A LABORATORY STUDY OF THE RETENTION AND FILTRATION CHARACTERISTICS OF GEOTEXTILE WRAPPED DRAINAGE PIPES

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ABSTRACT

A laboratory test has been developed for the evaluation of the mechanisms governing soil/geotextile drainage systems. The test is orientated toward applications that involve radial flow toward geotextile-wrapped drainage pipes. The influence of any given soil, geotextile or drainage pipe combination can thus be studied. A description of the test apparatus and procedures is given. The results of a test program show that filtration behaviour is dependent on soil compaction conditions and the onset of a soil filter at the soil/geotextile interface. A comparison of various grades of a non-woven geotextile showed only marginal variations in their performance. The impact of various drainage pipes were assessed and found to have minimal effect on the filtration system as a whole. The results are compared with data obtained from tests on geotextile discs located in a modified permeameter and good agreement was obtained. The validity of various retention and filtration design criteria was checked against test results and good agreement was observed.

INTRODUCTION

1. The last two decades have witnessed a dramatic increase in the use of geotextiles in geotechnical engineering. This increase has occurred because geotextiles have shown great versatility in performing several functions associated with separation, reinforcement and drainage.

2. Early uses of geotextiles were essentially temporary in nature, in that they were used only as construction expedients on low risk structures such as temporary roads over soft ground. Hence, no material specifications or design procedures were used. Recently, the employment of geotextiles in permanent works has increased, requiring satisfactory performance over the long term.

3. One of the major areas where geotextiles have found extensive use is as filters in permanent subsurface drainage. For this application geotextiles in conjunction with single size aggregates can be used as a replacement for graded granular filters because of their comparable performance, improved economy, consistent properties and ease of placement.

4. When used as a filter, a geotextile is placed adjacent to a soil and water is allowed to flow from the soil through the geotextile, and a complex interaction occurs between the soil particles and the pores in the geotextile. It is this interaction which is poorly understood, yet considered to underpin the performance of a soil/geotextile filtration system, particularly over the long term.

5. The modelling of this interaction in the complex environment of a geotextile wrapped drainage pipe forms the basis of the experimental investigations reported in this paper.

6. The objectives of the experimental work may be stated as follows:

(a) To design and construct and laboratory test device and procedure to model the filtration properties of a geotextile.
wrapped drainage pipe in a soil, with a view to development of a standard test.

(b) To isolate and gain a greater understanding of the mechanisms governing the filtration response of a soil/geotextile drainage system and determine what parameters best facilitate this.

(c) To compare the relative performance of various geotextile grades to determine the critical geotextile properties that influence performance.

(d) To assess the impact of various types of drainage pipe on the performance of the filtration system.

(e) To determine if an equilibrium flow condition exists for the adopted soil/geotextile system.

(f) To evaluate current design criteria.

7. A testing device and procedure has been developed that facilitates the simulation of a soil/geotextile and drainage pipe filtration system. The device is currently restricted to testing one-directional flow applications with constant heads.

APPLICATIONS

8. For geotextiles used in subsurface drainage a broad range of applications exist that are directly concerned with geotextile wrapped drainage pipes, including:

(a) Land drainage, such as reclamation schemes.

(b) Agricultural drainage, where drainage pipes are usually enveloped in synthetic or natural materials, particularly in arid areas where traditional filter materials such as gravels and sands are difficult to find and expensive to transport and construct;

(c) Drainage of areas associated with roadworks, where subsoil drains are typically located around the pavement formation edge to lower water table levels under the pavement.

MECHANISMS GOVERNING THE FILTRATION PROPERTIES OF A SOIL/GEOTEXTILE SYSTEM

9. Failure of the soil/geotextile system will depend on the reduction in permeability that can be tolerated. Reduction in the permeability of a soil/geotextile system with time usually occurs and may be due to one or more of the following factors:

(a) Through deposition of particles within the geotextile (clogging) by flowing water carrying suspended material.

(b) Through plugging (blinding) the openings in the geotextile.

(c) Through air coming out of solution of the test water and being trapped in the soil mass, reducing the permeability of the soil.

(d) Through compaction of the soil during the test period, decreasing the hydraulic conductivity of the soil.

(e) Biological growth which blocks the geotextile pores.

(f) Compression of the geotextile, reducing the porosity and hence pore size and permeability of the geotextile.

(g) Formation of a soil filter system in the soil layer immediately adjacent to the geotextile.

10. In order to accurately assess the performance of a soil/geotextile system the influence of each of the above factors needs to be evaluated.

