NUMERICAL SOLUTIONS OF RATE OF CONSOLIDATION IN LAYERED SOILS

by

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ABSTRACT

The numerical solutions of rate of consolidation in layered soils is studied. The pore water dissipation of compressible deposits is numerically determined based on the finite difference method. The advantegeous attained by the use of vertical drains is mentioned and a computer program is developed for a layered system which is vertically and radially drained.

The loading condition is also investigated and the computer programs for constant loading are further developed to take into account the effects of time-dependent loading. The results of the numerical solutions are compared with the available analytical procedures.

TABAKALI ZEMİNLERDE KONSOLİDASYON HIZINA AİT NÜMERİK ÇÖZÜMLER

ÖZET

Tabakalı zeminlerde konsolidasyon hızına ait nümerik çözümler işlenmiştir. Sıkıştırılabilir kütlelerin boşluk suyu kaçışı nümerik olarak sonlu farklar metoduna göre tanımlanmıştır. Dikey drenajların kullanılmasıyla elde edilen avantajlar anlatılmış ve dikey ve yatay drenajı yapılmış tabakalı sistemler için kompüter programı geliştirilmiştir.

Aynı zamanda yükleme durumları araştırılmış ve zamana bağımlı yüklemenin etkileri de göz önünde bulundurularak sabit yükleme için kompüter programları geliştirilmiştir. Nümerik çözümlerin sonuçları uygun analitik prosedürler ile karşılaştırılmıştır.

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Burak MALKOÇ

TABLE OF CONTENTS

Page

TABLE OF CONTENTS: - (cont'd)

LIST OF FIGURES

LIST OF FIGURES (cont'd)

LIST OF TABLES

LIST OF SYMBOLS

Symbol	Meaning
a, a_v	Coefficient of Compressibility
C_c	Compression Index
C_r	Compression Index for Recompression
C_s	Compression Index for Swelling
C_v	Coefficient of Consolidation
C_{vr}	Radial Coefficient of Consolidation
e	Void Ratio
e_o	Initial Void Ratio
G_s	Spesific Gravity of Soil Solids
h	Depth
h_e	Elevation Head
h_p	Pressure Head
H	Layer Thickness
H_s	Reduced Thickness = H / He
i	Hydraulic Gradient
k, kv	Vertical Coefficient of Permeability
k_h, k_r	Radial Coefficient of Permeability
k_s	Reduced Coefficient of Permeability
M	Dimensionless Factor =

LIST OF SYMBOLS-(cont'd)

Symbol	Meaning
P	Pressure
P_c	Preconsolidation pressure
P_o	Overburden pressure
R	Dimensionless Constant =
r_w	Radius of Well
r_e	Radius of Influence
r_s	Smear Radius
S	Degree of Saturation
t	Time
T, T_v	Dimensionless Time Factor=
T_h	Dimensionless Time Factor for Radial Drainage =
u, u_2	Pore Pressure for Vertical Drainage
u_r	Pore Pressure for Radial Drainage
U	Percent Consolidation
v	Velocity
V_s	Volume of Solids
W_s	Weight of Solids
w_L	Liquid Limit
w_p	Plastic Limit
w	Water Content

LIST OF SYMBOLS - (cont'd)

Symbol	Meaning
ρ	Dimensionless Depth Factor
τ	Arbitrary Time Constant
γ	Unit Weight
γ_s	Unit Weight of Solids
γ_{wo}	Initial Unit Weight of Water
γ_w	Unit Weight of Water
ε	Strain
ε_v	Volumetric Strain
β	Dimensionless Factor $= \frac{C_{vr} \ \Delta T}{(\Delta r)^2}$

I. INTRODUCTION

The water which moves through the pores of any soil under externally applied stresses form an important area of study in geotechnical engineering. Since the permeabilities are rather low, the motion of this pore water does not occur immediately but it takes some times to escape from the compressible layer. As the water is squeezed from the center of the deposit towards the boundary, the pressure increment, is carried by the soil skeleton and a reduction in void ratio occurs. This procedure results in a reduction of thickness which is called as settlement. The amount of settlement is constant for an arbitrary loading and its value depends on the compression index. The coefficient of consolidation is another parameter obtained from a consolidation test. It relates how long will it take place for the total settlement to occur. The consolidation settlement and its time rate solutions are rewieved in the second and third chapters.

The consolidation of two contiguous compressible layers, posessing different consolidation characteristcs, is studied in the fourth chapter. The analytical solution first developed by Hamilton Gray (5) in 1944 is presented with the method of averaging soil properties of K.Terzaghi, proposed in 1940 (15). The numerical solution of time rate of consolidation is studied and the results of the computer program are compared with analytical and strain-based solutions.(JANBU, 1965)

Most compressible soils are alluvial deposits and are more pervious in the direction of the bedding. If such a soil deposit is loaded it is desirable to put the radial flow into effect and thus accelerate the rate of consolidation. This is usually performed by the use of vertical sand-filled holes known as drain wells. The analytical solution of Barron, A in 1947 and the numerical one is presented.

In chapter IV and V the external load was assumed to be constant which seems to be practical in many cases. However, it is not representative in some cases. Therefore in chapter VI. the effect of time-dependent loading is also investigated and a numerical solution is developed.

The problems mentioned above could be solved using computer programs available the appendices CONVER, CONVER 1, CONRAD, CONRAD 1 which are developed for these purposes.

II. CONSOLIDATION SETTLEMENT

2.1 INTRODUCTION

The presence of water in soils materially affects the behaviour of the soil whether it is granular or cohesive Generally, in granular soils, only the effective unit weight is altered when water fills the voids; in chosive soils the conditions of their deposition, formation of the sediments, and future response of the soil to applied stresses are all dependent on the water environment of the grains.

Water exists in cohesive soils in chemically combined, adsorbed on the surface, or free, unbonded forms. No sharp distinction may be made between the adsorbed surface water on the finer particles and free pore water. However, we consider that there is a gradual transition from the ordered distribution of water molecules nearest the surface to the randomly oriented molecules some distance from the surface, a distance depending on the nature of the particles and their environment. It is dificult to define precisely what is meant by "free" water in the pores of a clay soil under such circumstances because of the gradual change in the degree of freedom.

However, we will consider free water to be that water in the pores of a soil which is caused to move through the pores by pressures applied to the soil structure or pore water.

The water which moves through the pores of any soil under external stresses forms an important area of study in geotechnical engineering. Water pressures and flow quantities under or inside dams, around foundations, cofferdams, or retaining walls, or in compressing soil layers are determining factors in the design of such structures.

Because of the low permeabilities of clays, the compression under and arbitrary load does not occur immediately since time is required for the water to drain out of the soil. This process of flow water through a soil structure under loading is called "consolidation". As for all soil settlements , consolidation is the elastoplastic deformation resulting in a permanent reduction in void ratio due to an increase in stress. The essential difference between ordinary compression and consolidation settlement is that consolidation is time-dependent.

2 .2 SOIL CONSOLIDATION

In the consolidation theory of clay deposits which was first offered by Karl Terzaghi in 1925 the following assumptions are made:

1. The soil is and remains, saturated (S= 100 %). Consolidation settlements can be obtained for nonsaturated soil, but the predicted time for settlement to occur is extremely unreliable.

2. Water and soil grains are imcompressible.

3. There is a linear relationship between applied pressure and volume change. ($a_v = \Delta e / \Delta p$)

4. The coefficient of permeability is a constant which will tend to produce error in the time for settlement to occur.

5. Darcy's law is valid ($v = ki$)

6. There is a constant temperature . A change in temperature from about 10 to 20°C (typical field and laboratory temperature, respectively) results in about 30 % change in the viscosity of water. It is important that the laboratory test be performed at a known temperature or preferably at the in situ temperature.

7. Consolidation is one dimensional (vertical) , that is , there is no lateral flow of water or soil movements. This is exactly true in the laboratory test and is generally nearly so in situ for large loaded areas.

8. To have undisturbed samples are nearly impossible especially for sensitive clays. During the sampling the soil is unloaded and so the orientation of clay particles changes, they become parallel to each other

resulting in a remolded sample, having less cohesion than its original state.

The consolidation parameters of a soil are the compression index C_c and the coefficient of consolidation C_v. The compression index relates to how much consolidation or settlement will take place. The coefficient of consolidation relates to how long it will take for an amount of consolidation to take place.

The consolidation parameters can be obtained from a laboratory consolidation test, schematically shown in Fig.2.1 The carefully trimmed soil specimen (usual diameter from 6.3 to 11.3 cm) is placed inside a metal confining ring. Uniform soil pressure is applied through the loading block, and the porous stones allow the excess pore pressure, due to the load increment to freely escape as the soil voids are compressed. A dial gage is used to measure the amount of compression at varying time intervals; thus, volume changes can be computed.

A new increment of load is periodically applied to the soil. It has been found that the best results are obtained when the load is doubled producing a ratio of $\Delta p/p = 1$; thus a typical sequence would be 25, 50, 100, 200, 400, 800, kPa. There is also evidence that if the initial load increment is too low, the excess pore pressure gradient may not be sufficent to initiate pore water flow in some clay soils. This should only affect the initial part of the curve of void ratio vs. pressure, as the later load

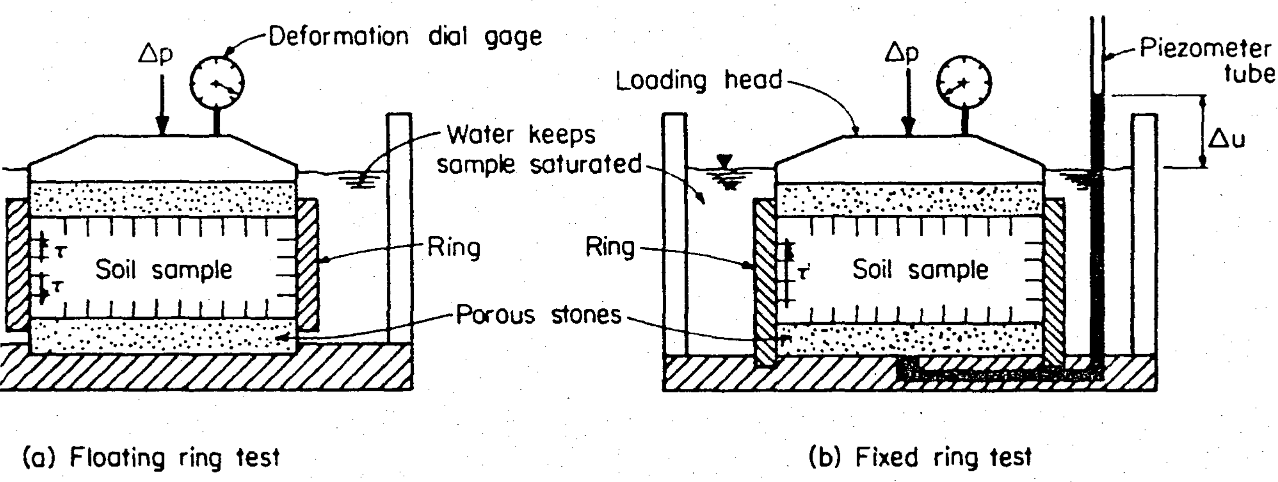


Fig. 2.1 Schematics of the Consolidation test

(Bowles, 1977)

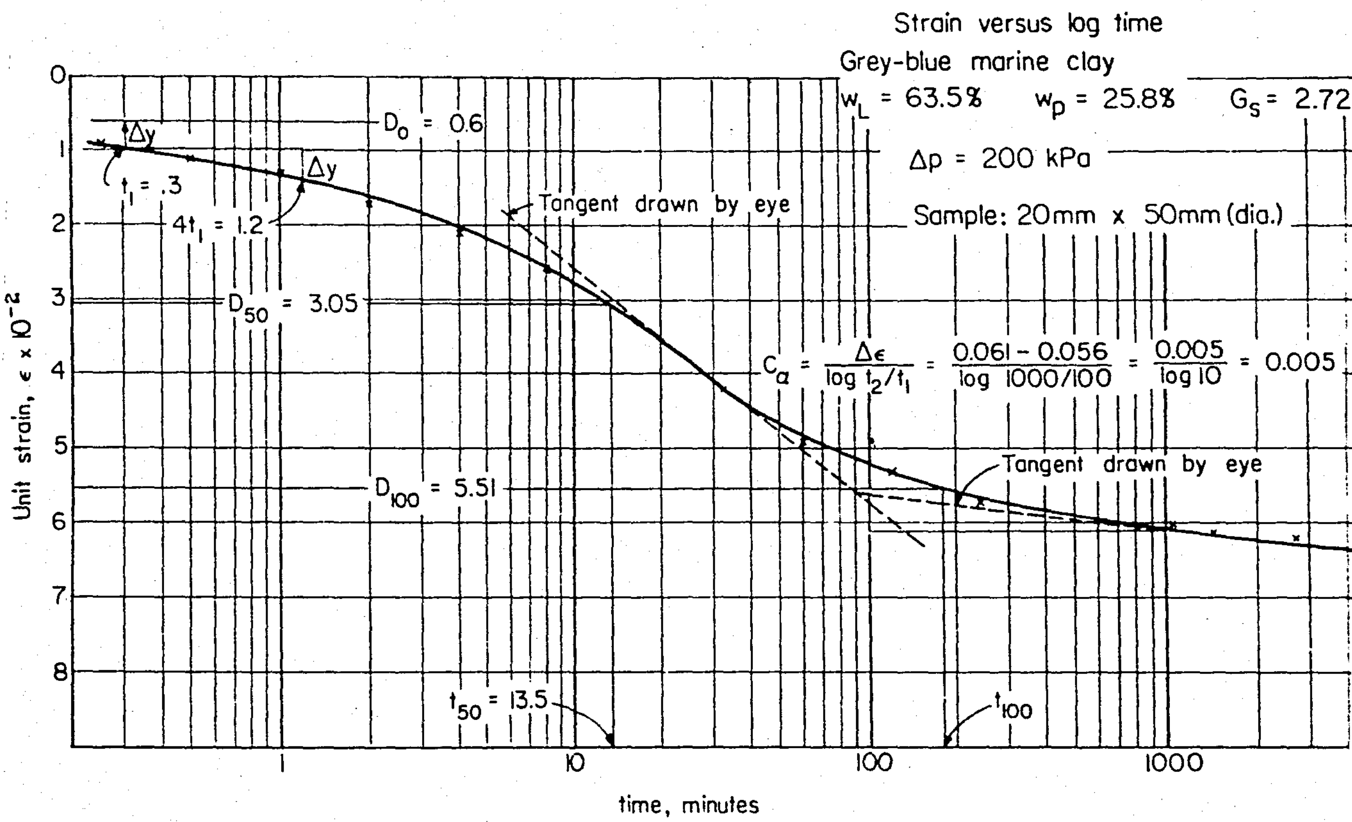


Fig. 2.2 Plot of strain v.s log time (Bowles, 1977)

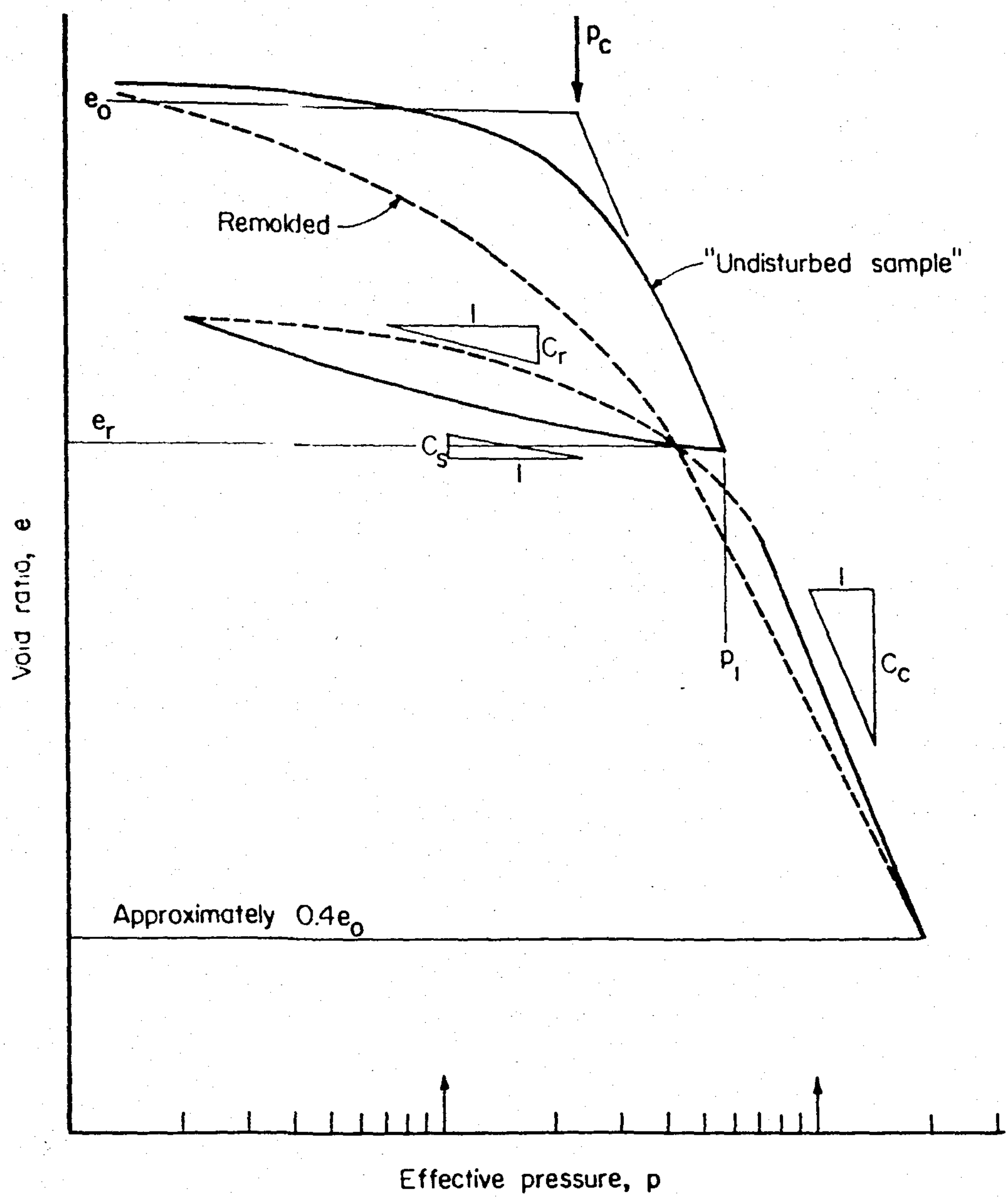


Fig. 2.3 Void ratio v.s Effective Pressure for Loading and Unloading of Cohesive Soils (Bowles, 1977)

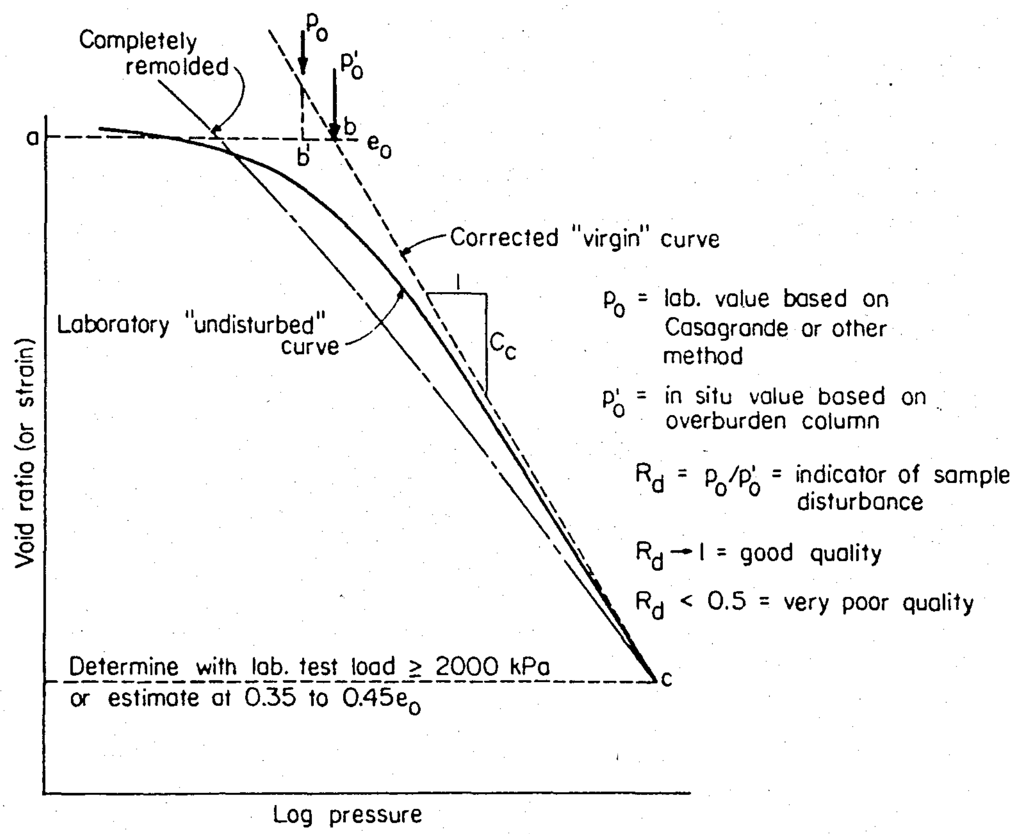


Fig. 2.4 e v.s log p curve for an Insensitive Clay

(Bowles, 1977)

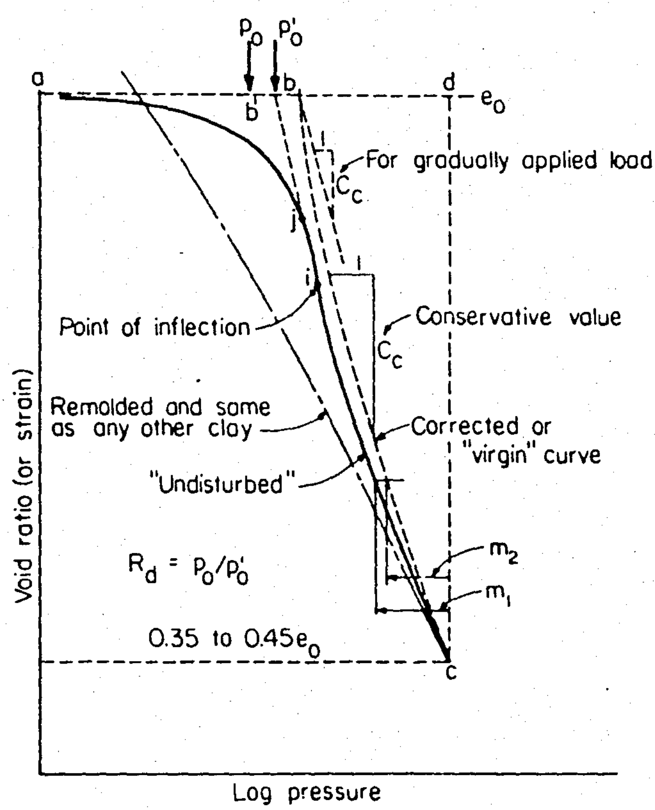


Fig. 2.5 e v.s log p curve for a sensitive soil (Bowles, 1977)

increments will be large enough to avoid this problem; also initial loads on the order of 25 kPa appear adequate to avoid it.

The tests loads are changed on the sample when consididation under the current load increment is complete. This may be taken as time when the dial reading has remained relatively unchanged for three successive readings, where the elapsed time of each reading is approximately double that of the previous reading. One may arbitrarily change loads every 24 h, which is generally satisfactory for samples of the usual 2 to 3 cm thickness and using the floating test equipment.

The results of a consolidation test are presented in the form of curves of settlement vs. time, and void ratio e vs. log pressure, as shown in Fig.2.3. Sometimes a plot of e vs. p is used instead of the semilogarithmic plots. Note that the effective pressure is used in these plots.

The semilogarithmic plot of e vs. log p for undisturbed cohesive soils has the following characteristics:

1. The initial branch of the curve has a relatively flat slope (due primarily to the initial load increment are less than the in situ overburden, and due also to soil expansion from loss of overburden pressure, which always occurs during sample recovery).

2. At a pressure close to the in situ overburden pressure (Po), the curve becomes much steeper and a curved portion

exists. For relatively insensitive clays the curve is rather flat (Fig 2.4); for sensitive clays it is much sharper(Fig.2.5)

3. Beyond the P_o point the curve is nearly linear for insensitive clays. For sensitive clays, the curve may exhibit some convavity , as shown in Fig. 2.5. This relatively steep and characteristic concave shape may be in part due to a sturucture collapse at a pressure greater than Po.

4. If an undisturbed soil sample, is loaded to some pressure such as P_1 of Fig. 2.3, then unloaded and reloaded , the curves form a hysteresis loop. The reload curve, has been found to consistently have the general shape of the initial branch of the load curve. When the new reload cycle exceed P_1, the reload curve will become an approximate extension of the original load curve.

5. a) The compression curve obtained for a remolded sample as shown in Fig. 2.4, 2.5, 2.6 always has a regular slope but less than the " undisturbed" samples, probably because the structure is more oriented.

   b) When the remolded samples are unloaded, hysteresis loops are formed as in Fig. 2.3

   c) From a) and b) it is concluded that:

      i) The initial branch of an undisturbed sample is a recompression branch of the field virgin curve, since the sample has been unloaded of the overburden pressure(12).

ii) The virgin curve would be expected to be somewhat to the right of the undisturbed curve.

iii) The laboratory undisturbed curve should be corrected to the virgin curve to obtain the compression parameters. Note that corrections should not be used unless e_o and e_c are reliably known, since "just making corrections" may produce a non conservative solution.

The pressure the soil has ever experienced is called preconsolidation pressure and denoted by P_c is equal to the effective in situ overburden pressure for normally consolidated clays. The effective overburden pressure is computed as weight of the column of soil from the point of interest to the ground surface. If P_c (as obtained from the e versus log p curve using Cassagrande's (1936) procedure) is larger than in situ overburden pressure the soil has been subjected to a pressure at some time in the geologic past larger than the present pressure P_o, and this past pressure may have been due to:

1. Agreater amount of overburden which has since been eroded away
2. Drying and resulting shrinkage stresses
3. A change in the water table (lowering)
4. A combination of drying and wetting in the presence of certain sodium, calcium or magnesium salts (particularly in uplifted marine deposits)

In this case the soil is said to be preconsolidated (or overconsolidated) The overconsolidation ratio is defined as

$$OCR = \frac{P_c}{P_o} \qquad (2.1)$$

For normally consolidated clay, as the in situ pressure is increased from P_o to P_o $\Delta p = P_2$, the void ratio should decrease by an amount Δe, as shown in Fig 2.3. The slope of the straight line portion of the virgin compression curve can be denoted as the compression index C_c , computed as

$$C_c = \frac{\Delta e}{\log (P_o + \Delta p) - \log P_o} \qquad (2.2)$$

And rearranging,

$$\Delta e = C_c \log \frac{P_o + \Delta p}{P_o} \qquad (2.3)$$

Equations (2-2) and (2-3) cannot be used to compute Δe for preconsolidated soils when the value of P_o is less than P_c for these conditions either C_r , C_s must be used depending on whether swell or compression (recompression) is desired. For settlements in preconsolidated soil, the change, in void ratio is computed in two stages as follows:

Stage 1 For Δp $P_o < P_c$

$$\Delta e_1 = Cr \log \frac{P_o + \Delta p}{P_o} \qquad (2.4)$$

Stage 2 For $P_2 = P_o + \Delta P > P_c$, i.e, when the increase in pressure extends beyond the preconsolidation pressure into the linear portion of the pressure plot, compute this extension as $\Delta p' = P_o \ \Delta p - p_c$. The additional void change is computed as

$$\Delta e_2 = C_c \log \frac{P_c + \Delta p'}{P_c} \quad (2.5)$$

The total change is the sum of the values

$$\Delta e = \Delta e_1 + \Delta e_2$$

2.3 COMPUTATION OF CONSOLIDATION SETTLEMENTS

The time dependent settlement of a layer of soil can be computed using consolidation parameters as follows:

For one dimensional consolidation $\varepsilon_z = \varepsilon_v$ and where ε_z = vertical strain and ε_z = volumetric strain

$$\frac{\Delta H}{H} = \frac{\Delta e}{1+e}$$

or , the settlement is equal to:

$$\Delta H = \frac{\Delta e}{1e} H$$

subsistuting from Eq. (2.2), obtain

$$\Delta H = \frac{C_c \ H}{1e} \log \frac{P + \Delta p}{Po} \quad (2.6)$$

The in situ effetive overburden pressure, P_o can be somewhat in error, since usual field exploration techniques often obtain only estimates of unit weights.

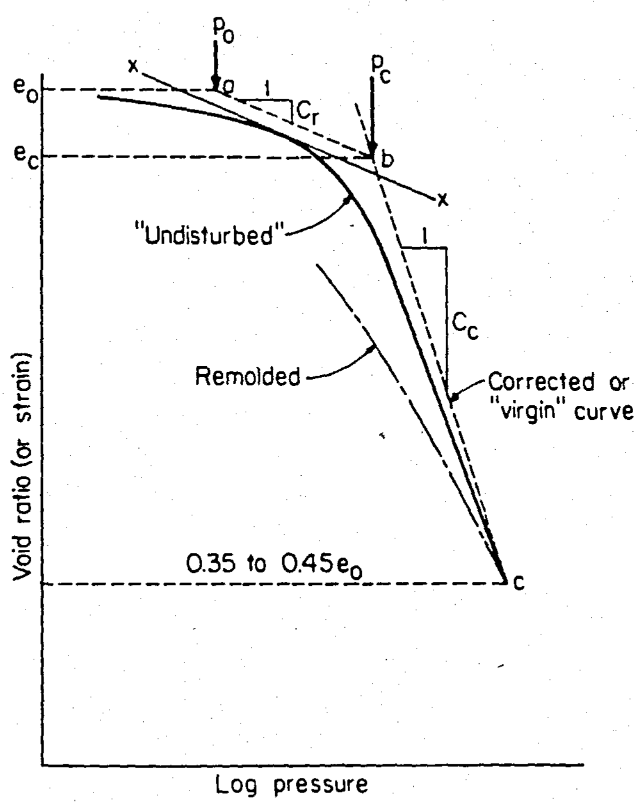


Fig. 2.6 Correcting the laboratory e v.s log p for preconsolidated soils (after schmertman, 1955)

Estimates generally tend to be low , which increases the computed settlement and is conservative.

2.4 DETERMINATION OF THE PRECONSOLIDATION PRESSURE

The preconsolidation pressure can be estimated with sufficient precision by using judgement and extending the straight line portion of the e vs. log p plot to a point at approximately the breaking of the two branches of the curve. Alternatively, one may use a method proposed by Casagrande(1936) to obtain the approximate P_c.

If one locates point of minimum radius of curvature he will easily obtain the value of P_c following the Fig. 2.8

2.5 SUMMARY

The presence of water and its motion in cohesive soil deposit give raise to a huge area of interest for the geotechnical engineers if the deposit is faced with the construction of a dam, building, road etc. Since the permeabilities are quite low the porewater dissipation under external loading takes a long time, the process named as consolidation. The consolidation theory first offered by Karl Terzaghi in 1925 has the following assumptions: the soil is saturated, permeability is constant, Darcy's law is valid, temperature is constant water and soil grains are incompressible, compression is one dimensional and there is a linear relation between void ratio and external stress.

