

## Proposed Criteria for Discharge Capacity of Prefabricated Vertical Drains

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### ABSTRACT

*Modified triaxial tests and ASTM-based discharge capacity tests were carried out to obtain specifications of discharge capacity. The test results indicate that, at straight condition, ASTM-based discharge capacity decreases with increasing lateral pressure, time and hydraulic gradient. With lateral pressure application, the filter jacket of a prefabricated vertical drain (PVD) is pressed into the channel system of the core, thereby reducing the flow area. Furthermore, the discharge capacity decreases at a high hydraulic gradient due to loss of flow energy as a result of turbulent flow. Moreover, discharge capacity has been investigated by simulating the different possible drain deformations in the field. The average percentage reductions of the discharge capacity from the straight condition to various PVD deformed conditions have been found as follows: 26, 32, 33, 43, 48 and 78% for conditions of 10% bent, 20% bent, 90° twisted, 180° twisted, 20% bent with one clamp and 30% bent with two clamps, respectively. Subsequently, reduction factors for discharge capacity have been formulated. Moreover, a simple method is proposed to evaluate specifications of discharge capacity with some established relationship considering the length of PVD, spacing, time required for consolidation and the magnitude of the horizontal coefficient of consolidation. Copyright © 1996 Elsevier Science Ltd.*

### NOTATION

$q_w$	rate of discharge of the drain under a unit hydraulic gradient
$Q$	volumetric flow rate of water
$i$	hydraulic gradient

$q_{\text{req}}$	required discharge capacity of the drain
$U_{10}$	10% degree of consolidation
$H$	driven depth of PVD
$Ch$	coefficient of consolidation for horizontal drainage
$Th$	horizontal time factor

#### *Greek letters*

$\epsilon_f$	final settlement of the soft clay layer; 25% of the total depth to be improved which is equal to depth $H$ of installed PVD
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## 1 INTRODUCTION

The function of a prefabricated vertical drain (PVD) is to facilitate radial flow of water from the consolidating ground, transport it in the vertical direction and discharge it into drainage layers with as little hydraulic resistance as possible. The discharge capacity, denoted as  $q_w$ , of a band drain has been defined as the rate of flow through the drain at a hydraulic gradient of unity. This can be expressed as the product of the longitudinal permeability of the drain and its cross-sectional area. Discharge capacity values given in manufacturers' brochures and technical papers for various commercial drains differ to such an extent that different values have been quoted for the same drain by various sources, mainly due to the different test conditions employed. Methods of determining the discharge capacity in the laboratory have been reviewed by Hansbo (1981) and more recent testing proposals have been discussed by Holtz *et al.* (1989). Hansbo (1981) cautioned that the discharge capacity measured in the laboratory is generally higher, since filtration characteristics, installation and deterioration effects in the field cannot be reproduced.

Modified triaxial and ASTM-based (ASTM, 1991) discharge capacity tests were conducted on PVD in the laboratory to determine the effects of lateral pressure and drain deformations on the reduction of discharge capacity. A simple method is suggested to evaluate specification of discharge capacity incorporating the reduction factors obtained from the laboratory tests with some established relationship considering the length of PVD, spacing, time required for consolidation and horizontal coefficient of consolidation.

### 1.1 Discharge capacity

Generally, the discharge capacity decreases non-linearly with hydraulic gradient. For a given hydraulic gradient, the discharge capacity depends primarily on the following factors:

- (a) The area of the drain core available for flow, sometimes termed as the free volume.
- (b) The effect of lateral earth pressure.
- (c) Possible folding, bending and crimping of the drain due to large settlements.
- (d) Infiltration of fine soil particles through the filter which can cause a reduction of flow capacity of the drain.

The design of a vertical drain system is generally based on the classic theoretical solution developed by Barron, in which the drains are assumed to function as ideal wells, i.e. their permeability is considered infinitely higher compared to the adjacent soils in which the drains are placed. However, because of the small size and flat shape of a prefabricated vertical drain, its discharge capacity is limited.

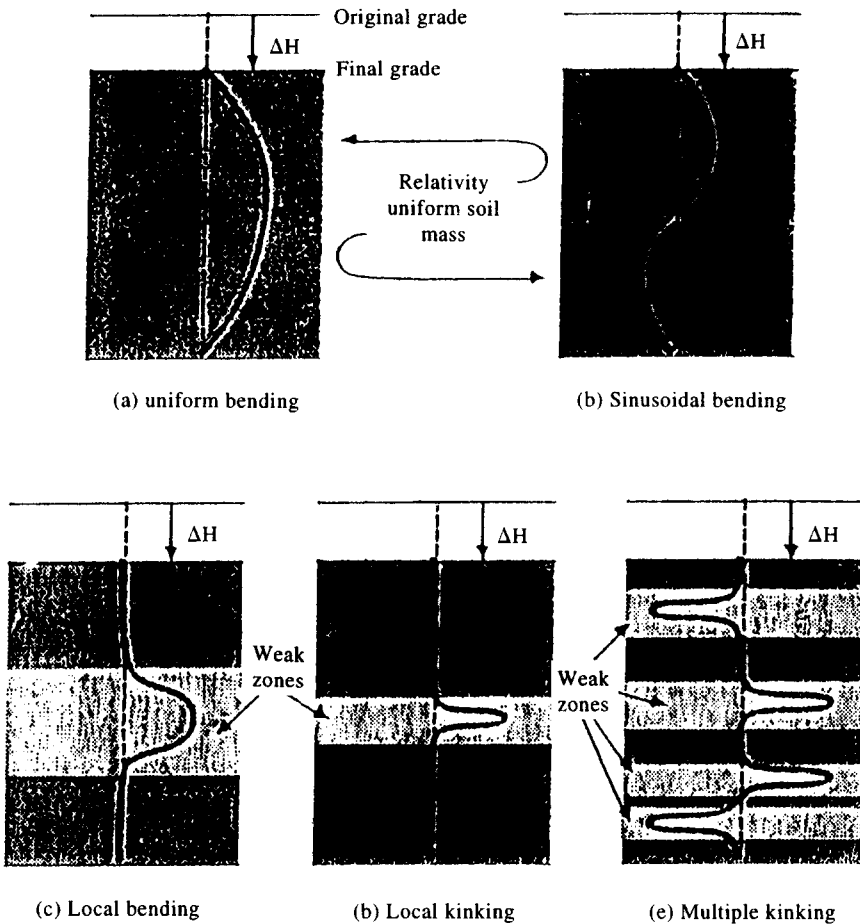
Tests have also shown that the discharge capacity can be substantially influenced by the lateral pressure on the drain, especially in cases of reclamation over thick clay layers. To maintain adequate discharge capacity, the band drain must be able to withstand the lateral earth pressure and to conform to the ground settlement without losing its effectiveness. For composite drains, the filter should not be pressed into the vertical channels of the core to such an extent that the discharge capacity is significantly affected.

Another factor that may affect discharge capacity is the folding of the drain that takes place under large vertical strains. During consolidation of soft soils, the ground will be subjected to considerable settlement. Any band drains installed will therefore tend to settle together with the ground, thereby resulting in bending (Fig. 1). If the compressible layer is relatively thick and uniform, the radius of curvature of the bending is likely to be large and discharge capacity may not be severely affected. In contrast, if thin layers of soft soils exist within a less compressible deposit, the band drain may be subjected to local crimping or kinking which may result in a considerable decrease in discharge capacity.

It is also important to consider the potential occurrence of clogging in considering the flow resistance of band drains. In the initial filtering process of flow from the soil through the band drain filter, the displaced pore water will contain a small proportion of fine soil particles. These may be deposited within the core and cause the drain to clog. Furthermore, discharge capacity may also be reduced by aging in the soil after installation (Koda *et al.*, 1984), probably due to bacteriological activity.