11. Previous investigations into the determination of which factors govern the decrease in permeability of a soil/geotextile system have often revealed that factors (a) to (f) above are not the primary factors, or at least are not fully accountable (Broughton et al. 1977). This has led to the proposed formation of a soil filter mechanism in the soil layer immediately adjacent to the geotextile, as described in (g) above.

12. The conditions leading to the formation of a soil filter mechanism are not fully understood, as current theories on the nature of the soil filter structure are not in full agreement. The following represents a simplified description of the current understanding of the soil filter structure development in a soil layer behind a geotextile.

13. During the initial flow period immediately following placement of the geotextile at the soil interface, soil particles in the layer immediately adjacent to the geotextile migrate into and through the geotextile under the influence of the soil water flow. The maximum size of such particles able to be carried into and through the geotextile has traditionally been considered critical in the determination of design criteria. Some sources (Hoare 1982; Christopher 1983) indicate that soil particles finer than the pore sizes of the geotextile can resist flow into the geotextile by orientating themselves to form a bridging network over the pores, and thus initiate a soil filter. It has been suggested (Giroud 1978) that cohesive forces between soil particles allow this to occur, although this phenomenon has been explained to occur for non cohesive soils. Alternatively, electrochemical forces between soil particles and geotextile fibres due to the chemical nature of the fibres have been considered significant (Kellner, Bally and Matei 1982). Other sources (Rosen and Marks 1975; McGown 1976; Broughton et al. 1977), are not clear on whether this phenomena usually occurs, or whether larger soil particles are necessary to partially block pores in the
geotextile surface and hence initiate a soil filter in the soil.

14. The formation of a soil filter is continued by further migration of fine material creating an internally graded filter system or soil bridge structure.

15. In this light, the geotextile only serves as a catalyst in the formation of a filter mechanism and is not acting as a filter itself.

16. It is considered that the soil bridging structure is more permeable than the insitu or undisturbed soil material. Hence, its presence does not explain a decrease of permeability of the soil geotextile filter system over time.

17. The decrease in permeability over time is explained in terms of a “filter cake formation” occurring as a separate layer between the soil bridge structure and the undisturbed soil.

18. The filter cake represents a layer of fine material created by continued migration of fines toward the soil bridge structure (but unable to flow through) until equilibrium conditions exist. The filter cake represents a layer of lower permeability than the undisturbed soil mass.

19. Other sources (Lawson 1982; Wei et al. 1985) do not isolate the filter cake as a separate layer and imply the nature of the soil filter or soil bridging structure accounts for the decrease in permeability, although no satisfactory explanation is given.

20. Some researchers (Rosen and Marks 1975) have been able to substantiate the formation of an internal filter cake. Samples of the soil above geotextile were impregnated with an epoxy resin to facilitate microscopic or pedographic analysis. Others (Koerner and Ko 1982) after numerous attempts (using grouts, image analysers, etc.) have failed to detect the soil filter mechanism.

21. The mechanism of a self induced filter forming in the soil due to the presence of the geotextiles represents a filter action which has previously been established in the period 1930 to 1960 in the chemical engineering and chemistry fields. However, as indicated above, the nature of this mechanism is not fully understood in soil/geotextile systems. This mechanism may not be unique but dependent on soil, geotextile (constituent fibre and construction) and flow conditions.

TEST METHODS, A REVIEW

22. For geotextiles to perform satisfactorily in the filtration application they must meet several criteria;

(a) Sufficiently permeable to allow removal of groundwater without excessive buildup of pore water pressures;

(b) The geotextile must be able to prevent piping of the soil mass being drained;

(c) Maintain its characteristics for the life of the installation, implying durability in terms of biological and chemical stability.

(d) Able to withstand handling and installation stresses.

23. Criteria (c) and (d) are not considered further in this paper. In order to ensure criteria (a) and (b) are met it is necessary to investigate relevant properties of geotextiles. These properties include;

(a) Initial permeability;

(b) Resistance to clogging and blinding;

(c) Resistance to piping;

24. The evaluation of geotextile properties by laboratory test means can be categorised into two main groups;

(a) Geotextile pore characterisation methods;

(b) Filtration and direct permeability tests.

25. Geotextile pore characterisation methods are normally adopted as a means of indirectly determining geotextile permeability and/or piping resistance. Two basic methods exist;

(a) Sieving; wet or dry, sand or glass beads;

(b) Image analyser, morphological analysis.

26. Sieving techniques are employed to determine the pore opening size distribution of the geotextile. Usually a representative pore opening size such as the 90% or 95% largest, is evaluated and called the Equivalent Opening Size (E.O.S.) of the geotextile. The sieving test were originally developed for woven geotextiles and some doubt exists to their applicability for non-woven geotextiles. Many sieving test procedures exist (Hoare 1982; Faure et al. 1986) and evidence indicates that test results are highly dependent on critical elements of the individual test procedure, such as sieving time (Ogink 1975). The advantage of typical E.O.S. tests are that they are fast and easy to perform.

