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Towards Solutions for Seepage Problems

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إيجاد حلول لمشاكل التسرب

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خلاصة : تحل مشاكل التسرب في التربة تقليدياً باستخدام طريقة شبكات الجريان ، وتناقش هذه الورقة استخدام طريقة القطع كبديل جيد لحل مشاكل التسرب . وقد تم ضمن هذا البحث تطوير برنامج حاسوب الي بسيط ومرن في تفاعله مع المستخدم لدراسة هذه الطريقة (طريقة القطع) . وتم إختيار عدة مشاكل بطريقة عشوائية ، حلت كل منها باستخدام طريقة شبكات الجريان ، وطريقة القطع وطريقة الفرق المحددة . ووجد ان طريقة القطع وطريقة الفرق المحددة تعطي تنبؤات جيدة جداً لكمية الجريان والضغط عند نهاية الشبكة وقوة الرفع . علاوة على ذلك ، تمت دراسة تأثير تغيير مواقع واطوال وأعداد الركائز المستعرضة المختلفة والبلاطة الافقية في قاع أعلى النهر على قيمة كمية الجريان ، والضغط عند مخرج الشبكة وقوة الرفع .

ABSTRACT: Flow nets are traditionally used for solving seepage problems in soils. In this paper, the method of fragments is presented as a good alternative for solving seepage problems. A user friendly and interactive computer program for the method of fragments has been developed. Several randomly selected problems are solved by the flow net method, the method of fragments and the finite difference method. It was found that the method of fragments and the finite difference method gave very close predictions of the quantity of flow, exit gradient and uplift force. Furthermore, the effects of different positions and lengths, and number of sheet piles, and upstream blankets on the values of quantity of flow, exit gradient and uplift force are examined.

The solution of seepage problems requires the computation of the quantity of flow, exit gradient, uplift force and safety factor with respect to piping and uplift. Piping is a phenomemon where the seepage water progressively erodes or washes away the soil particles creating a *pipe* beneath a dam. The passage begins at the downstream side and works backwards to meet the free water at the upstream side. Once the tunnel-shaped passage is formed, the downstream side of the dam gets flooded. The safety factor with respect to piping has been defined by Harza (1953) as:

$$[SF]_{piping} = \frac{\text{critical hydraulic gradient}}{\text{maximum exit gradient}}$$

Since failure due to piping is often catastrophic, very high safety factors of the order of 3-5 are generally recommended, (Harza, 1953, Holtz and Kovacs 1981 and Scott 1982).

Traditionally, seepage problems were solved by the flow net method. The major disadvantage in the flow net method is that it requires substantial effort in drawing a good quality flow net. In the preliminary design stages, where several alternatives are tried, drawing a separate flow net for every individual configuration becomes a tedious task. Therefore, there is a need for a method that overcomes this major drawback. The method of fragments was developed by Pavlovsky (1956) and provides quick and approximate solutions where the accuracy is quite sufficient for practical purposes. Later, this method became known in other parts of the world (Harr, 1962 and 1977). Seepage problems can also be solved by the finite difference method.

A user friendly computer program using the method of fragments has been developed by Al-Rawas et al. (1994). The quantity of flow, exit gradient, uplift force and safety factor with respect to piping can be computed using this program. In addition, the pressure distribution on the bottom of the dam can be plotted. Another computer program employing the finite difference method has been developed by Rushton and Redshaw (1979). Together with the traditional flow net this method will be employed to check the validity of the method of fragments. The values of the seepage parameters for ten arbitrarily selected seepage problems computed by the

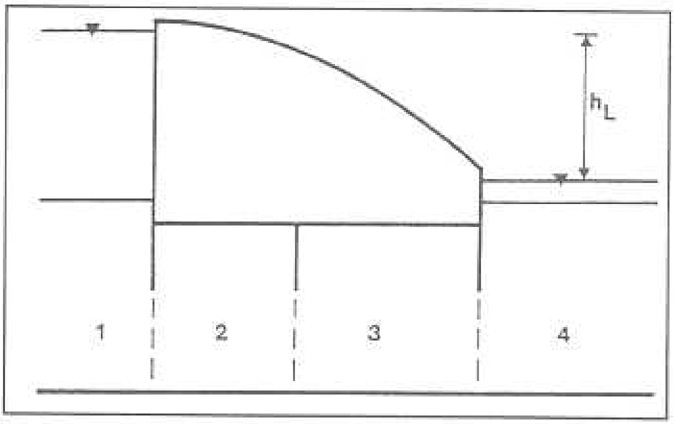


Figure 1. Fragments in the flow region.

flow net method, method of fragments and finite difference method will be compared. In addition, the effects of sheet piles and aprons are examined using the method of fragments.

Method of Fragments

The method of fragments is a quick, but approximate analytical tool for the solution of seepage problems. The basic assumption in this method is that the equipotential lines, at the selected critical points in a flow net, are vertical and can divide the flow region into fragments. The flow region in Fig. 1 is divided into four fragments. Each fragment has a dimensionless quantity known as form factor (Φ) which is given by:

$$\Phi_m = \frac{\text{No. of equipotential lines in the } m^{th} \text{ fragment}}{\text{No. of flow lines}} \tag{1}$$

The quantity of seepage per unit length of the dam is given by:

$$Q = kh_L / \sum \Phi \tag{2}$$

where k and h_L are the coefficient of permeability and the head loss across the dam, respectively, is given by:

$$\sum \Phi = \Phi_1 + \Phi_2 + \cdots + \Phi_n \tag{3}$$

The form factors for different types of fragments, as given by Harr (1977), are presented in Figs. 2a and 2b. The maximum exit gradient can be obtained from Fig. 2c. Since the flow is the same through all fragments,

$$\frac{Q}{k} = \frac{h_m}{\Phi_m} = \frac{h_1}{\Phi_1} = \frac{h_2}{\Phi_2} = \cdots = \frac{h_L}{\sum \Phi} \tag{4}$$

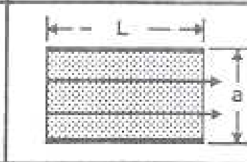
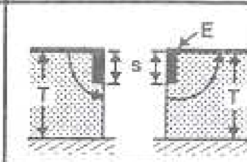
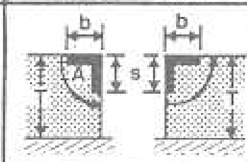
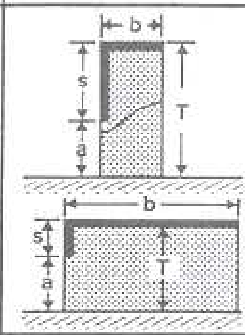
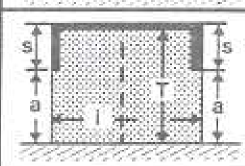
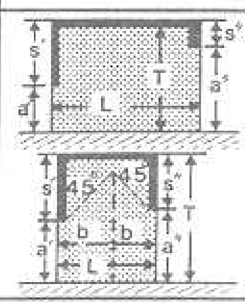
Fragment Type	Illustration	Form Factor, ϕ (h is head loss through fragment)
I		$\phi = \frac{L}{a}$
II		see Fig. 2b
III		see Fig. 2b
IV		$b \le s$: $\phi = \ln(1 + b/a)$ $b \ge s$: $\phi = \ln(1 + s/a) + (b - s)/T$
V		$L \le 2s$: $\phi = 2\ln(1 + L/2a)$ $L \ge 2s$: $\phi = 2\ln(1 + s/a) + (L - 2s)/T$
VI		$L \ge s' + s''$: $\phi = \ln[(1 + s'/a')(1 + s''/a'')] + (L - s' - s'')/T$ $L \le s' + s''$: $\phi = \ln[(1 + b'/a')(1 + b''/a'')]$ where $b' = (L + s' - s'')/2$ $b'' = (L - s' + s'')/2$