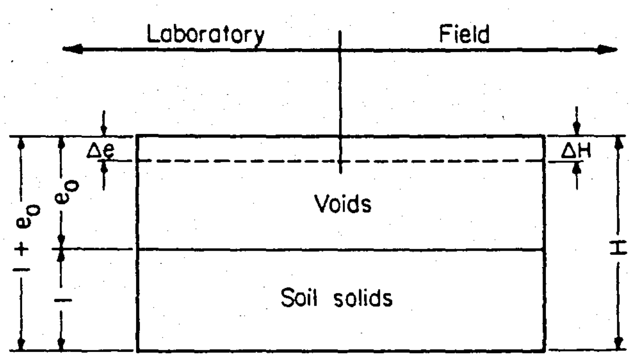


Fig. 2.7 Settlement of a soil sample of thickness H Institu (Bowles, 1977)

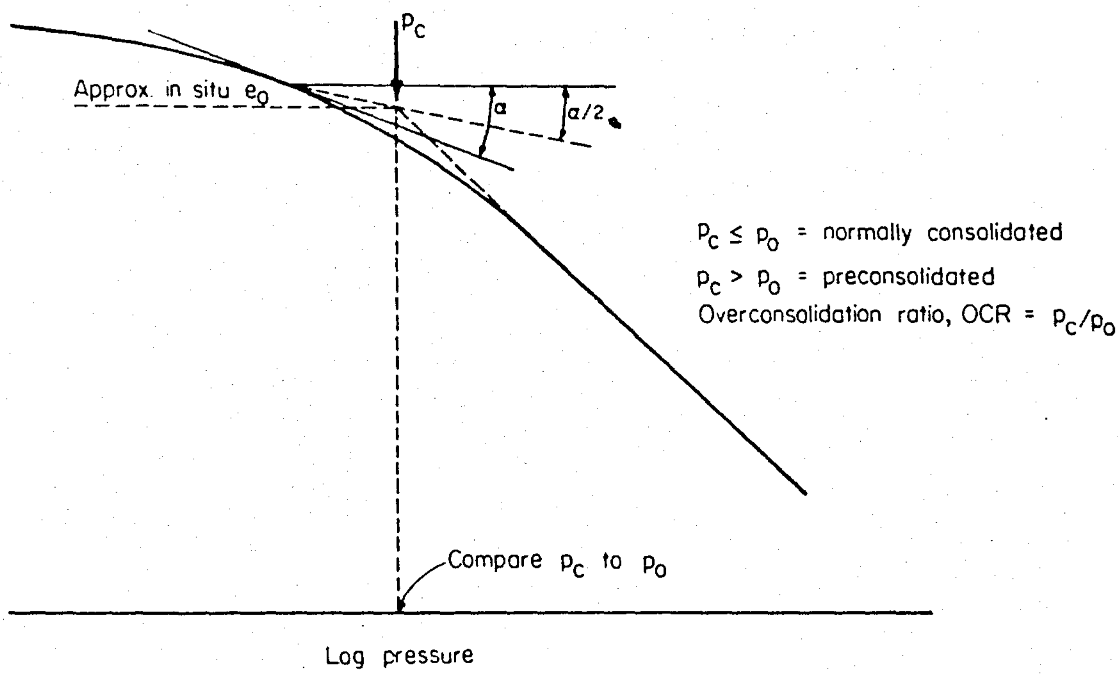


Fig. 2.8 Cassagrande s procedure for obtaining preconsolidaton pressure (Bowles ,1977)

The first important parameter, C_c, the compression index relates how much the consolidation settlement will happen. The value of C_c is obtained from a void ratio vs. log pressure (effective) curve which is the result of a laboratory oedometer test. The pressure which the soil has ever experienced is called the preconsolidation pressure P_c , and is also obtained from the e vs. log P curve using a method proposed by casagrande (1936). The effective overburden pressure, P_o , and P_c determine the situation of the deposit whether it is under,normally or over consolidated.

III. RATE OF CONSOLIDATION

3.1 INTRODUCTION

The second consolidation parameter of interest from a consolidation test is the coefficient of consolidation C_V. This parameter is obtained from an equation to be developed in the following section. The rate of pore water dissipation will be developed and Taylor's (1948) solution together with numerical approach will be supplied throughout the chapter. Since consolidation is directly dependent on the extrusion of pore water from the soil voids, let us consider continuity of flow and relate it to sources by which the weight of water in the element may vary in time.

3.2 RATE OF CONSOLIDATION

The equation of continuity representing the conservation of matter during the flow process where W is the weight of fluid stored in the volume dxdydz is,

Rate of change of storage =

$$\left[\frac{\partial}{\partial}(\gamma_w V_x) + \frac{\partial}{\partial}(\gamma_w V_z) + \frac{\partial}{\partial}(\gamma_w V_z)\right] d_x d_y d_z \qquad (3.1)$$

substitution of the velocities V_x , V_y , V_z by

$$V_x = - k_x \frac{\partial h}{\partial x} \quad , V_y = -k_y \frac{\partial h}{\partial y} \quad , V_z = -k_z \frac{\partial h}{\partial z} \qquad (3.2)$$

give rise to the following equation (13).

$$\frac{\partial}{\partial x} (\gamma_w k_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (\gamma_w k_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z} (\gamma_w k_z \frac{\partial h}{\partial z}) = \frac{\partial w}{\partial t} \qquad (3.3)$$

Both the intergranular soil pressure and the fluid pressure will vary from place to place in a soil medium during the flow of water, so that even an initially homogeneous soil may experience spatial variations in permeability as flow continues. We may expect that the permeability of granular media will not change appreciably as flow takes place, but finer-grained cohesive soils may well undergo large variations in permeability. But we usually assume, that permeabilities are invariant during the flow process so that they can be placed outside the derivatives in Eq.(3.3). With the assumption of constant coefficients of permeability and by expanding the deriva - tives, one obtains as derived by R.F.Scott (13).

$$\left[k_x \gamma_w \frac{\partial^2 h}{\partial x^2} + k_y \gamma_w \frac{\partial^2 h}{\partial y^2} + k_z \gamma_w \frac{\partial^2 h}{\partial z^2} \right] +$$

$$\left[k_x \frac{\partial \gamma_w}{\partial x} \frac{\partial h}{\partial x} + k_y \frac{\partial \gamma_w}{\partial y} \frac{\partial h}{\partial y} + k_z \frac{\partial \gamma_w}{\partial z} \frac{\partial h}{\partial z} \right] = \frac{\partial w}{\partial z} \qquad (3.4)$$

The second term of the left hand side of the Eq.(3.4) is negligible since pore-water is assumed to be incompressible. Therefore, as it is used in most soil engineering problems the equation (3.4) can be written

$$\gamma_w \left[k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} + k_z \frac{\partial^2 h}{\partial z^2} \right] = \frac{\partial w}{\partial t} \qquad (3.5)$$

The weight of water, W, in the element is equal to w W /100, where W is the weight of soil solids in the volume dxdydz. One can easily relate w to degree of saturation, unit weight of solids, and unit weight of water as follows,

$$Se\gamma_w = G_s \gamma_{wo} w \qquad (3.6)$$

which we can use to get

$$\frac{\partial W}{\partial t} = \frac{W_s}{100} \qquad \frac{\partial W}{\partial t} = \frac{W_s}{100} \frac{\partial}{\partial t} \left(\frac{Se\gamma_w}{G_s \gamma_{wo}} \right) \qquad (3.7)$$

since by the above reasing the weight of soil solids in the element does not change in time . When G is replaced by the ratio of the unit weights of soil and water s/ wo , Eq.(3.7) becomes

$$\frac{\partial w}{\partial t} = \frac{W_s}{100} \frac{\partial}{\partial t}\left(Se\gamma_w \frac{1}{\gamma_s} \right)$$

Expanding the differentiation, one may obtain

$$\frac{\partial W}{\partial t} = \frac{W_s}{100} \left(\underset{(A)}{e\gamma_w \frac{1}{\gamma_s} \frac{\partial S}{\partial t}} + \underset{(B)}{S\gamma_w \frac{1}{\gamma_s} \frac{\partial e}{\partial t}} + \underset{(C)}{Se \frac{1}{\gamma_s} \frac{\partial \gamma_w}{\partial t}} - \underset{(D)}{Se\gamma_w \frac{1}{\gamma_s^2} \frac{\partial \gamma_s}{\partial t}} \right) \qquad (3.8)$$

Where terms in the brackets of Eq. (3.8) represent, respectively, the rate of change of storage of water due to: (A) change of degree of saturation (B) change of void ratio, (C) change in the unit weight of pore water, and (D) change in the unit weight of the soil solids.

Since the pore water soil solids are assumed to be invariant together with the degree of saturation which is accepted at the very beginning as 100 % (3) the Equation (3.8) becomes.

$$\frac{\partial W}{\partial t} = \frac{W}{100} S \gamma_{w} \cdot \frac{1}{\gamma_s} \cdot \frac{\partial e}{\partial t}$$

or

$$\frac{\partial W}{\partial t} = \frac{W_s \gamma_w}{\gamma_s} \frac{\partial e}{\partial t} \qquad (3.9)$$

or

$$\frac{\partial W}{\partial t} = V_s \gamma_w \frac{\partial e}{\partial t} \qquad (3.10)$$

Since volume of solid particles is equal to V /e, and unit weight of water is equal to W /V , then Eq .(3.10) becomes

$$\frac{\partial W}{\partial t} = \frac{W_w}{e} \frac{\partial e}{\partial t} \qquad (3.11)$$

If one can find the variation of void ratio with time, he or she will be over with the time rate of consolidation. In order to achieve this purpose we'll go back to the variation of void ratio with effective stress as was covered in the carlier sections.

All data on the compressibility of soils are obtained through field or laboratory tests on material, and therefore a straight line is drawn on the curve of void ratio

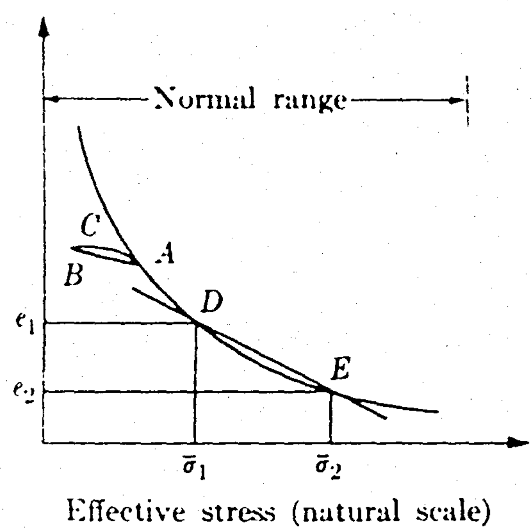


Fig. 3.1 Arithmetic plot void ratio v.s Effective pressure (Scott,1963)

versus intergranular or effective stress through two points on the curve representing the stress range to be expected : such a line is shown as DE in Fig. 3.1. Its equation is therefore,

$$e = a_v \bar{\sigma} + e_o \qquad (3.12\ a)$$

where e is the void ratio obtained by the hypothetical projection of the straight line back to zero stress and a_v is a coefficient of compressibility, describing the slope of the line, which is of course negative. If the value of a_v is taken as a positive number then the equation will be written

$$e = e_o - a_v \bar{\sigma} \qquad (3.12\ b)$$

If only a relatively small pressure increment is applied to a naturally existing clay so that the change in void ratio is also small, the approximation may be made that compression takes place as a linear function of pressure. Such an assumption would be far in error if applied in an attempt to describe a large change in void ratio of a soil such as that occuring between the time of its first deposition and its subsequent burial under deep layers of later sediments.

$$\frac{\partial e}{\partial \bar{\sigma}} = - av \qquad (3.13)$$

and writing a relation between and u :

$$\frac{\partial \bar{\sigma}}{\partial t} = \frac{\partial \sigma}{\partial t} - \frac{\partial u}{\partial t} \qquad (3.14)$$

then the variation of void ratio with time becomes

$$\frac{\partial e}{\partial t} = - av \left(\frac{\partial \sigma}{\partial t} - \frac{\partial u}{\partial t} \right) \qquad (3.15)$$

We note that , altough the treatment of water flow is based on the assumptions of a volumetric element fixed is space , with spatial coordinates (x,y,z) , we dealt with the possibility of a vertical expansion or contrac - tion of the soil. The summation of such incremental expansions or contractions would obviously result in a vertical displavement of all elements. Altough the storage rate of water referred to the volumetric element dxdydz, the analysis in fact proceeded on the assumption that the weight of soil in the element remained constant and therefore might be said to be based on material coordinates.

Substituting Eq. (3.15) in (3.11) and writing W_w in terms of void ratio and unit weight of water ($W_w = e\gamma_w/1+e$)

$$\frac{\partial W}{\partial t} = \frac{av \ \gamma_w}{1+e} \left(\frac{\partial u}{\partial t} - \frac{\partial \sigma}{\partial t} \right) \qquad (3.16)$$

On the left hand side of Eq. (3.5) the head is still the total head, i.e., in this case, sum of the static or steadystate and transient pore-water pressures:

$$h = (h_p + h_e) + \frac{u}{\gamma_w} \qquad (3.17)$$

Since in many problems a loaded surface, which is large in extent compared with the clay thickness is encountered, the water flow may be considered to occur in one direction, vertically. Having this in mind and taking the derivative of the Eq. (3.17) and substing those two into Eq. (3.5)

$$k_z \frac{\partial^2 u}{\partial z^2} = \frac{\partial w}{\partial t} \tag{3.18}$$

Equating the Equations (3.16) and (3.18) and rearranging with the constant in their initial values one obtains

$$\frac{k_z (1+e_o)}{\gamma_{wo} a_v} \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} - \frac{\partial \sigma}{\partial t} \tag{3.19}$$

The group of constant terms on the left hand side is given the name coefficent of consolidation, C_v, which can also be considered an hydraulic diffusion coefficient,

$$C_v = \frac{k_z (1 + e_o)}{\gamma_{wo} a_v} \tag{3.20}$$

If the external stress causing the transient condition is applied rapidly and held constant in time, the second term on the left hand side of Eq. (3.19) vanishes, and the equation becomes

$$C_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \tag{3.21}$$

In this form the equation of consolidation was first derived by Terzaghi and is similar to Fick's law of thermal diffusion.

The solution of Eq. (3.21) takes the form (Taylor,1948) of a series solution to give the instantaneous value of the excess pore water pressure u at a specified point in the soil mass as where n: any integer (generally 0,2,3 and 4 are sufficient)

y: depth into a stratum of length of drainage path H

H: length of longest drainage path in soil sample or mass

T: dimensionless number termed a time factor, or

$$U = \sum_{n=1}^{\infty}\left(\frac{1}{H}\int_0^H u_i \sin \frac{n\pi y}{H}\, dy\right)\left(\sin \frac{n\pi y}{H}\right) \exp\left(-\frac{1}{4} n^2\pi^2 T\right) \quad (3.22)$$

t_i: time of interest

u_i: initial pore pressure distrubution

Because of the linearity of Eq. (3.19), it is appropriate to normalize the various parameters to make , the equation nondimensional. In this way the solution obtained in term of dimensionless parameters in in a more suitable form for generel applications. The normalization in one-dimensional terms, for example , is accomplished by relatiing the variables to the characteristic constants of the systems as follows: A charactericstics length H ih the system is selected to give a dimensionless length variable q:

$$p = \frac{z}{H} \quad (3.23\ a)$$

when z is measured from the surface of the compressing layer. Next, choosing an arbitrary time constant T, we are able to obtain a dimensionless time variable T:

$$T = \frac{t}{\tau} \quad (3.23\ b)$$

subsituting in the one-dimensional Eq (3.21) gives.

$$\frac{C_V}{H^2} \frac{\partial u}{\partial \rho^2} = \frac{1}{\tau} \frac{\partial u}{\partial T}, \qquad (3.24)$$

where u is a function of ρ and T.

It is apparent that one of the characteristic constants can be selected for convenience to make

$$\frac{1}{\tau} = \frac{C_V}{H^2} \qquad (3.25)$$

and therefore Eq. (3.24) becomes

$$\frac{\partial^2 u}{\partial \rho^2} = \frac{\partial u}{\partial T} \qquad (3.26)$$

Most estimates of settlements are based on a one - dimensional analysis of consolidation under the center of the structure, using an initial applied vertical stress distrubution throughout the medium obtained from solutions based on the assupliton that the soil is an elastic material. The ultimate settlement is computed by dividing the layer into a number of laminae of finite thickness calculating the average increase in effective pressure p at the center of each layer from the elastic solution and summing the incremental settlements to get the overall settlement.

$$\Delta H = \Sigma \frac{a_v}{1+e_o} p\Delta z \qquad (3\text{-}27)$$

The history of settlement is then obtained by assuming that settlement fallows the curve expressed by Eq. (3.19) for the case of an initally uniform excess pore-pressure distrubution, so that , the settlement at time T, is calculated from

$$\Delta H_T = U. \Delta H \qquad (3.28)$$

where is the percent consolidation which is defined as

$$U = \int_0^1 (100-u)\ d\rho \qquad (3.29)$$

3.3 NUMERICAL ANALYSIS

The numerical solution to the Eq. (3.21) using finite difference technique is easy to handle and finds out lots of applications. Especially for layered clay deposits where the boundary conditions become complicated numerical solution is the best way to treat the problem. The loading condition is also very important if it is not constant in time. The consolidation of a layered clay deposit under a time - dependent loading will be best handled using numerical solution.

The left hand side of the Eq.(3.26) in one dimension can be represented in finite-difference form by the expression

$$\frac{\partial^2 u}{\partial \rho^2} = \frac{1}{(\Delta\rho)^2} (U_{i-1} + U_{i+1} - 2U_i) \qquad (3.30)$$

In Eq. (3.30) the values of u vary at each point in time, and therefore the equation must be associated with a time; hence a time subscript will be associated. On the right-hand side of Eq.(3.26), U must be associated with a point in space, which is conceniently taken to be the point, the increment of U in the numerator is a time increment , and the finite difference form of this side becomes.

$$\frac{\partial u}{\partial T} = \frac{1}{\Delta T} (U_{i,T+\Delta T} \quad U_{i,T}) \qquad (3.31)$$

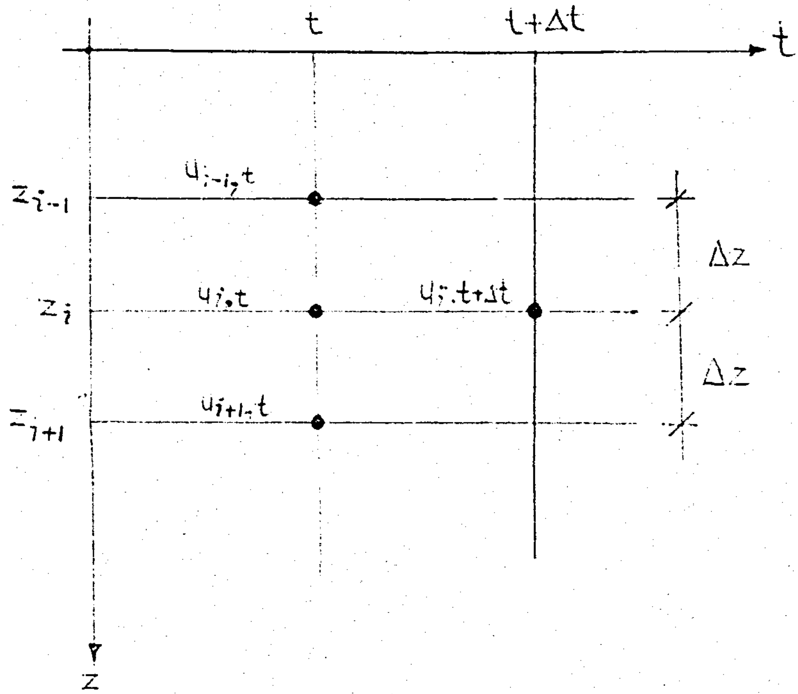


Fig. 3.2 Point - Numbering Convention

Combination of Eqs.(3.30) and (3.31) yields an e expression which can be used to determine the excess pore pressure at a point at a time in terms of the pore pressures at the point and adjacent points at a time T

$$U_{i,T+\Delta T} = \frac{\Delta T}{(\Delta \rho^2)} (U_{i-1} + U_{i+1} - 2U_i)_T + U_{i,T} \quad (3.32)$$

Since both T and P are dimensionless, the factor is also dimensionless and may be described as an operator on the prior values of u by whose agency the new values can be calculated. Therefore, if in a consolidating medium we have established a number of points a distance p apart at which the excess over hyrocstatic pore pressure is known at any time T , then the excess over hydrostatic pore pressure at each of these points may be computed at time by means of Eq. (3.32) the so-called explicit method used to derive Eq.(3.32) brings a problem with it which is the stability of equation in operation in order to be useful. In other words, if an error E is made in the determination of U at one cycle of the solution, i.c., at a time T, then the error in the subsequent value should not be more than E by reason of the iterative process of Eq.(3.32). If this is true, the step-by-step calculation of u; as a function of time will not be divergent, since the computational errors do not increase in the course of the solution. Then the restriction on (13)

$$M \leq \frac{1}{2} \quad (3.33)$$

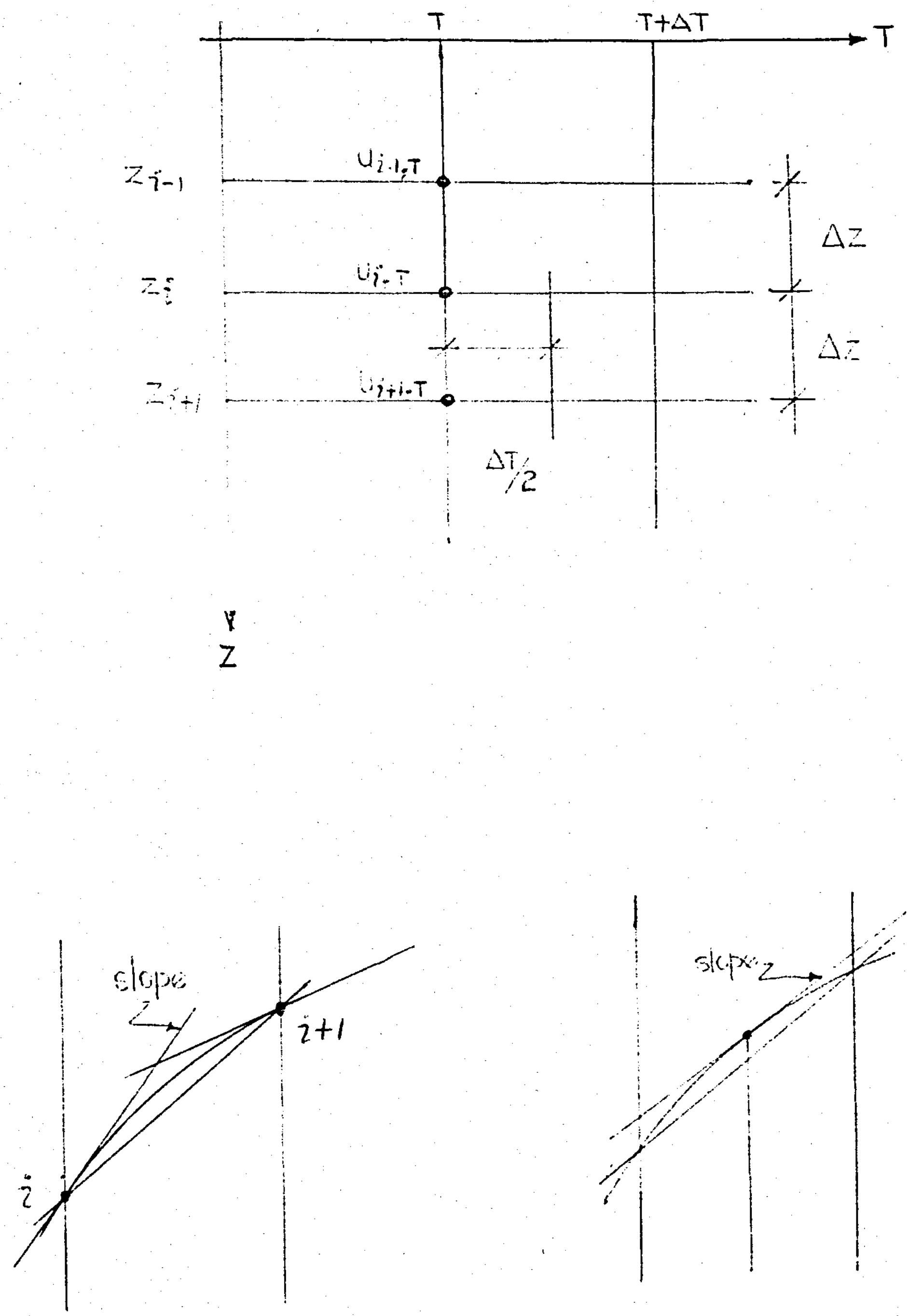


Fig. 3.3 The Idea In Deriving Implicit Relation

This limitation could be woided if the expression would be written in terms of the new values at three points. The model equation would then be an implicit function.

This can be done by rewriting the second difference of pore pressure with respect to space as an average over the time interval involved to give the implicit relation.

$$\left(\frac{\partial u}{\partial T}\right)_{i,T+\Delta T/2} = \frac{U_{i,T+\Delta T} - U_{i,T}}{\Delta T} \qquad (3.34)$$

$$\left(\frac{\partial^2 u}{\partial \rho^2}\right)_{i,T+\Delta T/2} = \frac{(U_{i-1}-2U_i+U_{i+1})_T + (U_{i-1}-2U_i+U_{i+1})_{T+\Delta T}}{2\ (\Delta\rho)^2} \qquad (3.35)$$

If we combine the Eqs. (3.34) and (3.35) and then seperate the terms containing T and terms of T on each side, we will obtain as R.F. Scott (12)

$$(U_{i+1}-2(1+\frac{1}{M})U_i+U_{i-1})_{T+\Delta T}$$

$$= -(U_{i+1} -2\ (1- \frac{1}{M})\ U_i+U_{i-1})_T = -b_{i,T} \qquad (3.36)$$

Using Eq. (3.36) in which the values will be known at time T, we establish a set of simulteneous equations in the unknowns, (T + ΔT) for a chosen Δp spacing and a on which no restriction is placed other than that the second difference must be a reasonable approximation to the actual second difference. The greater the changes in the excess pore pressure, in smaller the time steps which must be choosen.

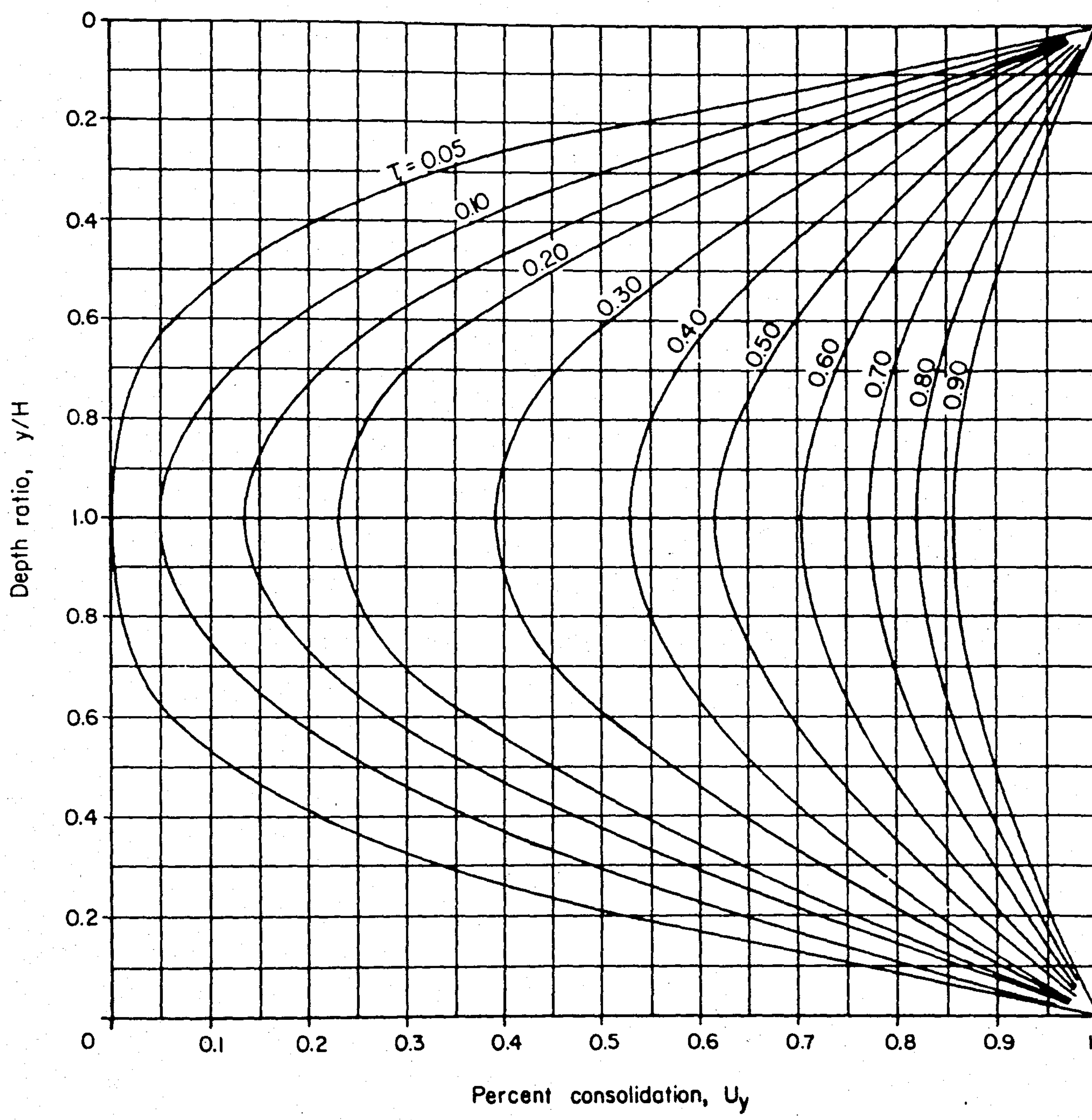


Fig. 3.4 Depth Ratio v.s Percent Consolidation for different time factor values (Bowles ,1977)

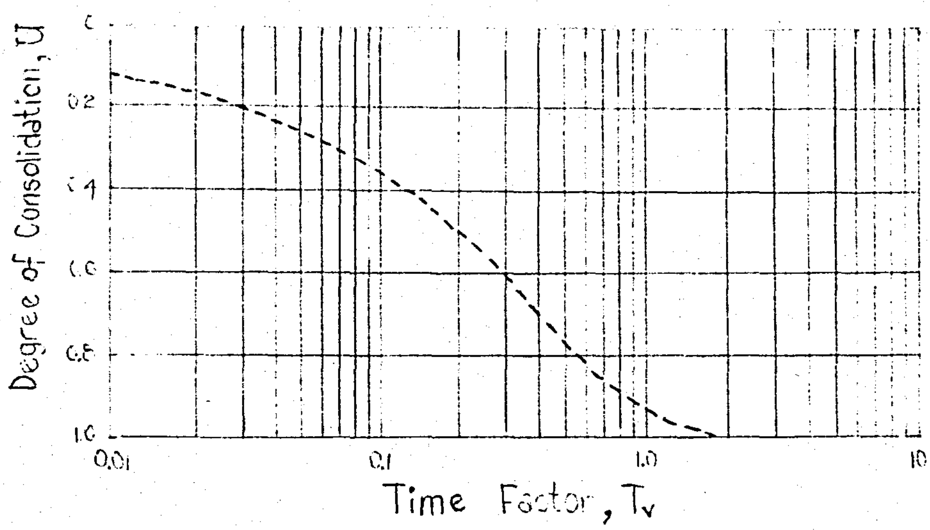


Fig. 3.5 U versus T_v (Gibson, 1953)

When the distribution of excess over hydostatic pore pressure with depth and time in the soil has been obtained , it si usually desirable to calculate the average value at any particular time over the thickness of the layer under consideration. This may be done either by the application of Simpson's rule to the pore pressures or by mechanical integration of the diagrams by a planimeter. Division of area underneath the isochrone by the depth of the layer fields the average value of pore-pressure, distribution at the given time.

If it is desired to examine the pore-pressure distribution with time in detail at any particular part of the layer under consideration, a network of fine p-spacing can be chosen in the zone of interest so that the pore - pressure distribution at small spatial intervals can be obtained. For a consistent solution, the time factor steps, , must be the same everywhere throghout the zone, and it will therefore be necessary to choose the factor in a zone of fine net size to ensure that the time steps remain constant.

With the computer program named CONVER available in Appendix A one can calculate the total settlement and its time rate of a campressible stratum under a constant load. The principles used to develop it for a layered system will be held in the next chapter. Here is a comparaison of the results obtained using CONVER with the conventional theory of Mr.Karl Terzaghi presented by GIBSON.R.E (4).