27. Image analyser techniques offer a more direct approach to the determination of geotextile pore size characteristics. Microscopic pictures of the geotextile are taken to assess average fibre diameters and relative fibre distribution over an area. This technique may give a more accurate representation of the geotextile morphology, but the high level of sophistication which requires expensive equipment may not be warranted.

28. Using either the sieving or image analyser techniques, the distribution of pore sizes in the geotextile may then be related to soil particles grading curves to assess the relevant properties of geotextiles outlined above. However, the pore size distribution obtained in such a laboratory determination does not give a unique measure of the geotextile’s particle
retention properties in the field. Other factors influence this including:

(a) Soil particle size distribution;
(b) Soil particle shape;
(c) Hydraulic gradient;
(d) Flow conditions, laminar or turbulent;
(e) Confining stresses

29. Pore characterization methods belong to a category of tests called "index tests". Such tests may typically include assessment of geotextile porosity, thickness, density, etc. Index tests provide a basis of comparing various geotextiles and can be used as a quality control indicator. However, results from index tests may not be particularly useful for design.

30. Geotextile permeability tests, often referred to as "in-isolation" tests are widely reported in the literature (Lawson 1982; Ogink 1975; Blair, Bell and Hicks 1981). These test generally relate the inplane permeability (transmissivity) or normal permeability of the geotextile to functions of the hydraulic gradient, thicknesses, etc. Permeability is essentially determined for drainage applications, but they also give an indication of the initial permeability of geotextiles in soil/geotextile filtration applications. Such tests actually belong to the "index" group of tests described above.

31. Soil/geotextile filtration tests are now becoming more commonly reported. Various reviews of soil/geotextile test procedures can be found in the literature (McGown and Andrawes 1982). These reviews highlight a complete lack of uniformity in test procedures.

32. Test methods reported in the literature for the evaluation of the filtration properties of a soil/geotextile system, are typically represented by the Permeameter shown in figure 1. The permeameter models two dimensional flow conditions and appears to be adequate in representing many of the applications outlined above.

33. For applications involving geotextile wrapped drainage pipes, a permeameter as shown in figure 1 is not representative of the more complicated flow and boundary conditions.

34. A review of test procedures for geotextile wrapped drainage pipe applications, revealed few existed that were orientated toward the evaluation of the filtration properties of geotextiles with naturally occurring soils. Most procedures were a product of research in the agricultural land drainage field using apparatus called "sand tanks", and not the civil engineering field. The procedures were designed for the acquisition of information on drain envelope materials in the shortest possible time (Knops 1978). Typically, such drainage materials would be natural or synthetic and used to envelope agricultural drainage pipes to minimise flow resistance into the drain. The assessment of entrance resistance into the drain yields comparative performance information for a given envelope/pipe combination that can be used to determine effects on water table levels.

35. The test procedures reviewed (Zuidema and Scholten 1978; Knops 1978; Sekandar 1984), consisted of relatively short test periods (1 to 5 days) and used sands with little fines content as the soil medium. Consequently, high flow rates with little delay for equilibrium conditions, allowed fast and accurate discharge and head loss measurements. However, the use of sand negates any potential soil/envelope interaction as might occur with naturally occurring soils of lower permeability. The development of a soil/envelope interaction would lead to a unsteady relationship of entrance resistance with time. All of the test results reviewed gave flow resistance of an envelope pipe combination as a static value independent of the test period and the soil environment.

**EXPERIMENTAL APPARATUS AND PROCEDURE**

36. The test apparatus was developed as a pressure controlled cell with a vertical pipe arrangement, as shown in figure 2, called the "radial permeameter".

37. The radial permeameter consists of a 300 mm diameter cylindrical perspex casing with steel end plates. A drainage pipe is located centrally between the end plates in a vertical position. Three types of pipe were used. Two rigid plastic drainage pipes of
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the bottom plate with the top plate removed a cylindrical steel sleeve separates the soil and the gravel. The gravel was placed around the soil mass on the outside of the steel sleeve. The water level in the cell was raised as soil and gravel was placed and lightly tamped to remove air. Once the level of the soil reached the top of the casing the sleeve was removed and the top plate was positioned and clamped into place. Flow was then initiated by opening 3 supply valves on the side of the perspex casing and opening the drain outlet in the bottom plate. The water supply used was tap water delivered at a constant head.

39. Flanges on the top and bottom end plates penetrate the soil to counteract the development any preferential flow paths along the boundary.