Figure 2a. Types of fragments and form factors (after Harr, 1977).

Sivakugan and Al-Aghbari (1993a) used the flow net method and the method of fragments to solve several different types of confined flow problems where the percentage differences are computed using the values computed from the flow net method as the reference. It was found that the error is generally within 5% for predicting quantity of flow, exit gradient and uplift force as compared to the flow net method.

Modified method of fragments

Sivakugan and Al-Aghbari (1993b) observed that the six types of fragments described in Fig. 2a can be

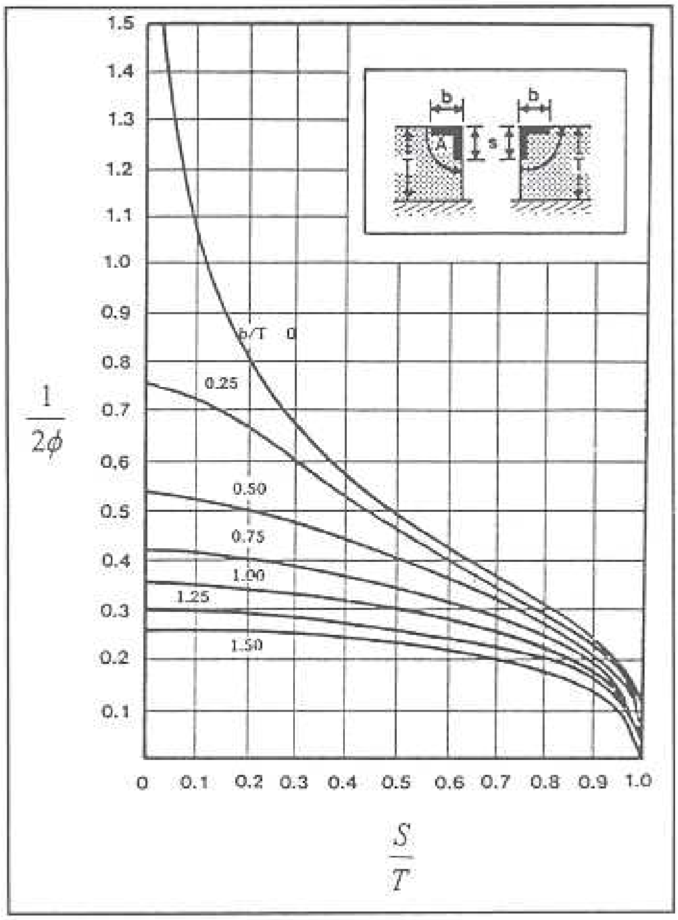


Figure 2b. Form factors for types II and III fragments (after Harr, 1997).

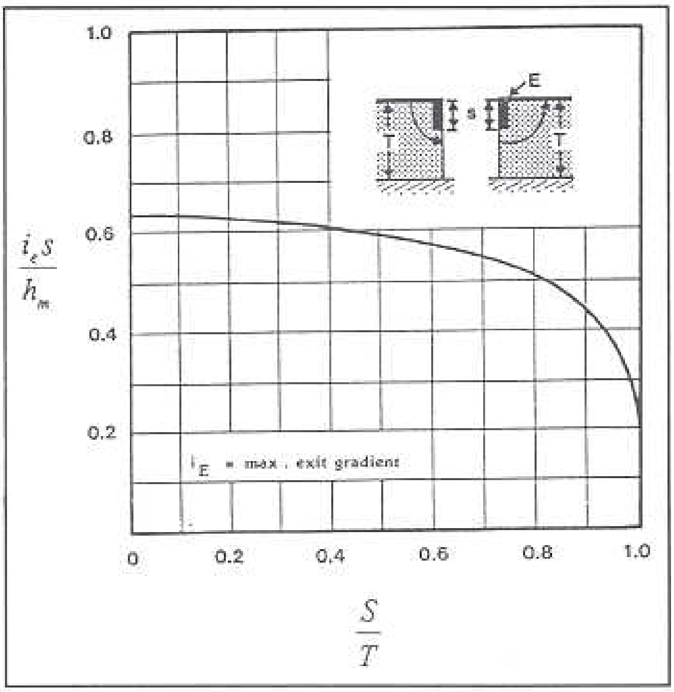


Figure 2c. Exit gradient for type II fragments (after Harr, 1997).

condensed into just two. These two fragments are referred to as Type A and Type B fragments and are shown in Fig. 3. A user friendly computer program has been written in QBASIC for the modified method of fragments.

THE COMPUTER PROGRAM: A user friendly and interactive program written in QBASIC for the modified method of fragments has been produced. From the input parameters, including the geometry and the soil characteristics, the program can compute the following: Critical gradient, Exit gradient, Quantity of discharge, Uplift force, Safety factor with respect to piping.

In addition, it can plot the pressure distribution on the bottom of a dam.

The execution of the program starts with *screen 1* which consists of six entries; the number of fragments, permeability, specific gravity, void ratio, water level in the upstream above the ground level and water level in the downstream above the ground level. All these parameters must be known and inputted into the program. Next, *screen 2* appears requesting the dimensions of the upstream and downstream fragments. The program allows the user to check the input values and make any corrections needed. These dimensions are: the depth of the sheet pile; the length of the upstream blanket; and the thickness of the soil layer. The dimensions of the middle fragment are required to be entered in *screen 3*. They consist of the depths of sheet piles and the width of the dam. Similar to *screen 2*, the user can check the input values and make any corrections needed. These input screens are given below.