## 1.2 Current recommended values of discharge capacity

There appears to be no consensus on the optimum test environment for band drains until now. Hansbo (1981) has the opinion that a repre-



**Fig. 1.** Possible deformation modes of band drains as a result of ground settlement (from Lawrence and Koerner, 1988).

sentative laboratory test of discharge capacity should involve surrounding the drain with soil instead of a rubber membrane and that the effective stresses employed in a testing should be similar to those that would be encountered in the field. On the contrary, Kremer (1983) prefers the use of a rubber membrane for the sake of simplicity and better repeatability, provided that the relative elasticity of the membrane and filter sleeve is taken into account. A wide range of values of  $q_w$  have been specified for proper functioning of drain. Kremer *et al.* (1982) stated that the minimum vertical discharge capacity must be  $160 \text{ m}^3/\text{year}$  under a hydraulic gradient of 0.625 applied across a 40 cm drain length and subjected to confining pressure of 100 kPa. Jamiolkowski *et al.*

**TABLE 1**  
Current recommended values for specification of discharge capacity

Source	Values	Lateral stress (kPa)
Jamiolkowski <i>et al.</i> (1983)	10–15	500–300
den Hoedt (1981)	95	50–300
Kremer <i>et al.</i> (1982)	256	100
Kremer (1983)	790	15
Hansbo (1987)	50–100	Not given
Rixner <i>et al.</i> (1986)	100	Not given
Van Zanten (1986)	790–1580	150–350
Holtz <i>et al.</i> (1989)	100–150	500–300
Lawrence and Koerner (1988)	150	Not given
Koda <i>et al.</i> (1984)	100	50
de Jager and Oostveen (1990)	315–1580	150–300

(1983) concluded that, based on laboratory data and their experience for an acceptable quality of drain,  $q_w$  should be at least 10–15 m<sup>3</sup>/year at a lateral stress range of 300–500 kPa and for drains that may be 20 m long. However, the typical laboratory determined values of  $q_w$  which were considered by Jamiolkowski *et al.* (1983) were too low and the required acceptable  $q_w$  was subsequently increased to 100–150 m<sup>3</sup>/year for 15–25 m long drains in clay soils with horizontal permeability,  $Kh$ , of 10<sup>-7</sup> cm/s (Holtz *et al.*). Hansbo (1987) specified that for long drains, vertical discharge capacity becomes a critical design property if the capacity of the drain is less than 50–100 m<sup>3</sup>/year. These values have been summarized in Table 1.

In summary, for an acceptable prefabricated vertical drain, values of  $q_w$  in the range of 10–1580 m<sup>3</sup>/year have been specified under lateral pressure ranging from 15 to 350 kPa based on experience on laboratory longitudinal flow test results or vertical strain and settlement rates for particular soil and vertical drain conditions.

## 2 LABORATORY TESTS

### 2.1 Modified triaxial test

The modified triaxial test facilitates the determination of discharge capacity of prefabricated vertical drains at straight, free bending, twisted and clamped conditions at different hydraulic gradient and lateral pressure. The discharge capacity apparatus is a 20 cm diameter modified triaxial cell with a height of 50 cm. The typical set-up of the apparatus is shown in Fig. 2.

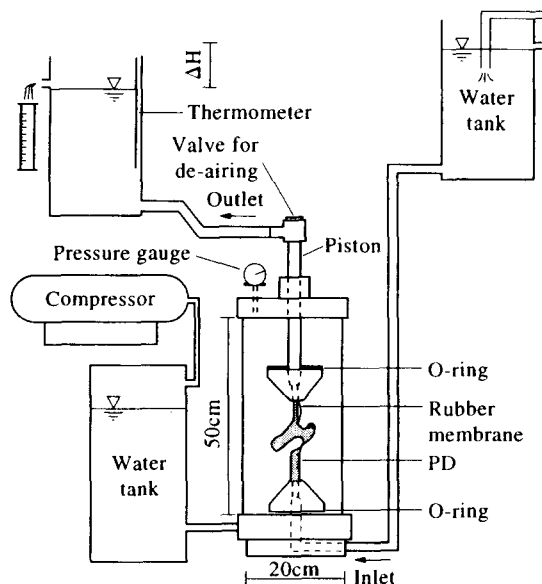


Fig. 2. Apparatus for longitudinal permeability of PVD.

The PVD specimen was wrapped with rubber membrane and O-rings were placed around the clamps to prevent the surrounding water from entering the specimen. The apparatus was assembled with the specimen in place. The apparatus was filled with tap water with open bleed valves to prevent entrapped air. The bleed and water control valves were closed once the container was full. Pressure was then applied by a water–mercury pressure system through the valve directly attached to the apparatus.

Two water tanks of the same size were connected to the apparatus. The inlet tank which was adjustable provided a constant head water supply at varying hydraulic gradients. The outer tank where water was collected had a weir-shaped opening.

To obtain a 10% bent condition of the drain, the piston was lowered 10% of the specimen length. To have a twisted condition, the straight specimen was twisted to the desired amount of rotation, i.e. 90° or 180°. To attain a clamped condition, the piston was lowered first to the desired percent bending of the drain, then the specimen was clamped. Discharge capacity tests were conducted for the following PVD conditions: 10% bent, 20% bent, 90° twisted, 180° twisted, 20% bent with one clamp and 30% bent with two clamps. Discharge capacity,  $q_w$ , which is defined as the rate of discharge of the drain,  $Q$ , under a unit hydraulic gradient,  $i$  (Ali, 1991), is expressed in the following equation:

$$q_w = Q/i \quad (1)$$

where  $Q = V/t$ ;  $V$  = volume of 500 ml of water;  $t$  = time required to collect  $V$ .

Ten different types of vertical band drains were tested. These included Alidrain, Amerdrain 408, Castle Board, Colbond CX-1000, Desol, Fibre-drain, Flodrain FD4-EX, Geodrain L-type, Hongplast GD75 and Mebra drain MD7007. Modified triaxial tests were repeated for each drain at different hydraulic gradients and at different deformation conditions.

## 2.2 ASTM discharge capacity test

Figure 3 shows the ASTM-based (ASTM, 1991) discharge capacity test apparatus. It consists of stainless steel plates of 10 mm thickness assembled together to form a  $200 \times 250 \times 150$  mm box. Slots were cut in the opposite sides with  $102 \times 10$  mm dimensions, enough to fit the fabricated drain wrapped with rubber membrane. Locally produced rubber membrane was used to isolate the drain from surrounding soil.

Two water tanks of the same size were connected to the opposite ends of the box. The inlet tank with adjustable height provided a constant head water supply at varying hydraulic gradients. The outer tank where water was collected had a weir-shaped opening. The prefabricated drain was placed between two sand layers which served as cushions to transmit the confining pressure to the drain during pressure application. Pressure was applied by a compressed air system through four rubber balloons placed on top of the sand layer. The discharge capacity was computed using the expression given in eqn (1).

## 3 RESULTS AND DISCUSSION

### 3.1 Modified triaxial test results

Modified triaxial discharge capacity test results have been presented in Figs 4–15. Figures 4–6 show the discharge capacity for the same drain with varying hydraulic gradient. The discharge capacity was found to be higher at a lower hydraulic gradient than at a higher hydraulic gradient. This might be attributed to the loss of flow energy as a result of turbulent flow at a high hydraulic gradient. Figures 6–15 show the discharge capacities of 10 drain types at the same hydraulic gradient of unity. The discharge capacity decreased almost linearly when lateral pressure increased. This behavior has been observed in all drains. Typically, by increasing the lateral pressure, the