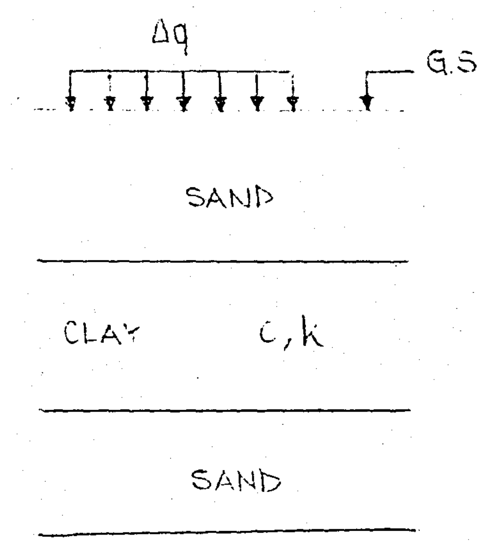


Fig. 3.6 Freely drained Clay layer

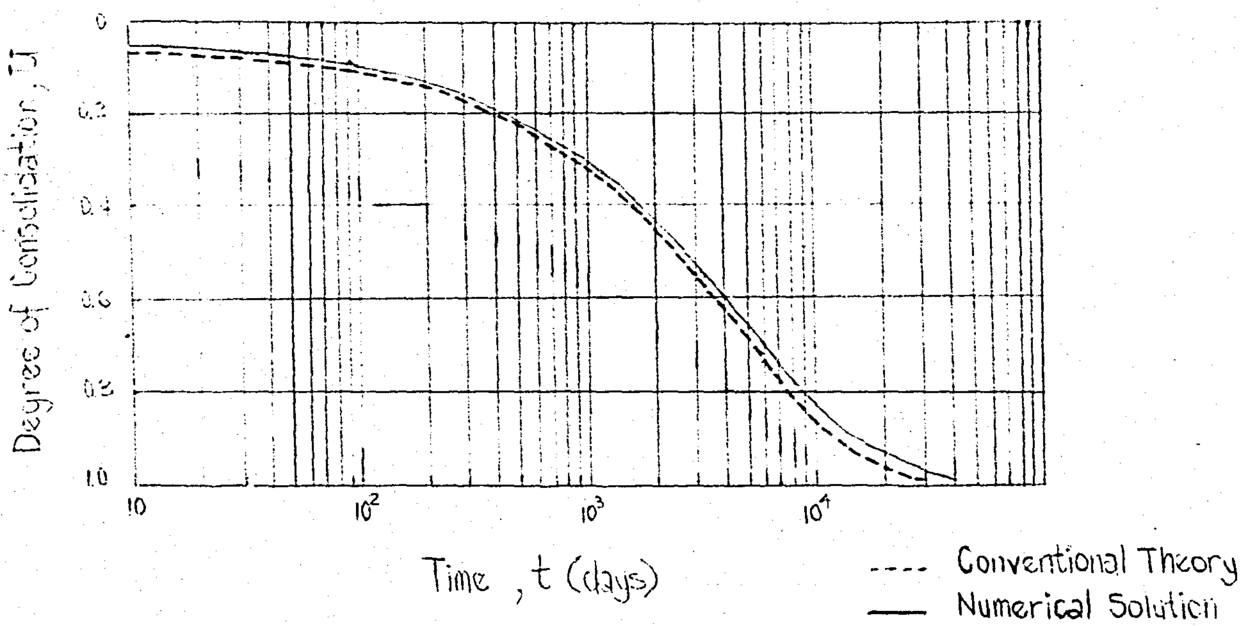


Fig. 3.7 Degree of Consolidation with Conventional therory and the results with CONVER

A sample of clay layer as shown in Fig. 3.6 of thickness 8 m. had the U vs. t curve as heavily drawn in Fig. 3.7. The conventional curve is somehow conservative. The pore water disspation with CONVER seems to be faster resulting in a higher degree of consolidation for the same amount of elapsed time.

3.4 SUMMARY

The pore water dissipation of a clay deposit takes sometimes a long time under externan loading and this is mainly governed by the coefficiend of consolidation, C_v, as given by Eq. (3.20).

The flow of fluid through the pores and the volume change of a cubic element of soil is considered in order to precise ond formulate the pore water pressure distribution. With the assumbtions made in the previons chapter the consolidation equation is obtained and given by Eq.(3.21) which was first developed by Karl Terzaghi. The solution to this differential equation gives the instanteneous vaule of pore water pressure , u, at a specified poind in the soil mass. The analytical solution, in the form of series suggested by Taylor (1948), is provided by Eq. (3.22). Numerical solution, having advantegeous over analytic one when the boundary and loading conditions represent some dificulties, is the main purpose of this study . Finite difference method is the basis of this numerical approach.

The ratio of the settlement at any time over the total one called the percent consolidation, U, at this spesific time. The plots of U versus depth or time for a clay layer are presented as well as the comparison of the results of the theoretical and numerical solutions, the ladder as obtained using the computer program named CONVER.

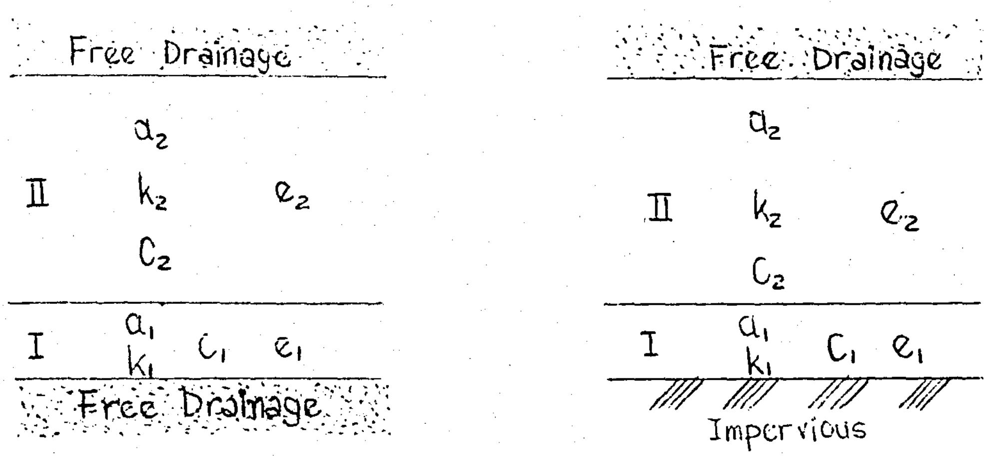
IV. LAYERED SYSTEM

4.1 INTRODUCTION

The consolidation of two adjacent layers of fine-grained soils, possesing different consolidation characteristics, is an other important area of study for geotechnical engineers. The analytical solution first developed by Hamilton Gray in 1944 will be supplied together with an approximate method given by Professor Karl Terzaghi in 1940. The numerical solution to this problem is considered in detail and the computer program CONVER available in Appendix A is well explained. The problem of time rate of consolidation solved on the strain-basis, but not on the stress, by N. JANBU in 1965 is presented at the end of the chapter.

4.2 THE ANALYTICAL SOLUTION

When two adjoining compressible strata are made to consolidate under an applied load, the behavior of each stratum is influenced by the presence and action of the other. The extent of the mutual interference or influence of the layers depends on the properties (compressibility and permeability) of the materials comprising each layer.



a) Free Drainage at Top and Bottom

b) Free Drainage at Top Only

Fig. 4.1 Drainage Conditions for Adjacent Layers of Consolidating Soils

The problem of two contiguous layers of consolidating soils is depicted in Fig. 4.1, there being two distinct cases to consider (a) . Free drainage top and bottom, and (b) drainage at top only, as given by Hamilton Gray in 1944 (5)- It should be repeated that the drainage conditions affect only the time rate of compression and have no influence on the total amount of settlement.

In Fig. 4.1 , "reduced" dimensions, are intoduced for mathematical simplicity and are related to the true dimensions by the equations:

$$H_s = \frac{H}{1+e} \tag{4.1}$$

and

$$Z = \frac{h}{1+e} \tag{4.2}$$

where, H_s : the layer thickness (reduced)

z : the depth from the datum line (reduced)

e : void ratio

The layers of soil are numbered I and II and the corresponding soil coefficients are identified by appropriate subscripts, 1 and 2.

For each material, the coefficient of permeability , k is equal to:

$$k = a C \gamma (1 + e) \tag{4.3}$$

where, a : coefficient of compressibility

c : coefficient of consolidation

γ : density of the liquid

In addition, the following transformations are convenient:

$$k_{s1} = \frac{k_1}{1+e_1} \qquad (4.4a)$$

$$k_{s2} = \frac{k2}{1+e_2} \qquad (4.4b)$$

and the introduction of three dimensionless numbers

$$\mu^2 = \frac{C_1}{C_2} \; ; \; \sigma = \frac{1}{\mu} \frac{k_{s1}}{k_{s2}} ; \quad \nu = \frac{h_2}{h_1} \qquad (4.5)$$

is useful.

Then it is possible to write the basic differential equation for the two layers consecutively as

$$C_1 \frac{\partial^2 u_1}{\partial z^2} = \frac{\partial u_1}{\partial t} \qquad (4.6a)$$

$$C_2 \frac{\partial^2 u_2}{\partial z^2} = \frac{\partial u_2}{\partial t} \qquad (4.6b)$$

and solve them simultaneously.

Here, it is preferred to give the results to a particular case and illustratee them graphically rather than going through the details of the solution of Eq.(4.6 a) and (4.6b) and obtain at the end the percent consolidations for the two layers. In this situation it is assumed that there is drainage at the top only, with the following relationships between the coefficients and dimensions: $\gamma=4$; $e_1=e_2$; $ks_1 / ks_2 = 10$; $a_1/a_2 = 0.4$; $C_1/C_2 = 25$;

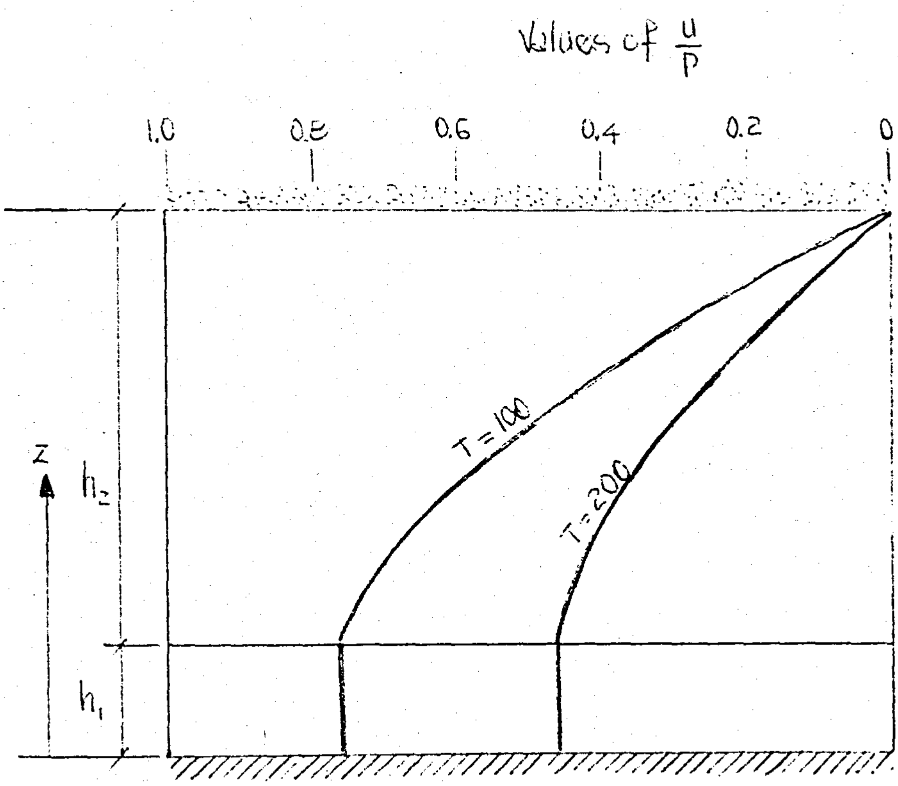


Fig. 4.2 Pore Water Distribution for Two Different T (Gray, 1944)

Fig. 4.2 shows the distributions of excess fluid pressures, u, in the soil layers at two different times corresporndíng T=100 and T=200. As is to be expected from the assumed relation between the soil coefficients, the lower layer consolidates as rapidly as the upper will permit, the variation in u through the lower layer at any instant being very small. In the upper layer the variation is similar to that found in the case of a layer of homogeneous material with free drainage at one surface. In Fig. 4.3 the curves of U versus T are plotted for the upper and lower layers, together with a "resultant" curve computed from.

$$U_r = \frac{U_1 h_1 + U_2 h_2}{h_1 \quad h_2} = \frac{4U_2 + U_1}{5} \tag{4.7}$$

as suggested by Hamilton Gray in 1944 (5).

Also shown are curves of U versus T which would result if the entire deposit of compressible soil were of material identical with that of (1) the upper layer, and(2) the lower layer.

Fig. 4.4 shows the"resultant" curve of Fig.4.3 together with a curve obtained by averaging the coefficients of the two layers in the following manner, as suggested by Professor Terzaghi in 1940 (14)

$$a_{aver} = \frac{a_1 h_1 + a_2 h_2}{h_1 \quad h_2} = \frac{a_1 h_1 + 2\frac{1}{2} a_1 4h_1}{h_1 \quad 4h_1} = \frac{11}{5} a_1 \tag{4.8a}$$

$$k_{aver} = \frac{h_1 + h_2}{\frac{h_1}{k_{s1}} + \frac{h_2}{k_{s2}}} = \frac{h_1 + 4h_1}{\frac{h_1}{k_{s1}} + \frac{4h_1}{k_{s1}} 10} = \frac{5h_1}{\frac{41 h_1}{k_{s1}}} = 0.122 k_{s1} \tag{4.8b}$$

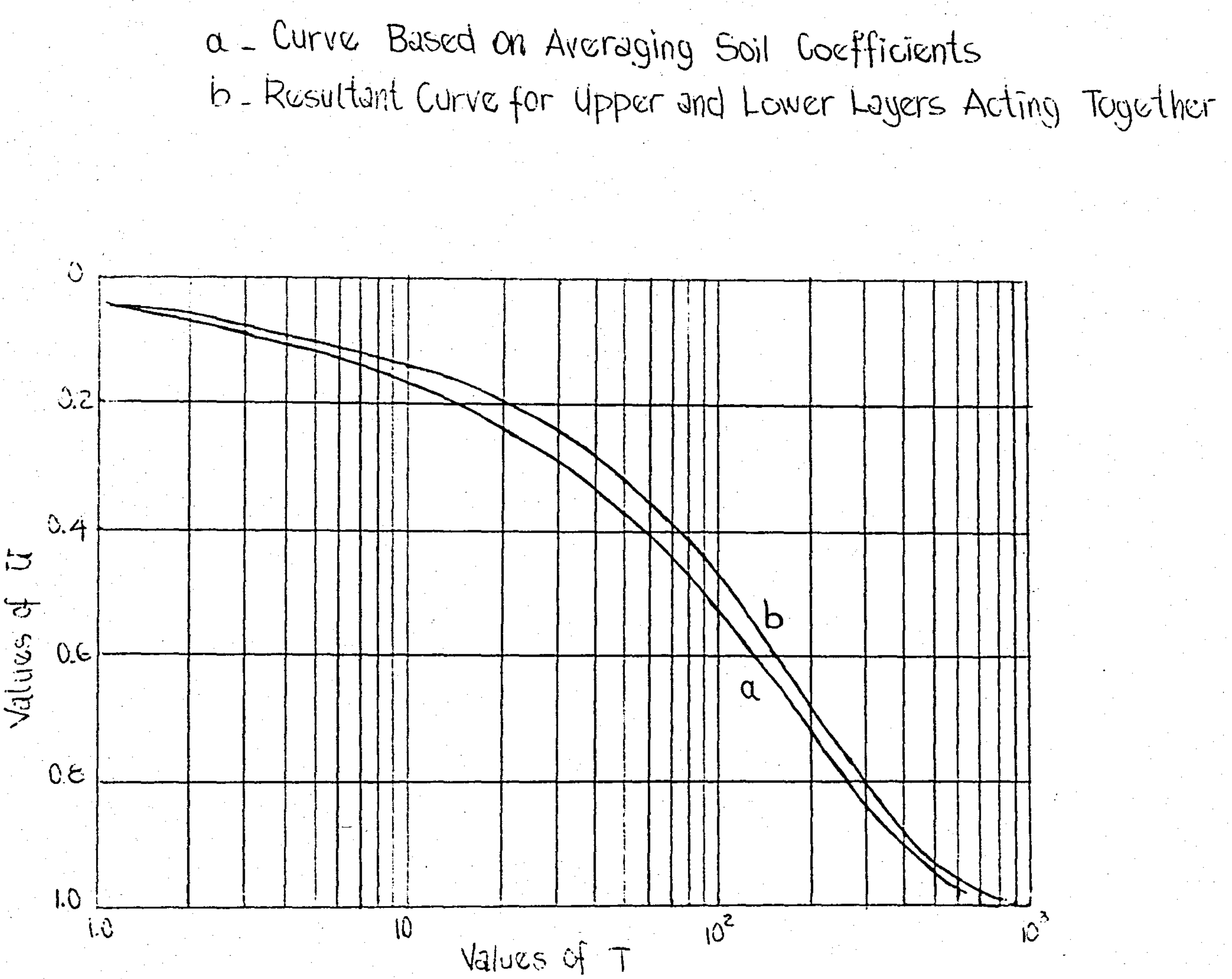


Fig. 4.4 U vs T (Gray,1944)

$$C_{aver} = \frac{k_{aver}}{\gamma a_{aver}} \quad \frac{0.122\ k_{s1}}{2.2\ a_1} = 0.0555 \ \frac{k_{s1}}{a_1} = 0.0555\ C_1 \qquad (4.8c)$$

Naturally, curve(a) , Fig. 4.4, secured by the method of averaging, is obtained with far less effort than the theoretically correct resultant curve which it approximates. It is evident from Fig. 4.4 that the discrepency between two is not excessive.

4.3 NUMERICAL ANALYSIS

Another way of solution of time rate of consolidation is the numerical approach. The ease brought by the use of numerical techniques was mentioned before in the third chapter. Even more, when the soil deposit is layered a computer program developed for this purpose will provide the fastest results. As the system is layered the numerical solution is the best approach since the differential equations in this case are almost impractical to deal with.

The numerical solution using finite difference technique will be derived as was done for a homogeneous comppressible layer. The main problem confronted here is boundary. But as shown in Fig. 4.5 this problem is over using imaginary points.

To start with, we will assume for simplicity the following equality:

$$\frac{\Delta Z_1}{\Delta Z_2} = \sqrt{\frac{C_1}{C_2}} \tag{4.9}$$

If one writes down the previous explicit equation for the upper and lower layers, he will have

1. $U_{i,T+\Delta T} = U_{i,T} + M\ (U_{i-1} + U_{i\ 1} - 2U_i\ )_T$ (4.10a)

2. $U_{i,T+\Delta T} = U_{i,T} + M\ (U_{i-1} + U_{i\ 1} - 2U_i\ )_T$ (4.10b)

Velocity below and above the boundary is same

$$V_1 = k_1 \left(\frac{\partial u}{\partial z}\right)_{i,z} = k_1 \frac{V_{i+1} - U_{i-1}}{2\ \Delta z_1} \tag{4.11 a}$$

$$V_2 = k_2 \left(\frac{\partial u}{\partial z}\right) = k_2 \frac{U_{i+1} - V_{i-1}}{2\Delta z_2} \tag{4.11b}$$

from which ene obtains equating Eqs. (4.11 a) and (4.11b)

$$V_{i+1} + \alpha V_{i-1} = \alpha U_{i+1} + U_{i-1} \tag{4.12}$$

where

$$\alpha = \frac{k_2}{k_1} = \frac{\Delta z_1}{\Delta z_2} \tag{4.13}$$

Replacing U_{i+1} an Eq. (4.10) by V_{i+1} and U_{i-1} in Eq. (4.10 b) by V_{i-i} and eliminating them using in Eq.(4.12) gives rise to the following equation

$$U_{i,T+\Delta T} = U_{i,T}\ \ 2M \left[\frac{\alpha\, U_{i+1} + U_{i-1}}{\alpha \mp 1}\ \ U_i\right]_T \tag{4.14}$$

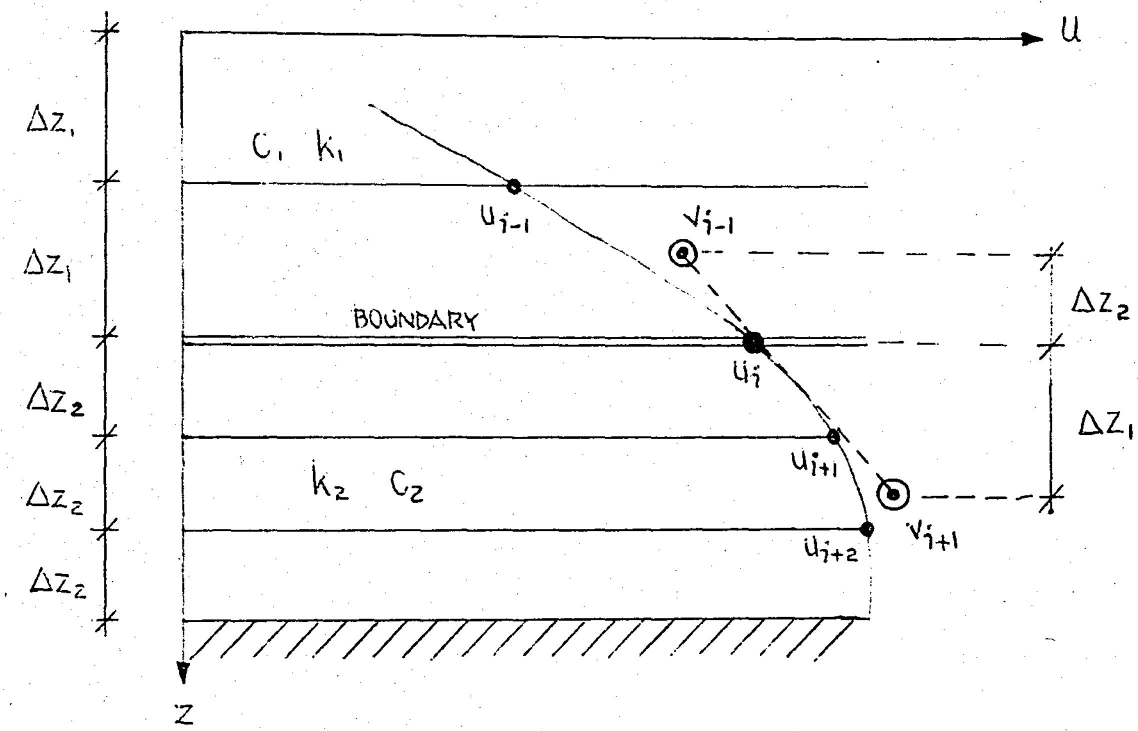


Fig. 4.5 Imaginary Points on the Boundary

which will be used on the boundary. At other points lying within the clay layer the allready known explicit equation given by Eq. (3.32) is the appropriate one.

Using the numerical approach the settlement versus time plot is obtained as the result of the program CONVER. The program is formed by one main and two subroutines. In the main program the total settlement than can occur under the externally applied stress is calculated. In the first subroutine the dissipation of pore pressure and then the percent consolidation is calculated. The second subroutine is used to plot the settlement vs. time relationship obtained from the first subroutine.

The structural idea of the main program is as was described in the second chapter. The input data consists of the soil properties such as, layer thickness, void ratio, compression index, overburden and preconsolidation pressures. Then pressure increment, for each layer is read by the program. Since the main is capable of taking care of the different consolidation situations there are three checks right after the pressure data. The first check is on the overconsolidation, the second on the normal consolidation, and the third on the under consolidation. The checks are of course on the pressure basis which are overburden , preconsolidation and the change in pressures. If the sum of overburden and the change in pressure is less than the preconsolidation pressure, the change in void ratio is computed using the Eq. (1.4) and the corresponding settlement is obtained by the Eq. (1.5). The void radio is reduced by the amount calculated as it is described above. If the sum of the overburden and change in pressure is greater than the preconsolidation pressure, the change in void ratio is evaluated from the Eq.(1.4) and the settlement from Eq.(1.5). These checks and settlement calculations are repeated as many times as the number of layers making up the system. (The maximum number being limited to sixteen) The individual settlements obtained for layer are added up to form the total settlement which is transferred to first subroutine as final settlement.

The first subroutine is named as TIMRAT because it serves to find out the time rate of consolidation. It is called right at the end of the main program and the following data are trasferred or say are common to the main and the subroutine: final settlement, number of layers, overburden, preconsolidation and change in pressures, compression indeces, void ratios and layer thicknesses.

The input data for the subroutine TIMRAT are the coefficient of consolidations, virgin and swelling, the coefficient of permeability, the drainage conditions and the time increment with final time to be considered. The first evaluations are the pressures at the boundary of each layer. In the calculation of settlement, the point of interest for the pressures was the midheight of each layer. Here, they are recalculated at the boundaries to simlify the work in the rest of the subroutine. Once the overburden, preconsolidation and change in pressure at layer boundaries are ready the initial excess pore water pressure is set up according to the consolidation condition. After selecting the drainage and setting the boundary conditions the pore pressures at layer boundaries are computed. The implicit method used here to develop the pore pressure, at an increment of time later than previous one which was defined at the start, is given as.

$$U_{i,t+\Delta T} = \frac{(B_i + U_{i-1} + \alpha U_{i+1})_t}{\left(1 + \frac{1}{T_i}\right) + \alpha\left(1 + \frac{1}{T_{i+1}}\right)} \qquad (4.15)$$

where, $B_i, t = \alpha\ U_{i-1,t} + U_{2-1;t}$

$$- U_{i,t}\left[\alpha\left(1 - \frac{1}{T_{i+1}}\right) + \left(1 - \frac{1}{T_i}\right)\right] \qquad (4.16)$$

and

$$\alpha = \frac{k_{i+1}}{k_i} \quad \frac{H_i}{H_{i+1}} \qquad (4.17)$$

After the computations for pore pressure at each boundary are over the gain in effective stress within the soil mass is calculated for each layer. The reduction in pore pressure within a time increment gives rise to a same amount of gain in effective stress. This additonal stress causes the soil mass to settle which is calculated according to previously presented knowledge of ultimate settlement. Then the settlement for each layer is added up to give the settlement until the time considered of any layered system. The serie of calculation are done for each increment of time until the final time or the per - cent consolidation reaches a value of ninety per cent.

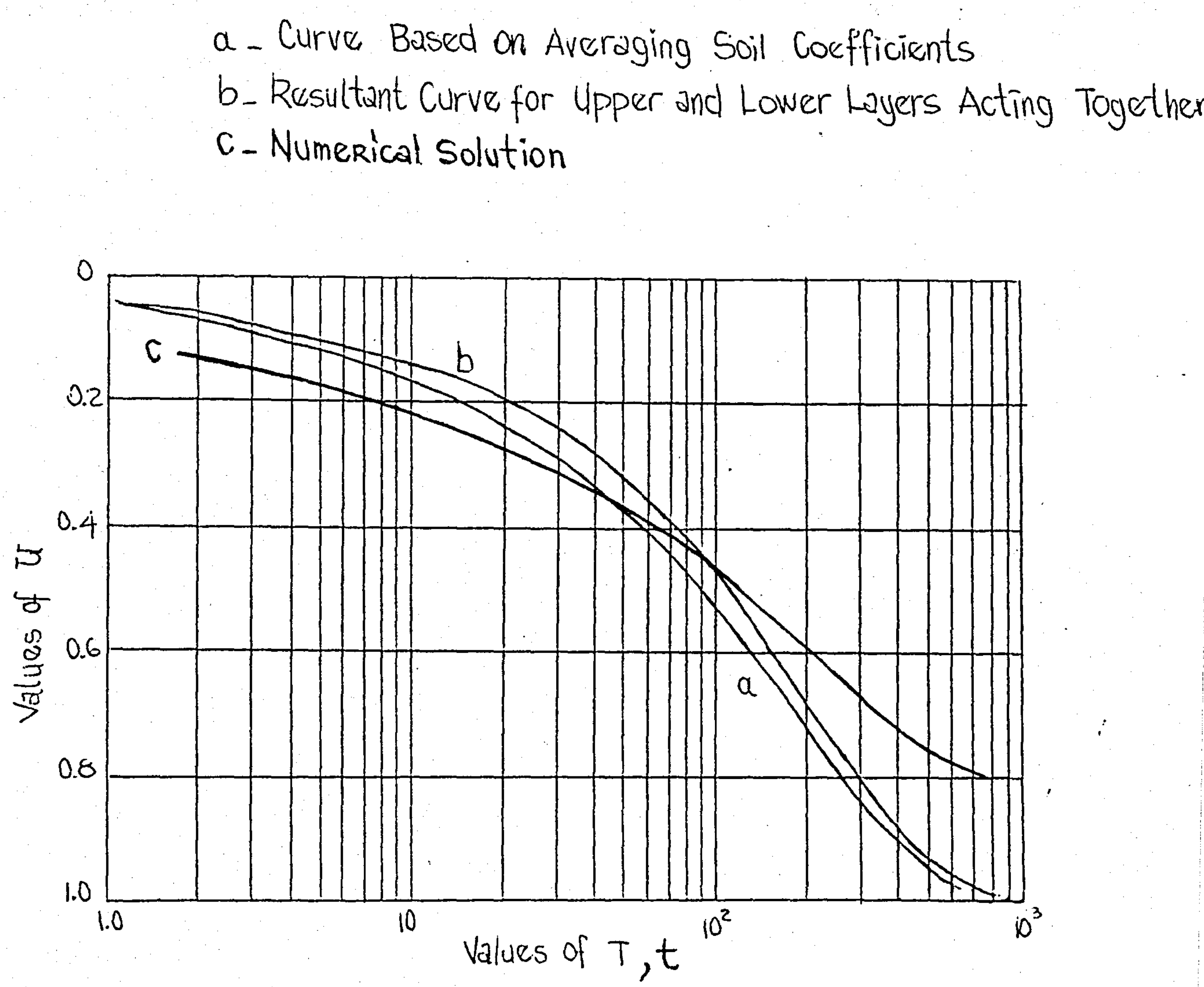

a - Curve Based on Averaging Soil Coefficients
b - Resultant Curve for Upper and Lower Layers Acting Together
c - Numerical Solution
0
0.2
0.4
0.6
0.8
1.0
Values of U
c
b
a
1.0
10
10²
10³
Values of T, t

Fig. 4.6 U vs. T

Then the ratio of the settlement obtained by this procedure to the total one as evaluated in the main program gives us the consolidation rate at this time t.

At the end of this subroutine, TIMRAT, the second one named PLOT is called and the time and settlement informations are transferred. Subroutine PLOT gives a plot of settlement vs time as the output. The results available by this program will be checked with analytical solution of GRAY and conventional theory which are already presented in this chapter.

4.4 STRAIN - BASED SOLUTION

The theory used in the previous section is the stress based one or in other words the value of u_i, pore water pressure, at t=0 for any pressure increment Δp is assumed to be, $U_i = \Delta p$

but in fact, this depends on the stress-strain relationships of the soil. Indeed, experimental evidence, collected internationally over decades, has clearly demonstrated that (for $t=\infty$) the effective stress-strain relationship for clays is non-linear, implying directly that there is generally no proportionality between the additional stress diagram and the primary consolidation. Hence, the entire basis for the conventional method of obtaining the time rate of consolidation is questionable, except for very thin layers, such as in an oedometer. The most serious objection is probably that the conventional theory is not capable of taking the effect of the stress history into account, an effect which is generally found to be of considerable magnitude. In order to arrive at an improved method is believed essential to base the entire analysis on strain instead of on additional pore pressure, and also use the experimentally determined relationships between effective stress and strain.

In the solution given by N.Janbu (6) in 1965 the externally applied pressure is not equated to excess pore pressure as was done in the conventional theory. Altough the derivation of the differential equation is the same, Janbu obtained the time rate of strain, ε, rather than pore pressure, u, as follows

$$\frac{\partial \varepsilon}{\partial} = \frac{\partial}{\partial z}\left(C_v \frac{\partial \varepsilon}{\partial z}\right) - \frac{\partial v_o}{\partial z} \qquad (4.18)$$

since he assumed a relationship between external stress and the strain. Using dimensionalless variables

$$T = t(C_v/H^2), \quad \rho = z/H$$

the differential equation is written (C_v=constant)

$$\frac{\partial \varepsilon}{\partial T} = \frac{\partial^2 \varepsilon}{\partial \rho^2} - \frac{H}{C_v} \frac{\partial v_o}{\partial \rho} \qquad (4.19)$$

Janbu then tried to find ε as a function of time and depth. In dimensionless scale $\varepsilon = f(\rho, T)$. This unknown function must satisfy both the differential equation and the boundary conditions at the start and at the end of the primary consolidation process.