Screen 1

Enter the number of fragments
Input the permeability
Input the specific gravity
Input the void ratio
Input the water level in the upstream above ground level
Input the water level in the downstream above ground level

Screen 2

Input the dimensions of the upstream fragment
Input the dimensions of the downstream fragment

Screen 3

Input the dimensions of fragment No. 2

At the completion of the input data, the program will show the results in *Screen 4*. This presents the values of the form factors and the head losses of the three fragments, the pressure distribution on the bottom of the

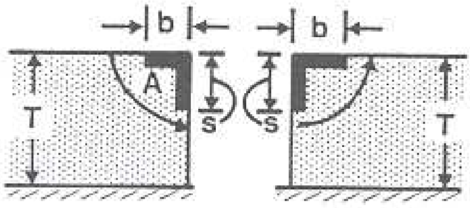
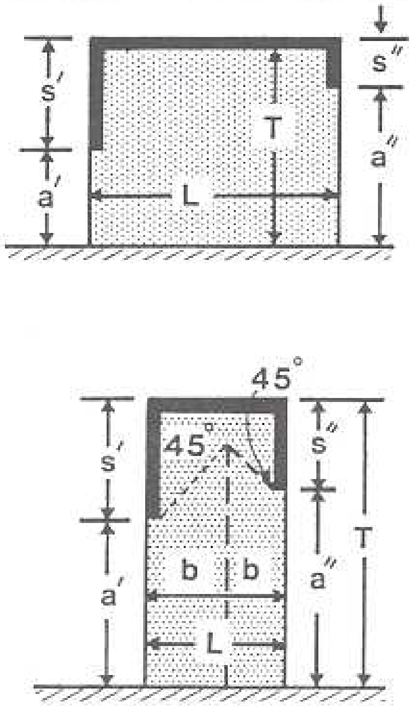
Fragment Type	Illustration	Form Factor, ϕ (h is head loss through fragment)
A		see Fig. 2b
B		$L > s' + s''$: $\phi = \ln[(1+s'/a')(1+s''/a'')] + L-(s'+s'')/T$ $L < s' + s''$: $\phi = \ln[(1+b'/a')(1+b''/a'')]$ where $b' = L+(s'-s'')/2$ $b'' = L-(s'-s'')/2$

Figure 3. Proposed type A and type B fragments.

dam, critical gradient, exit gradient, quantity of discharge, uplift force and safety factor with respect to piping. The output screen (screen 4) is given below.

Screen 4

Total head loss
Head loss and form factor per fragment
Pressure distribution on the bottom of the dam
Critical gradient
Exit gradient
Quantity of discharge
Uplift force
Safety factor with respect to piping.

A typical seepage problem illustrating the use of the program has been presented elsewhere (Al-Rawas et al, 1994). Ten randomly selected seepage problems (Fig. 4) are solved by using the program. The quantity of flow, the exit gradient and the uplift force are computed by this technique.

Comparative studies

A study has been undertaken to investigate how the seepage results obtained by the method of fragments and obtained by manual calculations and by the finite difference method are compared. The ten randomly selected seepage problems are shown in Fig. 4 as solved here by the three methods. The normalized quantity of flow (Q/kh_L per meter width), the maximum exit gradient (i_{exit}) and the uplift force (kN per m width) are computed by these methods. The values of these three parameters computed for these ten problems, are presented in Tables 1 and 2, and Fig. 5. The percentage differences are

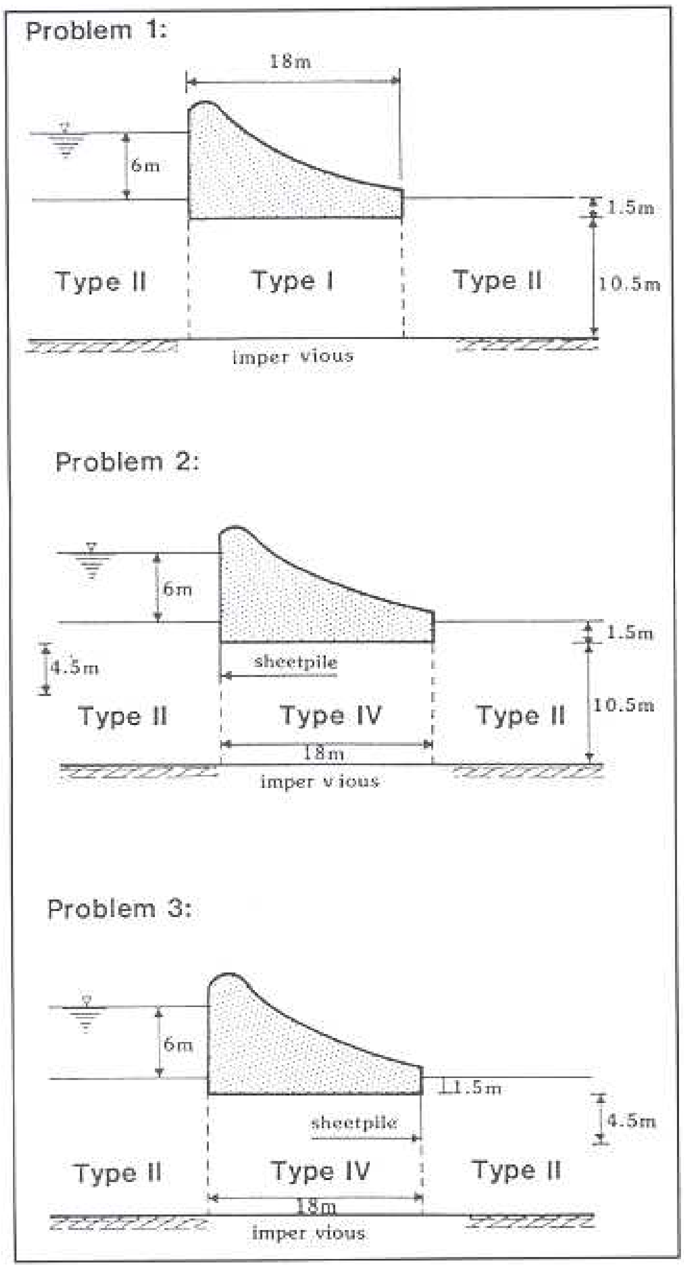


Figure 4a. Seepage problems.

