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SEEPAGE CALCULATION FOR OFFSHORE BUND DESIGN

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SYPNOSIS

The paper presents a dimensionless seepage chart for rapid estimation of the quantity of seepage for offshore homogeneous bunds. The bund cross section is trapezoidal on an impervious foundation where a finite tailwater is an essential feature in the boundary conditions. The method was developed from Dupuit's assumptions for a hypothetical dam with vertical faces and calibrated with finite elements. The chart gives a quick and simplified approach for obtaining seepage quantity. In comparison to finite element generated flownet and electric analog solutions, the method gives an average error of 3% and 4% respectively. Input variables are upstream and downstream slopes, permeability of bund material, both headwater and tailwater elevation and crest width. The method allows a reliable estimate of flow rate to be made for a wide range of unconfined flow problems, of practical interest in offshore bund design and in particular for waste disposal containment bunds in an offshore environment.

INTRODUCTION

One of the major environmental problems facing land-scarce countries such as Japan and Singapore with their high population density and growing industrial and commercial activities is the lack of suitable sites on land for waste disposal in response to the steadily increasing amount of wastes being produced. Constructing offshore earth bunds for use as waste storage is an increasingly viable option. In fact it has already been done in Japan (Aboshi, 1991) and is expected to be a popular alternative in the future elsewhere.

The construction of earth bunds for waste disposal offshore is constrained by the type of materials that can be used. Furthermore there is always the economic factor to consider. Thus to satisfy both the technical and economic requirements, a delicate balance has to be struck at the design stage. Therefore rapid estimation of the various design parameters will be of tremendous help to the design engineer.

Without doubt seepage flow is one of the most important design parameters that needs to be considered in containment bund design. The appropriate seepage flow for offshore bund design as calculated from seepage charts have been developed

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by the authors. The seepage charts are appropriate for homogeneous offshore bunds where a finite tailwater is a common feature.

BACKGROUND OF AVAILABLE METHODS FOR SEEPAGE FLOW ESTIMATION

The amount of seepage through dams and water-retaining structures has always been an important design consideration for geotechnical engineers.

For steady state conditions, the head within a soil mass with known boundary conditions is governed by Laplace's equation :

$$k_H \frac{\partial^2 h}{\partial x^2} + k_v \frac{\partial^2 h}{\partial y^2} = 0 \qquad (1)$$

and a wide variety of methods exists for its solution. The methods include analytical solutions using conformal mapping and complex variables (Pavlovsky, 1933; Harr and Deen, 1961; Polubarinova-Kochina, 1962; Harr, 1962; Verruijt, 1970), analogue methods (Aravin and Numerov, 1965) and stochastics analyses (Harr, 1977; Smith and Freeze, 1979). However the best known method in soil mechanics is flow net sketching. Although flow net sketching is a powerful and versatile method in experienced hands, it can be time consuming and the accuracy is sometimes difficult to assess.

In the last few decades researchers have made attempts to provide a more rapid approach in seepage flow calculation. Various approximate approaches for solving both confined (Griffith, 1984) and unconfined (Lo, 1971; Stello, 1987) seepage flows in the form of seepage charts have been developed. But in the latter case, tailwater has always been neglected in the analyses since the methods are meant for land-based dams. This paper attempts to show another simplified approach in calculating the quantity of unconfined flow in the form of charts for cases where the tailwater is non-zero as in the case of offshore bunds. The charts are developed based on the Dupuit's theory of a hypothetical dam with vertical faces and calibrated with the help of finite element analyses, using the PC-SEEP software developed by GEO-SLOPE (Krahn et al, 1987). For the examples considered the results are shown to be at least as accurate as those determined using methods such as finite difference and hydraulic models.

DUPUIT'S THEORY ON COMPUTATION OF UNCONFINED SEEPAGE FLOW

Dupuit first proposed his theory in 1863 (Dupuit, 1863) by looking at a hypothetical dam with vertical faces as illustrated in Fig. 1. In his theory Dupuit relies on two important assumptions :

i) For small inclination of line of seepage the stream line can be taken as

horizontal (hence the equipotential lines approach the vertical).

ii) The hydraulic gradient is equal to the slope of the phreatic surface and is invariant with depth.

Dupuit's method is a powerful approximation to obtaining seepage quantities in free surface problems and studies of Dupuit's theory on dams with vertical sides have been well documented. Several versions of the rigorous analytical solution on Dupuit's theory in flow estimation exist in the literature, they differ only in form but yield the same numerical result. The first version is found in Muskat (1937). A comprehensive numerical evaluation of this version was made by Chapman (1957). The second version with numerical evaluation can be found in Polubarinova-Kochina (1952).

