0164	37.1421	0.83	0.88
20.0	21.5	12.10	0.00	0.36	0.44	0.52	0.60	11.50	11.81	12.10	0.6431	0.0159	40.4661	0.63	0.86
15.0	21.0	9.95	0.00	0.28	0.34	0.39	0.49	9.51	9.71	9.95	0.6078	0.0145	42.0078	0.50	0.86
10.0	21.0	6.65	0.00	0.17	0.21	0.24	0.29	6.35	6.64	6.65	0.6733	0.0144	47.0458	0.30	0.86
5.0	21.0	3.65	0.00	0.12	0.14	0.17	0.20	2.45	3.43	3.65	0.4824	0.0132	36.4089	0.21	0.86

Note:
Envelope thickness = 11.00 cm
Soil thickness = 10.00 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distance, re and pressure heads
Pipe OD = 23.60 cm
Envelope radius = 22.80 cm

TABLE 14A--Pressure Head Determination in the Soil/Envelope System

Envelope type: Typar
Pipe I.D.: 10.16 cm

			Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability				
Flow Rate Q (ml/min) (1)	Water Temper-ature (°C) (2)	Total Head Loss, Δh (cm) (3)	r_d 5.08 (4)	r_{e1} 6.99 (5)	r_{e2} 10.79 (6)	r_{e3} 14.64 (7)	r_{e4} 17.21 (8)	r_{e5} (9)	r_{e6} (10)	r_s 18.24 (11)	K_{env} (cm/min) (12)	K_s (13)	K_{env}/K_s ratio (14)	Head Loss Across Envelope (cm) (15)	$*R^2$ (16)
5.0	21.5	2.70	0.00	1.33	2.56	2.63	2.67			2.70	0.0260	0.0721	0.3607	0.75	0.87
10.0	21.5	4.40	0.00	1.20	4.07	4.22	4.38			4.40	0.0459	0.0793	0.5794	0.85	0.91
15.0	21.5	6.55	0.00	1.80	6.05	6.37	6.55			6.55	0.0465	0.0798	0.5824	1.26	0.91
20.0	22.0	9.05	0.00	2.45	8.30	8.82	9.02			9.05	0.0454	0.0768	0.5912	1.72	0.92
25.0	22.0	11.30	0.00	3.20	10.37	11.02	11.23			11.30	0.0442	0.0774	0.5706	2.21	0.92
30.0	21.5	22.10	0.00	7.35	20.85	21.98	22.07			22.10	0.0242	0.0489	0.4947	4.84	0.90
35.0	21.5	25.75	0.00	8.97	24.60	25.67	25.73			25.75	0.0234	0.0495	0.4729	5.84	0.90
40.0	22.0	29.65	0.00	11.18	28.53	29.55	29.62			29.65	0.0221	0.0499	0.4422	7.08	0.89
35.0	22.0	25.85	0.00	10.32	25.10	25.77	25.85			25.85	0.0212	0.0507	0.4190	6.43	0.88
30.0	22.0	20.75	0.00	8.55	20.17	20.73	20.75			20.75	0.0222	0.0545	0.4075	5.27	0.88
25.0	21.0	13.35	0.00	5.83	13.03	13.30	13.35			13.35	0.0277	0.0716	0.3874	3.52	0.88
20.0	21.0	9.10	0.00	3.95	8.88	9.05	9.10			9.10	0.0327	0.0838	0.3895	2.39	0.88
15.0	21.0	7.70	0.00	3.92	7.48	7.67	7.70			7.70	0.0263	0.0772	0.3403	2.23	0.86
10.0	21.0	5.70	0.00	2.92	5.52	5.67	5.70			5.70	0.0235	0.0696	0.3376	1.66	0.86
5.0	21.0	2.75	0.00	1.38	2.60	2.68	2.72			2.75	0.0250	0.0714	0.3504	0.78	0.87

Note:
Envelope thickness = 0.036 cm
Soil thickness = 11.80 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 11.80 cm
Envelope radius = 5.936 cm