The strain distribution within the compressible layer is determined according to the end strain distribution which is assumed to be constant, linear or parabolic. To illustrate this, Fig. 4.7 is used where the strain at any depth at a time, $t = \infty$ is denoted as ε_1 and is defined as

$$\varepsilon_1 = \varepsilon_s - \varepsilon_d (1 - \rho^r) \qquad (4.20)$$

where, ε_s: strain at the surface

ε_b: strain at the bottom

ε_d: differential strain, $\varepsilon_d = \varepsilon_s - \varepsilon_b$

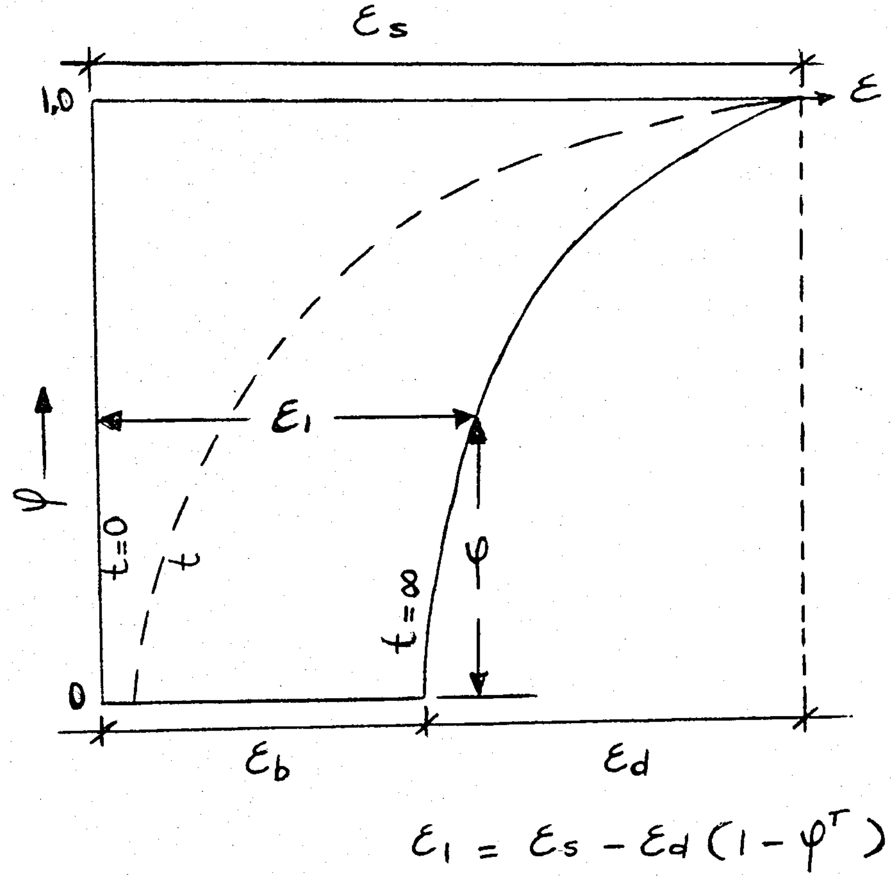


Fig. 4.7 Strain Distribution (Janbu, 1965)

It is seen that r = 0 corresponds to a constant ε_1, such as may be the case in an oedometer, while r=1 and r=2 correspond to a linear and parabolic strain distribution.

Then the amount of settlement occured at a time T may be computed as the area under the ε curve,

$$\Delta H_T = \int_0^1 \varepsilon \, d\rho \tag{4.21}$$

and the degree of consolidation

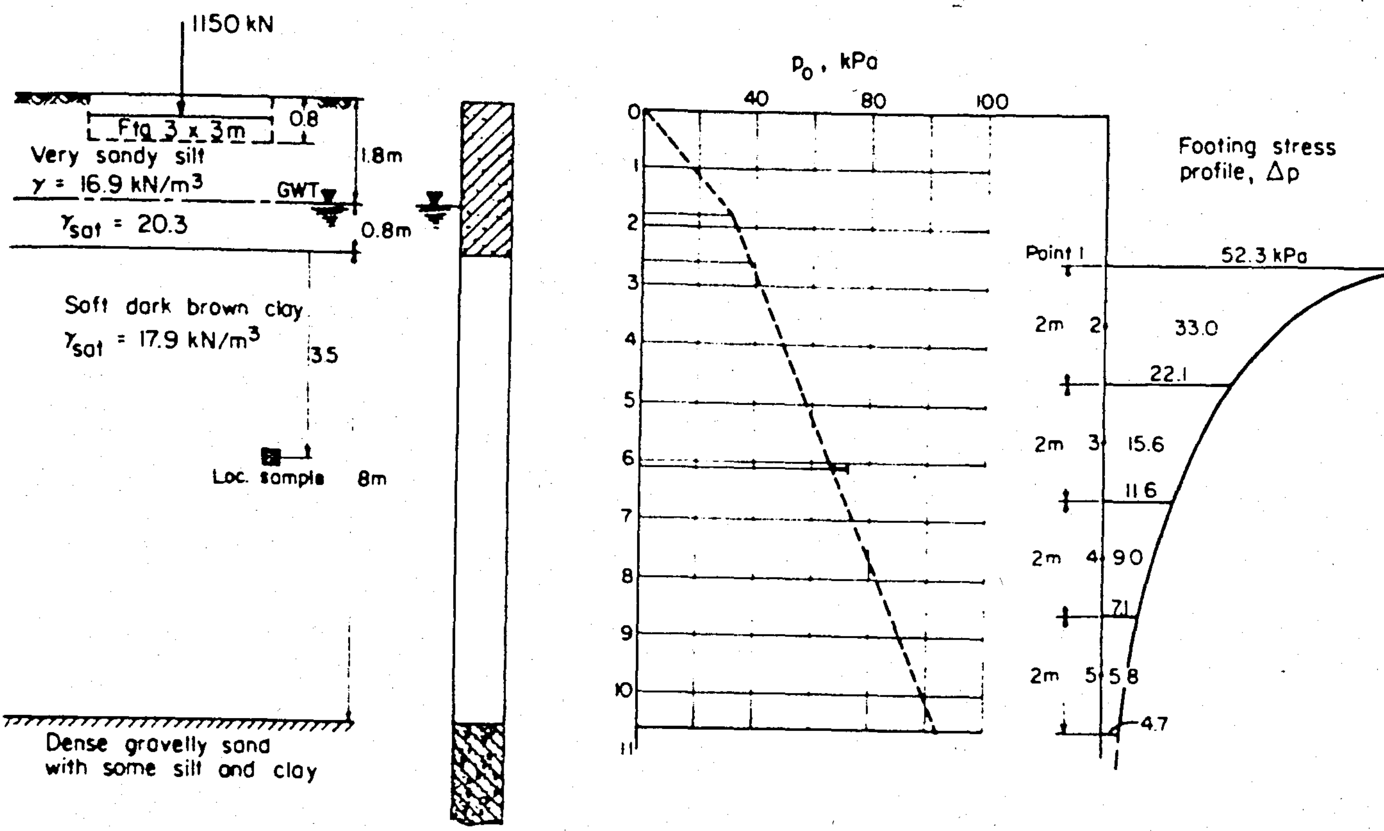
$$U = \int_0^1 \varepsilon \, d\rho \Big/ \int_0^1 \varepsilon_1 d\rho \tag{4.22}$$

In Fig. 4..7 since ε_1 decreases with depth, for linear and parabolic case, even when the additional stress is constant, it is evident that the of consolidation on the basis of ε is more rapid than that obtained from the conventional method.

Using the computer program CONVER provided in Appendix A the consolidation of a thick clay deposit may be treated in the form of sublayers making up the deposit. In order to investigate the difference between the method presented here in and the method offered by N.Janbu (6) the following problem is calculated using both methods.

Given the soil profile and the e vs log p curve of Fig. 4.8 with a coefficient of consolidation C_V=0.032 cm^2/min; find the expected total settlement and a plot of settlement vs time.

Comparing now both results, it is clear that the



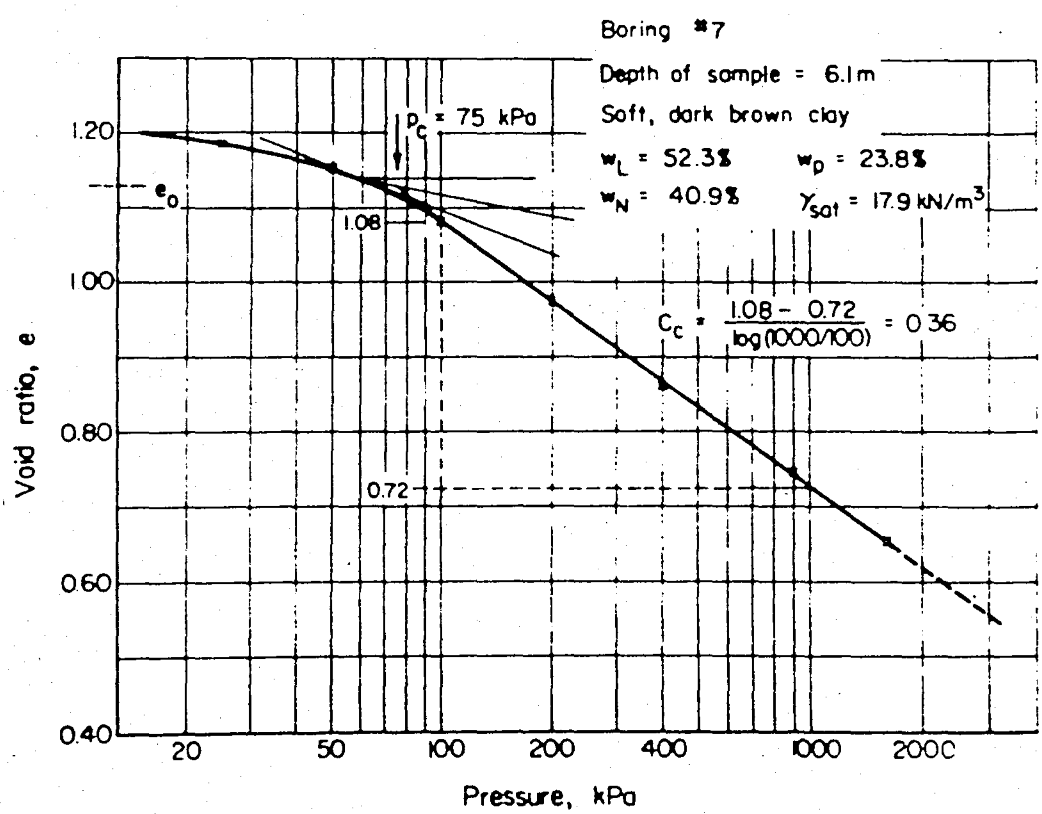


Fig. 4.8 Soil Profile and e vs log p

		At midheight of any sublayer			
Point	H_i(m)	p_o (kPa)	Δp (kPa)	ε_z	ΔH_i
1	–	38.8	52.3	0.063 $= \varepsilon_1$	–
2	2.0	46.9	33.0	0.039	0.078
3	2.0	63.1	15.6	0.016	0.032
4	2.0	79.3	9.0	0.008	0.016
5	2.0	95.5	5.8	0.004	0.008
Bottom	–	103.6	4.7	0.003	–

$$\Sigma \Delta H_i = \Delta H = 0.134 \text{ m}$$

Table 4.1 Results with JANBU (Bowles, 1979)

Layer	Thickness (m)	Void ratio	CC	CS
1	2.0	1.13	0.36	0.051
2	2.0	1.13	0.36	0.051
3	2.0	1.13	0.36	0.051
4	2.0	1.13	0.36	0.051

Layer	Overburden pressure (kPa)	Preconsolidation pressure (kPa)	Change pressure (kPa)	Settlement at top of layer (m)
1	46.9	46.9	33.35	0.164
2	46.9	46.9	15.6	0.085
3	46.9	46.9	9.0	0.043
4	46.9	46.9	5.8	0.017

Table 4.2 Results with CONVER

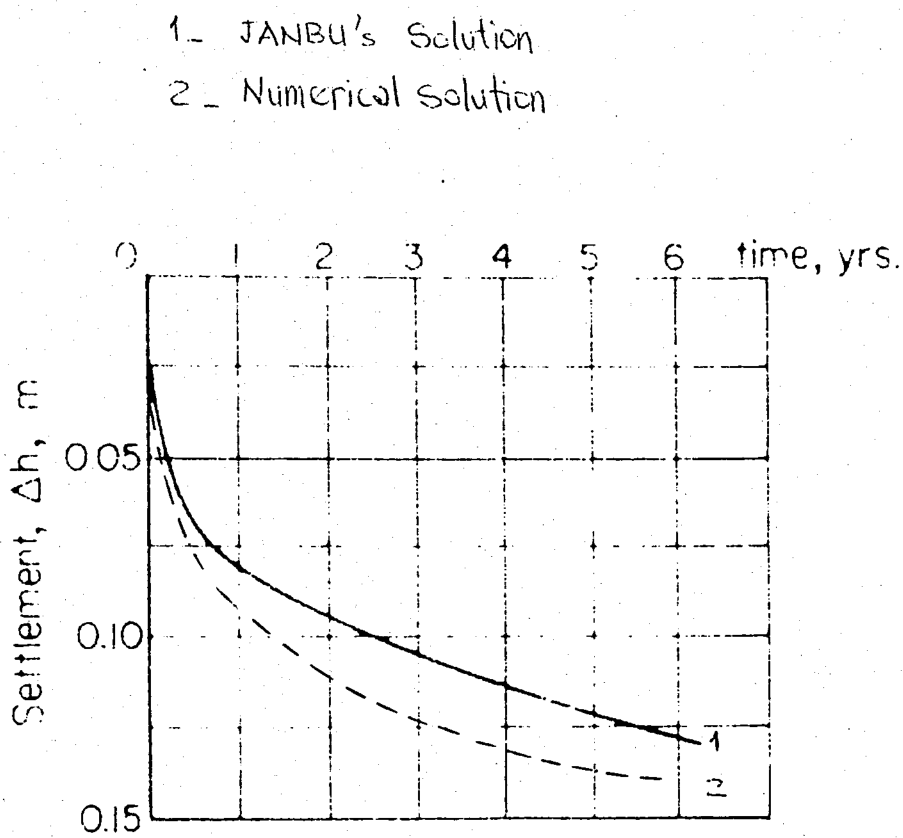


Fig. 4.9 Δh vs t curves

difference is not so great on they are quite similar. This is due to the fact that dividing a thick layer into sublayers permit us to calculate percent consolidation with more precise pressure increments at the midheight of each one. This is the reason why the results obtained with CONVER converges to the strain - based solution.

4.5 SUMMARY

The consolidation behaviour of a two layer clay deposit or more is the subject of this chapter. The most common problem faced is the one with a compressible layer overlain by an incompressible one. The basic differential equation of instantaneous pore water pressure , u, may be written for the upper and lower layers and be solved with regards of the boundary and initial conditions. U vs T plots for different drainage conditions are given in Figs. 4.2, 4.3, 4.4 after H.Gray(5)

Before going through numerical analysis of a layered system the approximate method averaging soil coefficients proposed by K.Terzaghi (14) is presented. The ease provided by the numerical approach to handle a layered deposit consolidation is rather considerable and was mentioned before.

The results of computer program CONVER available in the Appendix A is checked against the strain based solution given by Janbu (1965) which is thought ta be the best approach for the consolidation setttlement of a thick compressible layer.

Using CONVER , one is capable of subdividing and produce thinner strata and so do not overestimate the excess pore water pressure. Thus the curves of Fig. 4.9 are too far apart from each other. The sample problem of Fig. 4.4 is solved numerically using CONVER and U vs T is plotted and presented in Fig. 4.6

V. CONSOLIDATION OF FINE-GRAINED SOILS BY DRAIN WELLS

5.1 INTRODUCTION

Most compressible soils are alluvial deposits and are more pervious in the direction of the bedding than in a perpendicular direction. When such soils are loaded , horizontal flow accelerates the consolidation of the soil mass as compared with strictly vertical flow.

Some-times an economical method may be to accelerate the consilidation process, by the use of vertical sand - filled holes konwn as drain wells.

So in this chapter the analytical solution in case of radial drainage will be investigated together with the numerical approach for a homogeneous soil layer. The solution of time rate of consolidation of a layered system which is radially and vertically drained will be tried from a numerical approach point of view as well.

5.2 VERTICAL CONSOLIDATION DUE TO RADIAL FLOW OF WATER-GENERAL

The treatment of consolidation due to radial flow is an extension of the Terzaghi consolidation theory. The boundary conditions in the vicinity of a drain well will be discussed in the following lines.

Excess pore pressure will begin dissipate first near the drainage boundaries. Thus the vertical settlement will not be uniform from the center to the edge of the sand drain. When the loading surface is considered flexible so that the stress distrubution on the soil remains constant regardless of the deflection of the surface, we have the "free-strain" case.

If the surface of the clay yields more at one location than at other , then it might be expected that the applied stress at the region of greatest yielding would diminsh somewhat as the stress is distributed by the rigidity of the gravel, and this extra load would be thrown on those area which would have settled less. Then we might expect no differential settlement to occur whatsoever. This situation is called the "equal strain" case.

When the effect of drain wells is being studied, it is likely that the material in nature behaves in a manner intermediate between the free-and equal-strain.

Drain wells in the field are usually prepared by driving a hollow tube to the depth required (usually the thickness of most compressible layer) and washing out the clay soil contained within the tube with water jets. Obviously, the process of driving will result in a zone of disturbed soil immediately adjacent to the hollow tube. Thus causing a "smeared" zone. The permeability in the

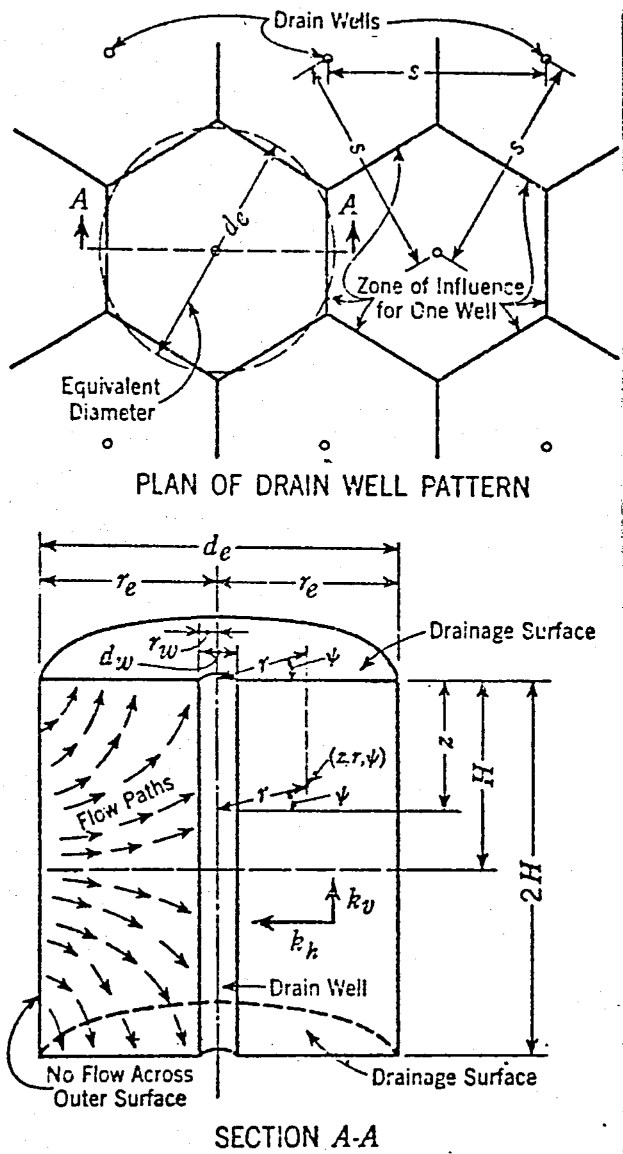


Fig. 5.1 Plan and Vertical Section of a Drain Well (Richart, 1957)

smeared zone will be considerably than the horizontal permeability of the undisturbed soil.

The smeared zone forms a barrier to the horizontal flow of water, there by slowing down considerably the process of consolidation.

5.3 ANALYTICAL SOLUTION - CONSOLIDATION WITH NO SMEAR

5.3.1 The Free Strain Case

As indicated in Fig. 5.1 by A.Barron (2), for a triangular spacing of drain wells, a zone of influence exist having a hexagonal plan form. By approximating the hexagon by a circle of equivalent diameter, d_e, this can be used as the outer limit of the zone of influence of influence of each drain well.

Before proceeding fith the solutions, the following basic assumptions are made:

A. All vertical loads are initially carried by excess pore water pressure u

B. All compressive strains within the soil mass occur in a vertical direction. Thus the basic partial differential equation for consolidation by three - directional flow in stratified soils is developed by Barron (2)

$$\frac{k_h}{\gamma_w}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{k_v}{\gamma_w}\left(\frac{\partial^2 u}{\partial z^2}\right)=\frac{a_v}{1+e}\left(\frac{\partial u}{\partial t}\right) \quad (5.1a)$$

in which k_h and k_v are horizontal and vertical permeabilities: x,y and z are rectangular coordinates.

For a symmetrical flow to a central drain well Eq. (5.1 a) becomes:

$$\frac{k_h}{\gamma_w}\left(\frac{1}{r}\,\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial r^2}\right)+\frac{k_v}{\gamma}\left(\frac{\partial^2 u}{\partial z^2}\right)=\frac{a_v}{1+e}\left(\frac{\partial u}{\partial t}\right) \qquad (5.1b)$$

in which r and z are cylindrical coordinates as defined by Fig. 5.1

C. The most economical pattern of drain wells is that shown in Fig. 5.1. An exact analysis should include the load disribution and the effect of each well on the rate of consolidation at any point in the foundation. However, it is believed that such a solution would be extremely cumbersome when consideration is given to the foundation and the present incomplete konwledge of three-dimensional stress-strain consolidation properties of fine grained soils.

D. The zone of influence of each well is a circle

E. Load distribution is uniform over this area

The vertical flow part of Eq.(5.1b) will be disregarded for the time being for the ease and sake that is brought about it. The radial and vertical pore pressures may be calculated separately and then combined as follows:

$$U_{r,z} = \frac{U_r \quad U_z}{U_o} \qquad (5.2)$$

Having this in mind and combining the constant terms in Eq. (4.1 b) one obtains the variation of pore pressure for radial flow only.

$$\frac{\partial u}{\partial t} = Cvr\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\quad\frac{\partial u}{\partial r}\right) \qquad (5.3)$$

The boundary conditions that must be satisfied are:

A. The initial pore water pressure, U_o, is uniform throughout the soil mass when t=0

B. The excess pore water pressure at the drain well surface (r_w) is zero when t>0

C. The external radius, r_e, is considered impervious because of symmetry. Thus, when $r=r_e$

With basic assumptions and boundary conditions the variation of U_r is determined by A.Barron (2) in 1947 and assumed to not be worth of repeating it here once more.

5.3.2 The Equal Strain Case

In an actual installation, as mentioned before, the fact that consolidation proceeds faster near the drain well, there by causing a greater surface settlement in that region, could be very well cause a resdistribution of the surface loading. The redistribution occurs in such a fashion that the surface settlement is the same at all points. Then the analytical solution is as follows

$$U_r = \frac{4\bar{u}}{d_e^2 f(n)} \left[r_e^2 \ln\left(\frac{r}{r_w}\right) - \frac{r^2 - r_w^2}{2} \right] \quad (5.4)$$

in which

$$\bar{U} = Uo\ \varepsilon^{\lambda} \quad (5.5)$$

$$\lambda = -\frac{8T_h}{f\ (n)} \quad (5.6)$$

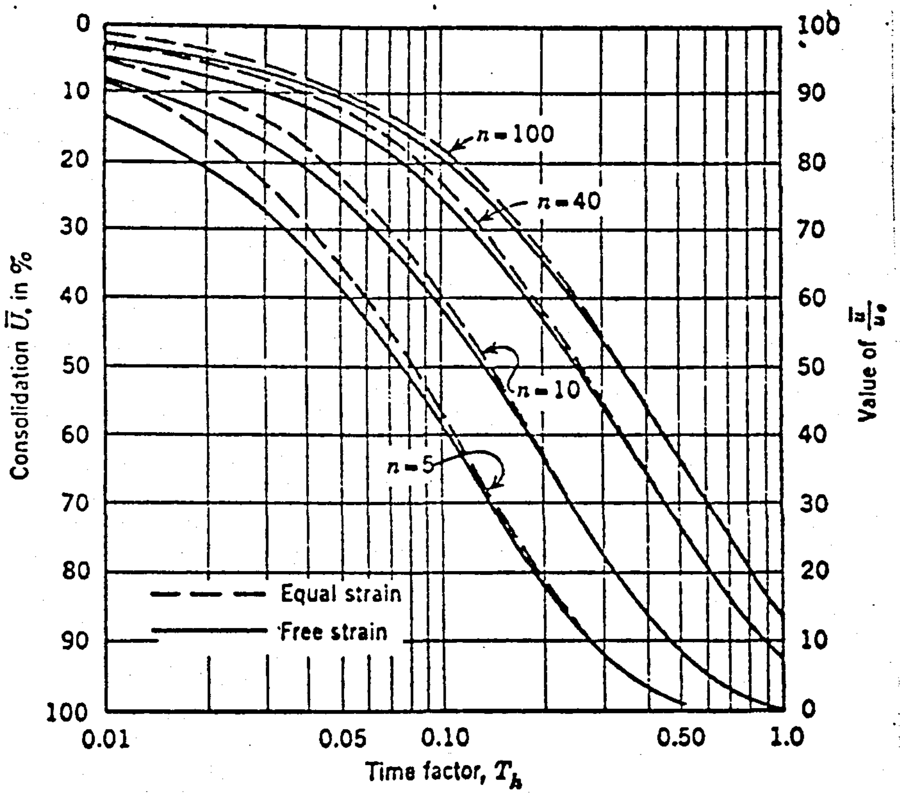


Fig. 5.2 U vs T_h (Richart, 1957)

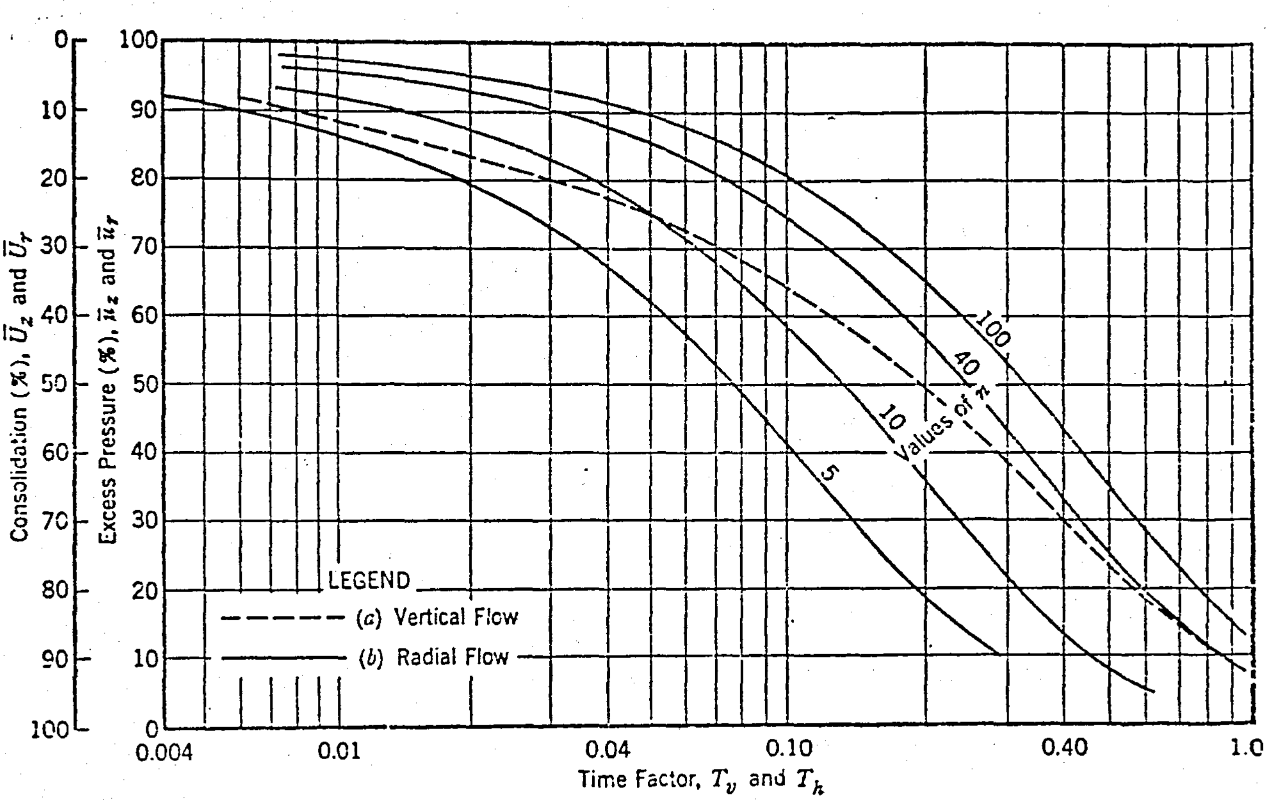


Fig. 5.3 Average Consolidation Rates (Barron, 1947)

$$f(n) = \frac{n^2}{n^2-1} \ln(n) - \frac{3n^2-1}{4n^2} \qquad (5.7)$$

Curves showing the relation between the average pore water pressure , U and the time factor, T_h , can be obtained using Eq. (5.5). Such curves for n = 5,10,40 and 100 are show on Fig. 5.2, together with the corresponding curves determined by the free strain case .

The difference between the results obtained by the two extreme considerations of the process of consolidation is small, particularly for the curves representing values of n gretater than approximately 10. For n= 5 the discrepancy is somewhat greater for the first part of consolidation, but above approximately 50 % consolidation, the curves are almost identical. Since the results are nearly identical, but the time needed to evaluate U_r for the free strain case is of the order of ten to fifteen times that needed to evaluate Eq. (5.8) , the equal strain solution is prefable.

Fig. 5.2 indicates that the curves representing the equal strain solutions for different values of n have the same shape, but are displaced horizontally.

5.4 EFFECT OF SMEAR ON THE CONSOLIDATION

The remolded or smeared zone at the periphery of the drain well creates an additional resistance that must be overcome by the excess water being expelled. This additional resistance retards the consolidation process. This is well studied by F.Richart (9) in 1957.

The smeared zone very likely consists of a thin layer of actual smear plus an adjacent region in which the soil has undergone a considerable amount of disturbance. The important quantities to be considered in analyzing the effects of this smeared region are (a) the ratio, s, of the radius of the smeared zone to the well radius ($s = r_s/r_w$) and (b) the ratio of the coefficients of horizontal permeability in the undistirbed soil (k_h) and in the smeared zone (k_s). For s = 1 , there is no thickness to the smeared ring and if $k_h/k_s = 10$ then the disturbed zone does not change the water flow characteristics of the soil cylinder.

By ignoring the consolidation of the smeared zone, the smeared region is treated as one where flow exists between one boundary value of zero and another boundary value that is time dependent.

Since the equal strain case was preferred to the free strain one, only the solution for the former case is given below. Hence, the solution for the excess pore water pressure in a soil cylinder undergoing equal vertical strains and containing a smeared region around the drain well is

$$Ur = Ur \frac{\ln \frac{r}{r_s} - \frac{r^2 - r_s^2}{2 r_e^2} + \frac{k_h}{k_s} \left(\frac{n^2 - s^2}{n^2}\right) \ln(s)}{\nu} \qquad (5.8)$$

in which

$$\nu = \frac{n^2}{n^2 - s^2} \ln\left(\frac{n}{s}\right) - \frac{3}{4} + \frac{s^2}{4n^2} + \frac{k_h}{k_s}\left(\frac{n^2 - s^2}{n^2}\right) \ln(s) \qquad (5.9)$$

and U_r can be determined from

$$U_r = U_o \varepsilon^m \qquad (5.10)$$

in which

$$m = -\frac{8\,T_h}{\nu} \qquad (5.11)$$

5.4.1 Evaluation of Smear Effects

The paper presented by F.Richart (9) in 1957 deals with the evaluation of smear effect.

