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SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF CIVIL ENGINEERING

SOFTWARE DEVELOPMENT FOR CONSOLIDATION AND SETTLEMENT ANALYSIS

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN CIVIL ENGINEERING (GEOTECHNIQUES)

BY: AYENEW YIHUNE

ADVISOR: PROF. ALEMAYEHU TEFERRA

November, 2011 Addis Ababa, Ethiopia

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Approved by board examiners:

1.	______________________ Advisor	______________ Signature	______________ Date
2.	______________________ External Examiner	______________ Signature	______________ Date
3.	______________________ Internal Examiner	______________ Signature	______________ Date
4.	______________________ Chairman	______________ Signature	______________ Date

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First of all, I would like to thank God for His help in my life.

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COMMENTS

The user is advised to close and restart the software after each analysis to start another analysis. The user should not select secondary settlement analysis without selecting primary settlement analysis for the case when the thickness is required to be calculated by the software (i.e. when the “Large” radio button in the “Soil Property” dialog box of the settlement analysis part of the software is checked). The term “primary consolidation settlement” is changed to “primary settlement”. The software may also have other errors.

ABSTRACT

Consolidation and settlement analysis is one of the main tasks of a geotechnical engineer. There are different methods of analyzing consolidation and settlement. In this study, software for the analysis of consolidation and settlement is developed.

The developed software analyzes one dimensional consolidation for saturated and unsaturated soils. Consolidation analysis for saturated soils is done by the Fourier series solution and by finite difference solution of Terzaghi's one dimensional consolidation equation for saturated soils. Consolidation analysis for unsaturated soils is done by finite difference method. The analysis is done for different loadings, scenarios, drainage conditions and soil conditions.

The software analyzes immediate settlement, primary settlement and secondary settlement. Primary settlement calculation is done by compression index method, average modulus of compressibility method and coefficient of volume compressibility method. Secondary settlement calculation is done by constant modulus of compressibility method and variable modulus of compressibility method. The analysis is done for different loadings, foundation types, and locations of the foundation, drainage conditions and soil conditions.

The result of consolidation analysis by Fourier series method and finite difference method give approximately similar result. For the consolidation analysis by finite difference method, the stability of the calculation is very sensitive to the beta value. The result may not be reliable for inappropriate beta values. The developed software can be used to analyze consolidation and settlement simply, quickly and accurately. Comparison of results obtained from different analysis methods of consolidation and settlement can be also made with the software. The developed software is also important to study the properties of the results for different values of input parameters.

CHAPTER ONE

Introduction

1.1 Background

Now a days, the use of software has become very important in many fields of studies. This even goes further with the progressive development of computers which enables users to do their works with easily portable desktops and laptops. The use of software makes many works which were tedious and even impractical manually to be done within seconds.

In engineering, software application has become common for many purposes. One reason for this is that many engineering subjects involve large amount of calculations which are time consuming and at times difficult to tackle. The other reason is the development of numerical methods including the well known methods like finite difference and finite element.

This study is aimed at developing software for consolidation and settlement analysis, which play major role in geotechnical engineering.

The basic differential equation for one dimensional consolidation of saturated soils was first derived by Terzaghi [8] [1] [9]. For unsaturated soils, different contributions have been done by Biot, Larmour, Hill, Olson, Scott, Blight, Barden, Fredlund and Hasan and other researchers. Fredlund and Hasan developed two partial differential equations from which pore air and pore water pressures could be calculated. [2]

Different ways have been suggested to use the above equations for practical purpose. The first way is solving by using Fourier series. By this method, a solution can be obtained for Terzaghi's one dimensional consolidation equation. The problem here is that it is difficult to compute the sum up to a reasonable accuracy with hand calculation. The problem even goes further if the series do not converge with few sums. The second method is to use tables which correlate one value to the other. This method, even if it is less accurate, is easy and workable method for hand calculation. The third method of solving the equations is to use numerical methods like finite difference method and finite element method. This method is the most powerful method which can be used for various cases. The problem of this method is again the large amount of calculation work involved.