TABLE 14B--Pressure Head Determination in the Soil/Envelope System

Envelope type: Drainguard
Pipe I.D.: 10.16 cm

Flow Rate Q (ml/min)	Water Temper-ature (°C)	Total Head Loss, Δh (cm)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability		K_{env}/K_s Ratio	Head Loss Across Envelope (cm)	$*R^2$
			r_d 5.08	r_{e1} 7.01	r_{e2} 10.76	r_{e3} 14.54	r_{e4} 17.16	r_{e5}	r_{e6}	r_s 18.41	K_{env} (cm/min)	K_s (cm/min)			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
5.0	21.5	1.14	0.0	0.41	1.00	1.11	1.14			1.14	0.0788	0.1583	0.4982	0.24	0.93
10.0	22.0	2.20	0.00	0.65	1.77	2.15	2.20			2.20	0.0970	0.1574	0.6166	0.39	0.96
15.0	22.0	3.70	0.00	1.14	3.08	3.68	3.69			3.70	0.0823	0.1420	0.5795	0.69	0.95
20.0	23.0	5.40	0.00	1.76	4.56	5.31	5.38			5.40	0.0714	0.1313	0.5439	1.06	0.94
25.0	22.5	7.80	0.00	2.60	6.77	7.75	7.80			7.80	0.0595	0.1147	0.5189	1.59	0.93
30.0	21.0	10.95	0.00	4.01	9.81	10.83	10.93			10.95	0.0471	0.1001	0.4708	2.41	0.92
35.0	21.5	13.60	0.00	5.13	12.35	13.45	13.55			13.60	0.0429	0.0949	0.4519	3.09	0.91
40.0	21.5	17.40	0.00	7.57	16.28	17.25	17.40			17.40	0.0343	0.0877	0.3913	4.41	0.89
35.0	22.0	13.40	0.00	6.05	12.60	13.29	13.40			13.40	0.0380	0.1006	0.3772	3.49	0.89
30.0	22.0	11.23	0.00	5.12	10.58	11.15	11.20			11.23	0.0385	0.1032	0.3729	2.95	0.88
25.0	21.5	9.30	0.00	4.13	8.73	9.15	9.25			9.30	0.0394	0.1032	0.3819	2.40	0.89
20.0	22.0	8.20	0.00	3.70	7.78	8.17	8.20			8.20	0.0352	0.0942	0.3738	2.15	0.88
15.0	22.0	7.10	0.00	3.26	6.70	7.03	7.07			7.10	0.0304,	0.0817	0.3716	1.87	0.88
10.0	22.0	4.70	0:00	2.11	4.40	4.63	4.67			4.70	0.0310	0.0819	0.3790	1.22	0.89
5.0	21.0	2.75	0.00	1.24	2.55	2.68	2.73			2.75	0.0267	0.0698	0.3817	0.71	0.89

Note:
Envelope thickness = 0.008 cm
Soil thickness = 12.50 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 11.80 cm
Envelope radius = 5.908 cm