It is obvious that Dupuit's assumptions simplify the problem of unconfined flow considerably. By making an approximation such that the hydraulic gradient is equal to the slope of the phreatic surface, i.e. :

$$i = \frac{\Delta y}{\Delta x}$$

the seepage per unit width between the two vertical faces for steady state flow (refer to Fig. 1) can then be obtained as follows :

Applying Darcy's law; $q = k\, i\, A$

$$q = k \left(\frac{dy}{dx}\right) (y \times 1)$$

Integrating and substituting the boundary conditions $x = 0$, $y = Hh$ and $x = D$, $y = Ht$, yields the Dupuit's formula

$$q = \frac{k\,(Hh^2 - Ht^2)}{2D} \qquad (2)$$

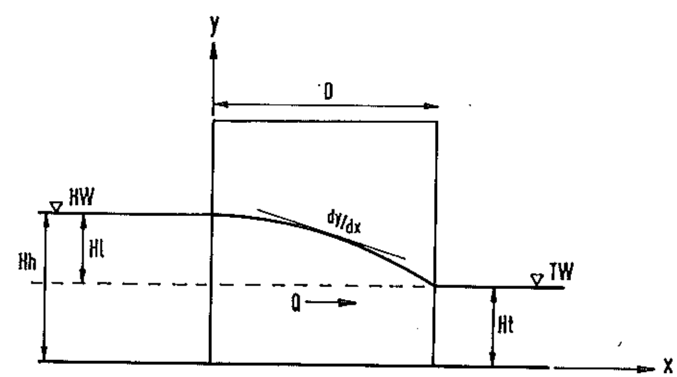

Fig. 1 Vertical face bund with finite tailwater.

THE PRESENT METHOD FOR A HOMOGENEOUS BUND

The direct application of Dupuit's theory to the problem of seepage flow through dams of trapezoidal corss section is not realistic due to its limitations. This is because in the derivation of Dupuit's formula, no cognizance has been taken of the entrance or exit conditions of the line of seepage or of the development of a surface of seepage. Also, it should be noted that both the discharge quantity and the locus of the free suface are independent of the slopes of the dam. As such, large errors can be expected and the need for a correction factor when using approximate methods based on Dupuit's formula has long been recognized (Harr, 1962).

By first modifying the geometry i.e. transforming the trapezoidal bund into an equivalent vertical face bund, a more accurate approximation can be achieved.

The concept of the present method is to transform a bund of normal trapezoidal cross section to an equivalent hypothetical bund with vertical faces of similar bund height, HB as illustrated in Fig. 2. The case of an isotropic homogeneous bund of trapezoidal geometry on an impermeable foundation was first considered where the boundary conditions for the flow region consist of a headwater on the upstream slope of value Hh and a tailwater of value Ht. Chapman (1957) has shown that the height of seepage surface, or as it is more commonly known, the position of exit point of line of seepage, decreases as the ratio of width to depth of the bund system increases, and rapid reduction in this height occurs as the downstream tailwater height Ht is increased. When Ht is greater than 0.5 Hh, the shape of the seepage surface is negligible and the position of exit point of the line of seepage essentially coincides with that of the downstream tailwater height Ht. As such Dupuit's assumption of a relatively flat phreatic surface can be well adapted to the present analysis for the case of the offshore bund. By taking the total flow in both systems to be equal and applying the same boundary conditions of headwater Hh and tailwater Ht to the transformed bund the problem then reduces to one of obtaining the corresponding equivalent 'Dupuit's width Du of the transformed bund. The finite element software PC-SEEP (Krahn et al, 1987) was used to compute the flow magnitude of the trapezoidal dam. The equivalent 'Dupuit's width Du of the transformed bund can then be obtained from Equation (2).

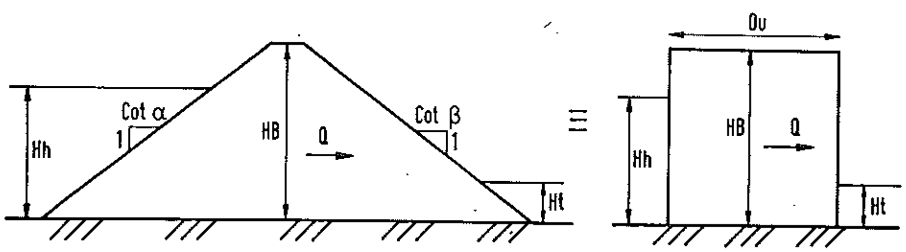

Fig. 2 The present concept of transforming trapezoidal bund to vertical face bund.