There are three settlement types. These are immediate settlement, primary settlement and secondary settlement. Calculation of primary settlement and secondary settlement involves calculation of pressure distribution under the point at which settlement is to be calculated. This can be done by using pressure distribution calculation equations. Pressure distribution calculation using these equations can be done by using the equations directly or by using tables prepared from these equations. Calculation using the equations directly, and even using tables prepared from these equations, could be difficult for manual calculation because pressure distribution calculation involves pressure calculation at different points for a given depth. And, if primary settlement after a given time is needed, the degree of consolidation should be first calculated which is part of consolidation analysis. [8]

Tesfahun Redi developed earlier software for consolidation analysis by finite difference method for saturated soils. The developed software performs consolidation analysis for different scenarios, initial excess pore water pressure distributions, drainage conditions, for variable c_v case and for multi-layered soils. [3]

1.2 Objective of the Thesis

The general objective of this thesis is to develop software that analyzes consolidation process and settlement. The specific objectives of the thesis are the following.

- To develop a simple, faster and accurate way of analyzing consolidation process and settlement.
- To develop an easy way of comparing results obtained by different methods of consolidation and settlement analysis.

1.3 Problem Statement

Hand calculations of consolidation process and settlement analysis are laborious and time consuming. The development of software would enhance the calculation process and would serve as a tool for the practice.

1.4 Organization of the Thesis

This thesis has five chapters. The first chapter contains a general introduction about the study, the objective of the study and the problem statement of the study. The second chapter is about the previous works done regarding consolidation and settlement of soils. In the third chapter, the methodology of the study is provided. This includes the works done to arrive to the final result (i.e. the software), the inputs required for the software, the cases considered and the outputs obtained from the software. In the fourth chapter, the procedures to use the software are presented. In the fifth chapter, the application of the software is presented. In the sixth chapter, which is the last chapter, the conclusions made from the study and the recommendations for further studies are stated.

CHAPTER TWO

Literature Review

2.1 Consolidation Analysis

The application of loading on a soil layer will cause a change in stress in the soil. This change in stress will be carried by the soil grains and the pore fluid in the soil. The component carried by the soil grains is called effective stress and the component carried by the pore fluid is called pore pressure. In general, the total stress will be carried by the pore fluid initially and as time progresses the stress will be transferred from pore fluid to the soil structure. This rate of transfer is influenced by the permeability of the soil. The increase in stress in the pore fluid will cause the pore fluid to escape from the soil which in turn will cause a volume change in the soil. This process of escape of pore fluid from the soil due to change in stress in the soil and transfer of pressure from the pore fluid to the soil structure is called consolidation.

2.1.1 One dimensional consolidation for saturated clay soils

The theory of one dimensional consolidation for saturated clay soils was proposed by Terzaghi [9]. Assumptions used to derive Terzaghi's one dimensional consolidation theory are [1]:

- The clay layer is homogeneous.
- The clay layer is saturated.
- The compression of the soil layer is due to the change in volume only, which in turn, is due to the squeezing out of water from the void spaces.
- Darcy's law is valid.
- Deformation of soil occurs only in the direction of the load application.
- The coefficient of consolidation c_v is constant during the consolidation.

With the above assumptions, the governing equation for one dimensional consolidation of saturated soils was derived [9].

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} \tag{2.1}$$

Where:

u = Pore water pressure

z = Depth

c_v = Coefficient of consolidation ($c_v = k/\rho_w g m_v$)

k = Permeability

ρ_w = Unit weight of water

m_v = Coefficient of volume compressibility

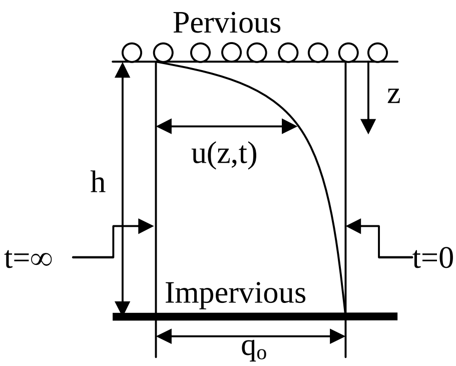
Different ways are attempted to solve Eq. (2.1). A rigorous solution can be obtained by using Fourier series. A solution can also be obtained using finite difference method.

2.1.1.1 Solution using Fourier series

The governing differential equation is solved for different boundary conditions and different initial excess pore water pressure distributions. The solutions for excess pore water pressure and degree of consolidation for cases that are usually encountered in practice are given below [6].