By comparing the equations it is seen Eqs. (5.8) and (5.7), (5.9) and (5.5), (5.10) and (5.6) and (5.11) and (5.7) become identical when s = 1

For the ideal wells , the position of the consolidation time curve for any particular value of n depends on the value of f(n) (Eq.5.7) which is a function of n only. For the wells with smear, the position of the resulting consolidation-time curves depens upon (Eq.5.9) which is a function of n, s, and k_h/k_s.

Thus, it is possible to interpret various combinations of n, s, and k_h/k_s in the treatment of a well with smear as if they define an ideal well having a larger value of n.For a given radius of influence, a larger value of n determines the radius of an equilvalent ideal well which is smaller than the radius of the actual well surrounded by a

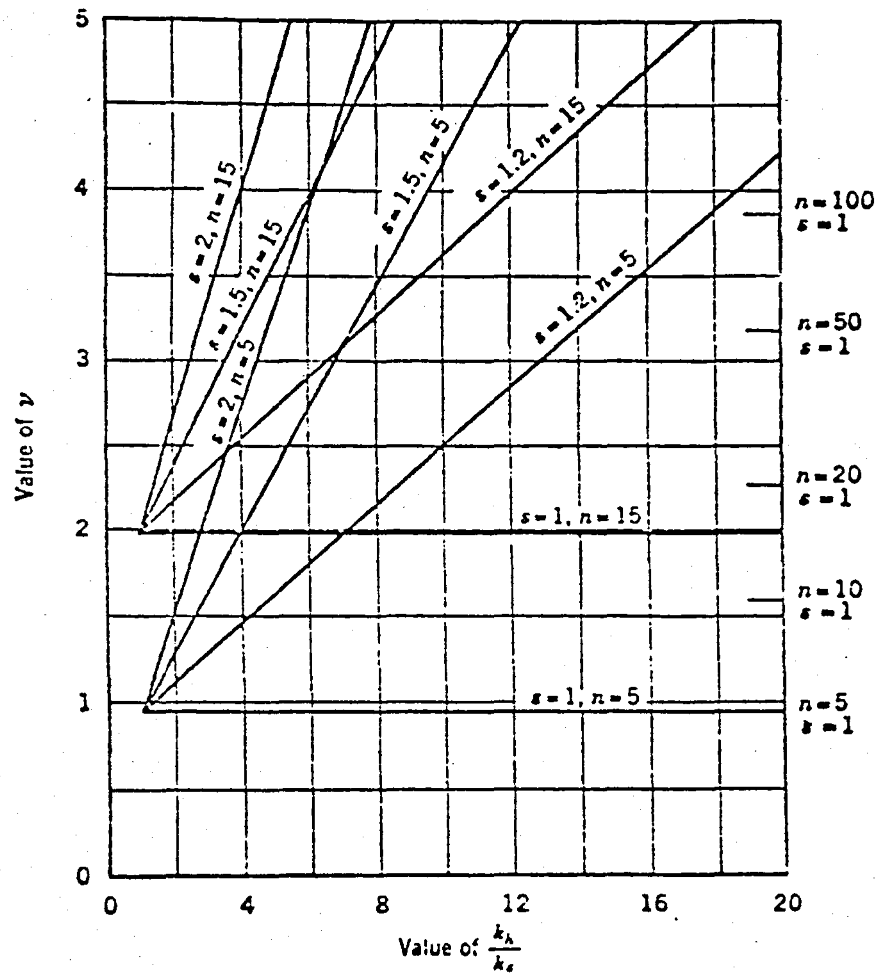


Fig. 5.4 Relation Between k_h/k_s and r for n = 15 (Richart, 1957)

zone of smear. The effect of the soil cylinder caused by the introduction of a smeared zone at well periphery is identical to the effect caused by reducing the size of the ideal well. Fig.5.4 shows the combination of n, s and k_h/k_s that may be used to give the same value of ν . This figure obtained by evaluating Eq. (5.9), uses the value of as ordinate and the ratio k_h/k_s as abseissa. Families of lines for each selected value of n show the influence of variations in s. Only the lines for n=5 and n=15 are show on Fig.5.4

However, by the use of Fig. 5.5 diagrams similar to Fig. 5.4 can be established for a wide range of values of n.

5.5. NUMERICAL ANALYSIS

Another way of solving the problem in question might be possible if one could develop a computer program for this purpose.

Here, the finite difference technique, used to derive equations of numerical solutions to consolidation problems in earlier sections, is going again to be tool of the following analysis.

Expressing Eq. (5.3) in terms of finite differences leads to

$$\frac{U_{i,t+\Delta t} - U_{i,t}}{\Delta t} = Cvr \left[\frac{U_{i-1} - 2\,U_i + U_{i+1}}{(\Delta r)^2} + \frac{1}{r_i} \quad \frac{U_{i+1} - U_{i-1}}{2\Delta r} \right] \qquad (5.12)$$

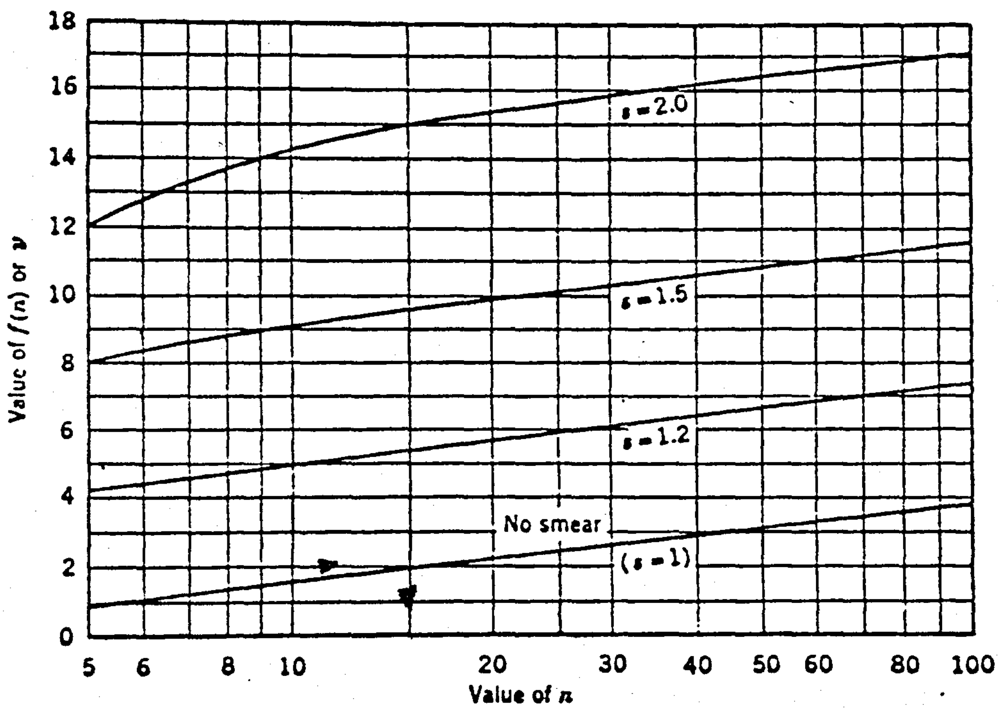


Fig. 5.5 Relation Between n and f (n) or for $k_h / k_s = 20$

(Richart, 1957)

To handle this formula let's define

$$r_i = i.\, r_w \tag{5.13}$$

or

$$r_i = i.\Delta r \tag{5.14}$$

Rewriting Eq. (5.15) and solving for the unkonwn

$$U_{i,t+\Delta t} = U_{i,t} + \beta \left[\left(1 - \frac{\Delta r}{2r_i}\right) U_{i-1} + \left(1 + \frac{\Delta r}{2r_i}\right) U_{i+1} - 2\, U_i \right]_t \tag{5.15}$$

where

$$\beta = \frac{Cvr\ \Delta t}{(\Delta r)^2} \tag{5.16}$$

and combining Eq. (5.14) into Eq. (5.15) one obtains

$$U_{i,t+\Delta t} = U_{i,t} + \beta \left[\left(1 - \frac{1}{2i}\right) U_{i-1} + \left(1 + \frac{1}{2i}\right) U_{i+1} - 2U_i \right] \tag{5.17}$$

By taking the average value of the excess pressure at any time, a curve U_r versus T_h can be constructed that corresponds to within a few percent of the values obtained by analytical solution.

With all these informations in mind and the computer program CONVER ready a computer program called CONRAD available in Appendix C has been developed capable of calculating the time rate consolidation of a layered clay deposit which is vertically and radially drained.

The program CONRAD again consists of three parts:

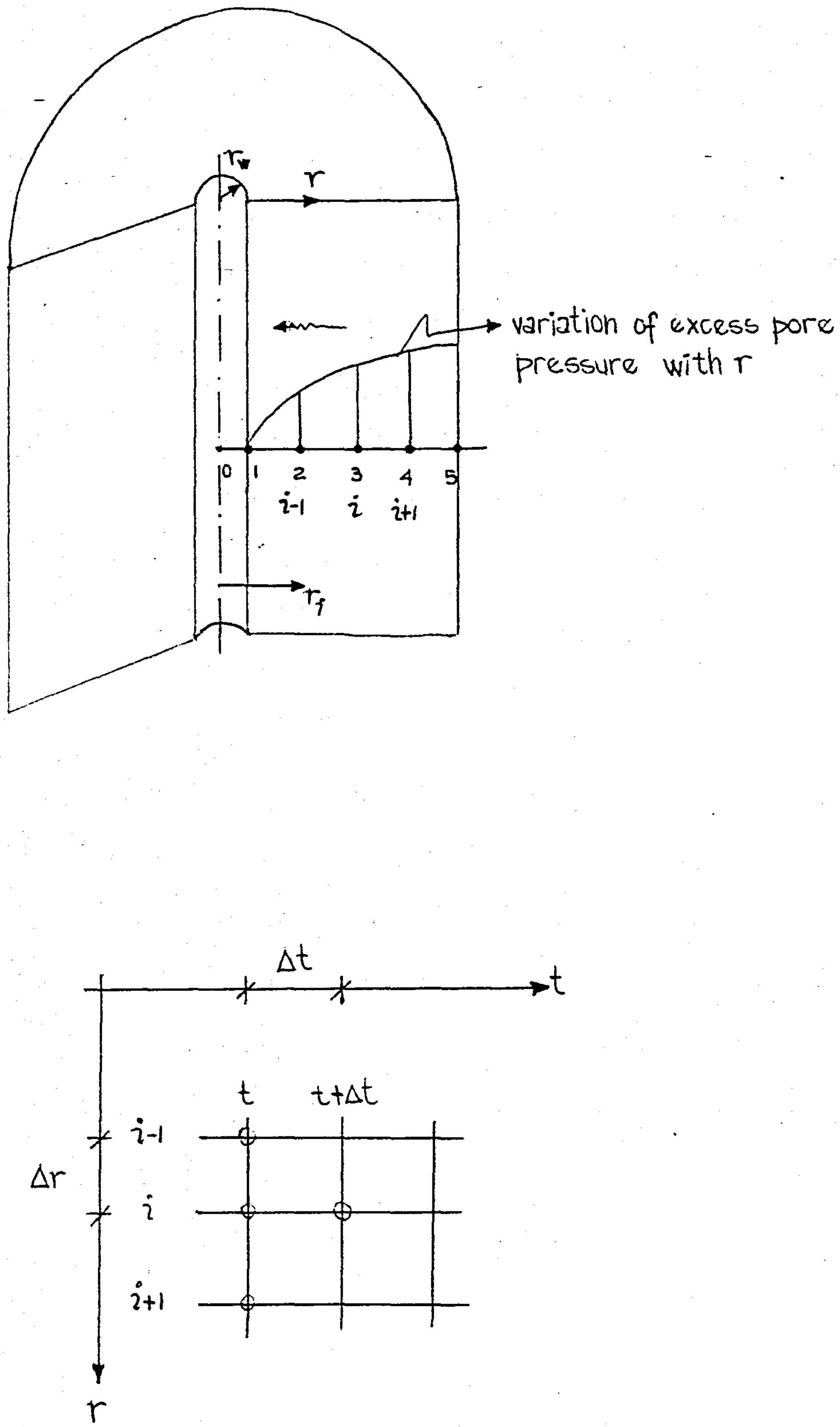


Fig. 5.6 Pore Water Pressure Variation with Radius of Influence

The main program and two subroutines. The use of vertical drains which put the radial drainage into the effect does not change the amount of settlement at all compared to the situation where they weren't installed. This is of course correct if the loading and other conditions are not altered. This installation of drain wells do only affect the rate of consolidation. Thus they are used wherever it is worth to speed up the degree of consolidation. Hence the main program of CONRAD is identical to the one of CONVER. It is not going to be considered here because its logic was given bireefly in the previous chapter.

The subroutine TIMRAT called at the end of the main program has the followings as input data: the drainage condition, time increment, final time to be considered , the well, smear and influence radii, coefficient of permeability in the smear zone, the coefficient of consolidation virgin, swelling and radial, vertical and horizontal coefficient of permealebilities.

At first the overburden, perconsolidation and change in pressures are recalculated at the layer interfaces. This is done to evaluate excess pore pressure only at the boundaries and so to provide ease in the ensuing steps. As soon as the boundary conditions are set up the excess pore pressures are initialized to the externally applied pressure increment.

The difference between free and equal strain cases was mentioned before and this is shown in Fig.5.2 by

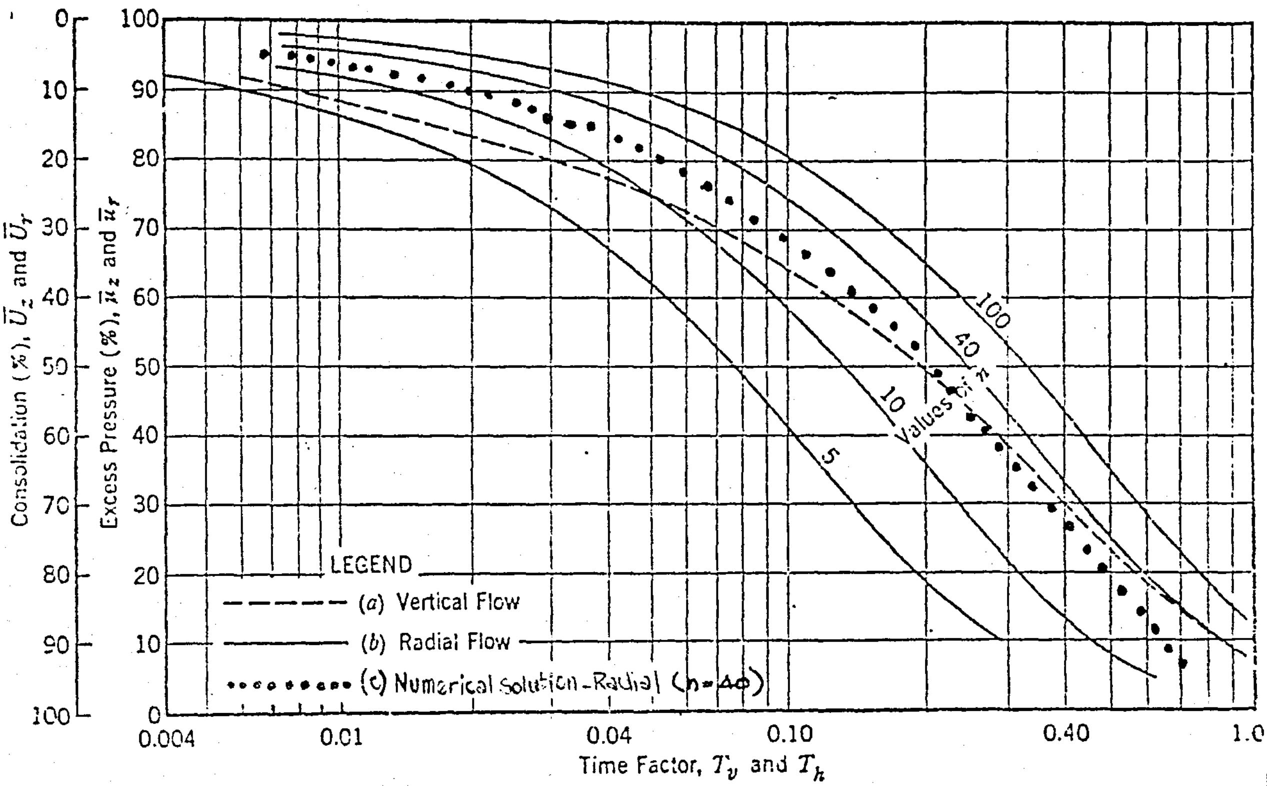


Fig. 5.7 Average Consolidation Rates

F.Richart (9). Since the gap is rather unimportant, the equal strain solution is chosen in order to take the radial drainage into account. The simplicty of the equal strain solution is another convenience for the convenience for the sake of computations. The Eqs. (5.4) to (5.8) are used to deal with radial pore water distribution and is combined with vertical one using Eq. (5.2) in order to produce the pore water distribution for a radially and vertically drained layer system. The rest of the subroutine TIMRAT is the same as one of CONVER . As pore-water dissipation occur there happens an increase in the effective stress. Settlement which happens as the effective stress builds up is calculated and divided by the settlement final to give the percent consolidation. This loop is repeated until the final time is reached or consolidation exceeds ninety percent.

The output of the subroutine PLOT is giving time versus settlement plot and is obtained in same way as was described for CONVER.

The results of CONRAD for a sample are given in Fig. 5.7 to illustrate and make a comparison between analytical and numerical solutions.

In order to investigate the effect of radial drainage over the consolidation rate, a serie of calculations are made of the sample below for different thickness, vertical permeability and horizontal to vertical permeability ratios.

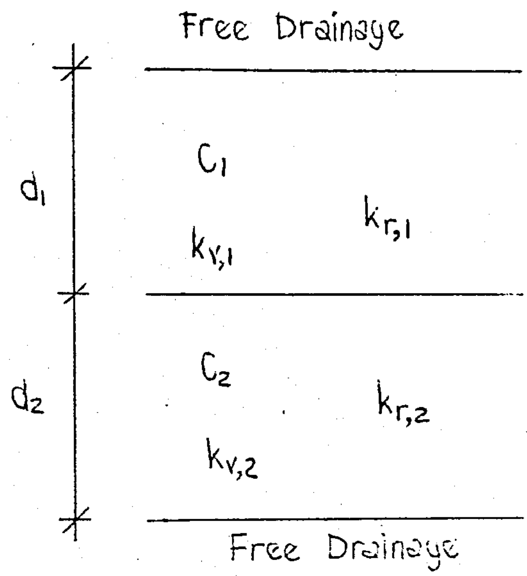


Fig. 5.8 Vertically and Radially Drained Sample Soil Profile

In Fig. 5.8 the well radius is considered to be 0.1m. To begin with, the k_r/k_v ratio is set to 4.0.

Increasing the well radius by five times had only caused an increase of only one percent in the related consolidation rate. So the effect of the well radius my supposed to be negligible.

If one carefully examines the tabulated data given in Table5.1he will judge in the following manner: for the same thickness of clay layers, altough the permeability of the upper layer is set to eight times of the lower one the percent consolidation are assumed to be equal. The reason for these results is that the consolidation process is mainly affected by the horizontal permeability. To check this in the following section the consolidation which would occur for different permeability ratios of the upper and lower layers for a fixed thickness ratio without the vertical drains is going to be calculated.

If the effect of radial darainage is taken into account the other variables do interfere very little and the consolidation rate is greatly affected by the presence of drain wells or not. Placing of drain-wells is not so important either in this case since consolidation rates do not differ too much for different influence radii.

In the calculations of TABLE 5.1, 5.2, 5.3 the horizontal permeability is assumed to be four times the vertical one which is qui reasonable. In order to catch the great effectiveness provided by radial drainage the consolidation

TIME	CONSOLIDATION RATE (%) ; $k_r = 4k_v$; $k_1 = k_2$						
	$d_2 = 2d_1$		$d_2 = 4d_1$			$d_2 = 8d_1$	
	$r_e = d_1$	$r_e = 3d_1$	$r_e = d_1$	$r_e = 2d_1$	$r_e = 5d_1$	$r_e = d_1$	$r_e = 10d_1$
1	56.62	56.69	46.94	46.91	46.90	39.20	39.15
2	72.42	72.37	62.87	62.80	62.79	54.31	54.20
3	84.40	84.33	74.27	74.17	74.15	63.60	63.40
4	93.89	93.83	85.62	85.50	85.48	74.17	73.89
5	—	—	95.10	95.02	95.01	86.27	85.99
6	—	—	—	—	—	95.77	95.60

Fig. 5.l Results of CONRAD with Fig. 5.8

TIME	CONSOLIDATION RATE (%) ; $k_r = 4k_v$; $k_1 = 4k_2$						
	$d_2 = 2d_1$		$d_2 = 4d_1$			$d_2 = 8d_1$	
	$r_e = d_1$	$r_e = 3d_1$	$r_e = d_1$	$r_e = 2d_1$	$r_e = 5d_1$	$r_e = d_1$	$r_e = 10d_1$
1	56.80	56.77	47.08	47.04	47.04	39.29	39.24
2	72.75	72.70	63.16	63.09	63.08	54.52	54.41
3	84.82	84.75	74.72	74.62	74.60	63.97	63.78
4	94.21	94.16	86.11	86.00	85.98	74.69	74.43
5	—	—	95.42	95.35	95.33	86.80	86.53
6	—	—	—	—	—	96.08	95.92

Table 5.2 Results of CONRAD with Fig. 5.8

TIME	CONSOLIDATION RATE (%) ; $k_r = 4k_v$; $k_1 = 8k_2$						
	$d_2 = 2d_1$		$d_2 = 4d_1$			$d_2 = 8d_1$	
	$r_e = d_1$	$r_e = 3d_1$	$r_e = d_1$	$r_e = 2d_1$	$r_e = 5d_1$	$r_e = d_1$	$r_e = 10d_1$
1	56.95	56.92	47.22	47.19	47.18	39.40	39.35
2	73.03	72.98	63.46	63.39	63.38	54.76	54.65
3	85.17	85.10	75.18	75.07	75.05	64.40	64.21
4	94.48	94.43	86.61	86.50	86.48	75.30	75.03
5	—	—	95.73	95.66	95.65	87.39	87.14
6	—	—	—	—	—	96.41	96.27

Table 5.3 Results of CONRAD with Fig. 5.8

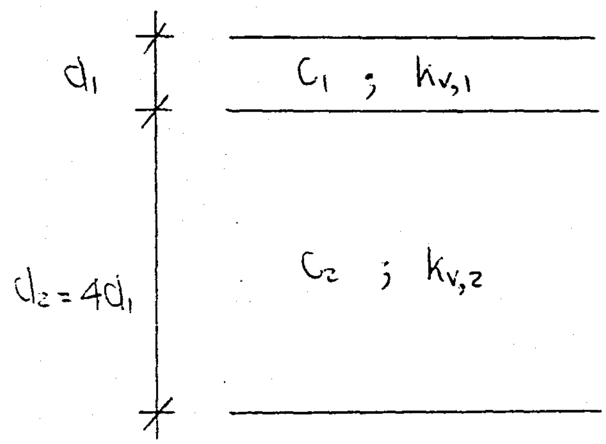


Fig. 5.9 Vertically Drained Sample Soil Profile

TIME	CONSOLIDATION RATE (%)		
	$k_{v,1} = k_{v,2}$	$k_{v,1} = 4\,k_{v,2}$	$k_{v,1} = 8\,k_{v,2}$
1	21.75	21.85	21.96
2	21.79	22.00	22.22
3	21.83	22.14	22.47
4	21.87	22.29	22.72
5	21.91	22.43	22.97

Table 5.4 Results of CONVER with Fig. 5.9

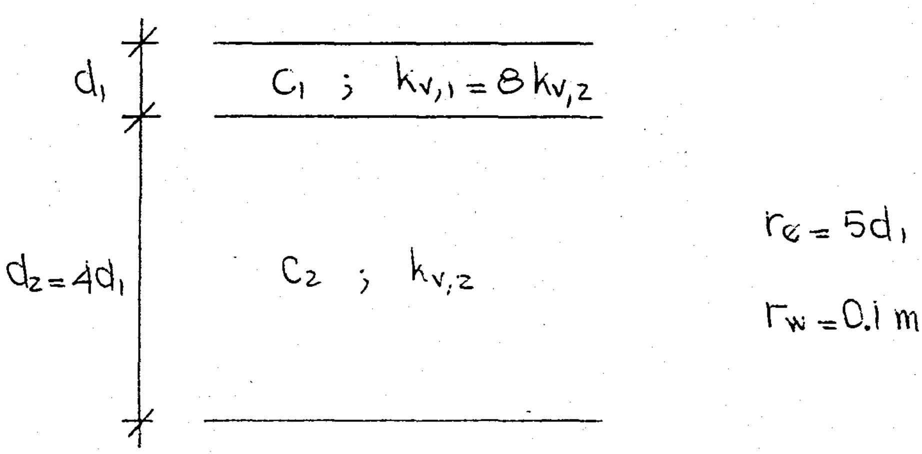


Fig. 5.10 Vertically and Radially Drained Sample Soil Profile

TIME	CONSOLIDATION RATE (%)			
	$k_r = k_v$	$k_r = 2k_v$	$k_r = 5k_v$	$k_r = 10k_v$
1	47.18	47.18	47.18	47.18
2	63.38	63.38	63.38	63.38
3	75.05	75.05	75.05	75.05
4	86.48	86.48	86.48	86.48
5	95.65	95.65	95.65	95.65

Table 5.5 Results of CONRAD with Fig. 5.10

ratios for a fixed thickness and vertical permeability ratio but for varying horizontal permeability ratio to vertical one are calculated in the followin.

The consolidation attained with the presence of drain wells for different ratios of horizontal permealibilities to vertical ones ore not changing at all after the TABLE 5.5 given above. Even for k_r/k_v= 1.0 and with a spacing of five meter the consolidation of vertical plus radial is about twice the vertical only.

5.6 SUMMARY

Clayey soils suject to consolidation settlement are mostly alluvial deposits and are more pervious in the direction of the bedding. So the use of vertical drains makes the consolidation process accelerate and thus a gain is sheraring streng,where is needed.

In the presence of vertical drains, the load application causes a constant initial pore pressure which dissipates faster near the well and so makes the soil around settle faster. Hence the surface is distorted in a dish shape before it flattens again at the end of the process. If the surface is flexible the stress distribution on the soil is constant, this is called " free-strain". If the loading surface is rigid small or zero differential settlement will occur: this situation is called "equal strain".

While digging a hole in the soil mass the periphery is a lot disturbed and the permeability at this region called smear zone is below the horizontal one. This smear effect is considered, and a reduced well radius is used instead of the ideal one. The solution of both situations are given after Barron(1) and Schıffmann (13).

The numerical solution is investigated and a computer program is develaped for the equal strain case and put in the Appendix C. The effectiveness obtained by drain wells is varying due to disturbances and irrefularities encountered in the soil deposits. But theoretically the percent consolidation is at least if the wells are in use. This is well demonstrated at the end of the chapter. The numerical solution of radial drainage is compared with analytical solution of Barron (1) in Fig. 5.7

VI. TIME DEPENDENT LOADING

6.1 INTRODUCTION

So far the theory of consolidation under investigation is examined for a constant load in time which seems to be impractical in many cases. Indeed, in most applications, the externally applied load is varying in time but not constant, e.g. the erection of a structure at the surface or an erath fill placed in layers with regards of its stability.

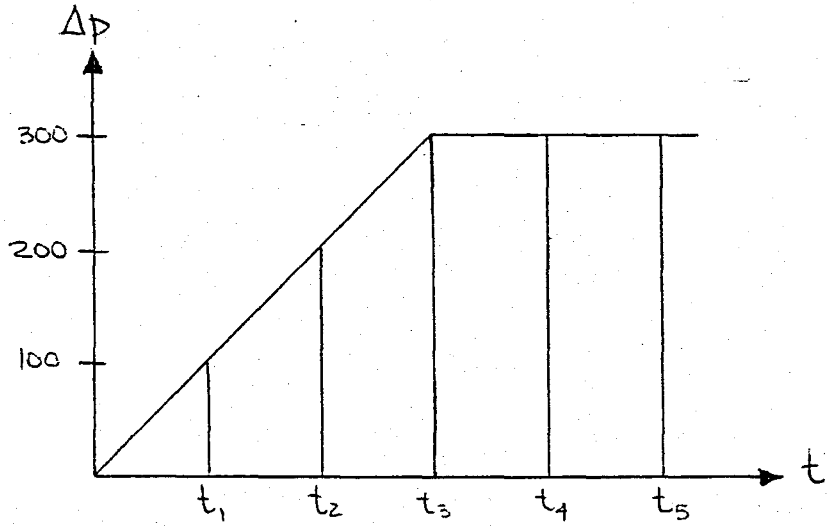
6.2 ANALYSIS

Although, there exist swelling - settlement type of problems which are faced in building of foundations or basement where the pore pressures increase with time, in a large number of practical cases, the applied load can be considered to increase only. If its increase is rapid in terms of the consolidation process, it may well be considered to be suddenly applied and remain constant thereafter, but frequently it is desirable to examine the effect of the construction time during which the applied stress is gradually built up, on the variation of excess pore-water pressure in the soil.

For the purpose of numerical analysis, the plot of real applied stress versus time is approximated by a step-wise incremental curve as illustrated in Fig. 6.1 which for simplicity, represents a uniformly increasing load to a layer compressing one-dimensionally. At each increase in incremental stress, the pore water pressure in the soil is increased by the same amount, while drainage takes place simultaneously. By writing the numerical solution in the form shown in Fig. 6.1, it can be seen that at any given time , the , the pore pressure at a point some time after the loading sequence has begun can be considered to be a sum of pore pressures obtained at different time stages of the simpler problem in which it was assumed that the excess over hydrostatic pore pressure was initially uniform every-where. This would be indicate that only the solution for an initial step change of loating is required to treat any case of the time - dependent loading. This reasoning is true for both radially and vertically drained and only vertically drained soils (10,11)

The computer programs named CONVER and CONRAD are further developed to take into account the effect of loading condition which increases linearly until a specified time stays constant thereafter.

CONVER1 is the program capable of evaluating time rate of consolidation of a vertically drained layered system under a time-dependent loading. However, CONRAD1 is



z/H	0	t_1	t_2	t_3	t_4	t_5
0 – ¼	0	0	0	0	0	0
¼ – ½	0	100	75+100	63+75+100	55+63+75	45+55+63
½ – ¾	0	100	100+100	94+100+100	88+94+100	80+88+94
¾ – 1	0	100	100+100	100+100+100	99+100+100	95+99+100

Fig. 6.1 Iteration Analysis (Scott, 1963)

able to solve the same problem in the presence of vertical drains.

Since there is no difference between the total settlement of a vertically, and a vertically and radially drained system the main program is identical for both cases. The logic of the main program is same as described in the third section of fourth chapter. An additional input is the time interval within which the external stress is increased. The settlement due to first increment of pressure is calculated and then the overburden and past pressure are increased by the amount of change in pressure. This loop of settlement calculations is repeated until the time at which loading becomes constant in time. For the subroutine TIMRAT almost everything is same with the first programs CONVER and CONRAD. The difference is right after pore pressure evaluations where they are added up according the principles described in the second section and illustrated in Fig.6.1

The problem treated and solved by three French engineers D.Queyroi, G.Pilot and J.P. magnan from Prais as given in the reference list has been a good example of comparison for the computer program CONVER 1 given in the Appendix B which deals with the consolidation of a layered clay deposit for a time-dependent.