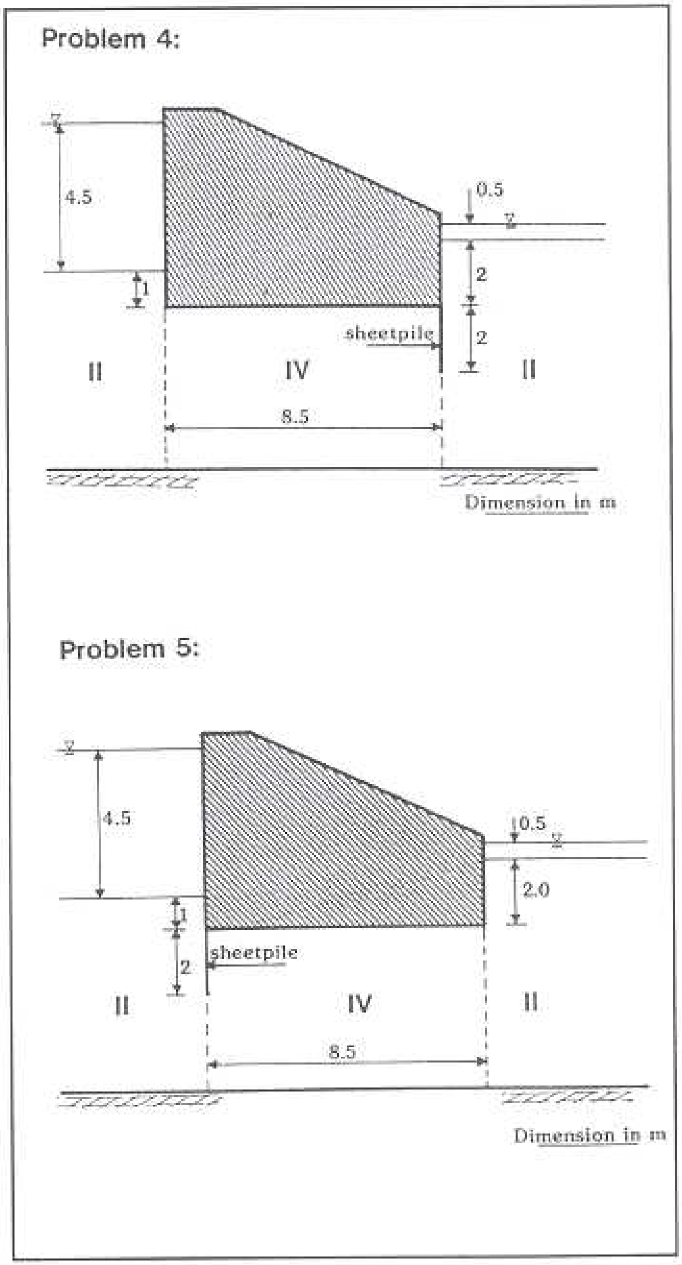


Figure 4b. Seepage problems.

TABLE 1

Results from flow net method, modified method of fragments and finite difference method

No.*	Flow Net Method			Modified Method of Fragments			Finite Difference Method		
	Q/kh_L per m	i_{exit}	uplift kN/m	Q/kh_L per m	i_{exit}	uplift kN/m	Q/kh_L per m	i_{exit}	uplift kN/m
1	.33	.44	796	.36	.48	795	.34	.34	740
2	.29	.38	681	.29	.39	661	.26	.24	556
3	.29	.19	908	.29	.18	928	.29	.12	884
4	.25	.15	327	.28	.14	323	.28	.14	305
5	.25	.19	267	.28	.19	269	.28	.19	266
6	.50	.31	–	.50	.25	–	.45	.23	–
7	.36	.38	323	.37	.48	329	.34	.46	275
8	.36	.40	822	.33	.45	834	.28	.40	847
9	.27	.33	660	.27	.30	748	.23	.26	591
10	.29	.14	1570	.30	.16	1683	.27	.12	1315

* Seepage problems

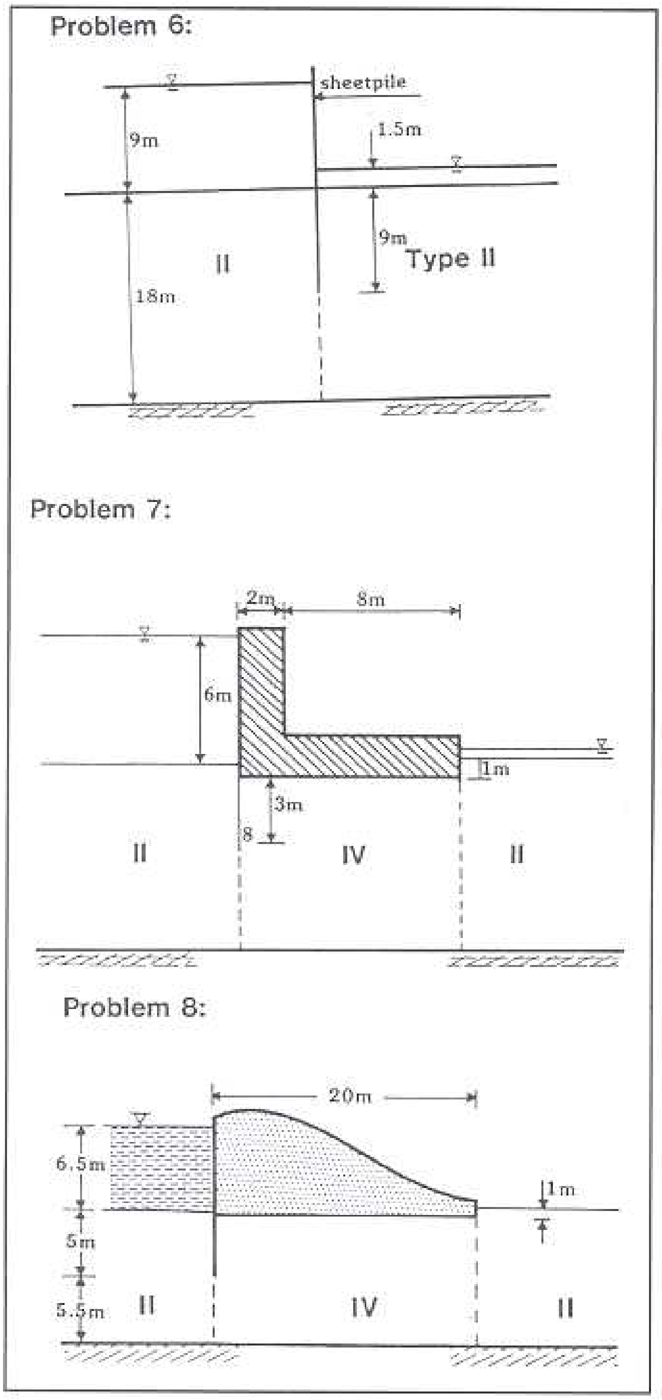


Figure 4c. Seepage problems.