40. As the water passes through the geotextile and drainage pipe it is drained through the bottom plate where flow rate is recorded and any fines passing collected. Head loss was recorded on the boundary of the soil mass on the top and bottom plates at various positions. An additional manometer in the bottom plate penetrated 75 mm into the soil mass to assess the effectiveness of the horizontal flow condition.

41. The pressure inside the drainage pipe was maintained at atmospheric by means of an air hole in the center of the top plate.

42. The change in head through the 100 mm thick soil annulus in the radial permeameter was 0.5 m. This value represented a compromise between minimising the hydraulic gradient to be more representative of field conditions and the need to generate sufficient head conditions in the radial permeameter for the test soil to remain fully saturated. Measurements of flow rate and headloss were recorded at regular intervals in time. Figure 4 shows the radial Permeameter during a filtration test.

Fig. 2 - Radial permeameter (clevational view)

90 mm diameter, one with 2 rows of longitudinal slots (9000 mm²/m) and the other with 4 rows of slots (4730 mm²/m). The third pipe was a flexible corrugated drainage pipe of 100 mm diameter (2200 mm²/m). Geotextile samples were cut and professionally sewn to form a sock which was placed over the drainage pipe.

38. The geotextiles used were of a non-woven polypropylene construction. Three grades were tested ranging in thickness from 1.5 mm for the U14, 2.3 mm for the U34 and 4.4 mm for the U64 grade. The test soil was a naturally occurring silty sand with grading curve shown in figure 3.

Placement of soil, gravel and water in the cell was achieved under no flow conditions by first blocking the drainage outlet in the middle of.

37. Flanges on the top and bottom end plates penetrate the soil to counteract the development any preferential flow paths along the boundary.

40. As the water passes through the geotextile and drainage pipe it is drained through the bottom plate where flow rate is recorded and any fines passing collected. Head loss was recorded on the boundary of the soil mass on the top and bottom plates at various positions. An additional manometer in the bottom plate penetrated 75 mm into the soil mass to assess the effectiveness of the horizontal flow condition.

41. The pressure inside the drainage pipe was maintained at atmospheric by means of an air hole in the center of the top plate.

42. The change in head through the 100 mm thick soil annulus in the radial permeameter was 0.5 m. This value represented a compromise between minimising the hydraulic gradient to be more representative of field conditions and the need to generate sufficient head conditions in the radial permeameter for the test soil to remain fully saturated. Measurements of flow rate and headloss were recorded at regular intervals in time. Figure 4 shows the radial Permeameter during a filtration test.

Fig. 3 - Grading curve for test soil (USCS=SP)
EXPERIMENTAL RESULTS

43. Two distinct test series were carried out with the radial permeameter. The first test series consisting of 10 tests (numbered from 1 to 10 in this paper) was performed by the Author after development of the apparatus. Unfortunately the first four test and test 10 were unreliable and are not presented in this paper. The second test series (tests numbered 11 to 13) was performed by Prove (1987) and Siganto (1987) as part of the continuing investigation of the radial permeameter.

44. Discharge results have been plotted against time in figure 5 for the radial permeameter. All tests show a decrease in discharge with time. The results generally show a broken linear decrease with time with a change in slope occurring around the 100 hour mark. Test 7 shows only the initial linear decrease in discharge as this test was aborted prematurely.

45. The discharge versus time plot for testing the hydraulic conductivity of the test soil in the standard constant head permeameter is presented in figure 6. The result is clearly characteristic in shape to the discharge curves of figure 5. This suggests the change in slope of the curves could be independent of the soil/geotextile interface. Although it was not possible to directly correlate with the observed discharge behaviour, consolidation of the test soil in the standard permeameter was clearly evident for the duration of the test.

46. Calculation of overall permeability for the radial permeameter can be modelled in terms of steady confined flow towards a well and is a direct function of the system discharge as given below.

\[ K_r = \frac{q}{2\pi h \cdot \ln \left( \frac{r_1}{r_0} \right)} \text{ (m/s/m)} \] (1)

where \( q \) = the discharge per unit length of drainage pipe.
\( h \) = the head loss through the system
\( r_1 \) = the distance from the centre of the drainage pipe to the outer edge of the soil.
\( r_0 \) = the internal radius of the drainage pipe.
47. Figure 7 shows the system permeability results plotted on a ln \(x\) vs ln scale. The plots are typical in shape to those reported by (Rosen and Marks 1975).

