INTERPRETATION OF IN SITU PERMEABILITY TESTS ON ANISOTROPIC DEPOSITS

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To caluclate the permeability of a soil from the results of in situ constant- or variable-head tests, one must know the intake factor for the porous tip used. The intake factor for a cylindrical tip of a piezometer is a function of its length and diameter only. No rigorous relationship has yet been derived, but an accurate empirical formula based on the best fit and previously published numerical solutions expresses the intake factor in a dimensionless form as a function of the ratio of the length to diameter of the tip. When tests are carried out in a horizontally bedded cross-anisotropic deposit (e.g., a laminated lacustrine clay), the permeability, calculated by assuming isotropy, will have a value intermediately between the horizontal and vertical permeabilities. If the ratio of these permeabilities is known from laboratory or other tests, a correction factor may be applied to the permeability (assuming isotropy) to determine the coefficients of permeability in the horizontal and vertical directions. The correction factor, which is a function of both the ratio of intake length to intake diameter and the ratio of the coefficient of the permeability in the horizontal position to that in the vertical position, is presented in graphical form to enable quick determination of the directional permeabilities.

THE RATE of consolidation of a layered clay deposit may be significantly affected by horizontal drainage ($\underline{1}$), and accurate predictions of rates of consolidation in such deposits require determination of values of vertical and horizontal coefficients of permeability in the horizontal and vertical direction respectively (assuming use of a cross-anisotropic soil).

The notation used in this paper is as follows:

A = cross-sectional area of the standpipe bore,
c_x = coefficient of consolidation in the horizontal direction,
c_z = coefficient of consolidation in the vertical direction,
D = diameter of the intake of the cylindrical piezometer,
F = intake factor for the piezometer in an isotropic deposit,
F_t = intake factor for the piezometer in a cross-anisotropic deposit,
H = excess head in a constant-head permeability test,
k = coefficient of permeability in an isotropic deposit,
k_i = coefficient of permeability assuming isotropy,
k_x = coefficient of permeability in the horizontal direction,
k_z = coefficient of permeability in the vertical direction,
k_e = equivalent coefficient of permeability ($k_e = \sqrt{k_x/k_z}$),
L = length of the intake of the cylindrical piezometer,
m = dimensionless ratio ($m = \sqrt{k_x/k_z}$),

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q_∞ = steady state discharge,
T = basic time lag,
z = vertical coordinate,
z' = transformed vertical coordinate, and
λ = dimensionless correction factor ($\lambda = k_x/k_1$).

Most in situ permeability tests are interpreted by assuming isotropy of permeability (3, 8). The permeability of a soil may be calculated from the results of variable-head permeability tests from the standard expression

$$k = \frac{A}{F \cdot T} \qquad (1)$$

From the results of constant-head tests more commonly used in the United Kingdom, k may be calculated by using the technique proposed by Gibson (4):

$$k = \frac{q_\infty}{F \cdot H} \qquad (2)$$

INTAKE FACTOR FOR ISOTROPIC DEPOSITS

Hvorslev (2) suggested that for isotropic homogeneous soil the intake factor could be calculated from

$$F = \frac{2\pi L}{\ln\left[\frac{L}{D} + \sqrt{1 + \left(\frac{L}{D}\right)^2}\right]} \qquad (3)$$

This was derived on the basis of work by Dachler (5), who studied the flow from a line source for which the equipotential surfaces were semiellipsoids. Hvorslev assumed that the flow lines were symmetrical through the center of the intake of the piezometer, with respect to a horizontal plane, and then he applied Dachler's solution for the upper and lower half of the intake. Therefore, Eq. 3 can only provide approximate values of intake factors when it is applied to a cylindrical intake.

Al-Dhahir and Morgenstern (6) published intake factors for cylindrical piezometers of various L/D ratios. Their analysis was based on the numerical integration of Laplace's equation. They pointed out that the presence or absence of an impervious borehole filling above the seal over the piezometer had an insignificant effect on the value of the intake factor. Therefore, their analysis could be applied to both cases shown in Figures 1a and 1b. They produced solutions for four different ratios of L/D and plotted the results in the dimensionless form of F/D against L/D.