Using a model with a bund of triangular geometry i.e. of zero crest width and varying the downstream slopes (Cot β) with respect to a constant upstream slope (Cot α), a linear relationship between the dimensionless ratio of 'Dupuit's equivalent width over the bund height Du/HB and the downstream slope (Cot β) was revealed as shown in Fig. 3. For a trapezoidal bund of known crest width, the plotted relationship in Fig. 3 is then adjusted by adding the crest width of the trapezoidal bund into the equivalent 'Dupuit's width Du as obtained from Fig. 3. Thus for an isotropic homogeneous bund of known upstream and downstream slopes and flow boundary conditions, the seepage flow is estimated using Fig. 3 and substituting in the respective values into Equation (2). The procedure, consisting of four steps, is illustrated in Fig. 4. For an anisotropic soil where the coefficient of permeability of the soil differs in the horizontal and vertical directions, an equivalent isotropic permeability coefficient can be applied in the equation. The equivalent isotropic permeability coefficient can be calculated as follow :

$$k = \sqrt{k_x k_z} \qquad (3)$$

A formal proof of Equation (3) has been given by Vreedenburgh (1936).

The chart in Fig. 3 was developed using an initial assumption that the tailwater height Ht and the total head loss Hl, are both equal to 0.25 of the bund height, HB. Correction factors have been developed for other proportions of tailwater height varying from 0.125 to 0.875 of HB (Fig. 5) and total head loss varying from 0.125 to 0.5 of HB (Fig. 6). For tailwater height less than 0.25 of HB, no correction factors

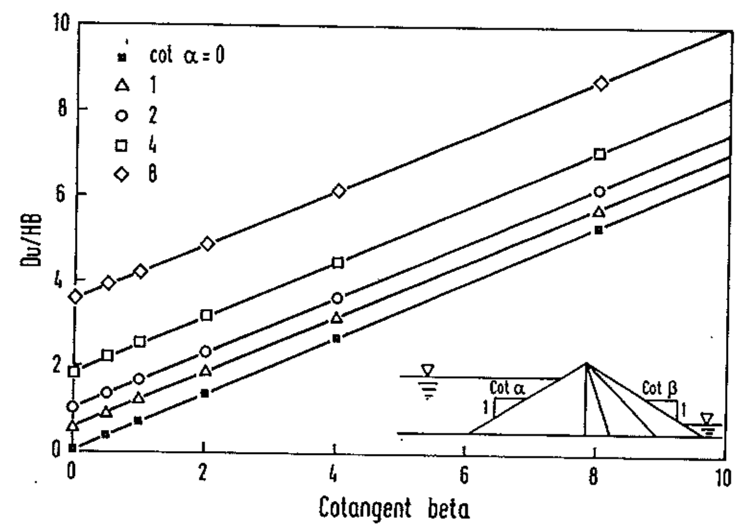

Fig. 3 Relationship between the equivalent Dupuit's width and the slopes of the trapezoidal bund.

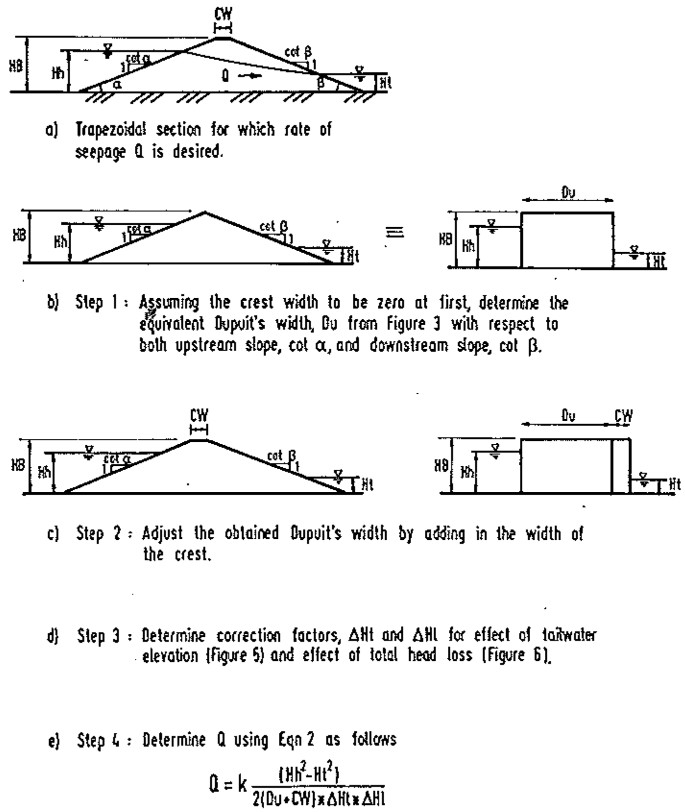

Fig. 4 Schematic of procedure for seepage calculation.