TABLE 14C--Pressure Head Determination in the Soil/Envelope System

Envelope type: Sand and Gravel
Pipe I.D.: 10.16 cm

Flow Rate Q (ml/min) (1)	Water Temperature (°C) (2)	Total Head Loss, Δh (cm) (3)	Pressure Head at Various Radial Distances From the Drain Center (cm) r_d 5.08 (4)	r_{e1} 7.00 (5)	r_{e2} 10.73 (6)	r_{e3} 14.58 (7)	r_{e4} 17.32 (8)	r_{e5} 21.10 (9)	r_{e6} 24.88 (10)	r_s 25.00 (11)	Permeability (cm/min) K_{env} (12)	K_s (13)	K_{env}/K_s Ratio (14)	Head Loss Across Envelope (cm) (15)	*R^2 (16)
5.0	22.0	0.50	0.00	0.09	0.12	0.17	0.23	0.47	0.50	0.50	0.7730	0.1704	4.5355	0.19	0.93
10.0	21.5	0.90	0.00	0.28	0.31	0.40	0.43	0.83	0.90	0.90	0.6386	0.2402	2.6590	0.46	0.82
15.0	21.5	1.65	0.00	0.35	0.53	0.66	0.76	1.52	1.64	1.65	0.5722	0.1801	3.1770	0.77	0.94
20.0	21.5	2.12	0.00	0.46	0.69	0.86	1.00	1.95	2.12	2.12	0.5875	0.1887	3.1134	1.00	0.94
25.0	21.5	2.52	0.00	0.52	0.79	0.99	1.12	2.32	2.51	2.52	0.6386	0.1928	3.3116	1.15	0.94
30.0	22.0	3.00	0.00	0.58	0.90	1.14	1.28	2.74	2.99	3.00	0.6676	0.1887	3.5380	1.32	0.95
35.0	22.0	3.60	0.00	0.68	1.04	1.31	1.52	3.29	3.59	3.60	0.6764	0.1778	3.8040	1.52	0.95
40.0	21.5	4.40	0.00	0.82	1.26	1.60	1.86	4.06	4.39	4.40	0.6351	0.1658	3.8317	1.85	0.95
300.0	21.5	33.15	0.00	3.15	5.32	6.96	17.33	31.60	33.12	33.15	1.1071	0.1258	8.7970	7.96	0.97
40.0	21.5	6.50	0.00	0.64	1.05	1.37	3.97	6.20	6.50	6.50	0.7484	0.0857	8.7291	1.57	0.97
35.0	21.5	5.40	0.00	0.55	0.89	1.16	3.31	5.19	5.40	5.40	0.7730	0.0909	8.5068	1.33	0.97
30.0	21.5	4.75	0.00	0.45	0.76	0.98	2.88	4.53	4.74	4.75	0.7798	0.0876	8.9054	1.13	0.97
25.0	21.0	4.05	0.00	0.42	0.64	0.85	2.35	3.84	4.03	4.05	0.7571	0.0858	8.8267	0.97	0.96
20.0	21.0	3.25	0.00	0.31	0.51	0.69	1.81	3.09	3.25	3.25	0.7532	0.0856	8.8029	0.78	0.98
15.0	21.5	2.20	0.00	0.27	0.40	0.50	1.40	2.13	2.20	2.20	0.7597	0.0978	7.7644	0.58	0.94
10.0	20.0	1.36	0.00	0.15	0.26	0.35	0.92	1.28	1.35	1.36	0.7343	0.1101	6.6716	0.40	0.98
5.0	20.0	0.80	0.00	0.07	0.14	0.19	0.52	0.74	0.79	0.80	0.5994	0.0895	7.8101	0.21	1.00

Note: Envelope thickness = 10.50 cm
Soil thickness = 8.60 cm
*R^2 obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 11.80 cm
Envelope radius = 16.40 cm

TABLE 15A.--Pressure Head Determination in the Soil/Envelope System *Envelope Type: Sand and Gravels*
Pipe I.D.: 10.16 cm

Flow Rate Q (ml/min) (1)	Water Temperature (°C) (2)	Total Head Loss, Δh (cm) (3)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability		K_{env}/K_s Ratio (14)	Head Loss Across Envelope (cm) (15)	$*R^2$ (16)
			r_d 5.08 (4)	r_{e1} 7.00 (5)	r_{e2} 10.73 (6)	r_{e3} 14.58 (7)	r_{e4} 17.32 (8)	r_{e5} (9)	r_{e6} (10)	r_s 18.58 (11)	K_{env} (cm/min) (12)	K_s (13)			
10.0	21.0	2.20	0.00	0.30	0.47	1.82	2.14			2.20	0.3752	0.0738	5.0868	0.54	0.94
20.0	21.0	5.32	0.00	0.62	0.97	4.43	5.29			5.32	0.3683	0.0580	6.3482	1.10	0.94
30.0	21.0	7.00	0.00	0.81	1.23	5.97	6.87			7.00	0.4310	0.0657	6.5603	1.41	0.93
40.0	21.5	10.60	0.00	0.99	1.59	9.22	10.45			10.60	0.4502	0.0556	8.0899	1.80	0.95
30.0	21.0	9.30	0.00	0.78	1.18	8.22	9.23			9.30	0.4502	0.0462	9.7447	1.35	0.93
20.0	21.5	7.28	0.00	0.54	0.84	6.51	7.19			7.28	0.4221	0.0387	10.8938	0.96	0.94
10.0	21.5	4.40	0.00	0.36	0.53	4.01	4.39			4.40	0.3321	0.0323	10.2812	0.61	0.92

Note:
Envelope thickness = 5.50 cm
Soil thickness = 8.00 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 11.80 cm
Envelope radius = 11.40 cm

TABLE 15B. --Pressure Head Determination in the Soil/Envelope System   Envelope type: Sand and Gravel
Pipe I.D.: 10.16 cm