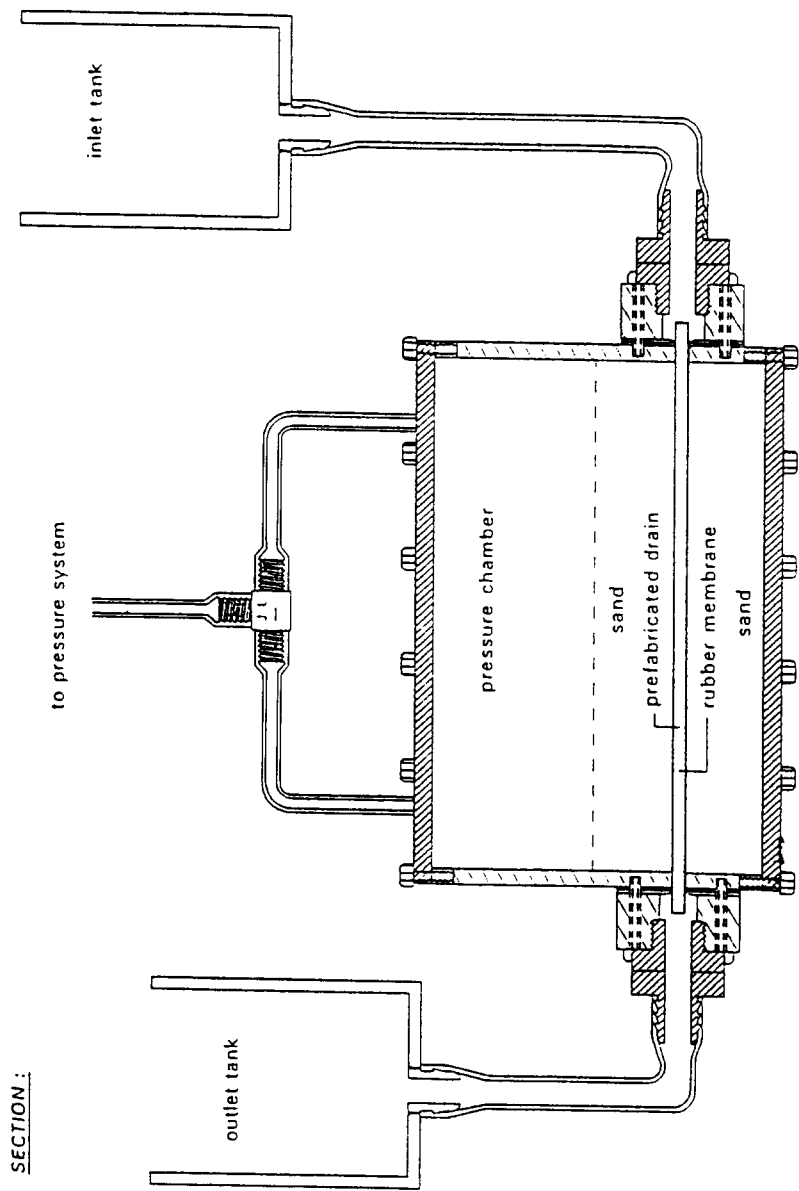


Fig. 3. ASTM discharge capacity apparatus.



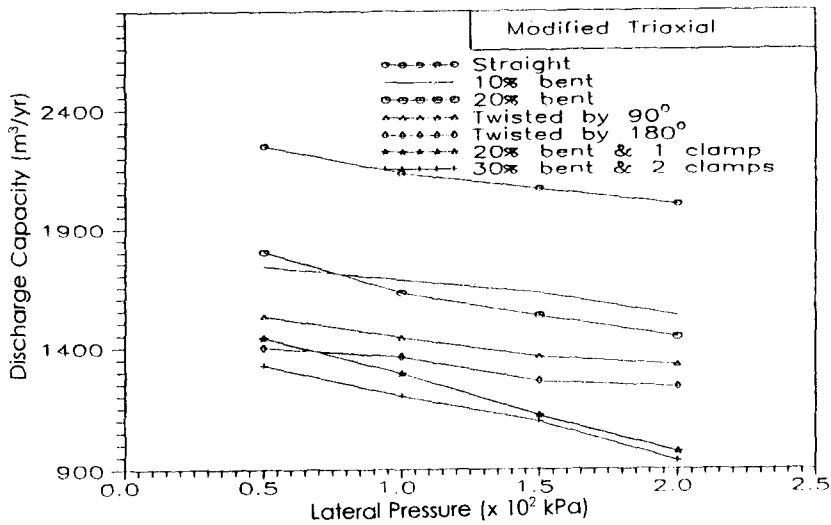


Fig. 4. Discharge capacity (modified triaxial) of Alidrain with lateral pressure of hydraulic gradient of 0.25.

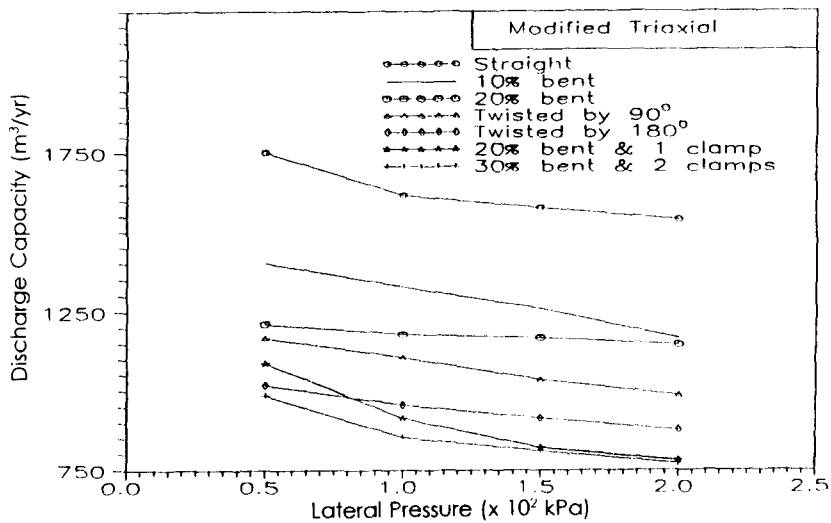
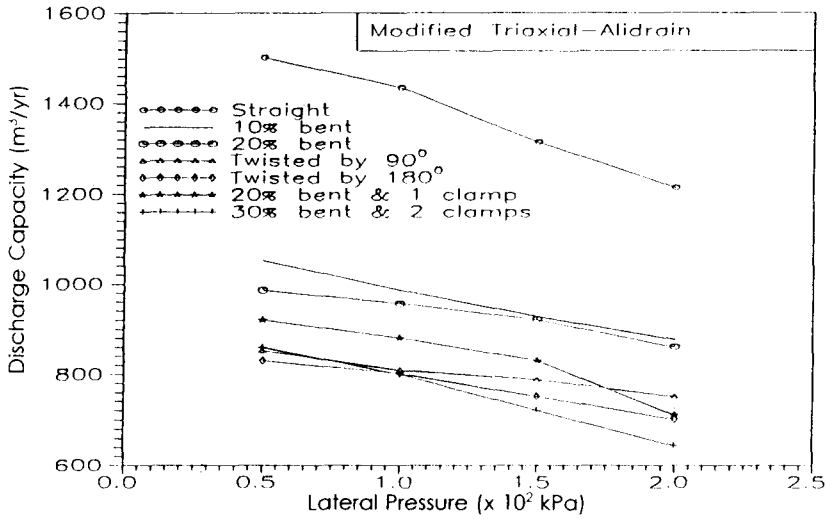


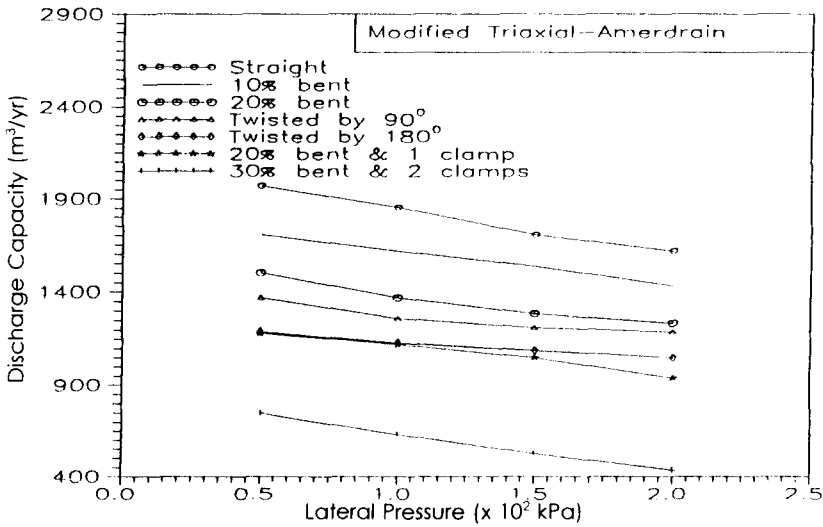
Fig. 5. Discharge capacity (modified triaxial) of Alidrain with lateral pressure at hydraulic gradient of 0.50.

filter passes into the core and subsequently decreases the discharge capacity due to a reduction in the area available for flow. In addition, the discharge capacities decreased, as expected, with an increased amount of deformation.