48. To gain an appreciation of the change in resistance occurring at the soil/geotextile interface with respect to the changing resistance to flow in the soil, the 'Gradient Ratio' can be evaluated. Gradient Ratio has been defined as follows:

\[
\text{Gradient Ratio} = \frac{\text{Hydraulic gradient through the 25 mm of soil plus geotextile}}{\text{Hydraulic gradient through the adjacent 50 mm of soil}}
\]

(Haliburton and Wood 1982; Sekandar 1984).

49. However, for the radial permeameter calculation of the gradient ratio was modified as follows:

\[
GR^p = \frac{(h_1-h_0)/(\epsilon_3-\epsilon_0)}{(h_1-h_0)/(\epsilon_1-\epsilon_3)}
\]

(2)

where \(h_0\) = represents atmospheric conditions inside the pipe taken as zero head values at manometer port location \(\epsilon_1\).

\(h_1\) = head values at manometer port location \(\epsilon_3\).

\(\epsilon_1\) = Distance from centre of the pipe to manometer port location 1 (125 mm).

\(\epsilon_3\) = Distance from the centre of the pipe to manometer port location 3 (90 mm).

50. Gradient Ratio versus time plots for the radial permeameter test results are presented in figure 8. Because of the radial geometry of the permeameter the GR\(^p\) will always be greater than 1, therefore (in addition to the modified form of the equation) the GR\(^p\) parameter is not directly comparable with Gradient Ratio results of other researchers.

51. The soil to system permeability results for the radial permeameter are plotted against log time in figure 9. The plots clearly indicate a dependence of the system permeability on the soil permeability during the first 100 hours of testing in each case. After approximately 100 hours the system permeability (which includes the effects of the soil/geotextile interface) appears to reduce relative to the soil permeability.
52. The change in weight of geotextile specimens was measured after testing. The results are shown in table 1. The change in geotextile porosity due to soil particle retention was calculated from geotextile properties and the measured density of the test soil ($\rho_s = 2.61$). Figure 10 shows geotextile and drainage pipe samples used in the test program.

53. The initial linear decrease in discharge shown in figure 5 corresponds to a period of approximately constant $GR^2$ shown in figure 8. This suggests that the initial decrease in discharge of the test results cannot be attributed to an increase in resistance to flow in the vicinity of the soil/geotextile interface. Hence factors governing the decrease in discharge must be acting in the soil mass or over the entire system. Since a constant hydraulic head was applied over the filtration system, a decrease in the permeability of the soil mass was considered responsible. This is supported by figure 9 which shows a direct dependence of the system permeability on the soil permeability during the initial flow period.

54. Potential mechanisms considered responsible for the decrease in soil permeability are;

1. Consolidation
2. Air coming out of solution.

55. The change in air content of the soil water was not measured. However, consolidation of the soil was considered a significant factor as this was observed in the radial permeameter and confirmed by the standard permeameter results.

56. The time at which the change in the rate of discharge decrease occurs in figure 5 is considered to be a function of the test soil and its initial compaction conditions. The change in discharge slope roughly corresponds to a corresponding increase in $GR^2$, figure 8. This indicates that resistance to flow in the vicinity of the soil/geotextile interface is now becoming greater than that of the surrounding soil mass. The increase in $GR^2$ indicates that the consolidation phase (in addition to observation) is essentially complete and other factors are now controlling filtration behaviour. Since the second phase mechanisms are occurring in the vicinity of the soil/geotextile interface, the following mechanisms are possible as described earlier;

1. Clogging of the geotextile
2. Blinding of the geotextile
3. Soil filter development with a filter cake
4. Build up of biological matter on the geotextile fibres
5. Build up of mineral deposits on the geotextile fibres.

57. Biological or mineral effects were not considered contributory at any stage. Close visual inspection of the geotextiles after use confirmed this.

58. Blinding represents a build up of soil fines directly adjacent to the geotextile pores, causing a masking effect. This effect would be accompanied by a continued decrease in discharge which was not observed. In addition, blinding was not visually observed and would normally be expected to occur with a high degree of clogging.

59. Table I highlights the increase in weight of geotextiles due to particle retention (clogging). While significant increases in geotextile weights were measured, the actual degree of clogging was considered small. This corresponds to the small change in geotextile porosity due to clogging, table 1.