A. Single drainage

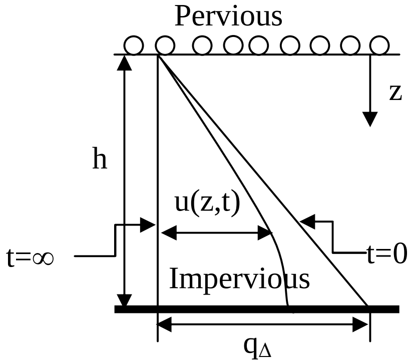
- Rectangular initial stress



$$u(z,t) = \frac{4}{\pi} q_o \sum_{m=1,3,5}^{m=\infty} \frac{1}{m} e^{-m^2 M t} \sin\frac{m\pi z}{2h} \tag{2.2}$$

$$\mu_R = 1 - \frac{8}{\pi^2} \sum_{m=1,3,5}^{m=\infty} \frac{1}{m^2} e^{-m^2 M t} \tag{2.3}$$

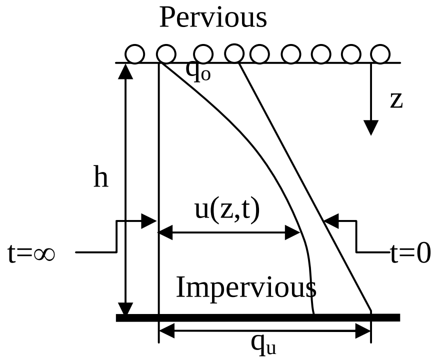
- Triangular initial stress



$$u(z,t) = \frac{8}{\pi^2} q_\Delta \sum_{m=1,2,3}^{m=\infty} \frac{(-1)^{m+1}}{(2m-1)^2} \, e^{-(2m-1)^2 Mt} \, sin \frac{(2m-1)\pi z}{2h} \quad (2.4)$$

$$\mu_T = 1 - \frac{32}{\pi^3} \sum_{m=1,2,3}^{m=\infty} \frac{(-1)^{m+1}}{(2m-1)^3} \, e^{-(2m-1)^2 Mt} \quad (2.5)$$

- Trapezoidal initial stress



$$u(z,t) = u_R(z,t) + u_T(z,t) \quad (2.6)$$

Where:

$$u_R(z,t) = \frac{4}{\pi} q_o \sum_{m=1,3,5}^{m=\infty} \frac{1}{m} \, e^{-m^2 Mt} \, sin \frac{m\pi z}{2h}$$

$$u_T(z,t) = \frac{8}{\pi^2} (q_\text{u} - q_\text{o}) \sum_{m=1,2,3}^{m=\infty} \frac{(-1)^{m+1}}{(2m-1)^2} \, e^{-(2m-1)^2 Mt} \, sin \frac{(2m-1)\pi z}{2h}$$

$$\mu_{TRP} = \frac{2\mu_R q_o + \mu_T(q_u - q_o)}{q_u + q_o} \tag{2.7}$$

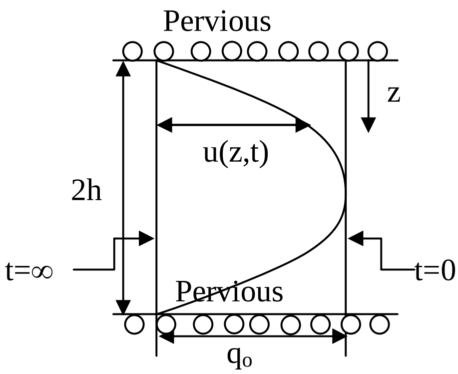
Where:

$$\mu_R = 1 - \frac{8}{\pi^2} \sum_{m=1,3,5}^{m=\infty} \frac{1}{m^2} e^{-m^2 Mt}$$

$$\mu_T = 1 - \frac{32}{\pi^3} \sum_{m=1,2,3}^{m=\infty} \frac{(-1)^{m+1}}{(2m-1)^3} e^{-(2m-1)^2 Mt}$$