The two curves of Fig.6.2 do not differ too much within a period of three months, but they begin to diverge thereafter. The reason for this gap is that the rate

Layer No.	H (m)	Mid-height (m)	$\Delta q/\Delta\sigma$	e_o	C_c	C_r	P_o (kPa)	P_p (kPa)	Δq (kPa)	CVV CVS $(m^2/day) \times 10^{-4}$	k_v $(m/day) \times 10^{-4}$
1	0.5	0.25	0.95	1.00	0.3	0.043	15.0	88.0	12.35	69.12	8.64
2	0.5	0.75	0.84	1.70	0.8	0.1143	16.0	80.0	10.92	63.10	8.64
3	1.0	1.5	0.68	1.47	0.7	0.100	18.0	70.0	8.84	58.752	8.64
4	1.0	2.5	0.47	2.50	1.4	0.200	20.0	60.0	6.11	57.84	6.912
5	2.0	4.0	0.243	2.30	1.3	0.1857	26.0	48.0	3.10	34.56	0.864
6	1.0	5.5	0.14	2.60	1.5	0.2143	28.0	50.0	1.82	8.64	0.78
7	4.0	8.0	0.068	1.80	0.9	0.1286	32.0	55.0	0.89	8.64	1.728

Table 6.1 Soil Properties

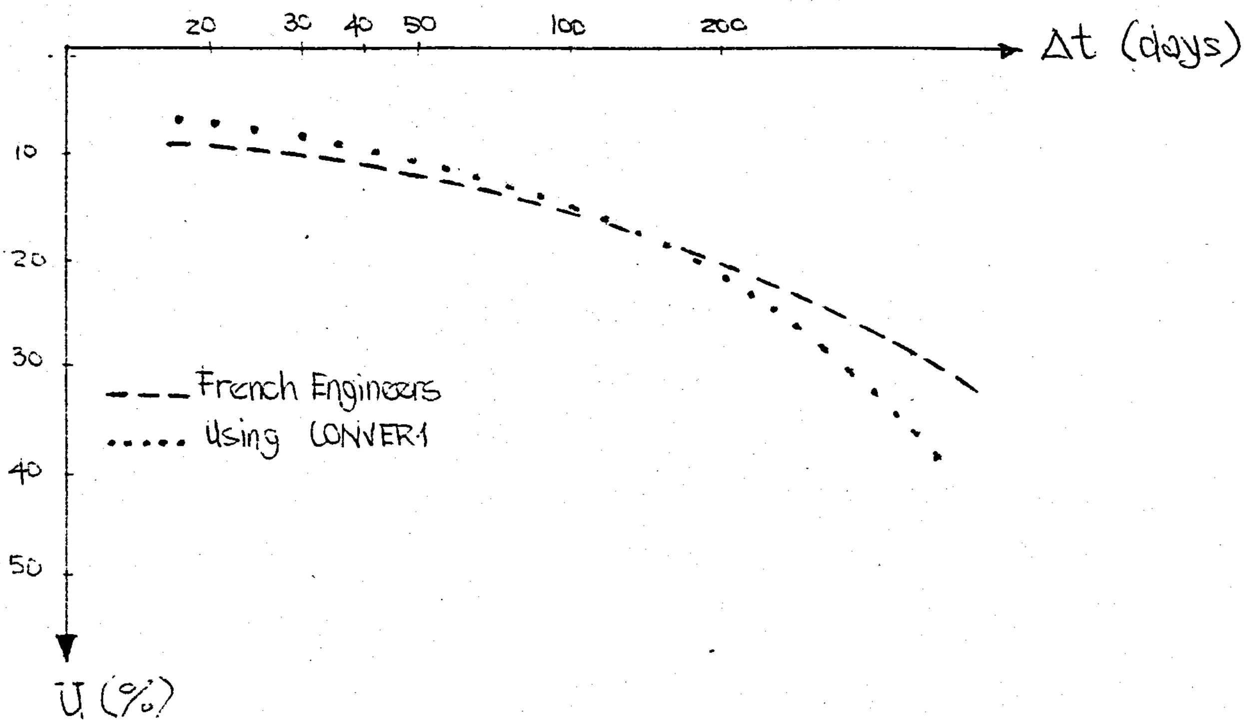


Fig. 6.2 Time vs Consolidation Curves

of loading in the field is decreasing with time due to fact that the French engineers in charge of this problem had looked for the stability of the fill in question which almost reaches a height of six meters as well as the consolidation of soil deposit underneath.

6.3 SUMMARY

The varying load in time, which happens to be the real case in most applications, is studied. The effects of this linearly encreasing loading case on the final setlement and time rate of consolidation are examined. The computer programs CONVER and CONRAD are improved so that they can take the effects mentioned above into account. These two program are available in the Appendices B and D.

The solution offered by three French engineers (9) to a vertically drained consolidation problem is checked with the numerical solution using the program CONVER 1. The curves of time vs percent are quite similar as illustrated in Fig. 6.2

VIII. SUMMARY AND CONCLUSIONS

Geotechnical engineers are very interested in the behaviour of free water in cohesive soils, if this one is faced with some type of loading. Low permeabilities imply a time-dependent settlement named as a consolidation. The consolidation theory first offered by Karl Terzaghi in 1925 had the following assumptions: the soil is saturated, permeability is constant, Darcy's law is valid, temperature is constant, water and soil grains are incompressible, compression is one dimensional and there is a linear relatio between void ratio and external stress.

The amount of settlement is related to compression index C_c obtained form e vs log p curve. This curve serves to locate the past pressure as well from which one can decide on the consolidation condition of cohesive soil.

The time needed for settlement to be completed is related to coefficient of consolidation. In order to formulate the pore water distribution the flow of fluid and volume change of a cubic element is considered as was first developed by Karl Terzaghi. The differential equation has the analytical solution suggested by Taylor (1948) in the form of series. Numerical solution having advantegeous over analytic one when the boundary and loading conditions represent some dificulties, is the main purpose of this study. Finite difference method is the basis of this numerical approach. If one solves the pore water distribution then he can obtain the percent consolidation which gives settlement at a specific time when multiplied by total settlement. The plots of U versus depth or time for a clay layer are presented as well as the comprasion of the results of theorical and numerical solutions, the user's manual and listing of developed computer program CONVER is available in Appendix A.

The consolidation behaviour of a layered system is studied starding with the most common problem faced by the geotechnical engineers: a compressible layers with different consolidation properties. The basic differential equation given in the third chapter is written for the upper and lower layers and solved simultaneously. U versus T plots for different drainage conditions are illustrated in Figs. 4.2 to 4.4 after H.Gray (5). Approximate solution using avering technique to a layered system given by Karl Terzaghi is supplied. After explaining the numerical solution and the computer program a comparison is presented for a single drained two layer system. The results of the computer program CONVER available in the Appendix A is checked against the strain based solution given by Janbu. (1965).

Settlement vs. time curves of Fig. 4.8 do not diverge because by subdividing a thick layer excess pore water pressure is not overestimated.

Compressible clayey soils are mostly alluvial deposits and thus horizontal permeabilities have considereable values. If such a deposit is loaded, radial drainage is of great help for the consolidation process which may be initiated by the use of vertical drains.

In the presence of vertical drains, pore water dissipation is faster near the well periphery. If the loading surface is flexible differential settlement occurs: this situation is called free strain. If the loading surface is rigid there won't be redistribution of the load resulting in no or small differential settlement. This second assumption is called equal strain. The analytical solution is provided after Barron (1). As the numerical solution is provided a computer program is developed for the equal strain case name CONRAD. This is available in Appendix C. Although theoretically the percent consolidation is doubled if vertical drains are in use, in practice they show varying success due to disturbances and irregularities encoutered in the soil deposits. The effectiveness is analysed at the end of chapter five.

The consolidation of fine-grained soils is studied throughout the thesis under a constant loading. But in reality loading is time-dependent and mostly is of the construction loading type. So the logic of this linearly increasing loading is studied and the two programs CONVER and CONRAD are improved to take this into account.

The results of the computer program CONVER 1 capable of evaluating consolidation under a construction loading is compared with the results of three French engineers (9) and this is illustrated in Fig.6.2 . It is seen that both curves do approximately match.

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APPENDIX A

USER'S MANUAL FOR PROGRAM CONVER

CONSTANT LOADED, LAYERED SYSTEM WITH VERTICAL DRAINAGE ONLY

INPUT DATA INFORMATION

A. General job description (20 A3)

B. PROPERTIES FOR LAYERS
(N must be in col. 17-18)

C. N Cards with the following soil property

```
Columns 1-10 .......... thickness of layer
        11-20 .......... void ratio of layer
        21-30 .......... CREC
        31-40 .......... CVIR
        41-50 ...........Po
        51-60 ...........Pp
```

D. PRESSURE FOR ..... LAYERS
(N must be in col. 17-18)

E. N data items containing the pressure changes (F 12.0)

F. TIME RATE REQUESTED

G. DRAIN 1 or DRAIN 2

H. TIME SPESIFICATION

```
Columns 1-10 ......... DT (time interval)
        11.20 ......... FINAL (maximum time to be
                              considered)
```

I. N Cards Containing

Columns 1-10...... C_v (coef. of virgin consolidation)
11-20...... C_{vs} (coef. of swelling consolidation)
21-30...... k (coef. of permeability)

1. PROGRAM CONVER (INPUT,OUTPUT)

```
      C      ONE-DIMENSIONAL CONSOLIDATION OF A LAYERED SYSTEM
      C      PROGRAM TO COMPUTE TOTAL SETTLEMENT BY SELECTING 1 OF 4 CASES
      C         CASE 1  NORMAL CONSOLIDATION
      C         CASE 2  UNDERCONSOLIDATED
      C         CASE 3  OVERCONSOLIDATED
      C         CASE 4  OVERCONSOLIDATION + NORMAL CONSOLIDATION
      C      USER IS TO SUBDIVIDE THE MAIN LAYERS INTO SUBLAYERS
      C                                     ( MUST BE 16 OR LESS)
      C
      C      INPUT DATA
      C      NO. 1  TITLE CARD FOR JOB DESCRIPTION  (10A6)
      C      NO. 2   CARD TO READ ... PROPERTIES FOR N LAYERS (N IN COL. 17,18)
      C              FOLLOWED BY N CARDS CONTAINING SOIL DATA FOR EACH LAYER
      C              (6F10.0)
      C      NO. 3   CARD TO READ ... PRESSURES FOR N LAYERS (N IN COL. 17,18)
      C              FOLLOWED BY N CARDS CONTAINING THE PRESSURE CHANGE
      C
      C              PRESSURES CAN BE CHANGED BY REPEATING STEPS 1 AND 3.
      C
      C      TIME-RATE OF SETTLEMENT CAN BE OBTAINED AS FOLLOWS--
      C      NO. 4  CARD TO READ ... TIME RATE REQUESTED
      C      NO. 5  CARD TO READ ... DOUBLE DRAINAGE OR SINGLE DRAINAGE
      C      NO. 6  CARD CONTAINING TIME DATA... DT AND FINAL (2F10.2)
      C             DT = TIME STEP AT WHICH PRINTOUT IS DESIRED
      C             FINAL = MAXIMUM TIME TO BE CONSIDERED
      C      NO. 7  N CARDS CONTAINING CV, CVS, PERMEABILITY     (3F10.2)
      C*****************************************************************
      C
             CHARACTER*3 TITLE(20),HEAD(20)
             CHARACTER*6 PRESS,PROPER,WORD
             DIMENSION SETT(20)
             COMMON SETINF,N,PP(20),PO(20),DELTP(20),CVIR(20),CREC(20),
           1        VOID(20),H(20)
             DATA PRESS,PROPER, TITLE(10)/'PRESSU','PROPER',' '/
             SET1=0.
             SET2=0.
           1 READ 1000, TITLE
             DO  33 I=1,20
          33 HEAD(I)=TITLE(I)
             IF (TITLE(1).EQ.TITLE(10)) STOP
             IF (TITLE(1).EQ.'TIM') GO TO 9
             READ 1001, WORD, N
             SETTLE=0.
             TOTAL=0.
             IF (WORD.EQ.PROPER) GO TO 2
             IF (WORD.EQ.PRESS)  GO TO 4
      C*****************************************************************
      C      READ SOIL PROPERTY DATA
      C*****************************************************************
           2 DO 3 I = 1,N
             READ 1002,H(I),VOID(I),CREC(I),CVIR(I),PO(I),PP(I)
           3 CONTINUE
             READ 1001, WORD, N
      C*****************************************************************


        PROGRAM TOTS        74/176  OPT=0,ROUND= A/ S/ R/-D,-DS      FTN 5.1+577        8

      C      READ PRESSURE DATA
      C*****************************************************************
           4 DO 5 I=1,N
             READ 1006, DELTP(I)
           5 CONTINUE
             DO 7 I=1,N
      C      OVERCONSOLIDATION
             IF(PO(I) + DELTP(I).LE.PP(I)) C2 = CREC(I)
             IF(PO(I) + DELTP(I).LE.PP(I)) PA2 = PO(I) + DELTP(I)
             IF(PO(I) + DELTP(I).LE.PP(I)) PB2 = PO(I)
             IF(PO(I).GT.PP(I)) PB2=PP(I)
             IF(PO(I) + DELTP(I).LE.PP(I)) GO TO 6
      C      NORMAL CONSOLIDATION
             IF(PO(I).EQ.PP(I).AND.DELTP(I).GE.0.0) C2=CVIR(I)
             IF(PO(I).EQ.PP(I).AND.DELTP(I).LT.0.0) C2=CREC(I)
             IF(PO(I).EQ.PP(I)) PA2 = PO(I) + DELTP(I)
             IF(PO(I).EQ.PP(I)) PB2 = PO(I)
             IF(PO(I).EQ.PP(I)) GO TO 6
```

```
C      UNDERCONSOLIDATION
       IF(PO(I) + DELTP(I).GT.PP(I)) C2=CVIR(I)
       IF(PO(I).GT.PP(I)) PA2 = PO(I) + DELTP(I)
       IF(PO(I).GT.PP(I)) PB2 = PP(I)
       IF(PO(I).GT.PP(I)) GO TO 6
C      OVERCONSOLIDATION + NORMAL CONSOLIDATION
       C1 = CREC(I)
       C2 = CVIR(I)
       PA1 = PP(I)
       PA2 = PO(I) + DELTP(I)
       PB1 = PO(I)
       PB2 = PP(I)
C*********************************************************************
C      COMPUTE SETTLEMENT
       DVOID1 = C1 * ALOG10(PA1/PB1)
       SET1 = (DVOID1/(1 + VOID(I))) * H(I)
       VOID(I) = VOID(I) - DVOID1
     6 DVOID2 = C2 * ALOG10(PA2/PB2)
       SET2 = (DVOID2/(1 + VOID(I))) * H(I)
       SETT(I) = SET1 + SET2
       SET1=0.
       SET2=0.
       TOTAL = TOTAL + SETT(I)
     7 CONTINUE
       SETINF = TOTAL
       PRINT 1003, TITLE
       PRINT 1004
       DO 8 I=1,N
       PRINT 1005, I, H(I), VOID(I), CVIR(I), CREC(I), PO(I), PP(I),
     1              DELTP(I), TOTAL
       TOTAL = TOTAL - SETT(I)
     8 CONTINUE
       GO TO 1
     9 CALL TIMRAT(HEAD)
       GO TO 1
  1000 FORMAT (20A3)
  1001 FORMAT (A6,9X,I3)
  1002 FORMAT (8F10.0)
  1003 FORMAT (1H1,5X,20A3///)
```

PROGRAM TOTS   74/176 OPT=0,ROUND= A/ S/ M/-D,-DS   FTN 5.1+577   85

```
  1004 FORMAT (1X,5HLAYER,6X,5HTHICK,7X,4HVOID,8X,2HCC,8X,2HCS,7X,10HOVER
     1URDEN,6X,9HPRECONSOL,7X,6HCHANGE,7X,13HSETTLEMENT AT/13X,4HNESS,7
     2X,5HRATIO,27X,8HPRESSURE,7X,8HPRESSURE,7X,8HPRESSURE,6X,12HTOP OF
     3LAYER/55(1H-),60(1H-)/)
  1005 FORMAT(2X,I2,6X,F9.3,4X,F6.3,5X,F6.3,4X,F6.3,6X,F7.3,8X,F7.3,
     14X,F7.3,8X,F8.3)
  1006 FORMAT(F12.0)
       END
```

```
      SUBROUTINE TIMRAT(HEAD)
C PROGRAM SOLVES FOR PORE PRESSURE AND TIME SETTLEMENT RELATIONSHIP)
C   DOUBLE OR SINGLE DRAINAGE CONDITIONS
      CHARACTER *5 HEAD(20)
      COMMON SETINF,N,PP(20),PO(20),DELTP(20),CVIR(20),CREC(20),
     1      VOID(20),H(20)
      DIMENSION U(16),CV(16),PERM(16),CVV(16),CVS(16),POLD(16),
     1BETA(16),T(200),TOTS(200),F(20),B(20),CC(200),W(16),PPP(16),
     2POO(16),DELTA(16)
      DATA F(1)/3HTIM/,F(2)/4HU(0)/,F(3)/4HU(1)/,F(4)/4HU(2)/
     1,F(5)/4HU(3)/,F(6)/4HU(4)/,F(7)/4HU(5)/,F(8)/4HU(6)/,F(9)/4HU(7)/,
     1F(10)/4HU(8)/,F(11)/4HU(9)/,F(12)/5HU(10)/,F(13)/5HU(11)/,
     1F(14)/5HU(12)/,F(15)/5HU(13)/,F(16)/5HU(14)/,F(17)/5HU(15)/,
     1F(18)/5HU(16)/
      DATA DRAIN1,DRAIN2/6HSINGLE,6HDOUBLE/
    1 READ 1000, WORD
      IF (WORD.EQ.DRAIN1) NDRAIN=1
      IF (WORD.EQ.DRAIN2) NDRAIN=2
      READ 1001, DT,FINAL
      IF (NDRAIN.EQ.1) PRINT 1004
      IF(NDRAIN.EQ.2) PRINT 1005
      PRINT 1007
      DO 2 I=1,N
      READ 1001, CVV(I),CVS(I),PERM(I)
      PRINT 1006,I,H(I),CVV(I),CVS(I),PERM(I)
    2 CONTINUE
C     COMPUTE PRESSURES AT LAYER BOUNDARIES
      POO(1) = (PO(1)-PO(2))*((H(1)+0.5*H(2))/(0.5*H(1)+0.5*H(2)))
     1+PO(2)
      PPP(1) = (PP(1)-PP(2))*((H(1)+0.5*H(2))/(0.5*H(1)+0.5*H(2)))
     1+ PP(2)
      DELTA(1) = (DELTP(1)-DELTP(2))*((H(1)+.5*H(2))/(0.5*H(1)+.5*H(2)))
     1+ DELTP(2)
      DO 3 I=2,N
      POO(I) = (PO(I-1)-PO(I))*(0.5*H(I)/(0.5*H(I-1)+0.5*H(I)))+PO(I)
      PPP(I)= (PP(I-1)-PP(I)) *(0.5*H(I)/(0.5*H(I-1)+0.5*H(I)))+PP(I)
      DELTA(I)=(DELTP(I-1)-DELTP(I))*(0.5*H(I)/(0.5*H(I-1)+0.5*H(I))) +
     1DELTP(I)
    3 CONTINUE
      POO(N+1) = 2.0*PO(N) - POO(N)
      PPP(N+1) = 2.0*PP(N) - PPP(N)
      DELTA(N+1) = 2.0*DELTP(N) - DELTA(N)
      SETTLE=0
      FINAL = FINAL/1.001
      DTIM=DT
      SUM = 0
      KK = 1
C     COMPUTE INITIAL BETA VALUES
    4 G=0.001
      DO 5 I=1,N
      IF(PO(I).GE.PP(I)) CV(I) = CVV(I)
      IF(PO(I).LT.PP(I)) CV(I) = CVS(I)
      POLD(I) = PO(I)
      BETA(I) = (CV(I)*DTIM)/(H(I)**2.0)
      IF(BETA(I).GT.G) G = BETA(I)
```

SUBROUTINE TIMRAT   74/176   OPT=0,ROUND= A/ S/ M/-D,-DS   FTN 5.1+577   85

```
    5 CONTINUE
      IF(G.LT.0.2) GO TO 6
      DTIM = DTIM/2.0
      GO TO 4
    6 NW=N+2
      PRINT 1009, (F(I),I=1,NW)
      L=N+1
      A=DT/1.001
      B=A
C     SET BOUNDARY CONDITIONS
      DO 7 I=1,L
      IF(PPP(I).GE.POO(I)) U(I) = DELTA(I)
      IF(PPP(I).LT.POO(I)) U(I) = POO(I)-PPP(I)+DELTA(I)
      W(I) = U(I)
    7 CONTINUE
```

```
      C     SELECT DOUBLE OR SINGLE DRAINAGE - SET BOUNDARY CONDITIONS
            GO TO (8,9), NDRAIN
          8 U(1)=0
            U(N+2)=U(N)
            PERM(N+1)=PERM(N)
            H(N+1)=H(N)
            GO TO 10
          9 U(1)=0
            U(L)=0
         10 TIM=0
            CON=0
            PRINT 1010,TIM,(U(I),I=1,L)
            GO TO 13
         11 IF(DTIM.GE.F) GO TO 13
      C     INCREASE TIME STEP AND BETA VALUES
            DTIM=2*DTIM
            DO 12 I=1,N
            BETA(I)=(CV(I)*DTIM)/(H(I)**2.0)
         12 CONTINUE
      C     COMPUTE PORE PRESSURES AT LAYER BOUNDARIES
         13 I=1
            DO 19 II=2,L
         14 IF(II.NE.L) GO TO 17
            GO TO (15,16) , NDRAIN
         15 U(N+2)=U(N)
            GO TO 17
         16 B(II)=0
            GO TO 19
         17 ALPHA=(PERM(I+1)/PERM(I))*(H(I)/H(I+1))
            BETAA=BETA(I)
            BETAB=BETA(I+1)
            I=I+1
            IF(II.EQ.L) BETAB=BETAA
         18 B(II)=ALPHA*U(II+1)+U(II-1)-U(II)*(ALPHA*(1.-1./BETAB)+(1.-1./
           1 BETAA))
         19 CONTINUE
            SOLD=100000
            S=0
            TIM=TIM+DTIM
         20 I=1
            DO 26 II=2,L
         21 IF(II.NE.L) GO TO 24
```

SUBROUTINE TIMRAT   74/176 OPT=0,ROUND= A/ S/ M/-D,-DS   FTN 5.1+577   85

```
            GO TO (22,23), NDRAIN
         22 U(N+2)=U(N)
            GO TO 24
         23 U(II)=0
            GO TO 26
         24 ALPHA=(PERM(I+1)/PERM(I))*(H(I)/H(I+1))
            BETAA=BETA(I)
            BETAB=BETA(I+1)
            I=I+1
            IF(II.EQ.L) BETAB=BETAA
         25 U(II)=(B(II)+U(II-1)+ALPHA*U(II+1))/((1.+1./BETAA)+ALPHA*
           1 (1.+1./BETAB))
            S=S+U(II)
         26 CONTINUE
            IF(ABS(S-SOLD).LE.0.0001) GO TO 27
            SOLD=S
            S=0
            GO TO 20
      C     COMPUTE GAIN IN EFFECTIVE STRESS - CHANGE BETA VALUES IF NECESSARY
         27 DO 28 I=2,N
            PO(1) = PO(1) +((W(2)/2.0)-(U(2)/2.0))
            PO(I) = PO(I) + ((H(I)+W(I+1))/2.0 - (U(I)+U(I+1))/2.0)
            IF(PO(I).LT.PP(I)) CV(I) = CVS(I)
            IF(PO(I).GE.PP(I)) CV(I) = CVV(I)
            BETA(I) = (CV(I)*DTIM)/(H(I)**2.0)
            W(I) = U(I)
         28 CONTINUE
```

```
      W(N+1) = U(N+1)
      IF(TIM.GE.A) GO TO 29
      GO TO 13
C     COMPUTE SETTLEMENT AND CONSOLIDATION
   29 DO 30 I=1,N
      IF(PO(I).GE.PP(I)) C = CVIR(I)
      IF(PO(I).LT.PP(I)) C = CREC(I)
      DPRES = PO(I) - POLD(I)
      SETTLE=SETTLE+C*(H(I)/(1+VOID(I)))*ALOG10((POLD(I)+DPRES)/POLD(I))
      POLD(I) = PO(I)
   30 CONTINUE
      CC(KK)=(SETTLE/SETINF)*100
      PRINT 1010,TIM,(U(I),I=1,L)
      TOTS(KK) = SETTLE
      T(KK)=TIM
      A=A+DT
      KK=KK+1
      IF(CC(KK-1).GE.90.0) GO TO 31
      IF(TIM.GE.FINAL) GO TO 31
      GO TO 11
   31 KK=KK-1
      TOMAX = TOTS(KK)
      TMAX = T(KK)
      PRINT 1013,SETINF
      PRINT 1011
      DO 32 I=1,KK
      PRINT 1012,T(I),TOTS(I),CC(I)
   32 CONTINUE
      CALL PLOTS (TOTS,T,TOMAX,KK,NDRAIN)
 1000 FORMAT (1A6)
```

SUBROUTINE TIMRAT   74/176 OPT=0,ROUND= A/ S/ M/-D,-DS   FTN 5.1+577   8

```
 1001 FORMAT (3F10.2)
 1002 FORMAT (I5,4E15.0)
 1003 FORMAT (1H1,35X,10A6//)
 1004 FORMAT (///15X,40HTIM RATE OF SETTLEMENT   SINGLE DRAINAGE//)
 1005 FORMAT (///15X,40HTIM RATE OF SETTLEMENT   DOUBLE DRAINAGE//)
 1007 FORMAT (19X,45HCOEFFICIENT OF CONSOLIDATION   COEFFICIENT OF,/,
     1        63H LAYER  THICKNESS   *VIRGIN*      *SWELLING*      PERME
     2ABILITY)
 1008 FORMAT (2X,I2,3X,1PE10.3,1PE13.3,1PE14.3,1PE17.4)
 1009 FORMAT (1H1,1A6,17(1X,1A6))
 1010 FORMAT (1X,2F6.2,16(1X,F6.1))
 1011 FORMAT (1H1,8X,3HTIM,8X,10HSETTLEMENT,6X,13HCONSOLIDATION)
 1012 FORMAT (5X,3(F8.2,8X))
 1013 FORMAT (29H-ULTIMATE SETTLEMENT WILL BE ,F7.3)
      RETURN
      END
```

```
      SUBROUTINE PLOTS (Y,X,YMAX,KK,NDRAIN)
      DIMENSION YS(10),DUM(6),ALINE(60),X(1),Y(1),KKK(7),NX(7),NNX(7)
      DATA YS/0.5,1.0,1.5,2.0,5.0,10.0,20.0,50.0,100.0,200.0/
      DATA KKK /10,15,24,50,100,150,200/
      DATA NX /1,1,1,1,2,3,4/
      DATA NNX /3,2,1,4,4,4,4/
      DATA BLANK,DOT,SPOT,PLUS /1H ,1H.,1H*,1H+/
      DO 10 J=1,10
      L = J
      IF (YMAX.LE.YS(L)) GO TO 20
   10 CONTINUE
   20 YPLOT = YS(L)
      DUM(1) = 0.0
      DUM(2) = YPLOT * 0.2
      DUM(3) = YPLOT * 0.4
      DUM(4) = YPLOT * 0.6
      DUM(5) = YPLOT * 0.8
      DUM(6) = YPLOT
      DO 30 J=1,7
      L = J
      IF (KK.LE.KKK(L)) GO TO 40
   30 CONTINUE
   40 N = NX(L)
      NN = NNX(L)
      PRINT 1000
      IF (NDRAIN.EQ.1) PRINT 2000
      IF (NDRAIN.EQ.2) PRINT 3000
      PRINT 4000, (DUM(7-J),J=1,6)
      DO 50 I=10,60
      ALINE(I) = DOT
   50 CONTINUE
      ALINE(10)=PLUS
      ALINE(20)=PLUS
      ALINE(30)=PLUS
      ALINE(40)=PLUS
      ALINE(50)=PLUS
      ALINE(60)=PLUS
      PRINT 5000, (ALINE(I), I=10,60)
      DO 60 I=10,60
      ALINE(I) = BLANK
   60 CONTINUE
      DO 90 J=N,KK,N
      J1 = 60.-(50.*Y(J)/YPLOT)
      ALINE(J1) = SPOT
      ALINE(10)=DOT
      ALINE(60)=DOT
      PRINT 6000, (ALINE(I),I=10,60),X(J)
      DO 70 I=10,59
      ALINE(I) = BLANK
   70 CONTINUE
      IF (NN.GT.3) GO TO 90
      DO 80 K=1,NN
      ALINE(10)=DOT
      ALINE(60)=DOT
      PRINT 5000, (ALINE(I),I=10,60)
```



```
   80 CONTINUE
   90 CONTINUE
      DO 100 I=10,60
      ALINE(I) = DOT
  100 CONTINUE
      ALINE(10)=PLUS
      ALINE(20)=PLUS
      ALINE(30)=PLUS
      ALINE(40)=PLUS
      ALINE(50)=PLUS
      ALINE(60)=PLUS
      PRINT 5000, (ALINE(I), I=10,60)
 1000 FORMAT (1H1,25X,22HTIME - SETTLEMENT PLOT)
 2000 FORMAT (28X,15HSINGLE DRAINAGE/)
 3000 FORMAT (28X,15HDOUBLE DRAINAGE/)
 4000 FORMAT (31X,10HSETTLEMENT,/,8X,6(F6.2,4X))
 5000 FORMAT (11X,60A1)
 6000 FORMAT (11X,51A1,F6.2)
      RETURN
      END
```

APPENDIX B

USER'S MANUAL FOR PROGRAM CONVER I

STEP LOADED, LAYERED SYSTEM WITH VERTICAL DRAINAGE ONLY

INPUT DATA INFORMATION

A. General job description (20 A 3)
Note: Card must start on column 1

B. PROPERTIES FOR.....LAYERS
(N must be in col. 17-18)

C. N cards with the following soil property

Columns 1-10 ....thickness of layer
11-20 ....void ratio of layer
21-30 ....CREC
31-40 ....CVIR
41-50 ....P_o
51-60 ....P_p

D. PRESSURE FOR .....LAYERS
(N must be in col 17-18)

E. N data items containing the pressure changes(F 12.0)

F. Time interval within-which the load is kept constant=DT
Time after which load remains constant= TO
FORMAT (2I4)

G. TIME RATE REQUESTED
Card must start on column 1

H. DRAIN 1 or DRAIN 2

I. TIME SPECIFICATION

Columns 1-10 .... DT (time interval)
11-20 .... FINAL (maximum time to be considered)

J. N Cards Containing

Columns 1-10 .....C_v (cef. of virgin consolidation)
11-20 .....C_{vs} (coef. of swelling consolidation)
21-30 .....k (coef. of permeability)