60. Additional evidence for the limited effects of clogging on the filtration behaviour is provided by noting the increase in weight of the geotextile for test 7. Test 7 was aborted as the change in porosity was considered small. Table I highlights the increase in weight of geotextiles due to particle retention (clogging). While significant increases in geotextile weights were measured, the actual degree of clogging was considered small. This corresponds to the small change in geotextile porosity due to clogging, table 1.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Geotextile Grade</th>
<th>Drainage Pipe No.</th>
<th>Weight of Soil Retained (g)</th>
<th>Increase in Weight of Geotextile</th>
<th>Change in Geotextile Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>U14</td>
<td>1</td>
<td>15.9</td>
<td>79%</td>
<td>0.1%</td>
</tr>
<tr>
<td>2</td>
<td>U34</td>
<td>1</td>
<td>15.4</td>
<td>43%</td>
<td>0.1%</td>
</tr>
<tr>
<td>3</td>
<td>U64</td>
<td>1</td>
<td>37.9</td>
<td>56%</td>
<td>0.1%</td>
</tr>
<tr>
<td>4</td>
<td>U64</td>
<td>1</td>
<td>37.9</td>
<td>56%</td>
<td>0.1%</td>
</tr>
<tr>
<td>5</td>
<td>U34</td>
<td>2</td>
<td>14.2</td>
<td>40%</td>
<td>0.1%</td>
</tr>
<tr>
<td>6</td>
<td>U14</td>
<td>1</td>
<td>6.0</td>
<td>30%</td>
<td>0.1%</td>
</tr>
<tr>
<td>7</td>
<td>U14</td>
<td>3</td>
<td>14.8</td>
<td>71%</td>
<td>0.1%</td>
</tr>
<tr>
<td>8</td>
<td>U14</td>
<td>3</td>
<td>11.4</td>
<td>55%</td>
<td>0.1%</td>
</tr>
<tr>
<td>9</td>
<td>U34</td>
<td>3</td>
<td>12.4</td>
<td>32%</td>
<td>0.1%</td>
</tr>
<tr>
<td>10</td>
<td>U64</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

AVERAGE = 50%
before the initial discharge phase was complete and before any increase in \( GR^2 \) was detected. However, a comparable degree of particle retention was clearly evident. This suggests much of the retention occurs in the initial soil compaction phase and has little bearing on the onset of mechanisms controlling the second discharge phase.

61. Hence, blinding and clogging are not considered significant mechanisms governing the second phase of the discharge curves shown in figure 5.

62. The formation of a reverse soil filter with a filter cake is the proposed mechanism governing the second phase discharge decrease with time. The precise structure of the soil filter above the geotextile was not measured. Hence, the points of conflict examined earlier relating to the bridging of geotextile pores are unable to be answered.

63. The continual decrease in discharge for the second phase supports the theory of a filter cake formation, consisting of fine material, adjacent to the soil filter. Such a layer would have a lower permeability than the surrounding soil mass, which is supported by a corresponding increase in \( GR^2 \). This mechanism would not be associated with continued clogging of the geotextile which is supported by the results for test 7.

64. A third flow phase representing equilibrium conditions appears to have been detected by tests 8 and 13. Equilibrium conditions are characterised by a constant discharge with time, figure 5. Equilibrium conditions should also be characterised by a constant \( GR^2 \) with time although this was not observed. A constant \( GR^2 \) represents a constant flow resistance at the soil/geotextile interface producing a constant discharge assuming consolidation of the test soil and other factors are no longer changing. The calculation of \( GR^2 \) was considered unreliable after the initial flow phase, although the change in \( GR^2 \) associated with the change from 1st to 2nd flow phase appears to be observed in most cases. The reliability of the measurement of \( GR^2 \) is affected by the measurement of hydraulic head in the soil at the Boundary of the soil mass on the bottom plate, also the relatively crude manometer gauges were prone to clogging.

65. The onset of equilibrium conditions may not necessarily occur, as this depends on the limited formation of the filter cake. Some soils may be considered inherently unstable and indefinite movement of fines toward the filter cake will continue formation of the filter cake.

**INFLUENCE OF GEOTEXTILE THICKNESS**

66. The performance of the various geotextile grades tested can be made by comparing the system permeability results for any given pipe type. Because most tests were performed with the corrugated drainage pipe, seven results are presented in Figure 11.

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**Fig. 11 - The comparative performance of geotextile grades using the corrugated drainage pipe**

67. The plots in figure 11 lie within the bounds of an order of magnitude. Thus, interpretation is difficult due to the usual magnitude of experimental variation expected when testing with soils.

68. Figure 9 demonstrated the dependence of system permeability on the soil permeability during the initial test period, therefore filtration performance of geotextile in figure 11 should be considered in terms of the relative decrease in permeability over the full test period. Table II reveals that the thicker the geotextile, the smaller the decrease in overall system permeability. The comparison of results in table II needs further verification to support a dependence of filtration behaviour on geotextile thickness. Thickness is the basic factor differentiating the geotextile grades tested, although marginal variations in pore size characteristics also exist. Should a dependence of filtration behaviour on geotextile thickness be established, then this would conflict with earlier findings which suggests filtration behaviour is primarily governed by the nature of the soil geotextile interface.