Flow Rate Q (ml/min) (1)	Water Temper-ature (°C) (2)	Total Head Loss, Δh (cm) (3)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability		K_{env}/K_s Ratio (14)	Head Loss Across Envelope (cm) (15)	$*R^2$ (16)
			r_d 5.08 (4)	r_{e1} 7.00 (5)	r_{e2} 10.75 (6)	r_{e3} 14.65 (7)	r_{e4} 17.20 (8)	r_{e5} 24.80 (9)	r_{e6} (10)	r_s 25.00 (11)	K_{env} (cm/min) (12)	K_s (cm/min) (13)			
10.0	20.0	3.40	0.00	0.30	0.44	0.67	2.38	3.37		3.40	0.4089	0.0512	7.9904	0.63	0.92
20.0	20.0	6.60	0.00	0.46	0.69	1.04	4.65	6.58		6.60	0.5205	0.0505	10.2981	0.99	0.93
30.0	20.5	10.30	0.00	0.55	0.88	1.35	7.46	10.27		10.30	0.6183	0.0470	13.1573	1.25	0.95
40.0	21.0	13.55	0.00	0.64	1.05	2.12	9.86	13.51		13.55	0.6916	0.0470	14.7092	1.49	0.96
30.0	21.0	12.40	0.00	0.53	0.85	1.13	9.53	12.37		12.40	0.6388	0.0380	16.8063	1.21	0.95
20.0	20.5	8.05	0.00	0.30	0.48	1.10	6.33	8.03		8.05	0.7578	0.0385	19.6964	0.68	0.95
10.0	21.0	4.65	0.00	0.22	0.34	0.61	3.75	4.44		4.65	0.5367	0.0340	15.7879	0.48	0.94

Note: *Envelope thickness = 8.30 cm*
Soil thickness = 10.80 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 11.80 cm
Envelope radius = 14.20 cm

TABLE 15C.--Pressure Head Determination in the Soil/Envelope System Envelope type: Sand and Gravel
Pipe I.D.: 10.16 cm

Flow Rate Q (ml/min)	Water Temperature (°C)	Total Head Loss, Δh (cm)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability		K_{env}/K_s Ratio	Head Loss Across Envelope (cm)	$*R^2$
			r_d 5.08	r_{e1} 7.00	r_{e2} 10.73	r_{e3} 14.58	r_{e4} 17.32	r_{e5} 21.10	r_{e6} 24.88	r_s 25.00	K_{env} (cm/min)	K_s (cm/min)			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
10.0	21.5	0.90	0.00	0.28	0.31	0.40	0.43	0.83	0.90	0.90	0.6386	0.2402	2.6590	0.46	0.82
20.0	21.5	2.12	0.00	0.46	0.69	0.86	1.00	1.95	2.12	2.12	0.5875	0.1887	3.1134	1.00	0.94
30.0	22.0	3.00	0.00	0.58	0.90	1.14	1.28	2.74	2.99	3.00	0.6676	0.1887	3.5380	1.32	0.95
40.0	21.5	4.40	0.00	0.82	1.26	1.60	1.86	4.06	4.39	4.40	0.6351	0.1658	3.8317	1.85	0.95
300.0	21.5	33.15	0.00	3.15	5.32	6.96	17.33	31.60	33.12	33.15	1.1071	0.1258	8.7970	7.96	0.97
40.0	21.5	6.50	0.00	0.64	1.05	1.37	3.97	6.20	6.50	6.50	0.7484	0.0857	8.7291	1.57	0.97
30.0	21.5	4.75	0.00	0.45	0.76	0.98	2.88	4.53	4.74	4.75	0.7798	0.0876	8.9054	1.13	0.97
20.0	21.0	3.25	0.00	0.31	0.51	0.69	1.81	3.09	3.25	3.25	0.7532	0.0856	8.8029	0.78	0.98
10.0	20.0	1.36	0.00	0.15	0.26	0.35	0.92	1.28	1.35	1.36	0.7343	0.1101	6.6716	0.40	0.98

Note: Envelope thickness = 10.50 cm
Soil thickness = 8.60 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distance, re and pressure heads
Pipe OD = 11.80 cm
Envelope radius = 16.40 cm