Wilkinson (7) argued that Hvorslev's formula (Eq. 3) underestimated intake factors and suggested that to obtain a more exact equation a cylindrical piezometer could be represented by a spheroid, which had its minor diameter and volume equal to those of the piezometer. The equation derived was

$$\frac{F}{D} = \frac{3\pi \cdot \frac{L}{D}}{\ln\left[1.5\frac{L}{D} + \sqrt{1 + \left(1.5\frac{L}{D}\right)^2}\right]} \qquad (4)$$

In Figure 2, the values of Al-Dhahir and Morgenstern are compared with the curves given by Eqs. 3 and 4. It appears that Hvorslev's method underestimates the intake

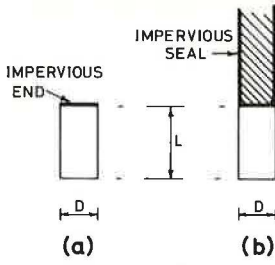Figure 1. Cylindrical intakes.

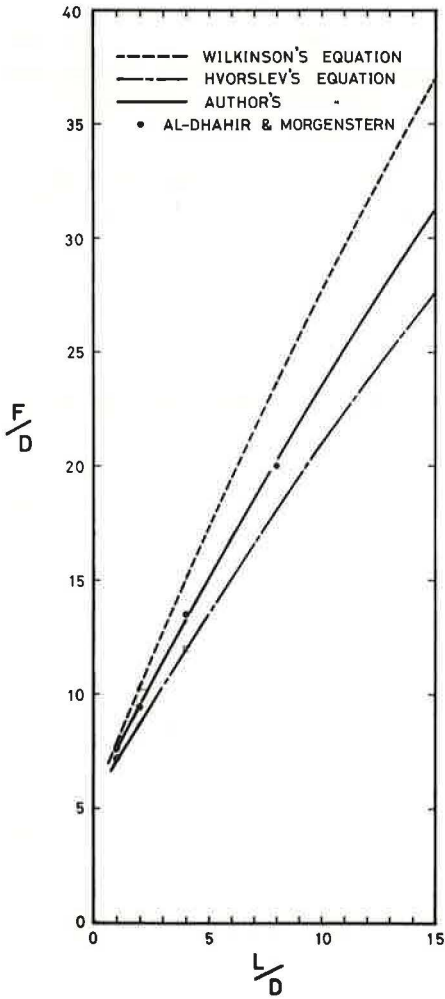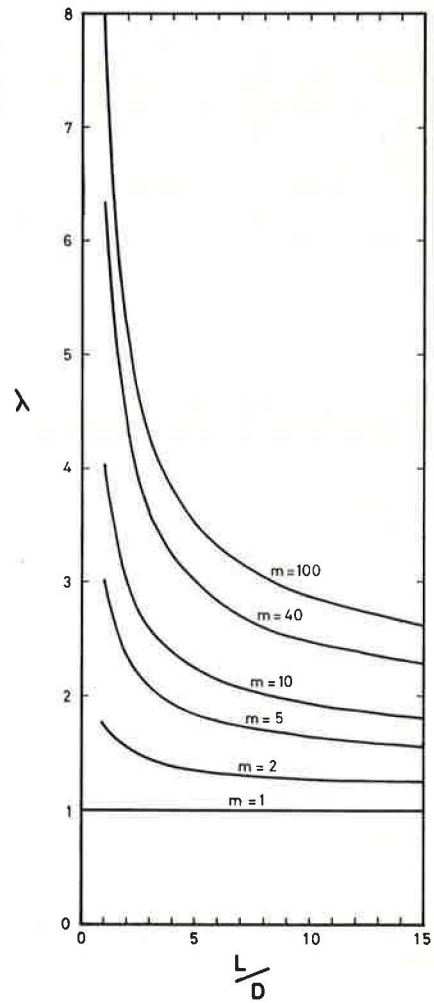Figure 2. F/D versus L/D for various equations.

Figure 3. λ versus L/D for six m values.

factors and Wilkinson's overestimates them because the numerically derived values of Al-Dhahir and Morgenstern lie almost midway between them.