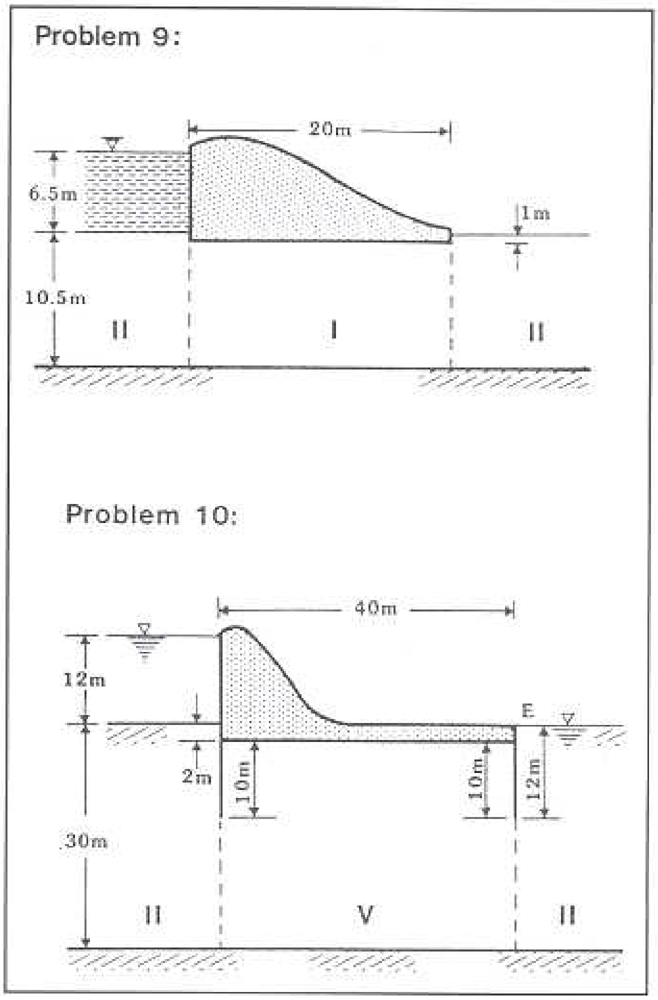


Figure 4d. Seepage problems.

computed using the values computed from the flow net method as the reference.

COMPARISON OF RESULTS OBTAINED BY FLOW NET METHOD AND MODIFIED METHOD OF FRAGMENTS: The values of the quantity of flow, the maximum exit gradient and the uplift force, computed by these two methods are compared in Fig. 5. The values of quantity of flow predicted by both methods, showed an excellent agreement. The differences are less than 5% for all the ten problems. The data points presented in Fig. 5a indicate that a linear relationship can be obtained between the two methods with a coefficient of correlation of 0.97. The values of maximum exit gradient predicted by both methods, compared reasonably well. The differences are within 6% for most of the cases, but, they were within 10% for all the ten cases. Figure 5b shows the scatter of the points which reveals a general linear trend. The coefficient of correlation is 0.96. In a few cases, where the differences are large, the method of fragments predicts higher values for the exit gradient, leading to a conservative solution to the problems. The values of the uplift forces computed by the two methods showed an excellent agreement for all the ten cases, Fig. 5c. The average difference between the values computed by the two methods is less than 5%.

COMPARISON OF RESULTS OBTAINED BY FLOW NET METHOD AND FINITE DIFFERENCE METHOD: The values of the quantity of flow, the maximum exit gradient and the uplift force, computed by these two methods are also compared in Fig. 5. The values of quantity of flow predicted by both methods, compared reasonably well, Fig. 5a. The average difference for most cases is within 7%, but, it is less than 10% for all the cases. The coefficient of correlation of these points is 0.91. The

TABLE 2

Percentage difference of the values given in Table 1.

No.	Flow Net Method versus Modified Method of Fragments			Flow Net Method versus Finite Difference Method		
	Q/kh_L	i_{exit}	uplift	Q/kh_L	i_{exit}	uplift
1	-9.0	-9.1	0.1	-3.0	22.7	7.0
2	0.0	-2.6	2.9	10.3	36.8	18.4
3	0.0	5.2	-2.2	0.0	36.8	2.6
4	-12.0	6.6	1.2	-12.0	6.6	6.7
5	-12.0	0.0	-0.7	-12.0	0.0	0.4
6	0	19.4	-	10.0	25.8	-
7	-2.7	-26.3	-1.8	5.5	-21.0	14.8
8	8.3	-12.5	-1.5	22.2	0.0	-3.0
9	0.0	9.1	-13.3	14.8	21.2	10.4
10	-3.4	-14.3	-7.2	6.8	14.3	16.2

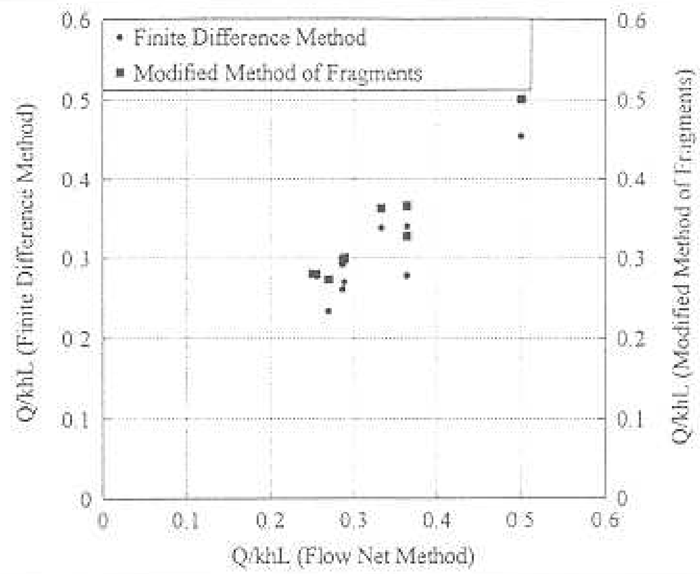


Figure. 5a Predicted values of quantity of flow.

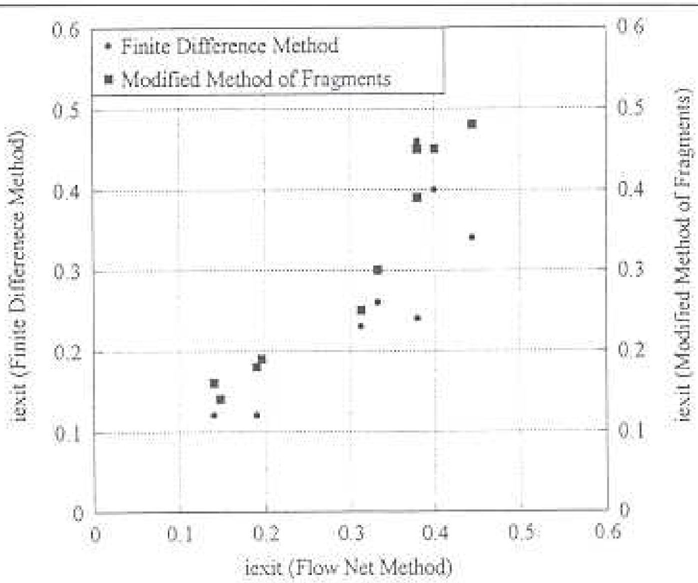


Figure 5b. Predicted values of maximum exit gradient.