B. Double drainage

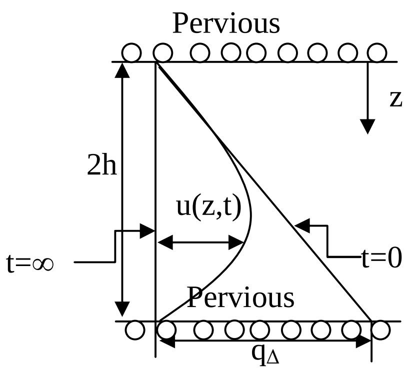
- Rectangular initial stress



$$u(z,t) = \frac{4}{\pi} q_o \sum_{m=1,2,3}^{m=\infty} \frac{1}{2m-1} e^{-(2m-1)^2 Mt} \sin\frac{(2m-1)\pi z}{2h} \tag{2.8}$$

$$\mu_R = 1 - \frac{8}{\pi^2} \sum_{m=1,3,5}^{m=\infty} \frac{1}{(2m-1)^2} e^{-(2m-1)^2 Mt} \tag{2.9}$$

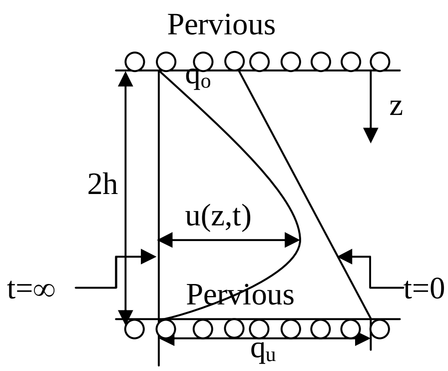
- Triangular initial stress



$$u(z,t) = \frac{2}{\pi} q_\Delta \sum_{m=1,2,3}^{m=\infty} \frac{(-1)^{m+1}}{m} \; e^{-m^2 Mt} \; sin \frac{m\pi z}{2h} \tag{2.10}$$

$$\mu_T = 1 - \frac{8}{\pi^2} \sum_{m=1,3,5}^{m=\infty} \frac{1}{m^2} \; e^{-m^2 Mt} \tag{2.11}$$

- <u>Trapezoidal initial stress</u>



$$u(z,t) = u_R(z,t) + u_T(z,t) \tag{2.12}$$

Where:

$$u_R(z,t) = \frac{4}{\pi} q_o \sum_{m=1,2,3}^{m=\infty} \frac{1}{2m-1} \; e^{-(2m-1)^2 Mt} \; sin \frac{(2m-1)\pi z}{2h}$$

$$u_T(z,t) = \frac{2}{\pi} (q_u - q_o) \sum_{m=1,2,3}^{m=\infty} \frac{(-1)^{m+1}}{m} \; e^{-m^2 Mt} \; sin \frac{m\pi z}{2h}$$

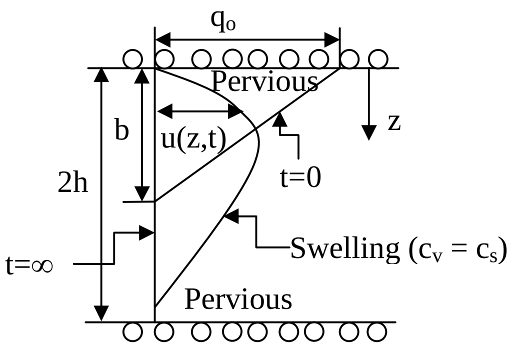
$$\mu_{TRP} = \frac{2\mu_R q_o + \mu_T (q_u - q_o)}{q_u + q_o} \tag{2.13}$$

Where:

$$\mu_R = 1 - \frac{8}{\pi^2} \sum_{m=1,3,5}^{m=\infty} \frac{1}{(2m-1)^2} \; e^{-(2m-1)^2 Mt}$$

$$\mu_T = 1 - \frac{8}{\pi^2} \sum_{m=1,3,5}^{m=\infty} \frac{1}{m^2} e^{-m^2 Mt}$$