PROGRAM CONVER 1 (INPUT, OUTPUT)

```
C     ONE-DIMENSIONAL CONSOLIDATION OF A LAYERED SYSTEM
C     PROGRAM TO COMPUTE TOTAL SETTLEMENT BY SELECTING 1 OF 4 CASES
C        CASE 1  NORMAL CONSOLIDATION
C        CASE 2  UNDERCONSOLIDATED
C        CASE 3  OVERCONSOLIDATED
C        CASE 4  OVERCONSOLIDATION + NORMAL CONSOLIDATION
C     USER IS TO SUBDIVIDE THE MAIN LAYERS INTO SUBLAYERS
C                                  ( MUST BE 16 OR LESS)
C
C     INPUT DATA
C     NO. 1  TITLE CARD FOR JOB DESCRIPTION  (10A6)
C     NO. 2   CARD TO READ ... PROPERTIES FOR N LAYERS (N IN COL. 17,18)
C             FOLLOWED BY N CARDS CONTAINING SOIL DATA FOR EACH LAYER
C             (6F10.0)
C     NO. 3   CARD TO READ ... PRESSURES FOR N LAYERS (N IN COL. 17,18)
C             FOLLOWED BY N CARDS CONTAINING THE PRESSURE CHANGE
C
C             PRESSURES CAN BE CHANGED BY REPEATING STEPS 1 AND 3.
C
C     TIME-RATE OF SETTLEMENT CAN BE OBTAINED AS FOLLOWS--
C     NO. 4  CARD TO READ ... TIME RATE REQUESTED
C     NO. 5  CARD TO READ ... DOUBLE DRAINAGE OR SINGLE DRAINAGE
C     NO. 6  CARD CONTAINING TIME DATA... DT AND FINAL (2F10.2)
C            DT = TIME STEP AT WHICH PRINTOUT IS DESIRED
C            FINAL = MAXIMUM TIME TO BE CONSIDERED
C     NO. 7  N CARDS CONTAINING CV, CVS, PERMEABILITY     (3F10.2)
C***********************************************************************
C
      CHARACTER*3 TITLE(20),HEAD(20)
      CHARACTER*6 PRESS,PROPER,WORD
      DIMENSION SETT(0:100,0:100)
      COMMON SETINF,N,PP(20),PO(20),DELTP(20),CVIR(20),CREC(20),
     1       VOID(20,500),H(20),TO
      DATA PRESS,PROPER, TITLE(10)/'PRESSU','PROPER',' '/
      SET1=0.
      SET2=0.
    1 READ 1000, TITLE
      DO  33 I=1,20
   33 HEAD(I)=TITLE(I)
      IF (TITLE(1).EQ.TITLE(10)) STOP
      IF (TITLE(1).EQ.'TIM') GO TO 9
      READ 1001, WORD, N
      SETTLE=0.
      TOTAL=0.
      IF (WORD.EQ.PROPER) GO TO 2
      IF (WORD.EQ.PRESS)  GO TO 4
C***********************************************************************
C     READ SOIL PROPERTY DATA
C***********************************************************************
    2 DO 3 I = 1,N
      READ 1002,H(I),VOID(I,1),CREC(I),CVIR(I),PO(I),PP(I)
    3 CONTINUE
      KFAD 1001, WORD, N
C***********************************************************************
C     READ PRESSURE DATA
C***********************************************************************
    4 DO 5 I=1,N
      READ 1006, DELTP(I)
    5 CONTINUE
      READ* ,DT,TO
      M=TO/DT
      DO 26 J=1,M
      DO 7 I=1,N
C     OVERCONSOLIDATION
      IF(PO(I) + DELTP(I).LE.PP(I)) C2 = CREC(I)
      IF(PO(I) + DELTP(I).LE.PP(I)) PA2 = PO(I) + DELTP(I)
      IF(PO(I) + DELTP(I).LE.PP(I)) PB2 = PO(I)
      IF(PO(I).GT.PP(I)) PB2=PP(I)
      IF(PO(I) + DELTP(I).LE.PP(I)) GO TO 6
C     NORMAL CONSOLIDATION
      IF(PO(I).EQ.PP(I).AND.DELTP(I).GE.0.0) C2=CVIR(I)
      IF(PO(I).EQ.PP(I).AND.DELTP(I).LT.0.0) C2=CREC(I)
      IF(PO(I).EQ.PP(I)) PA2 = PO(I) + DELTP(I)
      IF(PO(I).EQ.PP(I)) PB2 = PO(I)
      IF(PO(I).EQ.PP(I)) GO TO 6
C     UNDERCONSOLIDATION
      IF(PO(I) + DELTP(I).GT.PP(I)) C2=CVIR(I)
      IF(PO(I).GT.PP(I)) PA2 = PO(I) + DELTP(I)
      IF(PO(I).GT.PP(I)) PB2 = PP(I)
      IF(PO(I).GT.PP(I)) GO TO 6
C     OVERCONSOLIDATION + NORMAL CONSOLIDATION
      C1 = CREC(I)
      C2 = CVIR(I)
      PA1 = PP(I)
      PA2 = PO(I) + DELTP(I)
      PB1 = PO(I)
      PB2 = PP(I)
```

```
C*****************************************************************************
C      COMPUTE SETTLEMENT
       DVOID1 = C1 * ALOG10(PA1/PB1)
       SET1 = (DVOID1/(1 + VOID(I,J))) * H(I)
       VOID(I,J) = VOID(I,J) - DVOID1
     6 DVOID2 = C2 * ALOG10(PA2/PB2)
       SET2 = (DVOID2/(1 + VOID(I,J))) * H(I)
       VOID(I,J+1)=VOID(I,J)-DVOID2
       SETT(I,J) = SET1 + SET2
       SET1=SET2=0.0
       SETT(I,0)=0.
       SETT(I,J)=SETT(I,J)+SETT(I,J-1)
       TOTAL = TOTAL + SETT(I,J)
       PO(I)=PO(I)+DELTP(I)
       PP(I)=PP(I)+DELTP(I)
     7 CONTINUE
    28 CONTINUE
       SETINF = TOTAL
       PRINT 1003, TITLE
       PRINT 1004
       DO 8 I=1,N
       PO(I)=PO(I)-M*DELTP(I)
       PP(I)=PP(I)-M*DELTP(I)
       PRINT 1005, I, H(I), VOID(I,1), CVIR(I), CREC(I), PO(I), PP(I),
      1            DELTP(I), TOTAL
       TOTAL = TOTAL - SETT(I,M)
     8 CONTINUE
       GO TO 1
     9 CALL TIMRAT(HEAD)
       GO TO 1
  1000 FORMAT (20A3)
  1001 FORMAT (A6,9X,I3)
  1002 FORMAT (8F10.0)
  1003 FORMAT (1H1,5X,20A3///)
  1004 FORMAT (1X,5HLAYER,6X,5HTHICK,7X,4HVOID,8X,2HCC,6X,2HCS,7X,10HOVER
      1BURDEN,6X,9HPRECONSOL,7X,6HCHANGE,7X,13HSETTLEMENT AT/13X,4HNESS,7
      2X,5HRATIO,27X,8HPRESSURE,7X,8HPRESSURE,7X,8HPRESSURE,6X,12HTOP OF
      3LAYER/55(1H-),60(1H-)/)
  1005 FORMAT(2X,I2,6X,F9.3,4X,F6.3,5X,F6.3,4X,F6.3,6X,F7.3,8X,F7.3,
      38X,F7.3,6X,F8.3)
  5000 FORMAT (2I4)
  1006 FORMAT(F12.0)
       END
       SUBROUTINE TIMRAT(HEAD)
C PROGRAM SOLVES FOR PORE PRESSURE AND TIME SETTLEMENT RELATIONSHIP)
C    DOUBLE OR SINGLE DRAINAGE CONDITIONS
       CHARACTER *3 HEAD(20)
       COMMON SETINF,N,PP(20),PO(20),DELTP(20),CVIR(20),CREC(20),
      1         VOID(20,500),H(20),TO
       DIMENSION W(0:10,0:100)
       DIMENSION U(16,100),UP(16,100),CV(16),PERM(16),CVV(16),CVS(16),
      1BETA(16),T(200),TOTS(200),F(20),B(20,20),CC(200),PPP(16)
      2,POO(16),DELTA(16),POLD(16)
       DATA F(1)/3HTIM/,F(2)/4HU(0)/,F(3)/4HU(1)/,F(4)/4HU(2)/
      1,F(5)/4HU(3)/,F(6)/4HU(4)/,F(7)/4HU(5)/,F(8)/4HU(6)/,F(9)/4HU(7)/,
      1F(10)/4HU(8)/,F(11)/4HU(9)/,F(12)/5HU(10)/,F(13)/5HU(11)/,
      1F(14)/5HU(12)/,F(15)/5HU(13)/,F(16)/5HU(14)/,F(17)/5HU(15)/,
      1F(18)/5HU(16)/
       DATA DRAIN1,DRAIN2/6HSINGLE,6HDOUBLE/
     1 READ 1000, WORD
       IF (WORD.EQ.DRAIN1) NDRAIN=1
       IF (WORD.EQ.DRAIN2) NDRAIN=2
       READ* ,DT,FINAL
       IF (NDRAIN.EQ.1) PRINT 1004
       IF (NDRAIN.EQ.2) PRINT 1005
       PRINT 1007
       DO 2 I=1,N
       READ 1001, CVV(I),CVS(I),PERM(I)
       PRINT 1008,I,H(I),CVV(I),CVS(I),PERM(I)
     2 CONTINUE
C      COMPUTE PRESSURES AT LAYER BOUNDARIES
       POO(1) = (PO(1)-PO(2))*((H(1)+0.5*H(2))/(0.5*H(1)+0.5*H(2)))
      1+PO(2)
       PPP(1) = (PP(1)-PP(2))*((H(1)+0.5*H(2))/(0.5*H(1)+0.5*H(2)))
      1+ PP(2)
       DELTA(1) = (DELTP(1)-DELTP(2))*((H(1)+.5*H(2))/(0.5*H(1)+.5*H(2)))
      1+ DELTP(2)
       DO 3 I=2,N
       POO(I) = (PO(I-1)-PO(I))*(0.5*H(I)/(0.5*H(I-1)+0.5*H(I)))+PO(I)
       PPP(I)= (PP(I-1)-PP(I)) *(0.5*H(I)/(0.5*H(I-1)+0.5*H(I)))+PP(I)
       DELTA(I)=(DELTP(I-1)-DELTP(I))*(0.5*H(I)/(0.5*H(I-1)+0.5*H(I))) +
      1DELTP(I)
     3 CONTINUE
```

```
      POD(N+1) = 2.0*PO(N) - POD(N)
      PPP(N+1) = 2.0*PP(N) - PPP(N)
      DELTA(N+1) = 2.0*DELTP(N) - DELTA(N)
      SETTLE=0
      FINAL = FINAL/1.001
      DTIM=DT
      SUM = 0
      KK = 1
C     COMPUTE INITIAL BETA VALUES
      DO 5 I=1,N
      IF(PO(I).GE.PP(I)) CV(I) = CVV(I)
      IF(PO(I).LT.PP(I)) CV(I) = CVS(I)
      POLD(I) = PO(I)
      BETA(I) = (CV(I)*DTIM)/(H(I)**2.0)
    5 CONTINUE
    6 NN=N+2
      PRINT 1009, (F(I),I=1,NN)
      L=N+1
      A=DT/1.001
      E=A
C     SET BOUNDARY CONDITIONS
      DO 7 I=1,L
      IF(PPP(I).GE.POD(I)) U(I,1) = DELTA(I)
      IF(PPP(I).LT.POD(I)) U(I,1) = POD(I)-PPP(I)+DELTA(I)
      W(I,0) = U(I,1)
    7 CONTINUE
C     SELECT DOUBLE OR SINGLE DRAINAGE - SET BOUNDARY CONDITIONS
      GO TO (8,9), NDRAIN
    8 DO 3456 J=1,INT((FINAL/DTIM)+1)
      U(1,J)=0
 3456 U(N+2,J)=U(N,J)
      PERM(N+1)=PERM(N)
      H(N+1)=H(N)
      GO TO 10
    9 DO 3457 J=1,INT((FINAL/DTIM)+1)
      U(1,J)=0
 3457 U(L,J)=0
   10 TIM=0
      CON=0
      PRINT 1010,TIM,(U(I,J),I=1,L)
C     COMPUTE PORE PRESSURES AT LAYER BOUNDARIES
   13 M=TO/DTIM
      DO 65 J=1,INT((FINAL/DTIM)+1)
      I=1
      DO 19 II=2,L
   14 IF(II.NE.L) GO TO 17
      GO TO (15,16) , NDRAIN
   15 U(N+2,J)=U(N,J)
      GO TO 17
   16 U(II,J)=0
      GO TO 19
   17 ALPHA=(PERM(I+1)/PERM(I))*(H(I)/H(I+1))
      BETAA=BETA(I)
      BETAB=BETA(I+1)
      I=I+1
      IF(II.EQ.L) BETAB=BETAA
   18 B(II,J)=ALPHA*U(II+1,J)+U(II-1,J)-U(II,J)*(ALPHA*(1.-1./BETAB)+
     1 (1.-1./BETAA))
   19 CONTINUE
      TIM=TIM+DTIM
   20 I=1
      DO 26 II=2,L
   21 IF(II.NE.L) GO TO 24
      GO TO (22,23), NDRAIN
   22 U(N+2,J)=U(N,J)
      GO TO 24
   23 U(II,J)=0
      GO TO 26
   24 ALPHA=(PERM(I+1)/PERM(I))*(H(I)/H(I+1))
      BETAA=BETA(I)
      BETAB=BETA(I+1)
      I=I+1
      IF(II.EQ.L) BETAB=BETAA
   25 U(II,J)=(B(II,J)+U(II-1,J)+ALPHA*U(II+1,J))/((1.+1./BETAA)+
     1 ALPHA*(1.+1./BETAB))
      U(II,J+1)=U(II,J)
   26 CONTINUE
      IF(J.GT.M) GO TO 4040
      DO 6060 II=2,L
      DO 3030 JJ=1,J
      UP(II,JJ)=UP(II,JJ)+U(II,JJ)
 3030 CONTINUE
      U(I,J)=UP(II,JJ)
 6060 CONTINUE
      GO TO 27
 4040 DO 7070 II=2,L
      DO 5050 JJ=J-M,J
      UP(II,JJ)=UP(II,JJ)+U(II,JJ)
 5050 CONTINUE
      U(I,J)=UP(II,JJ)
 7070 CONTINUE
C     COMPUTE GAIN IN EFFECTIVE STRESS - CHANGE BETA VALUES IF NECESSARY
```

```
   27 DO 28 I=2,N
      PO(1) = PO(1) + ((H(2)/2.0 - (U(2)/2.0))
      PO(I) = PO(I) + ((H(I,J-1)+H(I+1,J-1))/2.0 - (U(I,J)+
     1 U(I+1,J))/2.0)
      IF(PO(I).LT.PP(I)) CV(I) = CVS(I)
      IF(PO(I).GE.PP(I)) CV(I) = CVV(I)
      BETA(I) = (CV(I)*DTIN)/(H(I)**2.0)
      W(I,J) = W(I,J-1)+ U(I,J)
   28 CONTINUE
      W(N+1,J) = W(N+1,J-1)+ U(N+1,J)
C     COMPUTE SETTLEMENT AND CONSOLIDATION
   29 DO 30 I=1,N
      IF(PO(I).GE.PP(I)) C = CVIR(I)
      IF(PO(I).LT.PP(I)) C = CREC(I)
      DPRES = PO(I) - POLD(I)
      SETTLE=SETTLE+C*(H(I)/(1+VOID(I,J)))*ALOG10((POLD(I)+DPRES)
     1 /POLD(I))
      POLD(I) = PO(I)
   30 CONTINUE
      CC(KK)=(SETTLE/SETINF)*100
      PRINT 1010,TIM,(U(I,J),I=1,L)
      TOTS(KK) = SETTLE
      T(KK)=TIM
      A=A+DT
      KK=KK+1
      IF(CC(KK-1).GE.90.0) GO TO 31
   85 CONTINUE
   31 KK=KK-1
      TOMAX = TOTS(KK)
      TMAX = T(KK)
      PRINT 1013,SETINF
      PRINT 1011
      DO 32 I=1,KK
      PRINT 1012,T(I),TOTS(I),CC(I)
   32 CONTINUE
      CALL PLOTS (TOTS,T,TOMAX,KK,NDRAIN)
 1000 FORMAT (I80)
 1001 FORMAT (3F10.2)
 1002 FORMAT (I5,4E15.0)
 1003 FORMAT (1H1,35X,10A6//)
 1004 FORMAT (///15X,40HTIME RATE OF SETTLEMENT   SINGLE DRAINAGE//)
 1005 FORMAT (///15X,40HTIME RATE OF SETTLEMENT   DOUBLE DRAINAGE//)
 1007 FORMAT (19X,45HCOEFFICIENT OF CONSOLIDATION   COEFFICIENT OF,/,
     1         63H LAYER  THICKNESS    *VIRGIN*       *SWELLING*      PERME
     2ABILITY)
 1008 FORMAT (2X,I2,3X,1PE10.3,1PE13.3,1PE14.3,1PE17.4)
 1009 FORMAT (1H1,1A6,17(1X,1A6))
 1010 FORMAT (1X,2F6.2,10(1X,F6.1))
 1011 FORMAT (1H1,8X,3HTIM,8X,10HSETTLEMENT,6X,13HCONSOLIDATION)
 1012 FORMAT (5X,3(F8.2,8X))
 1013 FORMAT ('ULTIMATE SETTLEMENT WILL BE ',F7.3)
      RETURN
      END
      SUBROUTINE PLOTS (Y,X,YMAX,KK,NDRAIN)
      DIMENSION YS(10),DUM(6),ALINE(60),X(1),Y(1),KKK(7),NX(7),NNX(7)
      DATA YS/0.5,1.0,1.5,2.0,5.0,10.0,20.0,50.0,100.0,200.0/
      DATA KKK /10,15,25,50,100,150,200/
      DATA NX /1,1,1,1,2,3,4/
      DATA NNX /3,2,1,4,4,4,4/
      DATA BLANK,DOT,SPOT,PLUS /1H ,1H.,1H*,1H+/
      DO 10 J=1,10
      L = J
      IF (YMAX.LE.YS(L)) GO TO 20
   10 CONTINUE
   20 YPLOT = YS(L)
      DUM(1) = 0.0
      DUM(2) = YPLOT * 0.2
      DUM(3) = YPLOT * 0.4
      DUM(4) = YPLOT * 0.6
      DUM(5) = YPLOT * 0.8
      DUM(6) = YPLOT
      DO 30 J=1,7
      L = J
      IF (KK.LE.KKK(L)) GO TO 40
   30 CONTINUE
   40 N = NX(L)
      NN = NNX(L)
      PRINT 1000
      IF (NDRAIN.EQ.1) PRINT 2000
      IF (NDRAIN.EQ.2) PRINT 3000
      PRINT 4000, (DUM(7-J),J=1,6)
      DO 50 I=10,60
      ALINE(I) = DOT
   50 CONTINUE
```

```
      ALINE(10)=PLUS
      ALINE(20)=PLUS
      ALINE(30)=PLUS
      ALINE(40)=PLUS
      ALINE(50)=PLUS
      ALINE(60)=PLUS
      PRINT 5000, (ALINE(I), I=10,60)
      DO 60 I=10,60
      ALINE(I) = BLANK
   60 CONTINUE
      DO 90 J=N,KK,N
      JI = 60.-(50.*Y(J)/YPLOT)
      ALINE(JI) = SPOT
      ALINE(10)=DOT
      ALINE(60)=DOT
      PRINT 6000, (ALINE(I),I=10,60),X(J)
      DO 70 I=10,59
      ALINE(I) = BLANK
   70 CONTINUE
      IF (NN.GT.3) GO TO 90
      DO 80 K=1,NN
      ALINE(10)=DOT
      ALINE(60)=DOT
      PRINT 5000, (ALINE(I),I=10,60)
   80 CONTINUE
   90 CONTINUE
      DO 100 I=10,59
      ALINE(I) = DOT
  100 CONTINUE
      ALINE(10)=PLUS
      ALINE(20)=PLUS
      ALINE(30)=PLUS
      ALINE(40)=PLUS
      ALINE(50)=PLUS
      ALINE(60)=PLUS
      PRINT 5000, (ALINE(I), I=10,60)
 1000 FORMAT (1H1,25X,22HTIME - SETTLEMENT PLOT)
 2000 FORMAT (28X,15HSINGLE DRAINAGE/)
 3000 FORMAT (28X,15HDOUBLE DRAINAGE/)
 4000 FORMAT (31X,10HSETTLEMENT,/,8X,6(F6.2,4X))
 5000 FORMAT (11X,60A1)
 6000 FORMAT (11X,51A1,F6.2)
      RETURN
      END
19.01.40.UCLP, AA, P03     ,        0.425KLNS.
```

APPENDIX C

USER'S MAUNAL FOR PROGRAM CONRAD

CONSTANT LOADED, LAYERED SYSTEM WITH VERTICAL AND RADIAL DRAINAGE

INPUT DATA INFORMATION

A. General job description (20 A 3)

B. PROPERTIES FOR .....LAYERS
(N must be in col. 17-18)

C. N cards with the following soil property

Columns 1-10 ...... thickness of layer
11-20 ...... void ratio of layer
21-30 ...... CREC
31-40 ...... CVIR
41-50 ...... P_o
51-60 ...... P_p

D. PRESSURE FOR .....LAYERS
(N must be in col. 17-18)

E. N data items containing the pressure changes (F 12.0)

F. TIME RATE REQUESTED

G. DRAIN 1 or DRAIN 2

H. DRAIN - Well Specification

Columns 1-10 ..... Smear radius
11-20 ..... Well radius
21-30 ..... Influence radius
31-40 ..... Smear permeability

I. Drain-well specifications

```
Columns  1-10 ...... smear radius
        11-20 ...... well radius
        21-30 ...... Influence radius
        31-40 ...... Smear permeability
```

J. N Cards containing

Columns 1-10 ...... C_v (coef. of virgin consolidation)
11-20 ...... C_{vs}(coef. of swelling consolidation)
21-30 ...... C_r (coef. of radial consolidation)
31-40 ...... k (coef. of permeability)
41-50 ...... k_r (coef. of radial permeability)

```
C      ONE-DIMENSIONAL CONSOLIDATION OF A LAYERED SYSTEM
C      PROGRAM TO COMPUTE TOTAL SETTLEMENT BY SELECTING 1 OF 4 CASES
C          CASE 1  NORMAL CONSOLIDATION
C          CASE 2  UNDERCONSOLIDATED
C          CASE 3  OVERCONSOLIDATED
C          CASE 4  OVERCONSOLIDATION + NORMAL CONSOLIDATION
C      USER IS TO SUBDIVIDE THE MAIN LAYERS INTO SUBLAYERS
C                                   ( MUST BE 16 OR LESS)
C
C      INPUT DATA
C      NO. 1  TITLE CARD FOR JOB DESCRIPTION  (10A6)
C      NO. 2  CARD TO READ ... PROPERTIES FOR N LAYERS (N IN COL. 17,18)
C             FOLLOWED BY N CARDS CONTAINING SOIL DATA FOR EACH LAYER
C             (6F10.0)
C      NO. 3  CARD TO READ ... PRESSURES FOR N LAYERS (N IN COL. 17,18)
C             FOLLOWED BY N CARDS CONTAINING THE PRESSURE CHANGE
C
C             PRESSURES CAN BE CHANGED BY REPEATING STEPS 1 AND 3.
C
C      TIME-RATE OF SETTLEMENT CAN BE OBTAINED AS FOLLOWS--
C      NO. 4  CARD TO READ ... TIME RATE REQUESTED
C      NO. 5  CARD TO READ ... DOUBLE DRAINAGE OR SINGLE DRAINAGE
C      NO. 6  CARD CONTAINING TIME DATA... DT AND FINAL (2F10.2)
C             DT = TIME STEP AT WHICH PRINTOUT IS DESIRED
C             FINAL = MAXIMUM TIME TO BE CONSIDERED
C      NO. 7  N CARDS CONTAINING CV, CVS, PERMEABILITY    (3F10.2)
C***********************************************************************
C
      CHARACTER*3 TITLE(20),HEAD(20)
      CHARACTER*6 PRESS,PROPER,WORD
      DIMENSION SETT(20)
      COMMON SETINF,N,PP(20),PO(20),DELTP(20),CVIR(20),CREC(20),
     1       VOID(20),H(20)
      DATA PRESS,PROPER, TITLE(10)/'PRESSU','PROPER',' '/
      SET1=0.
      SET2=0.
    1 READ 1000, TITLE
      DO 33 I=1,20
   33 HEAD(I)=TITLE(I)
      IF (TITLE(1).EQ.TITLE(10)) STOP
      IF (TITLE(1).EQ.'TIM') GO TO 9
      READ 1001, WORD, N
      SETTLE=0.
      TOTAL=0.
      IF (WORD.EQ.PROPER) GO TO 2
      IF (WORD.EQ.PRESS)  GO TO 4
C***********************************************************************
C      READ SOIL PROPERTY DATA
C***********************************************************************
    2 DO 3 I = 1,N
      READ 1002,H(I),VOID(I),CREC(I),CVIR(I),PO(I),PP(I)
    3 CONTINUE
      READ 1001, WORD, N
C***********************************************************************
C      READ PRESSURE DATA
C***********************************************************************
    4 DO 5 I=1,N
      READ 1006, DELTP(I)
    5 CONTINUE
      DO 7 I=1,N
C      OVERCONSOLIDATION
      IF(PO(I) + DELTP(I).LE.PP(I)) C2 = CREC(I)
      IF(PO(I) + DELTP(I).LE.PP(I)) PA2 = PO(I) + DELTP(I)
      IF(PO(I) + DELTP(I).LE.PP(I)) PB2 = PO(I)
      IF(PO(I).GT.PP(I)) PB2=PP(I)
      IF(PO(I) + DELTP(I).LE.PP(I)) GO TO 6
C      NORMAL CONSOLIDATION
      IF(PO(I).EQ.PP(I).AND.DELTP(I).GE.0.0) C2=CVIR(I)
      IF(PO(I).EQ.PP(I).AND.DELTP(I).LT.0.0) C2=CREC(I)
      IF(PO(I).EQ.PP(I)) PA2 = PO(I) + DELTP(I)
      IF(PO(I).EQ.PP(I)) PB2 = PO(I)
      IF(PO(I).EQ.PP(I)) GO TO 6
C      UNDERCONSOLIDATION
      IF(PO(I) + DELTP(I).GT. PP(I)) C2=CVIR(I)
      IF(PO(I).GT.PP(I)) PA2 = PO(I) + DELTP(I)
      IF(PO(I).GT.PP(I)) PB2 = PP(I)
      IF(PO(I).GT.PP(I)) GO TO 6
C      OVERCONSOLIDATION + NORMAL CONSOLIDATION
      C1 = CREC(I)
      C2 = CVIR(I)
      PA1 = PP(I)
      PA2 = PO(I) + DELTP(I)
      PB1 = PO(I)
      PB2 = PP(I)
C***********************************************************************
C      COMPUTE SETTLEMENT
      DVOID1 = C1 * ALOG10(PA1/PB1)
      SET1 = (DVOID1/(1 + VOID(I))) * H(I)
      VOID(I) = VOID(I) - DVOID1
```

```
    6 DVOID2 = C2 * ALOG10(PA2/PB2)
      SET2 = (DVOID2/(1 + VOID(I))) * H(I)
      SETT(I) = SET1 + SET2
      SET1=0.
      SET2=0.
      TOTAL = TOTAL + SETT(I)
    7 CONTINUE
      SETINF = TOTAL
      PRINT 1003, TITLE
      PRINT 1004
      DO 8 I=1,N
      PRINT 1005, I, H(I), VOID(I), CVIR(I), CREC(I), PO(I), PP(I),
     1             DELTP(I), TOTAL
      TOTAL = TOTAL - SETT(I)
    8 CONTINUE
      GO TO 1
    9 CALL TIMRAT(HEAD)
      GO TO 1
 1000 FORMAT (20A3)
 1001 FORMAT (A6,9X,I3)
 1002 FORMAT (8F10.0)
 1003 FORMAT (1H1,5X,20A3///)
 1004 FORMAT (1X,5HLAYER,6X,5HTHICK,7X,4HVOID,6X,2HCC,8X,2HCS,7X,10HOVER
     1BURDEN,6X,9HPRECONSOL,7X,6HCHANGE,7X,13HSETTLEMENT AT/13X,4HNESS,7
     2X,5HRATIO,27X,8HPRESSURE,7X,8HPRESSURE,7X,8HPRESSURE,6X,12HTOP OF
     3LAYER/55(1H-),6)(1H-)/)
 1005 FORMAT(2X,I2,6X,F9.3,4X,F6.3,5X,F6.3,4X,F6.3,6X,F7.3,8X,F7.3,
     38X,F7.3,8X,F8.3)
 1006 FORMAT(F12.0)
      END
      SUBROUTINE TIMRAT(HEAD)
C PROGRAM SOLVES FOR PORE PRESSURE AND TIME SETTLEMENT RELATIONSHIP)
C   DOUBLE OR SINGLE DRAINAGE CONDITIONS
      CHARACTER *3 HEAD(20)
      COMMON SETINF,N,PP(20),PO(20),DELTP(20),CVIR(20),CREC(20),
     1         VOID(20),H(20)
      DIMENSION U(16),CV(16),PERM(16),CVV(16),CVS(16),POLD(16),
     1BETA(16),T(200),TOTS(200),F(20),B(20),CC(200),W(16),PPP(16),
     2POU(16),DELTA(16),PERMR(16),CR(16),RK(16),BETAR(16)
      DATA F(1)/3HTIM/,F(2)/4HU(0)/,F(3)/4HU(1)/,F(4)/4HU(2)/
     1,F(5)/4HU(3)/,F(6)/4HU(4)/,F(7)/4HU(5)/,F(8)/4HU(6)/,F(9)/4HU(7)/,
     1F(10)/4HU(8)/,F(11)/4HU(9)/,F(12)/5HU(10)/,F(13)/5HU(11)/,
     1F(14)/5HU(12)/,F(15)/5HU(13)/,F(16)/5HU(14)/,F(17)/5HU(15)/,
     1F(18)/5HU(16)/
      DATA DRAIN1,DRAIN2/6HSINGLE,6HDOUBLE/
    1 READ 1000, WORD
      IF (WORD.EQ.DRAIN1) NDRAIN=1
      IF (WORD.EQ.DRAIN2) NDRAIN=2
      READ *, DT,FINAL
      IF (NDRAIN.EQ.1) PRINT 1004
      IF(NDRAIN.EQ.2) PRINT 1005
      PRINT 1015
      READ 1014, RS,RW,RE,RKS
      PRINT 1014, RS,RW,RE,RKS
C     RS=SHEARRAD,RW=WELLRAD,RL=INFRAD,RKS=PERMSHEAR
C     PERMR=RADIALPERM
      PRINT 1007
      DO 2 I=1,N
      READ 1001, CVV(I),CVS(I),CR(I),PERM(I),PERMR(I)
      PRINT 1008,I,H(I),CVV(I),CVS(I),CR(I),PERM(I),PERMR(I)
    2 CONTINUE
C     COMPUTE PRESSURES AT LAYER BOUNDARIES
      POU(1) = (PO(1)-PO(2))*((H(1)+0.5*H(2))/(0.5*H(1)+0.5*H(2)))
     1+PO(2)
      PPP(1) = (PP(1)-PP(2))*((H(1)+0.5*H(2))/(0.5*H(1)+0.5*H(2)))
     1+ PP(2)
      DELTA(1) = (DELTP(1)-DELTP(2))*((H(1)+.5*H(2))/(0.5*H(1)+.5*H(2)))
     1+ DELTP(2)
      DO 3 I=2,N
      POU(I) = (PO(I-1)-PO(I))*(0.5*H(I)/(0.5*H(I-1)+0.5*H(I)))+PO(I)
      PPP(I)= (PP(I-1)-PP(I)) *(0.5*H(I)/(0.5*H(I-1)+0.5*H(I)))+PP(I)
      DELTA(I)=(DELTP(I-1)-DELTP(I))*(0.5*H(I)/(0.5*H(I-1)+0.5*H(I))) +
     1DELTP(I)
    3 CONTINUE
      POU(N+1) = 2.0*PO(N) - POU(N)
      PPP(N+1) = 2.0*PP(N) - PPP(N)
      DELTA(N+1) = 2.0*DELTP(N) - DELTA(N)
      SETTLE=0
      FINAL = FINAL/1.001
      DTIM=DT
      SUM = 0
      KK = 1
C     COMPUTE INITIAL BETA VALUES
    4 G=0.001
      DO 5 I=1,N
      IF(PO(I).GE.PP(I)) CV(I) = CVV(I)
      IF(PO(I).LT.PP(I)) CV(I) = CVS(I)
      POLD(I) = PO(I)
      BETA(I) = (CV(I)*DTIM)/(H(I)**2.0)
      IF(BETA(I).GT.G) G = BETA(I)
    5 CONTINUE
```

```
      IF(G.LT.0.2) GO TO 6
      DTIM = DTIM/2.0
      GO TO 4
    6 NW=N+2
      PRINT 1009, (F(I),I=1,NW)
      L=N+1
      A=DT/1.001
      E=A
C     SET BOUNDARY CONDITIONS
      DO 7 I=1,L
      IF(PPP(I).GE.POO(I)) U(I) = DELTA(I)
      IF(PPP(I).LT.POO(I)) U(I) = POO(I)-PPP(I)+DELTA(I)
      W(I) = U(I)
    7 CONTINUE
C     SELECT DOUBLE OR SINGLE DRAINAGE - SET BOUNDARY CONDITIONS
      GO TO (8,9), NDRAIN
    8 U(1)=0
      U(N+2)=U(N)
      PERM(N+1)=PERM(N)
      H(N+1)=H(N)
      GO TO 10
    9 U(1)=0
      U(L)=0
   10 TIM=0
      CON=0
      PRINT 1010,TIM,(U(I),I=1,L)
      GO TO 13
   11 IF(DTIM.GE.E) GO TO 13
C     INCREASE TIME STEP AND BETA VALUES
      DTIM=2*DTIM
      DO 12 I=1,N
      BETA(I)=(CV(I)*DTIM)/(H(I)**2.0)
   12 CONTINUE
C     COMPUTE PORE PRESSURES AT LAYER BOUNDARIES
   13 I=1
      DO 19 II=2,L
   14 IF(II.NE.L) GO TO 17
      GO TO (15,16) , NDRAIN
   15 U(N+2)=U(N)
      GO TO 17
   16 B(II)=0
      GO TO 19
   17 ALPHA=(PERM(I+1)/PERM(I))*(H(I)/H(I+1))
      BETAA=BETA(I)
      BETAB=BETA(I+1)
      I=I+1
      IF(II.EQ.L) BETAB=BETAA
   18 B(II)=ALPHA*U(II+1)+U(II-1)-U(II)*(ALPHA*(1.-1./BETAB)+(1.-1./
     1 BETAA))
   19 CONTINUE
      SOLD=100000
      S=0
      TIM=TIM+DTIM
   20 I=1
      DO 26 II=2,L
      SR=RS/RW
      RN=RE/RW
      RM(I)=RN**2.0/(RN**2.0-1.0)*ALOG(RN)-(3.0*RN**2.0-1.0)/
     1(4.0*RN**2.0)+PERMR(I)*(SR-1.0)/RKS*RN**2.0/(RN**2.0-1.)
      BETAR(I)=(CR(I)*DTIM)/(RE**2.0)
   21 IF(II.NE.L) GO TO 24
      GO TO (22,23), NDRAIN
   22 U(N+2)=U(N)
      GO TO 24
   23 U(II)=0
      GO TO 26
   24 ALPHA=(PERM(I+1)/PERM(I))*(H(I)/H(I+1))
      BETAA=BETA(I)
      BETAB=BETA(I+1)
      IF(II.EQ.L) BETAB=BETAA
   25 U(II)=(B(II)+U(II-1)+ALPHA*U(II+1))/((1.+1./BETAA)+ALPHA*
     1 (1.+1./BETAB))
      U(II)=U(II)**2.0*EXP(-2.0*BETAR(I)/RM(I))/100
      S=S+U(II)
      I=I+1
   26 CONTINUE
      IF(ABS(S-SOLD).LE.0.0001) GO TO 27
      SOLD=S
      S=0
      GO TO 20
C     COMPUTE GAIN IN EFFECTIVE STRESS - CHANGE BETA VALUES IF NECESSARY
   27 DO 28 I=2,N
      PO(1) = PO(1) + ((W(2)/2.0 - (U(2)/2.0)
      PO(I) = PO(I) + ((W(I)+W(I+1))/2.0 - (U(I)+U(I+1))/2.0)
      IF(PO(I).LT.PP(I)) CV(I) = CVS(I)
      IF(PO(I).GE.PP(I)) CV(I) = CVV(I)
      BETA(I) = (CV(I)*DTIM)/(H(I)**2.0)
      W(I) = U(I)
   28 CONTINUE
```

```
      U(N+1) = U(N+1)
      IF(TIM.GE.A) GO TO 29
      GO TO 13
C     COMPUTE SETTLEMENT AND CONSOLIDATION
   29 DO 30 I=1,N
      IF(PO(I).GE.PP(I)) C = CVIR(I)
      IF(PO(I).LT.PP(I)) C = CREC(I)
      DPRES = PO(I) - POLD(I)
      SETTLE=SETTLE+C*(H(I)/(1+VOID(I)))*ALOG10((POLD(I)+DPRES)/POLD(I))
      POLD(I) = PO(I)
   30 CONTINUE
      CC(KK)=(SETTLE/SETINF)*100
      PRINT 1010,TIM,(U(I),I=1,L)
      TOTS(KK) = SETTLE
      T(KK)=TIM
      A=A+DT
      KK=KK+1
      IF(CC(KK-1).GE.90.0) GO TO 31
      IF(TIM.GE.FINAL) GO TO 31
      GO TO 11
   31 KK=KK-1
      TOMAX = TOTS(KK)
      TMAX = T(KK)
      PRINT 1013,SETINF
      PRINT 1011
      DO 32 I=1,KK
      PRINT 1012,T(I),TOTS(I),CC(I)
   32 CONTINUE
      CALL PLOTS (TOTS,T,TOMAX,KK,NDRAIN)
 1000 FORMAT (1A6)
 1001 FORMAT (5F10.2)
 1002 FORMAT (I5,4E15.0)
 1003 FORMAT (1H1,35X,10A6//)
 1004 FORMAT (///15X,40HTIME RATE OF SETTLEMENT    SINGLE DRAINAGE//)
 1005 FORMAT (///15X,40HTIME RATE OF SETTLEMENT    DOUBLE DRAINAGE//)
 1007 FORMAT (20X,'COEFF. OF CONSOLIDATION    COEFF. OF PERMEABILITY'/,
     1' LAYER THICKNESS    *VIRGIN*    *SWELLING*    *RADIAL*    ',
     2'*VERTICAL*    *RADIAL* ')
 1008 FORMAT (2X,I2,3X,1PE10.3,1PE13.3,1P2E14.3,1P2E17.4)
 1009 FORMAT (1H1,1A6,17(1X,1A6))
 1010 FORMAT (1X,2F6.2,16(1X,F6.1))
 1011 FORMAT (1H1,6X,3HTIM,8X,10HSETTLEMENT,6X,13HCONSOLIDATION)
 1012 FORMAT (5X,3(F8.2,8X))
 1013 FORMAT (29H-ULTIMATE SETTLEMENT WILL BE ,F7.3)
 1014 FORMAT (4F10.2)
 1015 FORMAT (16X,29HRADIUS   OF      COEFFICIENT  OF,/,
     1        43H   SHEAR     WELL    INFLUENCE   PERMEABILITY)
      RETURN
      END
      SUBROUTINE PLOTS (Y,X,YMAX,KK,NDRAIN)
      DIMENSION YS(10),DUM(6),ALINE(60),X(1),Y(1),KKK(7),NX(7),NNX(7)
      DATA YS/0.5,1.0,1.5,2.0,5.0,10.0,20.0,50.0,100.0,200.0/
      DATA KKK /10,15,24,50,100,150,200/
      DATA NX /1,1,1,1,2,3,4/
      DATA NNX /3,2,1,4,4,4,4/
      DATA BLANK,DOT,SPOT,PLUS /1H ,1H.,1H*,1H+/
      DO 10 J=1,10
      L = J
      IF (YMAX.LE.YS(L)) GO TO 20
   10 CONTINUE
   20 YPLOT = YS(L)
      DUM(1) = 0.0
      DUM(2) = YPLOT * 0.2
      DUM(3) = YPLOT * 0.4
      DUM(4) = YPLOT * 0.6
      DUM(5) = YPLOT * 0.8
      DUM(6) = YPLOT
      DO 30 J=1,7
      L = J
      IF (KK.LE.KKK(L)) GO TO 40
   30 CONTINUE
```

```
   40 N = NX(L)
      NN = NNX(L)
      PRINT 1000
      IF (NDRAIN.EQ.1) PRINT 2000
      IF (NDRAIN.EQ.2) PRINT 3000
      PRINT 4000, (DUR(7-J),J=1,6)
      DO 50 I=10,60
      ALINE(I) = DOT
   50 CONTINUE
      ALINE(10)=PLUS
      ALINE(20)=PLUS
      ALINE(30)=PLUS
      ALINE(40)=PLUS
      ALINE(50)=PLUS
      ALINE(60)=PLUS
      PRINT 5000, (ALINE(I), I=10,60)
      DO 60 I=10,60
      ALINE(I) = BLANK
   60 CONTINUE
      DO 90 J=N,KK,N
      J1 = 60.-(50.*Y(J)/YPLOT)
      ALINE(J1) = SPOT
      ALINE(10)=DOT
      ALINE(60)=DOT
      PRINT 6000, (ALINE(I),I=10,60),X(J)
      DO 70 I=10,59
      ALINE(I) = BLANK
   70 CONTINUE
      IF (NN.GT.3) GO TO 90
      DO 80 K=1,NN
      ALINE(10)=DOT
      ALINE(60)=DOT
      PRINT 5000, (ALINE(I),I=10,60)
   80 CONTINUE
   90 CONTINUE
      DO 100 I=10,60
      ALINE(I) = DOT
  100 CONTINUE
      ALINE(10)=PLUS
      ALINE(20)=PLUS
      ALINE(30)=PLUS
      ALINE(40)=PLUS
      ALINE(50)=PLUS
      ALINE(60)=PLUS
      PRINT 5000, (ALINE(I), I=10,60)
 1000 FORMAT (1H1,25X,22HTIME - SETTLEMENT PLOT)
 2000 FORMAT (28X,15HSINGLE DRAINAGE/)
 3000 FORMAT (28X,15HDOUBLE DRAINAGE/)
 4000 FORMAT (31X,10HSETTLEMENT,/,8X,6(F6.2,4X))
 5000 FORMAT (11X,60A1)
 6000 FORMAT (11X,51A1,F6.2)
      RETURN
      END
 18.58.01.UCLP, AA, P03     ,      0.428KLNS.
```