69. The maximum particle size retention characteristics of the geotextiles tested was not assessed. Insufficient material (consisting of fines) was filtered by the radial Permeameter in order to gain a sample size suitable for conventional grading tests.

**INFLUENCE OF TYPE OF DRAINAGE PIPE**

70. The comparison of the performance of the various drainage pipes was limited and inconclusive, although early evidence suggests that the impact of the various drainage pipe is minimal. This is consistent with earlier results indicating the dependence of filtration behaviour on the nature of the soil/geotextile interface over the long term.
TABLE II

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>GEOTEXTILE GRADE</th>
<th>DURATION OF TEST (HOURS)</th>
<th>RELATIVE DECREASE IN SYSTEM PERMEABILITY OVER TEST PERIOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>U34</td>
<td>192</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>U14</td>
<td>275</td>
<td>2.9</td>
</tr>
<tr>
<td>7</td>
<td>U14</td>
<td>141</td>
<td>2.7</td>
</tr>
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<td>8</td>
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</tr>
<tr>
<td>9</td>
<td>U34</td>
<td>318</td>
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<td>11</td>
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<td>12</td>
<td>U64</td>
<td>257</td>
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<td>13</td>
<td>U14</td>
<td>508</td>
<td>2.5</td>
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COMPARISON OF RESULTS WITH MODIFIED PERMEAMETER

71. Experimental results obtained with the radial permeameter were compared with those of a modified permeameter. The modified permeameter was adapted from a standard soil permeameter to measure the permeability of a soil/geotextile system, figure 12.

Figure 12 shows a geotextile disc clasped between the two parts of the permeameter with soil placed on top and a gravel support placed below. A constant head supply is fed to the top of the soil and filtered through the system to atmospheric conditions on the downstream side of the geotextile disc. A pressure head reading was taken above the geotextile on the soil boundary. As with the radial permeameter tests, discharge and head loss readings were taken over the test period.

72. Discharge results for the modified permeameter have been plotted against log time in figure 13. The results are not as consistent in depicting the characteristic broken linear decrease in discharge observed with the cell apparatus results. Only the result for test 3 closely resembles this trend.

73. System permeability results for the modified permeameter can be calculated as shown below:

\[
P_{\text{sys}} = \frac{q}{A \cdot h} \quad (\text{m/s})\]

where \( q \) = the direct discharge \((\text{m}^3/\text{s})\),
\( l \) = the height of the soil sample plus the geotextile \((\text{m})\),
\( A \) = the area of the soil sample perpendicular to the flow direction \((\text{m}^2)\),
\( h \) = the head loss through the system \((\text{m})\).

74. Figure 14 shows the results for System permeability vs time. These curves do not as...
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consistently show the same characteristic flattening off of permeability with time observed with the radial permeameter. This may be due to differing flow and boundary conditions. These results give a more pessimistic view of the performance of the soil/geotextile systems tested.

75. For the modified permeameter, Gradient Ratio may be calculated as shown below

\[ GR_{MP} = \frac{(h_1 - h_0)/1_1}{(h_2 - h_1)/(l_2 - l_1)} \]  

where \( h_0 \) = atmospheric pressure immediately downstream of the geotextile,

\( h_1 \) = the head value in the soil at a distance \( l_1 \) from the base of the geotextile;

\( h_2 \) = is the applied head value at the top of the soil sample a distance \( l_2 \) from the base of the geotextile.

76. Available GR_{MP} versus time plots for the modified permeameter test results are presented in figure 15. Although not directly comparable in magnitude, these results show a similar trend to those of figure 8.

77. For the modified permeameter because only one head value was recorded in the soil, it was impossible to get independent soil and system permeability results to compare with figure 9.

78. Soil particle retention results for geotextile samples tested in the modified permeameter are shown in table III. The results show similar retention trends to those of the radial permeameter.

79. A comparison of Tables II and IV also shows similar results between the two permeameters.

80. On the whole, the modified permeameter test results show a general correspondence to the radial permeameter test results, although the modified permeameter results do not as clearly depict the action of the governing mechanisms. Discounting the impact of the drainage pipe any differences in results can be attributed to either:

1. Size or scale effects, particularly with regard to the soil mass.
2. Differing boundary conditions and flow conditions.

81. In terms of comparing set-up procedures, the radial permeameter requires more time, expertise and effort than the modified permeameter. As a result the radial permeameter in its present form does not lend itself to widespread adoption as a standard test.

EVALUATION OF DESIGN CRITERIA

82. The known index properties of the geotextiles and the measured grading curve of the test soil (figure 3) can be used to test existing design criteria against observed experimental results.