- Special triangular initial stress

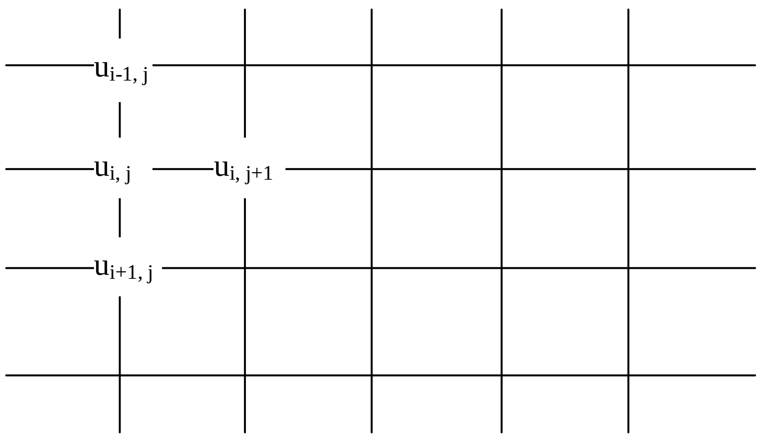


$$u(z,t) = \frac{2}{\pi} q_o \sum_{m=1,2,3}^{m=\infty} \frac{1}{m} \left\{1 - \frac{2h}{m\pi b} \sin\left(\frac{m\pi b}{2h}\right)\right\} e^{-m^2 Mt} \sin\frac{m\pi z}{2h} \tag{2.14}$$

$$\mu_{ST} = 1 - \frac{16}{\pi^2}\frac{h}{b} \sum_{m=1,3,5}^{m=\infty} \frac{1}{m^2} \left\{1 - \frac{2h}{m\pi b} \sin\left(\frac{m\pi b}{2h}\right)\right\} e^{-m^2 Mt} \tag{2.15}$$

2.1.1.2 Solution using finite difference method

Finite difference method can be used to solve the governing differential equation. To use the finite difference equations, the given depth and time should first be divided with an appropriate depth step and time step [1].



Excess pore water pressure at interior nodes is calculated as [4]:

$$u_{i,j+1} = u_{i,j} + \frac{c_v \Delta t}{(\Delta z)^2}\left(u_{i-1,j} - 2u_{i,j} + u_{i+1,j}\right) \tag{2.16}$$

Excess pore water pressure at boundary nodes is calculated as [4]:

$$u_{i,j+1} = u_{i,j} + \frac{c_v \Delta t}{(\Delta z)^2}\left(2u_{i-1,j} - 2u_{i,j}\right) \tag{2.17}$$

Excess pore water pressure at the interface for layered soils is calculated as [1]:

$$u_{i,j+1} = u_{i,j} + \frac{c_{v1} \Delta t}{(\Delta z)^2} \frac{1 + k_2/k_1}{1 + (k_2/k_1)(c_{v1}/c_{v2})}\left(\frac{2k_1}{k_1 + k_2} u_{i-1,j} - 2u_{i,j} + \frac{2k_2}{k_1 + k_2} u_{i+1,j}\right) \tag{2.18}$$

Degree of consolidation is calculated as [4]:

$$U = \frac{\left[\left(\frac{u_o + u_n}{2}\right) + \sum_{i=1}^{n-1} u_i\right]_{time=t}}{\left[\left(\frac{u_o + u_n}{2}\right) + \sum_{i=1}^{n-1} u_i\right]_{time=0}} \tag{2.19}$$

2.1.2 One dimensional consolidation for unsaturated soils

In 1941, Biot proposed a general theory of consolidation for unsaturated soil with occluded air bubbles. Assumptions used in Biot's theory were similar to those used in Terzaghi's theory. For one dimensional consolidation, Biot's theory resulted in an equation similar to Terzaghi's one dimensional consolidation equation, but the coefficient of consolidation, c_v, was modified to take into account the compressibility of the pore fluid. Larmour, Hill and Olson showed that Terzaghi's equation with a modified coefficient of consolidation can be used to describe the consolidation behavior of unsaturated soils with occluded air bubbles. Scott incorporated void ratio change and degree of consolidation change into the formulation of the consolidation equation for unsaturated soils with occluded air bubbles. Blight derived a consolidation equation for the air phase of dry, rigid, unsaturated soil. Barden presented an analysis of the one dimensional consolidation of compacted, unsaturated clay. [2]

Fredlund and Hasan presented two partial differential equations which could be solved for the pore air and pore water pressures during the consolidation process of an unsaturated soil. The air phase was assumed to be continuous. Both equations were solved simultaneously, and the method is commonly called a two phase flow approach. The formulation by Fredlund and Hasan was similar in form to the conventional one dimensional Terzaghi's derivation. The derivations also demonstrated a smooth transition between the unsaturated and saturated cases. Similar consolidation equations have also been proposed by Lloret and Alonso. The two partial differential equations are given below. [2]

2.1.2.1 Water phase partial differential equation

$$m_2^w \frac{\partial u_w}{\partial t} = -(m_{1k}^w - m_2^w)\frac{\partial u_a}{\partial t} + \frac{k_w}{\rho_w g}\frac{\partial^2 u_w}{\partial y^2} + \frac{1}{\rho_w g}\frac{\partial k_w}{\partial y}\frac{\partial u_w}{\partial y} + \frac{\partial k_w}{\partial y} \qquad (2.20)$$

Where:

m_{1k}^w = Coefficient of water volume change with respect to a change in the net normal stress

m_2^w = Coefficient of water volume change with respect to a change in the matric suction

k_w = Coefficient of permeability with respect to water

ρ_w = Density of water

g = Gravitational acceleration

The above equation is a general form of water phase partial differential equation. The equation can be simplified for special soil conditions.