Table 2 presents the maximum reductions of discharge capacity from a



**Fig. 6.** Discharge capacity (modified triaxial) of Alidrain with lateral pressure at hydraulic gradient of 1.0.



**Fig. 7.** Discharge capacity (modified triaxial) of Amerdrain with lateral pressure at hydraulic gradient of 1.0.

straight condition to different PVD conditions for all drains. Castleboard has minimal reaction to deformation with an average reduction of 25%, while Fibredrain has the highest average reduction of 78%. The other drains showed an average decrease ranging from 37 to 62% in discharge capacity values.

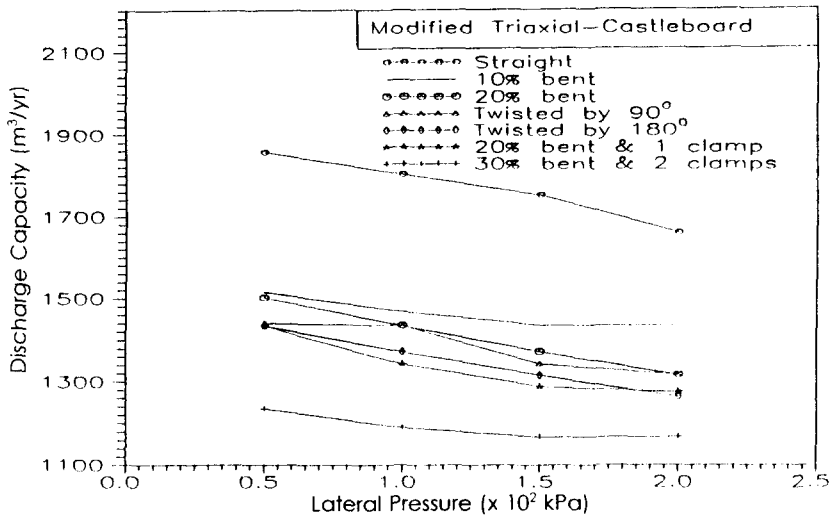


Fig. 8. Discharge capacity (modified triaxial) of Castleboard with lateral pressure at hydraulic gradient of 1.0.

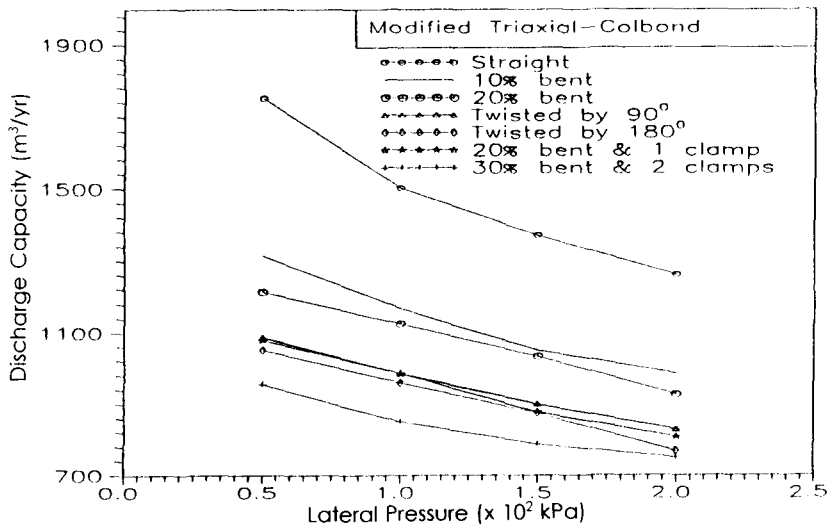
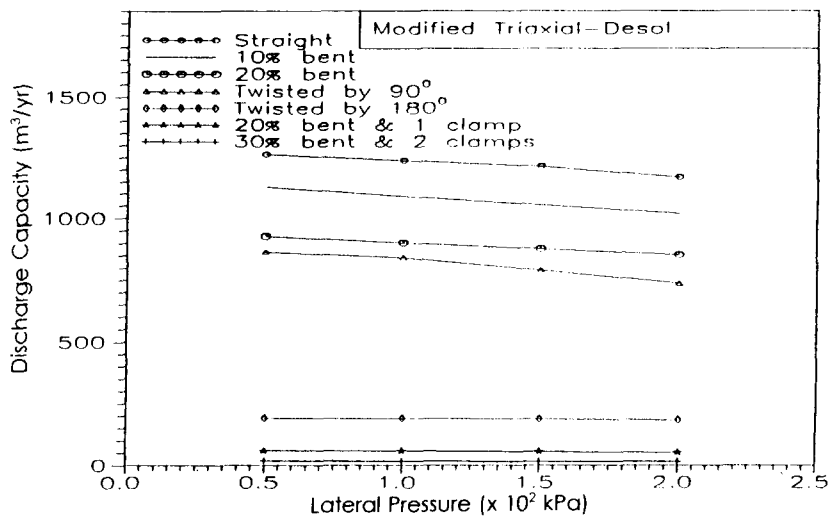
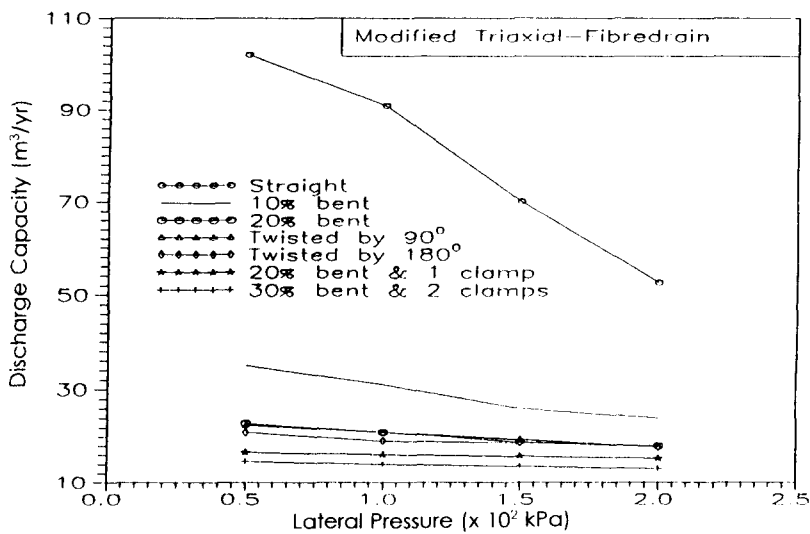


Fig. 9. Discharge capacity (modified triaxial) of Colbond with lateral pressure at hydraulic gradient of 1.0.

When subjected to 20% bent drain conditions, drains such as Castleboard and Flodrain showed 22 and 26% reductions in discharge capacity, respectively. Monolithic stiff-structures Desol drain showed a 28% discharge capacity reduction. Colbond, Amerdrain, Alidrain, Geodrain, Hongplast



**Fig. 10.** Discharge capacity (modified triaxial) of Desol with lateral pressure at hydraulic gradient of 1.0.



**Fig. 11.** Discharge capacity (modified triaxial) of Fibredrain with lateral pressure at hydraulic gradient of 1.0.

and Mebra drains showed 31, 32, 34, 36, 38 and 40% reductions in the discharge capacity values, respectively. Fibredrain registered the largest discharge capacity reduction of 78%.