APPENDIX D

USER'S MANUAL FOR PROGRAM CONRAD 1

STEP LOADED, LAYERED SYSTEM
WITH VERTICAL AND RADIAL DRAINAGE

INPUT DATA INFORMATION

A. General job description (20 A 3)

B. PROPERTIES FOR ..... LAYERS
(N must be in col. 17-18)

C. N Cards containing the soil property

Columns 1-10 ...... thickness of layer
11-20 ...... void ratio of layer
21-30 ...... CREC
31-40 ...... CVIR
41-50 ...... P_o
51-60 ...... P_p

D. PRESSURE FOR .... LAYERS
(N must be in col. 17-18)

E. N data items containing the pressure changes (F 12.0)

F. Time interval within which the load is kept constant= DT
Time after which load remains constant= TO
FORMAT (2I4)

G. TIME RATE REQUESTED

H. DRAIN 1 or DRAIN 2

I. Time Specification

Columns 1-10 ......DT (time interval)
11-20 ......FINAL (maximum time to be considered)

J. N Cards containing

Columns 1-10......C_v (coef. of virgin consolidation)
11-20......C_{vs} (coef. of swelling consolidation)
21-30......C_r (coef of radial consolidation)
31-40......k (coef. of permeability)
41-50......k_r (coef. of radial permeability)

PROGRAM CONRAD 1 (INPUT, OUTPUT)

```
C       ONE-DIMENSIONAL CONSOLIDATION OF A LAYERED SYSTEM
C       PROGRAM TO COMPUTE TOTAL SETTLEMENT BY SELECTING 1 OF 4 CASES
C          CASE 1  NORMAL CONSOLIDATION
C          CASE 2  UNDERCONSOLIDATED
C          CASE 3  OVERCONSOLIDATED
C          CASE 4  OVERCONSOLIDATION + NORMAL CONSOLIDATION
C       USER IS TO SUBDIVIDE THE MAIN LAYERS INTO SUBLAYERS
C                                  ( MUST BE 16 OR LESS)
C
C       INPUT DATA
C       NO. 1  TITLE CARD FOR JOB DESCRIPTION   (10A6)
C       NO. 2   CARD TO READ ... PROPERTIES FOR N LAYERS (N IN COL. 17,18)
C               FOLLOWED BY N CARDS CONTAINING SOIL DATA FOR EACH LAYER
C               (6F10.0)
C       NO. 3   CARD TO READ ... PRESSURES FOR N LAYERS (N IN COL. 17,18)
C               FOLLOWED BY N CARDS CONTAINING THE PRESSURE CHANGE
C
C               PRESSURES CAN BE CHANGED BY REPEATING STEPS 1 AND 3.
C
C       TIME-RATE OF SETTLEMENT CAN BE OBTAINED AS FOLLOWS--
C       NO. 4  CARD TO READ ... TIME RATE REQUESTED
C       NO. 5  CARD TO READ ... DOUBLE DRAINAGE OR SINGLE DRAINAGE
C       NO. 6  CARD CONTAINING TIME DATA... DT AND FINAL (2F10.2)
C              DT = TIME STEP AT WHICH PRINTOUT IS DESIRED
C              FINAL = MAXIMUM TIME TO BE CONSIDERED
C       NO. 7  N CARDS CONTAINING CV, CVS, PERMEABILITY     (3F10.2)
C**********************************************************************
C
      CHARACTER*3 TITLE(20),HEAD(20)
      CHARACTER*6 PRESS,PROPER,WORD
      DIMENSION SETT(0:100,0:100)
      COMMON SETINF,N,PP(20),PO(20),DELTP(20),CVIR(20),CREC(20),
     1        VOID(20,500),H(20),TO
      DATA PRESS,PROPER, TITLE(10)/'PRESSU','PROPER',' '/
      SET1=0.
      SET2=0.
    1 READ 1000, TITLE
      DO  33 I=1,20
 33   HEAD(I)=TITLE(I)
      IF (TITLE(1).EQ.TITLE(10)) STOP
      IF (TITLE(1).EQ.'TIM') GO TO 9
      READ 1001, WORD, N
      SETTLE=0.
      TOTAL=0.
      IF (WORD.EQ.PROPER) GO TO 2
      IF (WORD.EQ.PRESS)  GO TO 4
C**********************************************************************
C       READ SOIL PROPERTY DATA
C**********************************************************************
    2 DO 3 I = 1,N
      READ 1002,H(I),VOID(I,1),CREC(I),CVIR(I),PO(I),PP(I)
    3 CONTINUE
      READ 1001, WORD, N
C**********************************************************************
C       READ PRESSURE DATA
C**********************************************************************
    4 DO 5 I=1,N
      READ 1006, DELTP(I)
    5 CONTINUE
      READ* ,DT,TO
      M=TO/DT
      DO 28 J=1,M
      DO 7 I=1,N
C       OVERCONSOLIDATION
      IF(PO(I) + DELTP(I).LE.PP(I)) C2 = CREC(I)
      IF(PO(I) + DELTP(I).LE.PP(I)) PA2 = PO(I) + DELTP(I)
      IF(PO(I) + DELTP(I).LE.PP(I)) PB2 = PO(I)
      IF(PO(I).GT.PP(I)) PB2=PP(I)
      IF(PO(I) + DELTP(I).LE.PP(I)) GO TO 6
C       NORMAL CONSOLIDATION
      IF(PO(I).EQ.PP(I).AND.DELTP(I).GE.0.0) C2=CVIR(I)
      IF(PO(I).EQ.PP(I).AND.DELTP(I).LT.0.0) C2=CREC(I)
      IF(PO(I).EQ.PP(I)) PA2 = PO(I) + DELTP(I)
      IF(PO(I).EQ.PP(I)) PB2 = PO(I)
      IF(PO(I).EQ.PP(I)) GO TO 6
C       UNDERCONSOLIDATION
      IF(PO(I) + DELTP(I).GT.PP(I)) C2=CVIR(I)
      IF(PO(I).GT.PP(I)) PA2 = PO(I) + DELTP(I)
      IF(PO(I).GT.PP(I)) PB2 = PP(I)
      IF(PO(I).GT.PP(I)) GO TO 6
C       OVERCONSOLIDATION + NORMAL CONSOLIDATION
      C1 = CREC(I)
      C2 = CVIR(I)
      PA1 = PP(I)
      PA2 = PO(I) + DELTP(I)
      PB1 = PO(I)
      PB2 = PP(I)
```

```
C*******************************************************************************
C     COMPUTE SETTLEMENT
      DVOID1 = C1 * ALOG10(PA1/PB1)
      SET1 = (DVOID1/(1 + VOID(I,J))) * H(I)
      VOID(I,J) = VOID(I,J) - DVOID1
    6 DVOID2 = C2 * ALOG10(PA2/PB2)
      SET2 = (DVOID2/(1 + VOID(I,J))) * H(I)
      VOID(I,J+1)=VOID(I,J)-DVOID2
      SETT(I,J) = SET1 + SET2
      SET1=SET2=0.0
      SETT(I,0)=0.
      SETT(I,J)=SETT(I,J)+SETT(I,J-1)
      TOTAL = TOTAL + SETT(I,J)
      PO(I)=PO(I)+DELTP(I)
      PP(I)=PP(I)+DELTP(I)
    7 CONTINUE
   28 CONTINUE
      SETINF = TOTAL
      PRINT 1003, TITLE
      PRINT 1004
      DO 8 I=1,N
      PO(I)=PO(I)-M*DELTP(I)
      PP(I)=PP(I)-M*DELTP(I)
      PRINT 1005, I, H(I), VOID(I,1), CVIR(I), CREC(I), PO(I), PP(I),
     1             DELTP(I), TOTAL
      TOTAL = TOTAL - SETT(I,M)
    8 CONTINUE
      GO TO 1
    9 CALL TIMRAT(HEAD)
      GO TO 1
 1000 FORMAT (20A3)
 1001 FORMAT (A6,9X,I3)
 1002 FORMAT (8F10.0)
 1003 FORMAT (1H1,5X,20A3///)
 1004 FORMAT (1X,5HLAYER,6X,5HTHICK,7X,4HVOID,8X,2HCC,8X,2HCS,7X,10HOVER
     1BURDEN,6X,9HPRECONSOL,7X,6HCHANGE,7X,13HSETTLEMENT AT/13X,4HNESS,7
     2X,5HRATIO,27X,8HPRESSURE,7X,8HPRESSURE,7X,8HPRESSURE,6X,12HTOP OF
     3LAYER/55(1H-),60(1H-)/)
 1005 FORMAT(2X,I2,6X,F9.3,4X,F6.3,5X,F6.3,4X,F6.3,6X,F7.3,8X,F7.3,
     $8X,F7.3,8X,F8.3)
 5000 FORMAT (2I4)
 1006 FORMAT(F12.0)
      END
      SUBROUTINE TIMRAT(HEAD)
C PROGRAM SOLVES FOR PORE PRESSURE AND TIME SETTLEMENT RELATIONSHIP)
C   DOUBLE OR SINGLE DRAINAGE CONDITIONS
      CHARACTER *3 HEAD(20)
      COMMON SETINF,N,PP(20),PO(20),DELTP(20),CVIR(20),CREC(20),
     1       VOID(20,500),H(20),TO
      DIMENSION W(0:10,0:100)
      DIMENSION U(16,100),UP(16,100),CV(16),PERM(16),CVV(16),CVS(16),
     1BETA(16),T(200),TOTS(200),F(20),B(20,20),CC(200),PPP(16)
     2,POO(16),DELTA(16),POLD(16),PERMR(16),CR(16),RM(16),BETAR(16)
      DATA F(1)/3HTIM/,F(2)/4HU(0)/,F(3)/4HU(1)/,F(4)/4HU(2)/
     1,F(5)/4HU(3)/,F(6)/4HU(4)/,F(7)/4HU(5)/,F(8)/4HU(6)/,F(9)/4HU(7)/,
     1F(10)/4HU(8)/,F(11)/4HU(9)/,F(12)/5HU(10)/,F(13)/5HU(11)/,
     1F(14)/5HU(12)/,F(15)/5HU(13)/,F(16)/5HU(14)/,F(17)/5HU(15)/,
     1F(18)/5HU(16)/
      DATA DRAIN1,DRAIN2/6HSINGLE,6HDOUBLE/
    1 READ 1000, WORD
      IF (WORD.EQ.DRAIN1) NDRAIN=1
      IF (WORD.EQ.DRAIN2) NDRAIN=2
      READ* ,DT,FINAL
      IF (NDRAIN.EQ.1) PRINT 1004
      IF (NDRAIN.EQ.2) PRINT 1005
      PRINT 1015
      READ  1014,RS,RW,RE,RKS
      PRINT 1014,RS,RW,RE,RKS
C     RS=SHEARRAD,RW=WELLRAD,RE=INFRAD,RKS=PERMSHEAR
C     PERMR=RADIALPERM
      PRINT 1007
      DO 2 I=1,N
      READ*, CVV(I),CVS(I),CR(I),PERM(I),PERMR(I)
      PRINT 1008,I,H(I),CVV(I),CVS(I),CR(I),PERM(I),PERMR(I)
    2 CONTINUE
C     COMPUTE PRESSURES AT LAYER BOUNDARIES
      POO(1) = (PO(1)-PO(2))*((H(1)+0.5*H(2))/(0.5*H(1)+0.5*H(2)))
     1+PO(2)
      PPP(1) = (PP(1)-PP(2))*((H(1)+0.5*H(2))/(0.5*H(1)+0.5*H(2)))
     1+ PP(2)
      DELTA(1) = (DELTP(1)-DELTP(2))*((H(1)+.5*H(2))/(0.5*H(1)+.5*H(2)))
     1+ DELTP(2)
      DO 3 I=2,N
      POO(I) = (PO(I-1)-PO(I))*(0.5*H(I)/(0.5*H(I-1)+0.5*H(I)))+PO(I)
      PPP(I)= (PP(I-1)-PP(I)) *(0.5*H(I)/(0.5*H(I-1)+0.5*H(I)))+PP(I)
      DELTA(I)=(DELTP(I-1)-DELTP(I))*(0.5*H(I)/(0.5*H(I-1)+0.5*H(I))) +
     1DELTP(I)
    3 CONTINUE
```

```
      POO(N+1) = 2.0*PO(N) - POO(N)
      PPP(N+1) = 2.0*PP(N) - PPP(N)
      DELTA(N+1) = 2.0*DELTP(N) - DELTA(N)
      SETTLE=0
      FINAL = FINAL/1.001
      DTIM=DT
      SUM = 0
      KK = 1
C     COMPUTE INITIAL BETA VALUES
      DO 5 I=1,N
      IF(PO(I).GE.PP(I)) CV(I) = CVV(I)
      IF(PO(I).LT.PP(I)) CV(I) = CVS(I)
      POLD(I) = PO(I)
      BETA(I) = (CV(I)*DTIM)/(H(I)**2.0)
    5 CONTINUE
    6 NN=N+2
      PRINT 1009, (F(I),I=1,NN)
      L=N+1
      A=DT/1.001
      E=A
C     SET BOUNDARY CONDITIONS
      DO 7 I=1,L
      IF(PPP(I).GE.POO(I)) U(I,1) = DELTA(I)
      IF(PPP(I).LT.POO(I)) U(I,1) = POO(I)-PPP(I)+DELTA(I)
      W(I,D) = U(I,1)
    7 CONTINUE
C     SELECT DOUBLE OR SINGLE DRAINAGE - SET BOUNDARY CONDITIONS
      GO TO (8,9), NDRAIN
    8 DO 3456 J=1,INT((FINAL/DTIM)+1)
      U(1,J)=0
 3456 U(N+2,J)=U(N,J)
      PERM(N+1)=PERM(N)
      H(N+1)=H(N)
      GO TO 10
    9 DO 3457 J=1,INT((FINAL/DTIM)+1)
      U(1,J)=0
 3457 U(L,J)=0
   10 TIM=0
      CON=0
      PRINT 1010,TIM,(U(I,J),I=1,L)
C     COMPUTE PORE PRESSURES AT LAYER BOUNDARIES
   13 M=TO/DTIM
      DO 85 J=1,INT((FINAL/DTIM)+1)
      I=1
      DO 19 II=2,L
   14 IF(II.NE.L) GO TO 17
      GO TO (15,16) , NDRAIN
   15 U(N+2,J)=U(N,J)
      GO TO 17
   16 B(II,J)=0
      GO TO 19
   17 ALPHA=(PERM(I+1)/PERM(I))*(H(I)/H(I+1))
      BETAA=BETA(I)
      BETAB=BETA(I+1)
      I=I+1
      IF(II.EQ.L) BETAB=BETAA
   18 B(II,J)=ALPHA*U(II+1,J)+U(II-1,J)-U(II,J)*(ALPHA*(1.-1./BETAB)+
     1 (1.-1./BETAA))
   19 CONTINUE
      TIM=TIM+DTIM
   20 I=1
      DO 26 II=2,L
      SR=RS/RW
      RN=RE/RW
      RM(I)=RN**2/(RN**2-1.)*ALOG(RN)-(3.*RN**2-1.)/
     1(4.*RN**2)+PERMK(I)*(SR-1.)/RKS*RN**2/(RN**2-1.)
      BETAR(I)=(CR(I)*DTIM)/(RE**2)
   21 IF(II.NE.L) GO TO 24
      GO TO (22,23), NDRAIN
   22 U(N+2,J)=U(N,J)
      GO TO 24
   23 U(II,J)=0
      GO TO 26
   24 ALPHA=(PERM(I+1)/PERM(I))*(H(I)/H(I+1))
      BETAA=BETA(I)
      BETAB=BETA(I+1)
      IF(II.EQ.L) BETAB=BETAA
   25 U(II,J)=(B(II,J)+U(II-1,J)+ALPHA*U(II+1,J))/((1.+1./BETAA)+
     1 ALPHA*(1.+1./BETAB))
      U(II,J)=U(II,J)**2*EXP(-2.*BETAR(I)/RM(I))/100.
      U(II,J+1)=U(II,J)
      I=I+1
   26 CONTINUE
      IF(J.GT.M) GO TO 4040
      DO 6060 II=2,L
      DO 3030 JJ=1,J
      UP(II,JJ)=UP(II,JJ)+U(II,JJ)
 3030 CONTINUE
      U(I,J)=UP(II,JJ)
 6060 CONTINUE
      GO TO 27
 4040 DO 7070 II=2,L
      DO 5050 JJ=J-M,J
      UP(II,JJ)=UP(II,JJ)+U(II,JJ)
 5050 CONTINUE
      U(I,J)=UP(II,JJ)
 7070 CONTINUE
```

```
C     COMPUTE GAIN IN EFFECTIVE STRESS - CHANGE BETA VALUES IF NECESSARY
   27 DO 28 I=2,N
      PO(I) = PO(I) + ((W(2)/2.0 - (U(2)/2.0))
      PO(I) = PO(I) + ((W(I,J-1)+W(I+1,J-1))/2.0 - (U(I,J)+
     1 U(I+1,J))/2.0)
      PRINT *,'PO(I) =',PO(I)
      IF(PO(I).LT.PP(I)) CV(I) = CVS(I)
      IF(PO(I).GE.PP(I)) CV(I) = CVV(I)
      BETA(I) = (CV(I)*DTIM)/(H(I)**2.0)
      W(I,J) = W(I,J-1)+ U(I,J)
   28 CONTINUE
      W(N+1,J) = W(N+1,J-1)+ U(N+1,J)
C     COMPUTE SETTLEMENT AND CONSOLIDATION
   29 DO 30 I=1,N
      IF(PO(I).GE.PP(I)) C = CVIR(I)
      IF(PO(I).LT.PP(I)) C = CREC(I)
      DPRES = PO(I) - POLD(I)
      PRINT *,'POLD(I) =' ,POLD(I)
      PRINT *,'DPRES =',DPRES
      SETTLE=SETTLE+C*(H(I)/(1+VOID(I,J)))*ALOG10((POLD(I)+DPRES)
     1 /POLD(I))
      POLD(I) = PO(I)
   30 CONTINUE
      CC(KK)=(SETTLE/SETINF)*100
      PRINT 1010,TIM,(U(I,J),I=1,L)
      TOTS(KK) = SETTLE
      T(KK)=TIM
      A=A+DT
      KK=KK+1
      IF(CC(KK-1).GE.90.0) GO TO 31
   85 CONTINUE
   31 KK=KK-1
      TOMAX = TOTS(KK)
      TMAX = T(KK)
      PRINT 1013,SETINF
      PRINT 1011
      DO 32 I=1,KK
      PRINT 1012,T(I),TOTS(I),CC(I)
   32 CONTINUE
      CALL PLOTS (TOTS,T,TOMAX,KK,NDRAIN)
 1000 FORMAT (1A6)
 1001 FORMAT (3F10.2)
 1002 FORMAT (I5,4E15.0)
 1003 FORMAT (1H1,35X,10A6//)
 1004 FORMAT (///15X,40HTIM RATE OF SETTLEMENT   SINGLE DRAINAGE//)
 1005 FORMAT (///15X,40HTIM RATE OF SETTLEMENT   DOUBLE DRAINAGE//)
 1007 FORMAT (20X,'COEFF. OF CONSOLIDATION   COEFF. OF PERMEABILITY'/,
     1' LAYER THICKNESS   *VIRGIN*   *SWELLING*   *RADIAL*   ',
     2'*VERTICAL*   *RADIAL* ')
 1008 FORMAT (2X,I2,3X,1PE10.3,1PE13.3,1P2E14.3,1P2E17.4)
 1009 FORMAT (1H1,1A6,17(1X,1A6))
 1010 FORMAT (1X,2F6.2,16(1X,F6.1))
 1011 FORMAT (1H1,8X,3HTIM,8X,10HSETTLEMENT,6X,13HCONSOLIDATION)
 1012 FORMAT (5X,3(F8.2,8X))
 1013 FORMAT ('ULTIMATE SETTLEMENT WILL BE ',F7.3)
 1014 FORMAT (4F10.2)
 1015 FORMAT (16X, 'RADIUS  OF        COEFFICIENT   OF',/,
     1       ' SMEAR    WELL    INFLUENCE    PERMEABILITY')
      RETURN
      END
      SUBROUTINE PLOTS (Y,X,YMAX,KK,NDRAIN)
      DIMENSION YS(10),DUM(6),ALINE(60),X(1),Y(1),KKK(7),NX(7),NNX(7)
      DATA YS/0.5,1.0,1.5,2.0,5.0,10.0,20.0,50.0,100.0,200.0/
      DATA KKK /10,15,24,50,100,150,200/
      DATA NX /1,1,1,1,2,3,4/
      DATA NNX /3,2,1,4,4,4,4/
      DATA BLANK,DOT,SPOT,PLUS /1H ,1H.,1H*,1H+/
      DO 10 J=1,10
      L = J
      IF (YMAX.LE.YS(L)) GO TO 20
   10 CONTINUE
```

```
   20 YPLOT = YS(L)
      DUM(1) = 0.0
      DUM(2) = YPLOT * 0.2
      DUM(3) = YPLOT * 0.4
      DUM(4) = YPLOT * 0.6
      DUM(5) = YPLOT * 0.8
      DUM(6) = YPLOT
      DO 30 J=1,7
      L = J
      IF (KK.LE.KKK(L)) GO TO 40
   30 CONTINUE
   40 N = NX(L)
      NN = NNX(L)
      PRINT 1000
      IF (NDRAIN.EQ.1) PRINT 2000
      IF (NDRAIN.EQ.2) PRINT 3000
      PRINT 4000, (DUM(7-J),J=1,6)
      DO 50 I=10,60
      ALINE(I) = DOT
   50 CONTINUE
      ALINE(10)=PLUS
      ALINE(20)=PLUS
      ALINE(30)=PLUS
      ALINE(40)=PLUS
      ALINE(50)=PLUS
      ALINE(60)=PLUS
      PRINT 5000, (ALINE(I), I=10,60)
      DO 60 I=10,60
      ALINE(I) = BLANK
   60 CONTINUE
      DO 90 J=N,KK,N
      J1 = 60.-(50.*Y(J)/YPLOT)
      ALINE(J1) = SPOT
      ALINE(10)=DOT
      ALINE(60)=DOT
      PRINT 6000, (ALINE(I),I=10,60),X(J)
      DO 70 I=10,59
      ALINE(I) = BLANK
   70 CONTINUE
      IF (NN.GT.3) GO TO 90
      DO 80 K=1,NN
      ALINE(10)=DOT
      ALINE(60)=DOT
      PRINT 5000, (ALINE(I),I=10,60)
   80 CONTINUE
   90 CONTINUE
      DO 100 I=10,60
      ALINE(I) = DOT
  100 CONTINUE
      ALINE(10)=PLUS
      ALINE(20)=PLUS
      ALINE(30)=PLUS
      ALINE(40)=PLUS
      ALINE(50)=PLUS
      ALINE(60)=PLUS
      PRINT 5000, (ALINE(I), I=10,60)
 1000 FORMAT (1H1,25X,22HTIME - SETTLEMENT PLOT)
 2000 FORMAT (28X,15HSINGLE DRAINAGE/)
 3000 FORMAT (28X,15HDOUBLE DRAINAGE/)
 4000 FORMAT (31X,10HSETTLEMENT,/,8X,6(F6.2,4X))
 5000 FORMAT (11X,60A1)
 6000 FORMAT (11X,51A1,F6.2)
      RETURN
      END
 19.04.32.UCLP, AA, P03     ,     0.442KLNS.
```