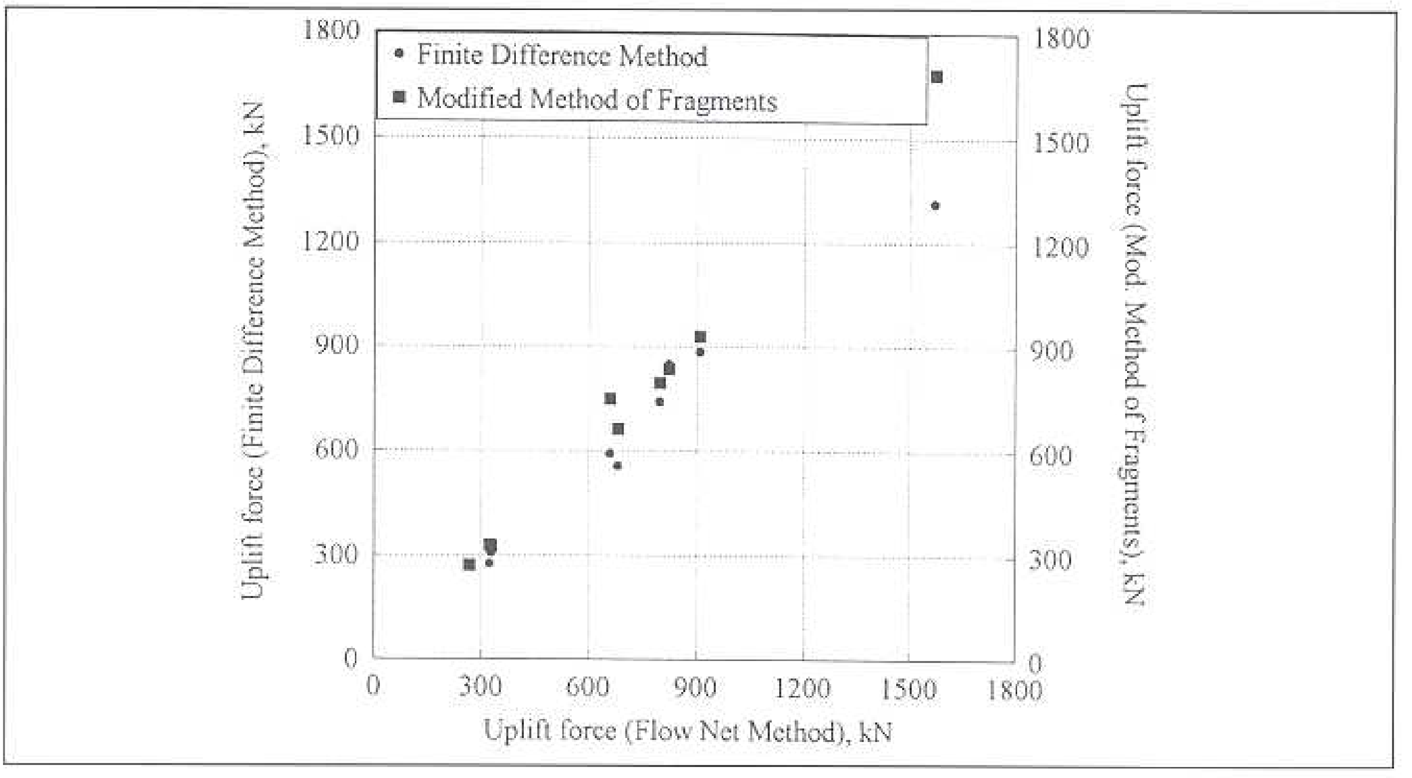


Figure 5c. Predicted values of uplift force.

uplift forces computed by the two methods show a very good agreement. The percentage differences are less than 10% for all the ten cases. The data points show a well defined linear trend, Fig. 5c.

Effect of sheet piles and aprons

The method of fragments has been used to study the effect of different positions and lengths of sheet piles, number of sheet piles and aprons on the quantity of flow, exit gradient and uplift force under a concrete dam. The dam selected is shown in Fig. 6.

SHEET PILES: The quantity of flow (Q/kh_L per m), exit gradient (i_{exit}) and uplift force (kN per m width) have been computed for different positions and lengths of a single sheet pile for the dam shown in Fig. 6. The values computed are given in Table 3 and Fig. 7. For a specific length of sheet pile, the quantity of flow is relatively the same for all the values of x. However, the exit gradient is significantly reduced by about 35% when the sheet pile is moved to the downstream end of the dam. The uplift force increases slightly with the increase of x, but this increase was only 10% at the downstream end of the dam. From these results, it is clear that the downstream end of the dam is the best position for placing a single sheet pile. The study revealed that the larger the length, the lower are the quantity of flow and exit gradient as shown in Figs. 7a and 7b, respectively. The uplift force increases with the length, but only slightly, as shown in

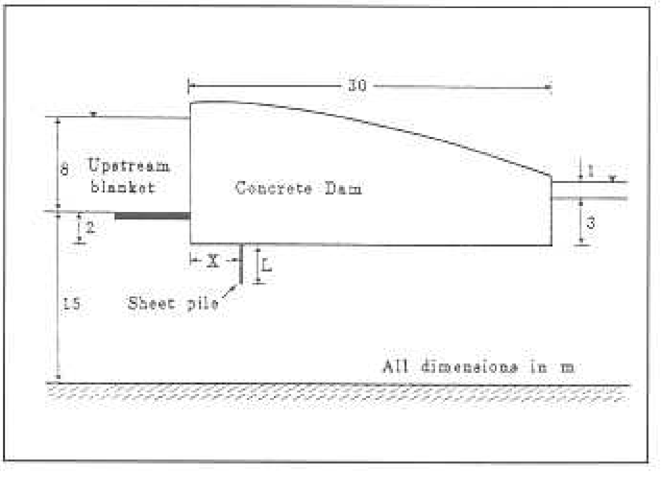


Figure 6. Concrete dam with a single sheet pile.

TABLE 3

Computed values for different positions of a single sheet pile.

x (m)	Q/kh_L (per m)	i_{exit}	Uplift (kN per m)
0	0.261	0.231	1842.4
5	0.281	0.249	1931.8
10	0.281	0.249	1950.9
15	0.281	0.249	1970.9
20	0.281	0.249	1991.1
25	0.281	0.249	2011.5
30	0.263	0.146	2092.6

Fig. 7c. The selection of the length may be governed by the economic considerations and design requirements. Furthermore, it was also found that there is no advantage in providing a sheet pile in addition to the one provided at the downstream end of the dam.

APRONS: The quantity of flow, exit gradient and uplift force have been computed for different lengths of upstream blanket as shown in Fig. 7. From Figs. 7a and 7b, it is clear that both the quantity of flow and exit gradient decrease slightly when the length of the blanket is increased. This decrease is much less than that observed in the case of the sheet pile. The uplift force increases slightly with the increase of the length of the blanket (Fig. 7c). From all these results, it evident that the upstream blanket is less effective in reducing the quantity of flow and exit gradient than the sheet pile.