When subjected to 90° twisted drain condition, Castleboard and

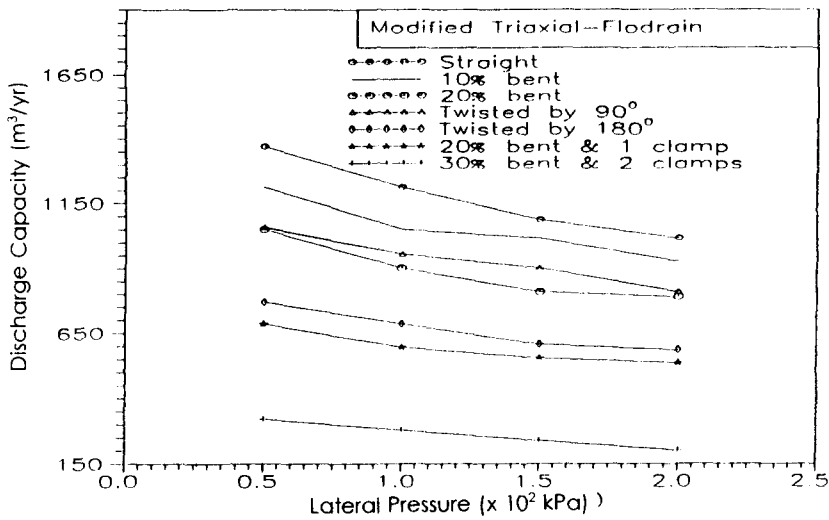


Fig. 12. Discharge capacity (modified triaxial) of Flodrain with lateral pressure at hydraulic gradient of 1.0.

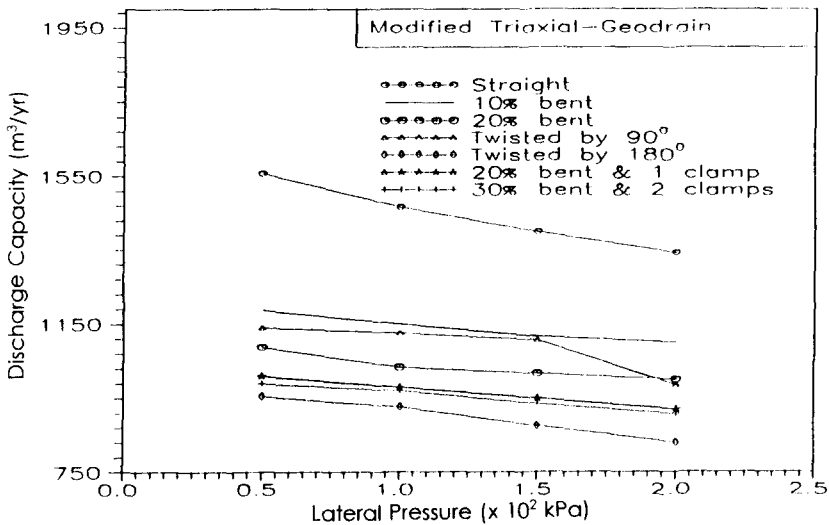


Fig. 13. Discharge capacity (modified triaxial) of Geodrain with lateral pressure at hydraulic gradient of 1.0.

Flodrain showed 22 and 23% discharge capacity reduction, respectively. Fibredrain showed a 78% reduction. The other drains indicated a discharge capacity reduction ranging from 31 to 59%. When subjected to 180° twist drain condition, Castleboard showed a 25% reduction in

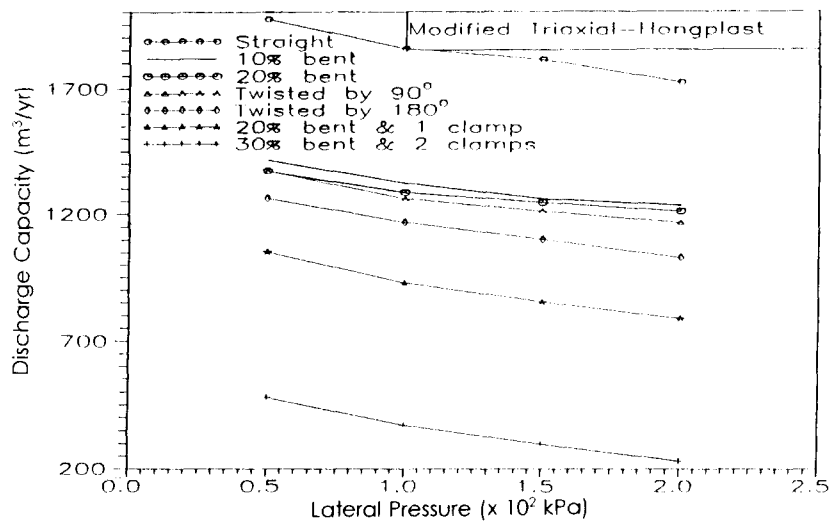


Fig. 14. Discharge capacity (modified triaxial) of Hongplast with lateral pressure at hydraulic gradient of 1.0.

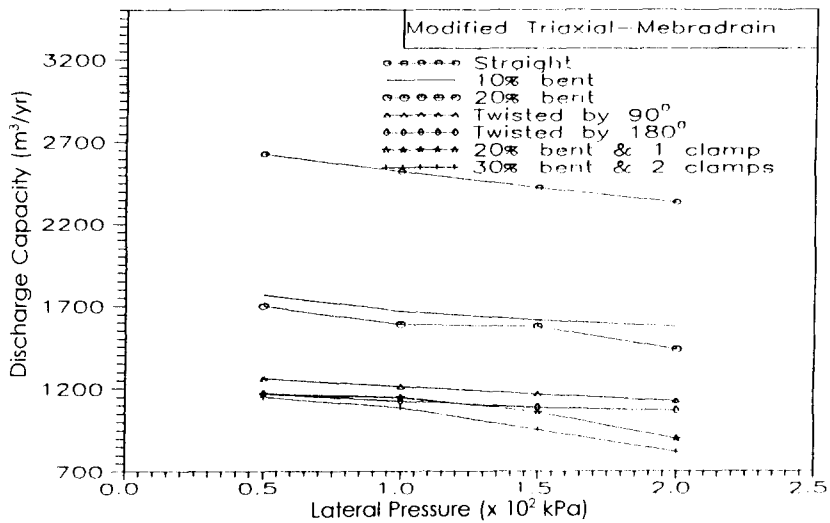


Fig. 15. Discharge capacity (modified triaxial) of Mebradrain with lateral pressure at hydraulic gradient of 1.0.

discharge capacity. Desol drain yielded an 85% reduction in discharge capacity values. Fibredrain showed a 79% discharge capacity reduction. The other drains demonstrated a 44–59% discharge capacity reduction.

When subjected to 20% strain and one-clamped condition, Castle-

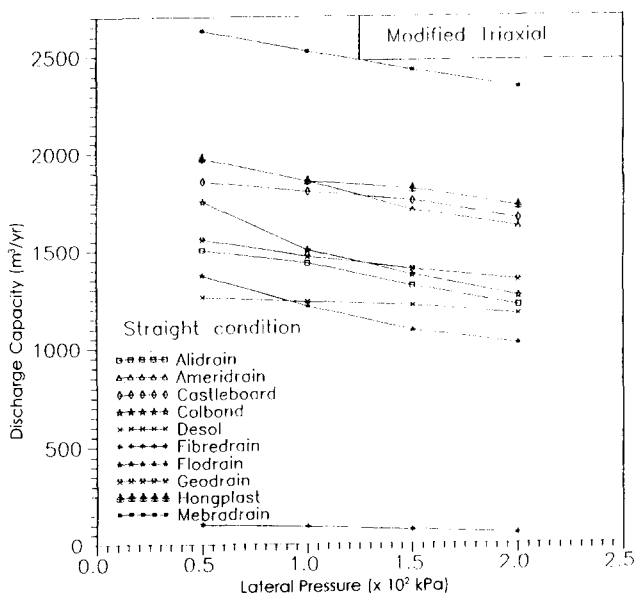
**TABLE 2**  
Percentages of discharge capacity of deformed drain condition

<i>Drain</i>	<i>10% Bent</i>	<i>20% Bent</i>	<i>90° Twist</i>	<i>180° Twist</i>	<i>One-clamp 20% Bent</i>	<i>Two-clamps 30% Bent</i>	<i>Average</i>
Alidrain	34	34	42	45	52	51	43
Amerdrain	18	32	32	50	47	75	42
Castleboard	19	22	22	25	27	34	25
Colbond	25	31	38	44	37	45	37
Desol	27	28	40	85	96	99	62
Fibredrain	66	78	78	79	84	86	78
Flodrain	14	26	23	44	52	81	40
Geodrain	28	36	31	45	62	70	45
Hongplast	35	28	27	46	54	91	50
Mebradrain	38	40	59	59	61	67	54
Average	26	32	33	43	48	78	48

board showed a 27% reduction. Desol drain and Fibredrain showed 96 and 84% discharge capacity reductions, respectively. The other drains indicated discharge capacity reductions ranging from 37 to 62%. When subjected to 30% strain and two-clamped drain condition, Castleboard yielded the lowest at 34% reduction, while Desol yielded the largest reduction at 99%. Amerdrain, Flodrain and Hongplast drains had their lowest discharge capacity values when subjected to 30% bent two-clamps condition with reductions of 75, 81 and 91%, respectively.