83. Table V lists various design criteria extracted from the literature. The criteria listed in table V are applicable to loose
Table V

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Author (Year)</th>
<th>Rule</th>
<th>Pass or Fail</th>
<th>Criterion</th>
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<th>U34</th>
<th>U64</th>
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<td>Retention</td>
<td>Calhoon (1972)</td>
<td>0.95 &lt; D_{85}</td>
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<td>✔️</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Ogink (1975)</td>
<td>0.90 &lt; 1.8D_{90}</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rankilor (1978)</td>
<td>0.90 &lt; D_{85}</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rycroft &amp;</td>
<td>0.50 &lt; D_{85}</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hurry (1979)</td>
<td></td>
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<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Schober &amp;</td>
<td>0.50 &lt; (3 to 5)D_{90}</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td>Teindl (1980)</td>
<td></td>
<td>✔️</td>
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<td>✔️</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Heerten (1982)</td>
<td>0.90 &lt; 10D_{90}(2:5)</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
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</tr>
<tr>
<td></td>
<td>Giraud (1982)</td>
<td>0.90 &lt; 9D_{90}</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Permeability

| Marks (1975)   | K > 5K_{soil} | ✔️ | ✔️ | ✔️ |
| Rankilor (1978)| 0.90 > D_{15} | ✔️ | ✔️ | ✔️ |
| Heerten (1982) | avK_{soil} > K_{soil} | ✔️ | ✔️ | ✔️ |
| Giraud (1982)  | K > 0.1K_{soil} | ✔️ | ✔️ | ✔️ |

* For sands or silts and non-woven geotextiles in uni-directional flow applications.

84. For silty-sands, the retention criteria are usually more critical in design and a greater number of retention criteria are available.

85. The experimental results showed that the soil particle retention characteristics of all the geotextiles used was adequate. This was evidenced in three ways:

1. The passing of fines through the geotextiles was limited to the first half hour of the test period.
2. Inspection of the soil/geotextile interface after completion of each test revealed no forms of instability in terms of voids or piping, etc.
3. Equilibration of flow-rate.

86. The results of Table V shows little more than the fact that the prediction of both earlier and more recent retention criteria were consistent with the experimental results.

87. The importance of well designed and efficient drainage systems cannot be underestimated in civil engineering applications. The modelling of filtration systems represents one of the essential tasks in achieving this goal. Typically a filtration system demonstrates complex behaviour and the need to develop representative models is essential to discover and evaluate the governing mechanisms.

88. A test apparatus has been developed specifically for modelling the filtration performance of geotextile wrapped drainage pipes in soil.

89. An experimental investigation was consequently, although limited to testing three grades of a non-woven geotextile, using three different drainage pipes with a silty-sand. The following conclusions resulted:

1. For uncompacted or soil-slurry soils the initial filtration performance is governed by consolidation of these soils. Once consolidation is complete, filtration performance is governed by the nature of the soil/geotextile interface, through development of a reverse soil filter and filter cake.
2. Due to the random structure of the non-woven geotextiles tested, visual examination of the soil/geotextile interface was insufficient to determine the presence or precise structure of the reverse soil filter and filter cake.
3. Additional data is needed to establish a firm difference in the performance of various geotextile grades tested. Variations in performance appear to fall within the bounds of experimental error, although indications are that the thicker non woven grades performed better than the very thin non woven grade.
4. A lack of reliable test results restricted the assessment of the impact of various drainage pipes, although it appears the impact was minimal for the soil/geotextile combination tested.
5. The predictions of recent design criteria were found to be adequate for the soil/geotextile combination adopted.
6. The adequacy of the proposed radial permeameter was also evaluated. The performance of the radial permeameter in terms of modelling the assumed boundary conditions was considered adequate although further tests, including comparative tests using more conventional permeameters are required to provide confirmation.
REFERENCES


Neil Bentley obtained a Bachelor degree in Civil Engineering from the University of Queensland in 1982. Since graduation he has worked for the Queensland Main Roads Department gaining experience in the investigation and design of road and bridge structures and more recently in the testing and evaluation of highway pavements. He is currently completing a Master of Engineering Science (part-time) at the University of Queensland conducting research into the filtration properties of geotextiles.

Andy Fourie graduated from the University of the Witwatersrand, South Africa, with Bachelors and Masters degrees in Civil Engineering. After working as a geotechnical engineer for Steffen, Robertson and Kirsten Inc. on the design and construction of mine tailings disposal facilities, he moved to the United Kingdom where he obtained a Ph.D. in Soil Mechanics from Imperial College in 1984. He took up his current position as a lecturer in Civil Engineering at the University of Queensland.