TABLE 15D. --Pressure Head Determination in the Soil/Envelope System

Envelope type: Sand and Gravel
Pipe I.D.: 10.16 cm

Flow Rate Q (ml/min) (1)	Water Temperature (°C) (2)	Total Head Loss, Δh (cm) (3)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability (cm/min)		K_{env}/K_s Ratio (14)	Head Loss Across Envelope (cm) (15)	$*R^2$ (16)
			r_d 5.08 (4)	r_{e1} 7.00 (5)	r_{e2} 10.73 (6)	r_{e3} 14.58 (7)	r_{e4} 17.32 (8)	r_{e5} 21.10 (9)	r_{e6} 24.88 (10)	r_s 29.00 (11)	K_{env} (12)	K_s (13)			
10.0	20.0	2.02	0.00	0.31	0.42	0.52	0.61	0.67	1.65	2.02	0.4995	0.0659	7.5843	0.70	0.93
20.0	21.0	4.30	0.00	0.63	0.86	1.06	1.24	1.38	3.54	4.30	0.4925	0.0604	8.1573	1.48	0.93
30.0	21.0	6.30	0.00	0.88	1.23	1.50	1.69	1.93	5.18	6.30	0.5298	0.0604	8.7753	1.98	0.93
40.0	20.0	9.50	0.00	0.99	1.42	1.75	1.97	2.27	8.21	9.50	0.6081	0.0483	12.5906	2.30	0.94
30.0	20.0	7.00	0.00	0.79	1.06	1.32	1.48	1.70	6.15	7.00	0.6064	0.0495	12.2520	1.73	0.92
20.0	20.5	4.77	0.00	0.49	0.73	0.90	0.99	1.15	4.30	4.77	0.5977	0.0483	12.3754	1.17	0.94
10.0	20.0	1.50	0.00	0.27	0.30	0.38	0.40	0.46	1.33	1.50	0.7285	0.0852	8.5467	0.48	0.83

Note:
Envelope thickness = 14.60 cm
Soil thickness = 8.50 cm
$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 11.80 cm
Envelope radius = 20.50 cm

Appendix V.--Optimum Granular Envelope Thickness, OGET

Cost of subsurface drain installations where drain envelopes are used include usually no less than 15 percent of the total cost which goes to the procurement, haulage and placement of the sand and gravel material. Generally, large volumes of the material are involved and at very high costs. The material is becoming scarce and its price is inevitably on the increase. Conservation measures which will moderate volumetric requirement without undermining the engineering requirement of the installation will result in some cost savings.

For this reason, a chart is devised in Fig. 14 to provide a means by which an optimum envelope thickness can be estimated. The chart is not meant to replace valid judgment and experience, but rather to supplement them in such an exercise. The use of the chart is illustrated with an example.

Example: Suppose a sand and gravel envelope is required around a 10.16 cm (4.0 in) I.D. plastic corrugated drain pipe. The proposed sand and gravel envelope material had been found to have satisfied the requirement of grain size analysis for the base material. Assuming a permeability ratio for the envelope to soil, K_{env}/K_s of 6.0. Determine optimum envelope thickness which will ensure no more than a permissible pressure head loss of 1.5 cm across the envelope.

Solution:

Locate from Fig. 14 the $K_{env}/K_s = 6.0$ curve.