Figure 16 shows discharge capacities at a straight condition and at a 1.0 hydraulic gradient under varying lateral pressures. At 2.0 ksc lateral pressure, Mebra drain showed the highest discharge capacity value of 2336 m<sup>3</sup>/year, followed by Hongplast, Castleboard and Amerdrain with 1723, 1660 and 1617 m<sup>3</sup>/year, respectively. Geodrain, Colbond, Alidrain, Desol and Flodrain followed closely with discharge capacity values equivalent to 1342, 1261, 1213, 1168 and 1017 m<sup>3</sup>/year, respectively. Fibredrain, being made of natural jute and coconut core without legitimate channel of flow, showed the least discharge capacity value of 53 m<sup>3</sup>/year.

Normally, when the drain is twisted, the core area is blocked and, consequently, discharge capacity decreases. Conversely, when it is clamped, almost the entire core area is blocked and the discharge capacity then becomes almost zero. Typically, this happened to rigid core or filters being subjected to local crimping, kinking or folding. Although a rigid and strong core is preferred in terms of mechanical properties, the discharge capacity reduction due to folding must also be taken into account, especially when a large settlement is expected.



**Fig. 16.** Discharge capacity (modified triaxial) of PVD types with lateral pressure at hydraulic gradient of 1.0.

### 3.2 ASTM discharge capacity test results

Figure 17 presents ASTM discharge capacity test results at 2.0 ksc lateral pressure. The discharge capacity decreases with time for all drains. It is also noted that reduction rate decreases with time. For composite drains, the filter is pressed into the core and the area available for discharge decreases. However, after a certain period, the filter itself may have attained the maximum limit of deformation at a given acting lateral pressure. Reduction of discharge capacity at this stage may be less significant. As shown in Fig. 17, Fibredrain has the highest reduction and Castleboard has the lowest reduction.

## 4 PROPOSED SPECIFICATIONS

### 4.1 Reduction factors

#### 4.1.1 Reduction factor due to time

The effect of lateral earth pressure on discharge capacity depends on several mechanical properties of the filter sleeve and core. The extensibility of the filter under pressure primarily controls the drain performance. If the filter is relatively extensible, it can be easily squeezed into the channels of the core.



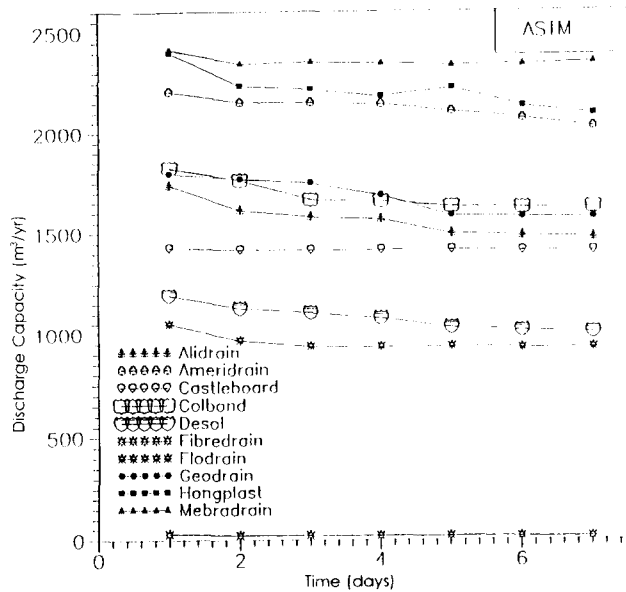


Fig. 17. Discharge capacity (ASTM-based) with time at lateral pressure of 2.0 ksc and hydraulic gradient of 1.0.

Thus, the discharge capacity of the drain is consequently reduced. Lateral pressure effect, therefore, must be included to find the specification of discharge capacity. Modified triaxial test results show the variation of discharge capacity with lateral pressure. This effect could be more pronounced with time  $t$ . Thus, the reduction ratio due to time can be defined in the following expression:

$$\text{Reduction ratio} = (\text{IDC} - \text{FDC}) / (\text{IDC} \times t) \tag{2}$$

where IDC = initial discharge capacity; FDC = final discharge capacity at time,  $t$ .

Table 3 tabulates the time required for the reduction ratio to become zero, i.e. when the discharge capacity of the drain tends to stabilize, and the final discharge capacity values at certain time,  $t$ , for all drains. The required discharge capacity,  $q_w$ , must therefore be multiplied by a time factor,  $Ft$ , which can be expressed as IDC/FDC to find the desired specification. From Table 3, this factor can be taken on average as 1.25.

4.1.2 Reduction factor due to folding or drain condition

Another eventuality which can reduce the discharge capacity of prefabricated drains is bending or folding, brought about by large settlement of the

**TABLE 3**  
Time required for the reduction ratio to become zero

<i>Drain</i>	<i>Time (days)</i>	<i>IDC (m<sup>3</sup>/year)</i>	<i>FCS (m<sup>3</sup>/year)</i>	<i>Ft = (IDC/FDC)</i>
Alidrain	18.0	1,736.6	1,174.0	1.48
Amerdrain	16.5	2,208.4	1,808.0	1.22
Castleboard	18.0	1,427.0	1,388.5	1.03
Colbond	13.0	1,822.9	1,479.0	1.23
Desol	81.0	1,192.7	111.5	10.70
Fibredrain	21.0	28.6	0.0	
Flodrain	10.6	1,049.8	833.0	1.26
Geodrain	13.0	1,793.9	1,420.0	1.26
Hongplast	13.0	2,400.0	1,845.0	1.30
Mebradrain	8.4	2,414.0	2,272.0	1.06

clay soil being drained. Kremer (1983) and Kremer *et al.* (1982) mentioned the possibility of a severe reduction in discharge capacity occurring in vertical drains because of folding in very soft soils. Kremer (1983) concluded that folding can reduce the discharge capacity of prefabricated drains to zero and the quality requirements with respect to folding are necessary when the relative settlement in the most compressible layers exceeds 15%. Hansbo (1981) stated that field results do not appear to be affected by folding, probably because its influence is only likely to be significant near the end of the consolidation process when the discharge capacity is of minor importance. Moreover, Fellenius and Castonguay (1985) mentioned the following results due to folding of drains:

- (a) Drains with stiffer plastic cores had a reduced discharge capacity by factors ranging from 5 to 15.
- (b) Drains with flexible plastic core had only moderate reductions in discharge capacity, by factors ranging between 1.5 and 2.

Table 2 presents percentages of discharge capacity from a straight condition to other possible PVD deformed conditions. These values reflect the core and filter strength for different types of drains. Desol and Fibredrain had the highest reductions. Desol, being a one-piece monolithic drain, had a higher reduction because the area for flow was almost completely blocked when it was clamped. Fibredrain, being composed of natural jute and coconut core without a legitimate channel of flow may have had an insufficient cross-sectional area available for flow.