have been determined. This is because when the tailwater shifts towards the zero value, the line of seepage will move closer towards intersecting the impervious boundary (taken to be another stream line), causing Dupuit's assumptions to be significantly violated. For similar reasons the correction factors for total head loss in the range 0.125 to 0.5 of HB only are determined as this represents the practical range of total head loss applicable in the field.

COMPARISON WITH OTHER METHODS

The accuracy of the present approximate solution was assessed by determining the rate of seepage for several examples of trapezoidal shape and by comparing the results in Table 1 with those obtained by the finite element generated flownet and electric analog method. In general, the results obtained by the present method were

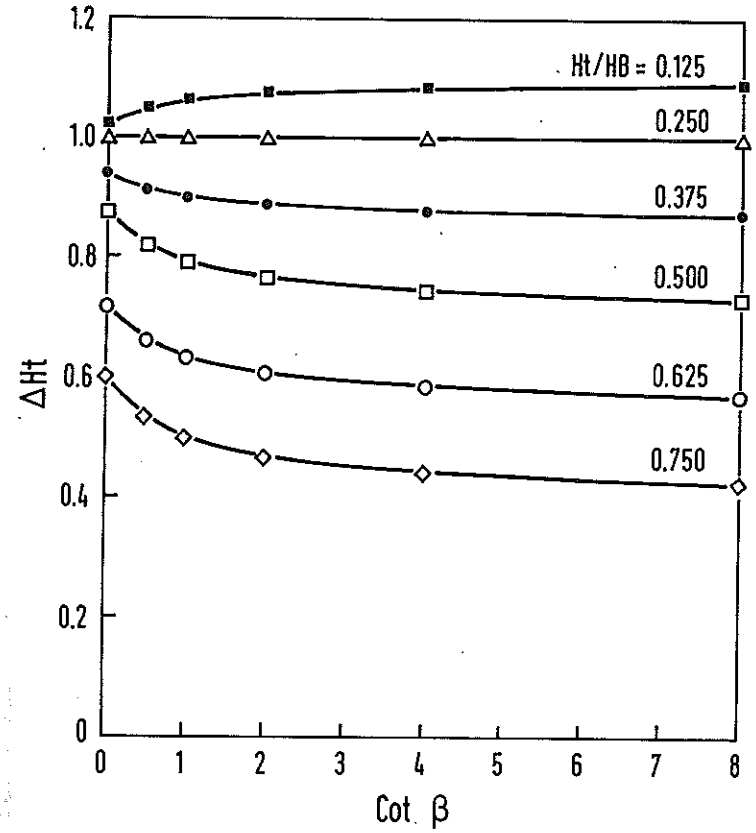

Fig. 5 ΔHt - Correction factor for effect of different tailwater elevation from a Ht/HB ratio of 0.25.

found to be in good agreement with the other results, giving an average error of 3% and 4% respectively.

ASSESSMENT OF THE FINITE ELEMENT SOFTWARE : PC-SEEP

The accuracy of the present method depends almost exclusively on the reliability of the finite element software PC-SEEP in computing the flow magnitude in which the present analysis made use of. A comparison of the flow magnitude from published flownets by Cedergren (1977) against those produced by PC-SEEP shows good agreement. Apart from this, further studies were carried out, to compare the contour plots of equipotentials produced by PC-SEEP with those obtained from electric analog by the authors. The comparisons are given in Fig. 7 which shows very close agreement between the two methods.