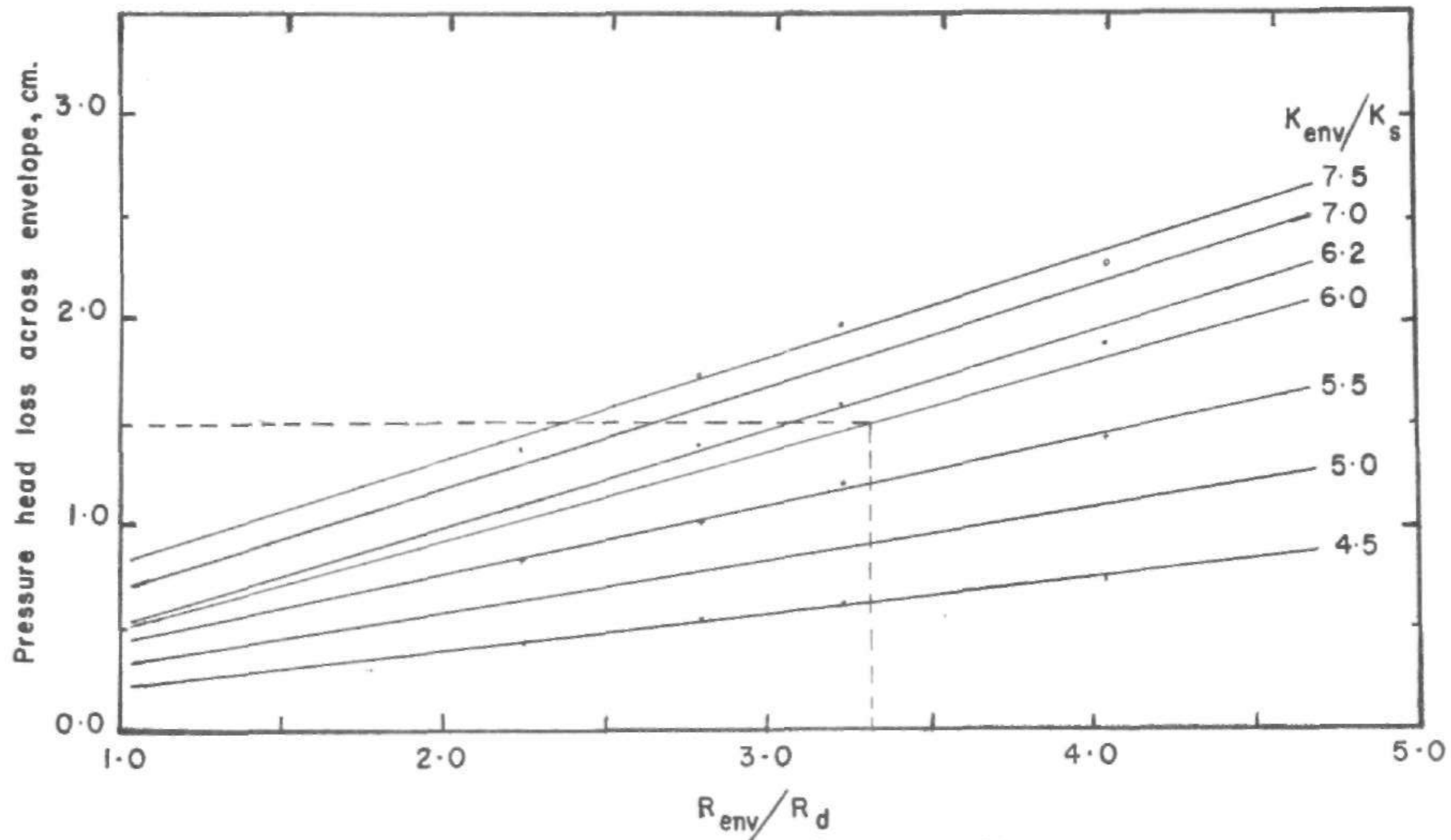

FIG. 14.--Influence of Granular Envelope Thickness on Pressure Head Loss.

From vertical axis at 1.5 follow dotted line to the point where it strikes the $K_{env}/K_s = 6.0$ curve.

Then follow dotted line vertically down.

Read on the horizontal axis $R_{env}/R_d = 3.31$

Estimate $R_{env} = 3.31\ R_d$ (where R_d is the inside radius of the pipe = 5.08 cm), i.e., $R_{env} = 3.31 \times 5.08 = 16.81$ cm

But also R_{env} = drain outside radius plus envelope thickness . . . envelope thickness = R_{env} - drain outside radius = 16.81 - 5.90 = 10.91 cm.

Use 11 cm (about 4.5 inches).

In practice one may find that perhaps the K_{env}/K_s is much higher than the value given in this example and so the optimum thickness may still be even thinner than 11.0 cm. The approach to the estimation is exactly the same.

TABLE 16A.--Pressure Head Determination in the Soil/Envelope System, Interface Head Loss Verification