The following average values can be taken as the percentage reduction of discharge capacities for all drains at deformed conditions. Reduction factors from straight to 10% bent, 20% bent, twisted by 90°, twisted by 180°, one clamp and two clamps were 26, 32, 33, 43, 48 and 78%, accordingly. Some

high values and low values have been omitted in the calculation of the averages. The condition of two clamps under 30% bent condition is an extreme case. Therefore, one clamp with 20% bent case can be evaluated to determine the reduction factor of discharge capacity due to folding. From Table 2, the average reduction can be taken as 48%. Since the discharge capacity is expected to be reduced by one-half due to folding, the factor of drain condition,  $F_c$ , to be used in the specification should be twice the initial discharge capacity, in order to retain its effectiveness. Thus, the reduction factor of the deformed drain condition,  $F_c$ , can be taken as 2.0.

#### 4.1.3 Reduction factor due to filtration and clogging

Filtration tests separately conducted (Manivannan, 1995) showed that as filtration time increased, the permeability of the system decreased because the soil particles can be trapped by the geotextile filter. This general trend towards clogging showed that, initially, the flow increased and then gradually decreased. Finally, it stabilized at a certain value. It is difficult to find out the reduction factor due to clogging and biological growth from filtration tests because the initial flow was controlled by the hydraulic properties of the soil and not by the geotextile–soil system. It also takes time to reach equilibrium conditions. In order for a filter to be effective, it must retain soil particles on the upstream side of the geotextile and flow must reach equilibrium. The results indicated that the Mebra drain had a very small amount of loss of soil particles, indicating a good soil–filter system. It must be noted that the Mebra drain reached an equilibrium condition quickly. The same occurred with the Fibredrain but the loss of soil particles was very high, making it susceptible to clogging problems. Reductions of flow due to filtration and clogging for Amerdrain, Castleboard, Colbond, Fibredrain, Flodrain, Hongplast and the Mebra drain were 4, 1.7, 3.28, 3, 6.75, 2 and 1.3, respectively, with an average value of 3.15. Koerner and Ko (1982) have done long-term filtration tests on soil–geotextile systems and obtained a reduction factor in the range of 2.84–4.2, thus showing an average value of 3.52. However, in the long run, biological growth within the system will decrease the flow. Its influence on the flow rate, however, is not yet known. Thus, considering biological growth, the reduction factor due to filtration and clogging,  $F_{fc}$ , can be taken as 3.5.

## 4.2 Required discharge capacity

With reduction factors due to time,  $F_t$ , due to deformed drain condition,  $F_c$ , and due to filtration and clogging,  $F_{fc}$ , determined, a simple method for evaluating the specification of discharge capacity of prefabricated drains is

proposed. The following assumptions are made in order to calculate the required discharge capacity ( $q_{\text{req}}$ ) of a prefabricated drain:

- (a) The evaluation of discharge capacity is computed using the time required for a 10% degree of consolidation.
- (b) The final settlement of the soft clay ground is about 25% of the depth of the soft clay layer to be improved.
- (c) Barron's theoretical solution for sand drains can be applied.
- (d) Three partial factors of safety can be considered to evaluate the proposed specification and to accommodate the discharge capacity reduction factors due to time ( $F_t$ ), deformed drain condition ( $F_c$ ) and filtration and clogging ( $F_{fc}$ ) of clay particles in long-term conditions. Values of  $F_t$ ,  $F_c$  and  $F_{fc}$  can be taken as 1.5, 2.0, and 3.5, respectively, as discussed in the preceding sections.

The required discharge capacity,  $q_{\text{req}}$ , can then be calculated by considering the consolidation of a cylindrical soil mass with diameter,  $D_e$ , and depth,  $H$ , and is defined in the following expression given by Kamon *et al.* (1984):

$$q_{\text{req}} = \epsilon_f U_{10} \cdot H \cdot \pi Ch / (4 \cdot Th) \quad (\text{m}^3/\text{year}) \quad (3)$$

where  $\epsilon_f$  = final settlement of the soft clay layer equivalent to 25% of the total depth of the layer to be improved which is equal to depth  $H$  of installed PVD;  $U_{10}$  = 10% degree of consolidation;  $H$  = driven depth of PVD;  $Ch$  = coefficient of consolidation for horizontal drainage;  $Th$  = dimensionless horizontal time factor of consolidation.

Figures 18–20 show the calculated values of required discharge capacity,  $q_{\text{req}}$ , that have been plotted against the length of prefabricated drain  $H$  (m) with the values of  $Ch$  being taken as 1–7 m<sup>2</sup>/year for varying values of  $n$  equal to 20, 25 and 30. It can be observed that  $q_{\text{req}}$  decreases as the drain interval  $n$  increases. This is attributed to the increase in consolidation time as the drain interval increases. The times ( $t_{90}$ ) required for a 90% degree of consolidation of the soft clay ground have been calculated and plotted against parameter  $n$  in Fig. 21. Based on these figures, the specification criterion of discharge capacity can be established.

The coefficient of horizontal consolidation,  $Ch$ , which easily varies by a factor of 10, is a dominant factor on consolidation time. Bergado *et al.* (1993; 1990) obtained the ratio  $Ch(\text{field})/Ch(\text{lab})$  of 4 for the soft Bangkok Clay. The  $Ch$  value based from settlement records was found to be equal to about 5 m<sup>2</sup>/year (Bergado *et al.*, 1991). From a Rowe cell consolidation test, the average field  $Ch$  value can be taken as 5 m<sup>2</sup>/year (Manivannan, 1995).

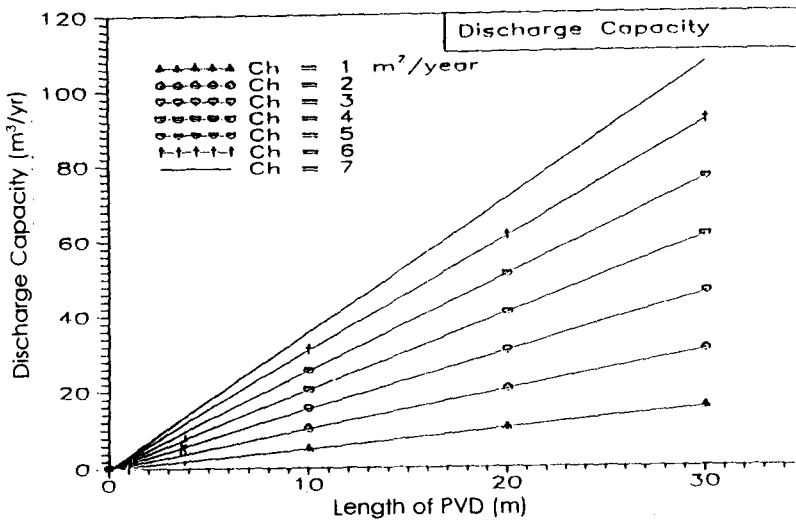


Fig. 18. Discharge capacity,  $q_{req}$  ( $m^3/yr$ ), versus PVD length with smear effect for  $n = 20$ .

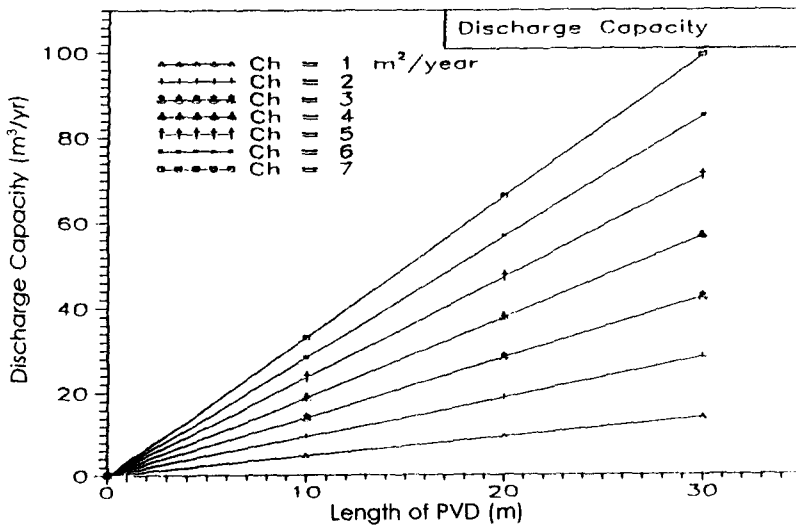


Fig. 19. Discharge capacity,  $q_{req}$  ( $m^3/yr$ ), versus PVD length with smear effect for  $n = 25$ .