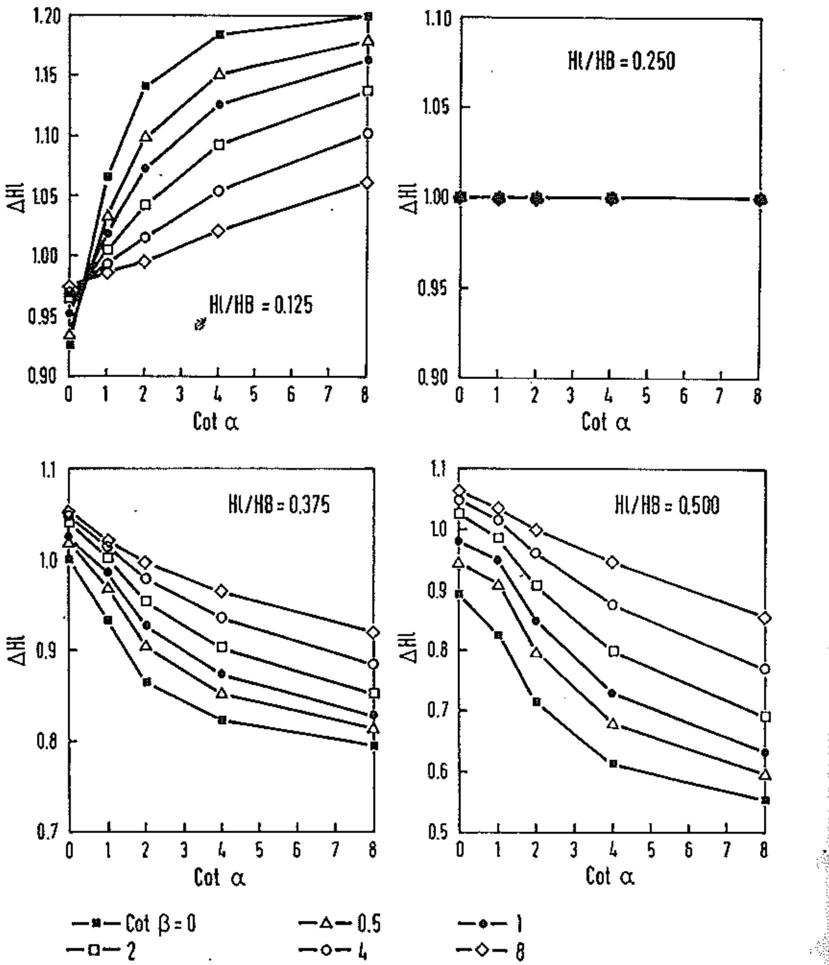

Fig. 6 ΔHl - Correction factor for effect of different total head loss from a Hl/HB ratio of 0.25.

SUMMARY AND CONCLUSIONS

Seepage through homogeneous isotropic bunds of trapezoidal cross section which feature a finite tailwater is estimated using a method based on Dupuit's theory. A trapezoidal bund is transformed into an equivalent model with a vertical face. Using the computed results, the equivalent Dupit's width can be obtained from a simple chart as shown in Fig. 3. A comparison of the solutions obtained with both the flownet and electric analog method shows that the results give an average error of 3% and 4% respectively.

Table 1 Comparison of solutions for rate of seepage obtained by three different methods.

Example number	1	2	3	4	5	6
Input variables						
Upstream slope Cot α	4	1	2	1	1	8
Downstream slope Cot β	6	4	2	0	1	4
Crest width CW (m)	10	15	5	0	0	10
Bund height BH (m)	20	20	20	20	20	20
Headwater Hh (m)	12.5	17.5	12.5	5	15	10
Tailwater Ht (m)	5	10	7.5	2.5	5	5
Permeability k (m/s)	1e-09	1e-05	1e-03	1e-07	1e-06	1e-08
Dimensionless parameter						
Du/Bh	5.76	3.18	2.33	0.57	1.19	6.20
Correction factors						
Tailwater elevation ΔHt	1	0.741	0.887	1.023	1	1
Total seepage head ΔHl	0.945	1.013	1	1.065	0.948	1
Seepage quantity Q/k						
Present method	0.553	1.748	1.092	0.755	4.432	0.279
Flownet analysis	0.538	1.692	1.079	0.760	4.362	0.285
% of error	+2.80	+3.31	+1.20	−0.66	+1.61	−2.10
Electric analog	0.525	1.689	1.063	0.722	4.585	0.268
% of error	+5.33	+3.50	+2.73	−4.57	−3.33	+4.10

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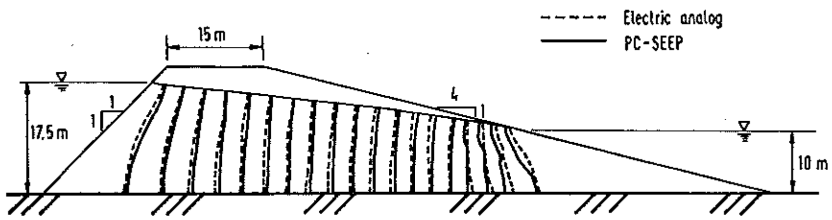

Fig. 7 Comparison of eletric analog solution with PC-SEEP for contour plots of equipotential lines.

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