Envelope type: Sand and Gravel
Pipe I.D.: 10.16 cm

Flow Rate Q (ml/min) (1)	Water Temper-ature (°C) (2)	Total Head Loss, Δh (cm) (3)	Pressure Head at Various Radial Distances From the Drain Center (cm)								Permeability (cm/min)		K_{env}/K_s Ratio (14)	Head Loss Across Envelope (cm) (15)	*R^2 E/S (16)
			r_d 5.08 (4)	r_{e1} 7.03 (5)	r_{e2} 10.75 (6)	r_{e3} 14.62 (7)	r_{e4} 17.20 (8)	r_{e5} 21.05 (9)	r_{e6} 24.85 (10)	r_s 26.20 (11)	K_{env} (12)	K_s (13)			
10.0	22.0	2.00	0.00	0.22	0.37	0.45	1.45	1.75	1.95	2.00			7.3295	0.53/1.42	0.96/1.00
20.0	22.5	3.95	0.00	0.42	0.68	0.88	2.72	3.53	3.73	3.95			7.5910	1.02/2.72	0.97/0.95
30.0	22.5	5.95	0.00	0.53	0.93	1.20	4.23	5.18	5.90	5.95			8.6693	1·39/4.15	0.98/0.99
40.0	22.0	8.75	0.00	0.55	1.00	1.32	6.08	7.73	8.70	8.75			12.5697	1.52/6.01	0.99/0.98
67.3	21.5	13.80	0.00	0.55	0.98	1.27	8.97	12.48	13.77	13.80			22.1655	1.47/9.04	0.98/0.94
100.0	21.0	19.65	0.00	0.80	1.47	1.97	13.70	17.87	19.52	19.65			20.3340	2.26/13.73	0.99/0.95
40.0	21.0	11.10	0.00	0.47	0.80	1.03	6.82	9.58	11.07	11.10			21.8015	1.20/6.75	0.97/0.97
30.0	21.0	7.30	0.00	0.33	0.57	0.78	4.83	6.37	7.28	7.30			19.0327	0.89/4.77	0.98/0.97
20.0	20.5	6.10	0.00	0.28	0.48	0.67	3.90	5.37	6.08	6.10			18.5678	0.76/3.88	0.99/0.96
10.0	20.5	2.80	0.00	0.13	0.21	0.30	1.70	2.43	2.80	2.80			19.1200	0.34/1.69	0.98/0.96

Note:
Envelope thickness = 10.80 cm
Soil thickness = 9.50 cm
*R^2 obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 11.80 cm
Envelope radius = 16.70 cm