A. *Saturated condition* For saturated condition, m_{1k}^w and m_2^w will be equal to the coefficient of volume change, m_v. The saturated coefficient of permeability is usually assumed to remain constant during consolidation process. So, the above equation will take the form of Terzaghi's equation for saturated soils.

$$\frac{\partial u_w}{\partial t} = \frac{k_w}{\rho_w g m_v}\frac{\partial^2 u_w}{\partial y^2} \qquad (2.21)$$

B. ***Dry soil condition*** For this condition, the coefficients of water volume change, m_{1k}^{w} and m_2^w, and the coefficient of permeability with respect to water, k_w will go to zero. Substituting zero value for these parameters, the water phase partial differential equation will vanish.

C. ***Special case of unsaturated soils*** In an unsaturated soil air and water flows can take place simultaneously during consolidation. The consolidation equation, presented in Eq. (2.20), for the water phase can be rearranged as follows:

$$\frac{\partial u_w}{\partial t} = -\mathrm{C_w}\frac{\partial u_a}{\partial t} + c_v^w\frac{\partial^2 u_w}{\partial y^2} + \frac{c_v^w}{k_w}\frac{\partial k_w}{\partial y}\frac{\partial u_w}{\partial y} + c_g\frac{\partial k_w}{\partial y} \qquad (2.22)$$

Where:

$\mathrm{C_w}$ = Interactive constant associated with the water phase partial differential equation, $\mathrm{C_w} = (1 - m_2^w/m_{1k}^w)/(m_2^w/m_{1k}^w)$

c_v^w = Coefficient of consolidation with respect to the water phase, $c_v^w = k_w/\rho_w g m_2^w$

c_g = Gravity term constant, $c_g = 1/m_2^w$

If the last two terms are neglected, a simplified form of water phase partial differential equation can be obtained.

$$\frac{\partial u_w}{\partial t} = -\mathrm{C_w}\frac{\partial u_a}{\partial t} + c_v^w\frac{\partial^2 u_w}{\partial y^2} \qquad (2.23)$$

There are many cases where the dissipation of the excess pore air pressure occurs almost instantaneously. For these cases, the above equation will be further simplified to a form similar to Terzaghi's equation.

$$\frac{\partial u_w}{\partial t} = c_v^w\frac{\partial^2 u_w}{\partial y^2} \qquad (2.24)$$

2.1.2.2 Air phase partial differential equation

$$-\left(m_{1k}^{a}-m_{2}^{a}-\frac{(1-S)n}{\bar{u}_a}\right)\frac{\partial u_a}{\partial t} = m_{2}^{a}\frac{\partial u_w}{\partial t}-\frac{D_a^*}{(\omega_a/RT)\bar{u}_a}\frac{\partial^2 u_a}{\partial y^2}-\frac{1}{(\omega_a/RT)\bar{u}_a}\frac{\partial D_a^*}{\partial y}\frac{\partial u_a}{\partial y} \quad (2.25)$$

Where:

m_{1k}^{a} = Coefficient of air volume change with respect to a change in the net normal stress

m_{2}^{a} = Coefficient of air volume change with respect to a change in the matric suction

S = Degree of saturation

n = Porosity

D_a^* = Coefficient of transmission for the air phase

ω_a = Molecular mass of air $(kg/kmol)$

R = Universal gas constant $(R = 8.31432\ J/(mol.K))$

T = Absolute temperature $(T = t^o + 273.16)(K)$

t^o = Temperature (°C)

$\bar{u}_a$ = Absolute pore air pressure $(\bar{u}_a = u_a + \bar{u}_{atm})(kPa)$

u_a = Gauge pore air pressure (kPa)

$\bar{u}_{atm}$ = Atmospheric pressure $(\bar{u}_{atm} = 101kPa)$

The above equation is a general form of air phase partial differential equation. The equation can be simplified for special soil conditions.