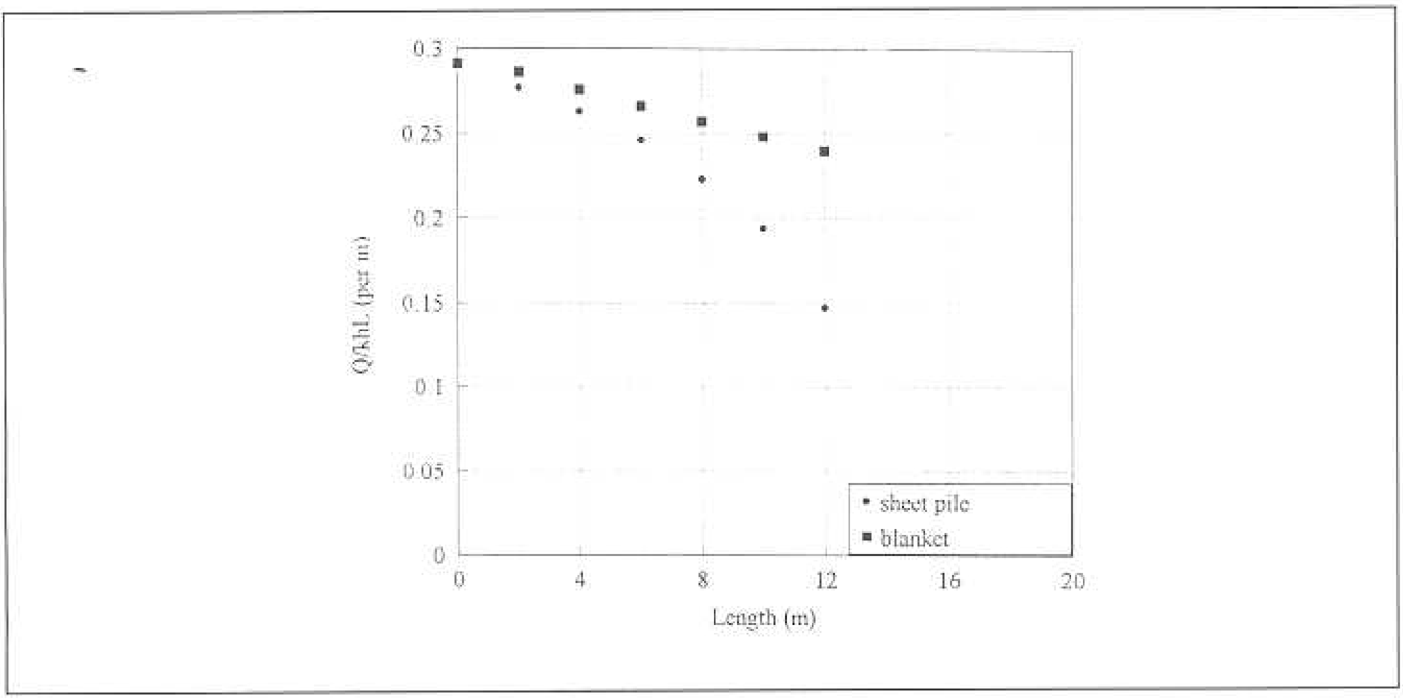


Figure 7a. Quantity of flow versus length.

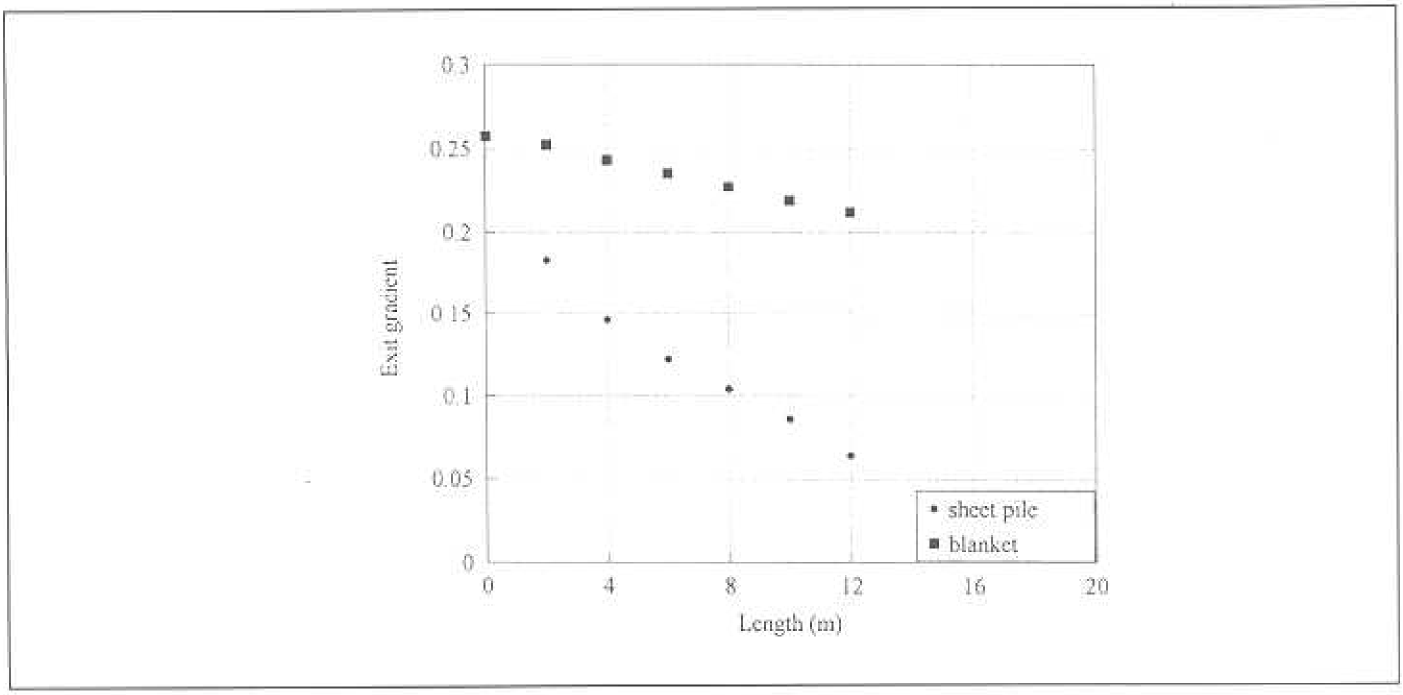


Figure 7b. Predicted values of uplift force.