By retaining the form of Eqs. 3 and 4 and by simply adjusting the constants to give the best fit to the numerical solutions, one obtains

$$\frac{F}{D} = \frac{2.32\pi\frac{L}{D}}{\ell n\left[1.1\frac{L}{D} + \sqrt{1 + \left(1.1\frac{L}{D}\right)^2}\right]} \tag{5}$$

This is likely to be the most precise formula available for determining the intake factors of cylindrical piezometers.

ANISOTROPIC PERMEABILITY

In a laminated clay in which thin layers of clay are interbedded with thin layers of silty or sandy soil, there may be a high degree of anisotropy. If these layers are numerous and make up a uniform structure that is of a thickness significantly greater than the length of the piezometer buried in it, then it is permissible to treat the deposit as homogeneous and anisotropic (7).

Consider the length and diameter of a cylindrical piezometer buried in a thick stratum of cross-anisotropic soil having permeabilities k_z and k_x. By using the standard method of transformation of the vertical scale:

$$z' = mz \tag{6}$$

The problem of flow into the piezometer may be solved by considering a piezometer of length mL in an isotropic soil of permeability:

$$k_e = \sqrt{k_x \cdot k_z} \tag{7}$$

so that

$$k_x = mk_e \tag{8}$$

and

$$k_z = \frac{k_e}{m} \tag{9}$$

The intake factor may be expressed in terms of the transformed dimension, and Eq. 5 becomes

$$\frac{F_t}{D} = \frac{2.32\pi m\frac{L}{D}}{\ell n\left[1.1\,m\frac{L}{D} + \sqrt{1 + \left(1.1\,m\frac{L}{D}\right)^2}\right]} \tag{10}$$

The value of m may not be known at the time that an in situ permeability test is carried out, and the coefficient of permeability will be calculated from Eqs. 1 or 2, assuming isotropic conditions, by using Eq. 5 to determine the intake factor. The value so calculated, k_i, is neither equal to k_z nor k_x.

From Eqs. 1, 2, 5, and 10, it follows that

$$\frac{k_x}{k_i} = \frac{mk_e}{k_i} = \frac{mF}{F_t} = \frac{\ell n \left[1.1\,m\frac{L}{D} + \sqrt{1 + \left(1.1\,m\frac{L}{D}\right)^2}\right]}{\ell n \left[1.1\frac{L}{D} + \sqrt{1 + \left(1.1\frac{L}{D}\right)^2}\right]} \tag{11}$$

Putting $\lambda = mF/F_t$, Eqs. 8 and 9 become

$$k_x = \lambda k_i \tag{12}$$

and

$$k_z = \frac{\lambda k_i}{m^2} \tag{13}$$

Values of λ calculated from Eq. 11 are plotted against L/D in Figure 3 for a range of m values.

The ratio of k_x/k_z may be determined on undisturbed samples in the laboratory. Constant-head permeability tests may be carried out on cube samples (consolidated under the mean in situ effective stress in a triaxial cell) first normal to the bedding planes and then along the bedding planes as described by Chan and Kenney (9). Alternatively, one can perform consolidation tests on large undisturbed samples in a Rowe type of consolidation cell by permitting vertical drainage only and then horizontal drainage only to determine the directional coefficients of consolidation. The permeability ratio is then calculated from the relationship $(k_x/k_z) = (c_x/c_z)$. The actual representative value of k_x/k_z for interpretation of the field tests should be decided on the basis of a total study of the field and laboratory results and a visual study of an undisturbed continuous core taken from a position close to the field test.

It is not the purpose of this paper to discuss sources of error in in situ permeability tests, but spurious results may be obtained if precautions are not taken to avoid smearing of clay soils at the boundary between the porous intake and the soil. Because serious smearing is likely to occur in the case in which the piezometer is pushed directly into the soil, use of the formulas presented is probably unwarranted in such circumstances. Other sources of error are described by Wilkinson (7) and Hvorslev (2).

CONCLUSION

A formula has been derived for calculating the intake factor of any cylindrical intake sealed on its top surface and buried in a homogeneous isotropic soil. When an in situ permeability test is carried out in a horizontally bedded cross-anisotropic deposit, the directional permeabilities may be calculated from the results provided that the ratio of the horizontal to vertical permeabilities is known.

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