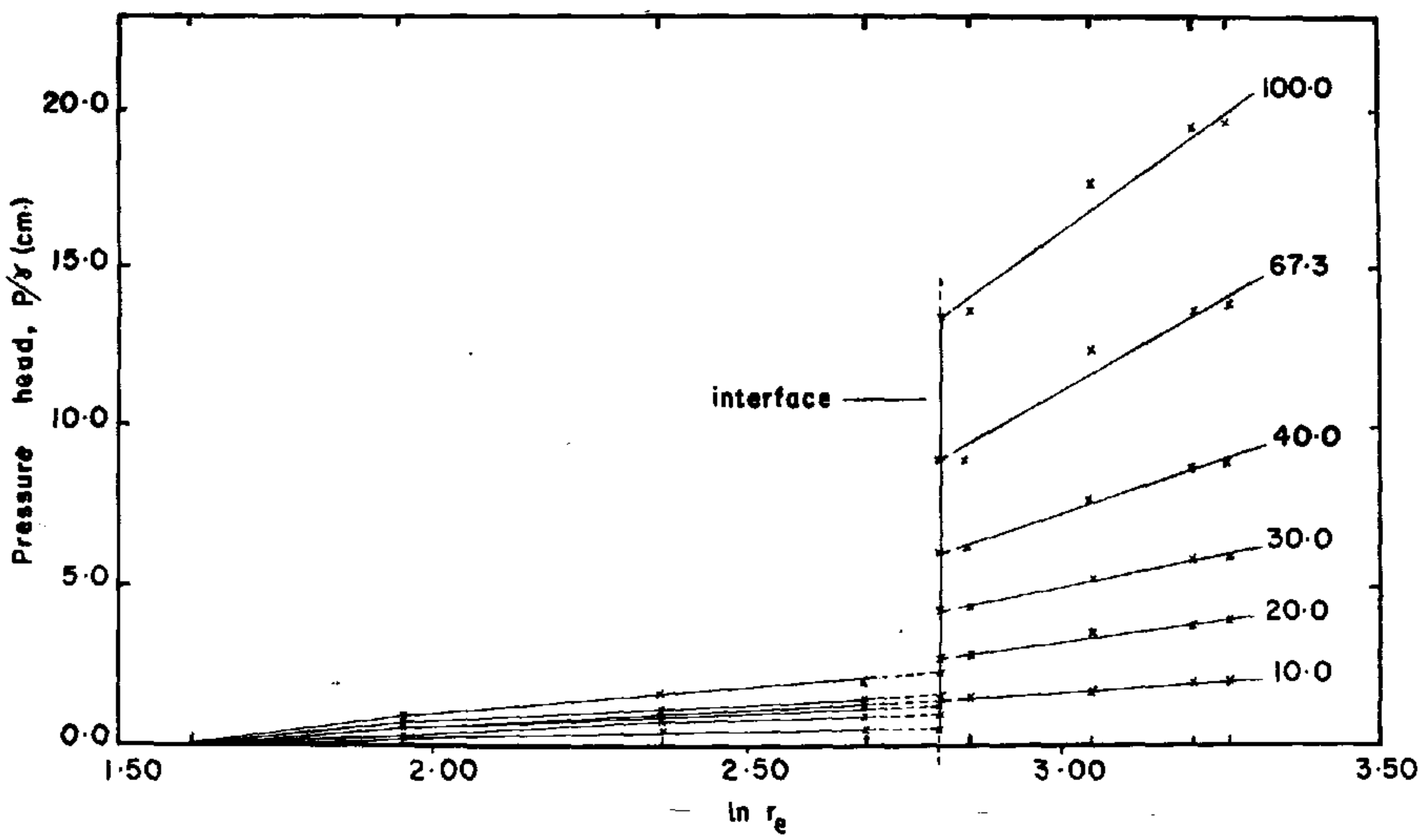

FIG. 15.--Pressure Head Plots for the Determination of Head Loss at the Soil/Envelope Interface

Appendix VI.--Pressure Head Loss at Interface

At the start of the research, it was anticipated that head loss in the system occurred only in the envelope and soil. However, it was later found that some head loss also occurred in the soil/envelope interface. To confirm this, and determine its relative magnitude, two additional tests were conducted.

In one of the tests titled "interface head loss verification," one piezometer was located at about 0.50 cm above the interface. Soil and envelope thicknesses of 9.50 cm and 10.80 cm respectively were used. Test results are given in Table 16A. The results are also plotted in Fig. 15. For a particular flow rate, the estimated head loss at the interface was found from the arithmetic difference between values shown in the column under head loss across envelope in Table 16A. Pressure head loss at the interface appears to increase with increase in flow rate. The semi-log plot of pressure head, P/γ, versus radial distance, r_e in Fig. 15 shows the line at the interface as a straight line. This is misleading because it infers that the hydraulic gradient at the interface is infinite. The line is so shown because at this stage the precise nature of drawdown in the vicinity of the interface is unknown.

In the second test which was also aimed at quantifying pressure head loss at interface, a 5.0 cm layer of granular envelope was sandwiched in between soil 7.50 cm thick below and above it. Typar envelope was placed between the drain pipe and the lower soil layer. Piezometric heads measured at various radial distances are given in Table 16B.

TABLE 16B.--Pressure Head Determination in the Soil/Envelope System, Gravel Envelope Sandwich Test

Envelope type: Typar and Gravel Sandwiched
Pipe I.D.: 10.16 cm

Flow Rate Q (ml/min) (1)	Water Temperature (°C) (2)	Total Head Loss, Δh (cm) (3)	Pressure Head at Various Radial Distances From the Drain Center (cm) r_d 5.08 (4)	r_{e1} 6.94 (5)	r_{e2} 10.74 (6)	r_{e3} 14.60 (7)	r_{e4} 17.21 (8)	r_{e5} 21.04 (9)	r_{e6} 24.84 (10)	r_s 25.94 (11)	Permeability K_{env} (cm/min) (12)	K_s (13)	K_{env}/K_s Ratio (14)	Head Loss Across Envelope (cm) (15)	$*R^2$ (16)
10.0	21.0	7.75	0.00	1.20	5.00	7.63	7.66	7.72	7.75	7.75					
20.0	20.5	14.70	0.00	2.28	10.07	14.55	15.48	14.65	14.70	14.70					
30.0	21.0	22.50	0.00	6.07	17.55	22.30	22.35	22.42	22.50	22.50					
40.0	21.0	30.53	0.00	11.53	25.28	30.32	30.37	30.45	30.51	30.53					
30.0	21.0	20.85	0.00	7.93	17.43	20.66	20.73	20.80	20.84	20.85					
20.0	21.0	14.50	0.00	5.18	12.12	14.40	14.43	14.48	14.50	14.50					
10.0	21.0	6.95	0.00	1.95	5.77	6.88	6.93	6.93	6.95	6.95					

Note: Envelope thickness = 0.036 cm Typar
5.00 cm gravel
Soil thickness = 7.50 cm, top and bottom

$*R^2$ obtained from statistically best fit natural log curve relating radial distances, re and pressure heads
Pipe OD = 11.80 cm
Envelope radius = 13.44 cm and 18.44 cm