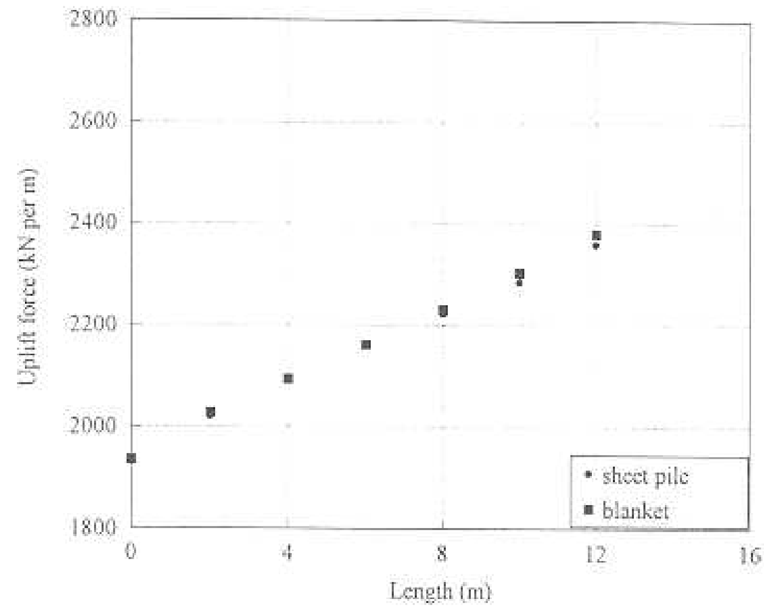


Figure 7c. Upligt force versus length.

Effect of varying dimensions of a dam

The effect of varying the width and depth of the dam shown in Fig. 8 on the computed values of the quantity of flow has been studied. Figure 9a examines the relationship between the quantity of flow and the depth of the dam for four cases, each one with constant width. From the results, it is clear that Q/kh_L decreases when the depth of the dam is increased.

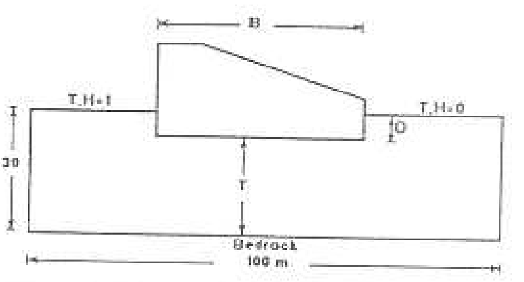


Figure 8. Outline dimensions of a dam.

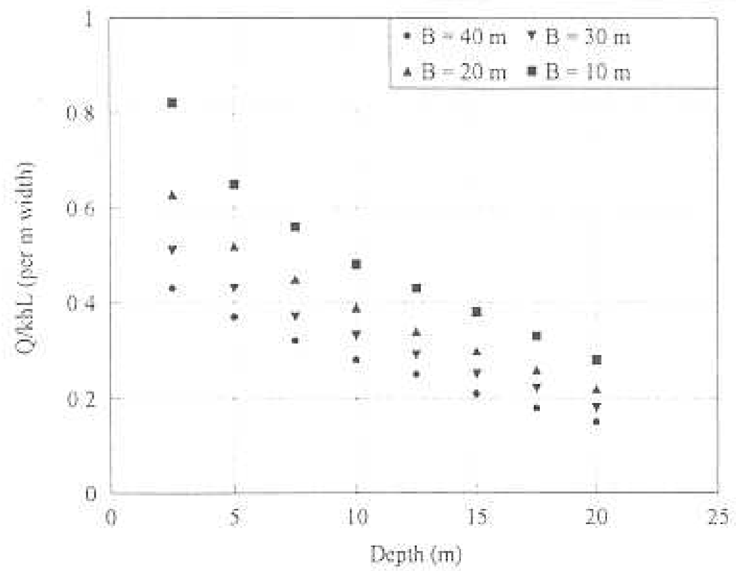


Figure 9a. Quantity of flow versus depth.

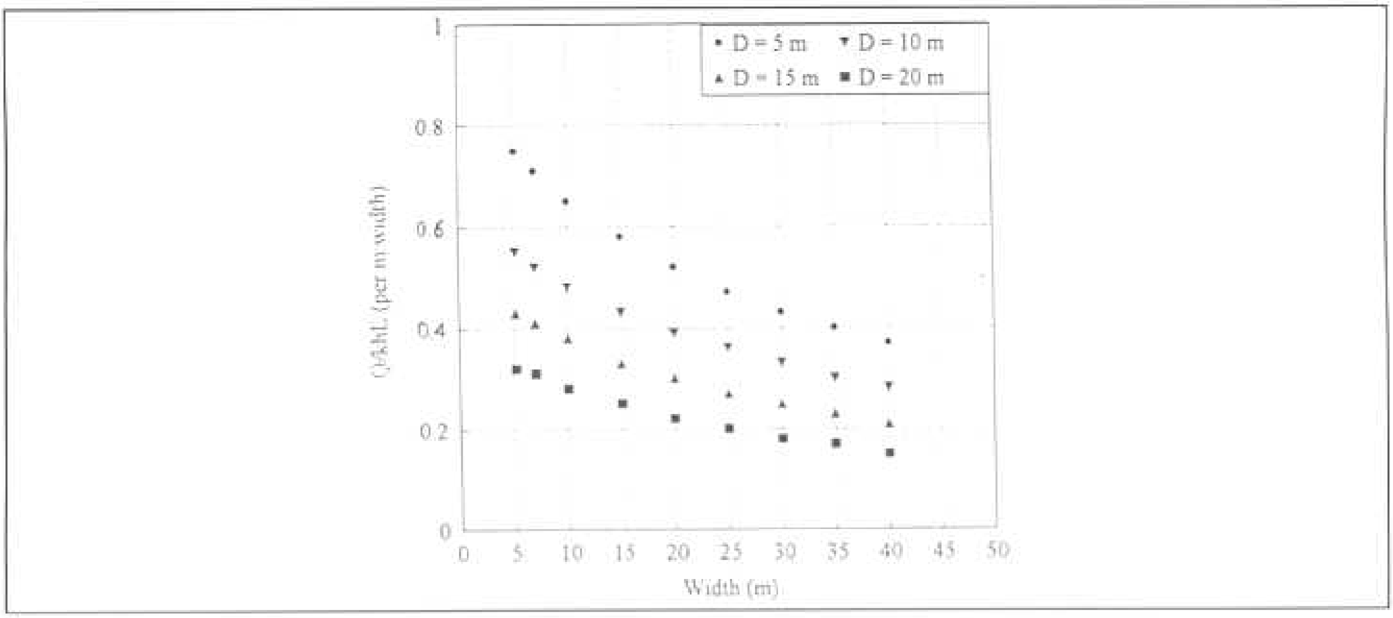


Figure 9b. Quantity of flow versus width.

Figure 9b examines the relationship between the quantity of flow and the width of the dam for four cases, each one with constant depth. It shows that Q/kh_L decreases when the width of the dam is increased.

Conclusions

It has been established that the modified method of fragments computer program provides a quick solution for the seepage problems and that the procedure is very simple. The study showed an excellent agreement between the calculations performed manually by the finite difference method and by the program. It has been shown from the present study that the modified method of fragments gives very comparable predictions of the quantity of flow, exit gradient and uplift force for the ten randomly selected seepage problems.

The study confirmed that the downstream end of the dam is the best position for placing a single sheet pile. Furthermore, there is no advantage in providing a sheet pile in addition to the one provided at the downstream end of the dam. It is also confirmed that the upstream blankets are less effective in reducing the quantity of flow and exit gradient than the sheet piles.

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