For soft clay with  $Ch$  of  $5 m^2/year$ , if the depth of clay layer to be improved is 12 m, then the required discharge capacity of PVD to be used should be  $30 m^3/year$  and  $26 m^3/year$  for  $n$  equal to 20 and 30, respectively. Values of maximum flow rates estimated from field measurements vary from  $7.88 m^3/year$  (de Jager & Oostveen, 1990) to  $52.56 m^3/year$  (Lawrence & Koerner, 1988).

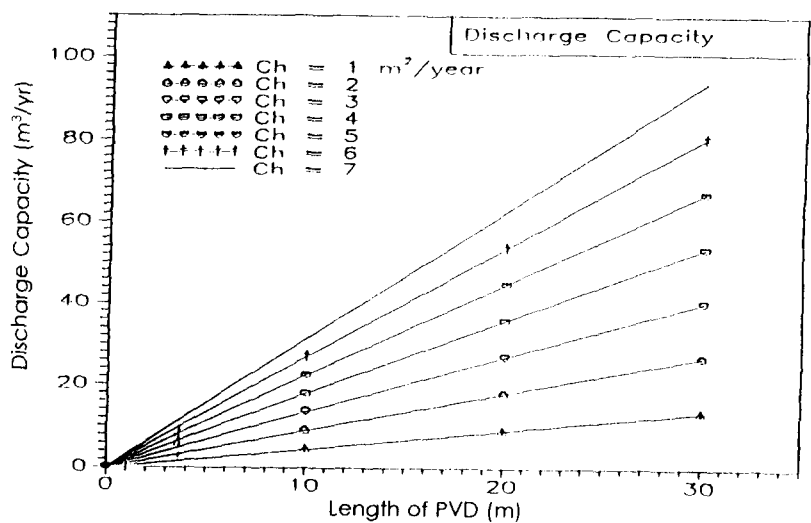


Fig. 20. Discharge capacity,  $q_{req}$  ( $m^3/yr$ ), versus PVD length with smear effect for  $n = 30$ .

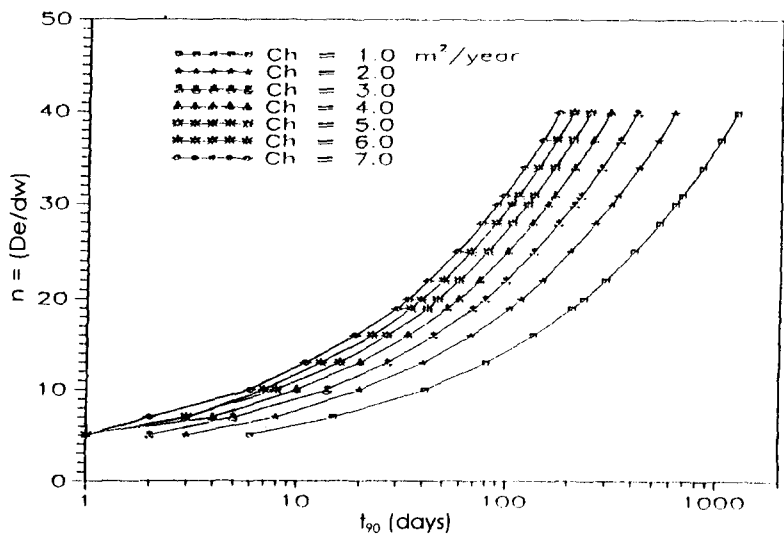


Fig. 21. Values of  $t_{90}$  versus  $n$  for different  $Ch$  values.

The proposed specification for discharge capacity,  $q_w$ , can then be written as

$$q_w = (Ft)(Fc)(Ffc)q_{req} \tag{4}$$

where  $Ft$  = reduction factor due to time;  $Fc$  = reduction factor due to deformation;  $Ffc$  = reduction factor due to filtration and clogging.

To establish the desired specification,  $q_{\text{req}}$  must be multiplied by the reduction factors,  $F_t$ ,  $F_c$  and  $F_{fc}$ , with values of 1.25, 2.0 and 3.50, respectively.

### 4.3 Proposed specification

From Fig. 18, for soft clay with  $Ch$  of  $5 \text{ m}^2/\text{year}$  and the depth of clay layer to be improved of 20 m, the required discharge capacity,  $q_{\text{req}}$ , of PVD to be used should be  $52 \text{ m}^3/\text{year}$  for an  $n$  value of 20. After multiplying by  $F_c$ ,  $F_t$  and  $F_{fc}$  factors, the discharge capacity is equal to  $455 \text{ m}^3/\text{year}$ . Thus, the proposed specification for discharge capacity can be taken as  $500 \text{ m}^3/\text{year}$  at a straight condition with a hydraulic gradient,  $i$ , of 1 under maximum lateral pressure. At 20% bent, one-clamped drain condition, the required discharge capacity which is multiplied by  $F_t$  and  $F_{fc}$  only must be higher than  $227.5 \text{ m}^3/\text{year}$  at a hydraulic gradient,  $i$ , of 1 and maximum lateral pressure. The proposed discharge capacity to be used in the specification can, therefore, be taken as  $250 \text{ m}^3/\text{year}$ . Based on the ASTM D4716-87 testing method, at 7 days duration, the required discharge capacity multiplied by  $F_c$  and  $F_{fc}$  must be higher than  $364 \text{ m}^3/\text{year}$  at maximum lateral pressure. Thus, discharge capacity to be used in the proposed specification can be taken as  $400 \text{ m}^3/\text{year}$ .

## 7 CONCLUSIONS

Based on the laboratory studies conducted and analysis of the results, the following conclusions can be drawn:

- (1) Discharge capacity decreases almost linearly when lateral pressure, time and hydraulic gradient increases for all drains. The increase in lateral pressure presses the filter into the core and the cross-sectional area available for discharge decreases. Thus, the discharge capacity decreases. The discharge capacity at a low hydraulic gradient is higher than the discharge capacity at a high hydraulic gradient. This might be attributed to the loss of flow energy as a result of turbulent flow at a high hydraulic gradient.
- (2) The average percentage reduction of discharge capacity at conditions 10% bent, 20% bent, twisted by  $90^\circ$ , twisted by  $180^\circ$ , 20% bent with one clamp and 30% bent with two clamps are 26, 32, 33, 43, 48 and 78%, respectively. Considering discharge capacity reductions due to folding at 20% bent with one-clamp drain condition, the reduction factor due to deformation,  $F_c$ , can be taken as 2. Discharge capacity at constant lateral pressure and hydraulic gradient decreases with time by a factor of 1.25. Thus, reduction factor due to time,  $F_t$ , also expressed as the ratio of the initial discharge capacity and the final discharge capacity at time  $t$ , can be

taken as 1.25. From filtration tests, the reduction factor due to filtration and clogging,  $Ffc$ , can be taken as 3.5. The specified discharge capacity,  $q_w$ , is proposed to be the required discharge capacity,  $q_{req}$ , multiplied by reduction factors,  $Fc$ ,  $Ft$  and  $Ffc$ .

- (3) The assembled drain shall have a minimum discharge capacity of  $500 \text{ m}^3/\text{year}$  when measured in modified triaxial equipment in its straight condition at a hydraulic gradient of one under the maximum effective pressure that the drain will experience. Moreover, the assembled drain shall have a minimum specified discharge capacity of  $250 \text{ m}^3/\text{year}$  when measured in modified triaxial equipment in its 20% bent with one-clamp condition at a hydraulic gradient of one under the maximum effective pressure that the drain will experience. Furthermore, the assembled drain shall have a minimum discharge capacity of  $400 \text{ m}^3/\text{year}$  when measured according to the ASTM D4716-87 test at a hydraulic gradient of one under maximum effective pressure for a period of 7 days.

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