A. *Saturated condition* For saturated condition, m_{1k}^{a} and m_{2}^{a} will be equal to zero. The coefficient of transmission, D_a^*, will approach to zero. So, the air phase partial differential equation will vanish.

B. *Dry soil condition* For this condition, the coefficients of volume change with respect to the matric suction approach zero. The coefficient of transmission, D_a^*, will change to a constant value of D_d^*. So, the air phase partial differential equation will be:

$$-\left(m_{1k}^{a}-\frac{n}{\bar{u}_a}\right)\frac{\partial u_a}{\partial t}=\frac{D_d^*}{(\omega_a/RT)\bar{u}_a}\frac{\partial^2 u_a}{\partial y^2} \tag{2.26}$$

Rearranging the above equation will give an equation of form similar to Terzaghi's equation.

$$\frac{\partial u_a}{\partial t}=\frac{D_d^*}{(\omega_a/RT)}\frac{1}{(m_{1k}^{a}\bar{u}_a+n)}\frac{\partial^2 u_a}{\partial y^2} \tag{2.27}$$

C. *Special case of unsaturated soils* For this condition air and water flows can take place simultaneously during consolidation. The consolidation equation, presented in Eq. (2.25), for the air phase can be written as:

$$\frac{\partial u_a}{\partial t}=-\mathrm{C_a}\frac{\partial u_w}{\partial t}+c_v^a\frac{\partial^2 u_a}{\partial y^2}+\frac{c_v^a}{D_a^*}\frac{\partial D_a^*}{\partial y}\frac{\partial u_a}{\partial y} \tag{2.28}$$

Where:

$\mathrm{C_a}$ = Interactive constant associated with the air phase partial differential equation,

$$\mathrm{C_a}=\frac{m_2^a/m_{1k}^a}{1-m_2^a/m_{1k}^a-(1-S)n/(\bar{u}_a m_{1k}^a)}$$

c_v^a = Coefficient of consolidation with respect to the air phase,

$$c_v^a=\frac{D_a^*}{(\omega_a/RT)}\frac{1}{\bar{u}_a m_{1k}^a(1-m_2^a/m_{1k}^a)-(1-S)n}$$

If the variation of D_a^* with space is neglected, the above equation will be simplified as:

$$\frac{\partial u_a}{\partial t}=-\mathrm{C_a}\frac{\partial u_w}{\partial t}+c_v^a\frac{\partial^2 u_a}{\partial y^2} \tag{2.29}$$

Equation (2.23) and Equation (2.29) are solved simultaneously using finite difference method [2].

Pore water pressure is calculated as:

$$u_{w(i,j+1)}=u_{w(i,j)}+\frac{\beta_w g_1^w}{(1-C_aC_w)}-\frac{C_w}{(1-C_aC_w)}\beta_a f_1^a \tag{2.30}$$

Pore air pressure is calculated as:

$$u_{a(i,j+1)} = u_{a(i,j)} + \frac{\beta_a f_1^a}{(1 - C_a C_w)} - \frac{C_a}{(1 - C_a C_w)} \beta_w g_1^w \quad (2.31)$$

Where:

$\beta_w = c_v^w \frac{\Delta t}{\Delta y^2}$

$\beta_a = c_v^a \frac{\Delta t}{\Delta y^2}$

$g_1^w = u_{w(i-1,j)} - 2u_{w(i,j)} + u_{w(i+1,j)}$

$f_1^a = u_{a(i-1,j)} - 2u_{a(i,j)} + u_{a(i+1,j)}$

Pore water pressure and pore air pressure values for the given time step are calculated using pore water and pore air pressure values of previous time step. To pass to the next time step the pore water pressure and pore air pressure values for the time step should be calculated.

2.2 Settlement Analysis

Settlement is a vertical movement of structures due to stresses in soils. The total settlement of a structure is the sum of three components namely; immediate settlement, primary settlement and secondary settlement. [1]

2.2.1 Immediate settlement

Immediate settlement or elastic settlement is caused by the elastic behavior of soils. It is calculated from the elastic parameters of the soil. [8]

$$S_i = qB \frac{1 - \mu^2}{E} I_w \quad (2.32)$$

Where:

S_i= Immediate settlement

q = Contact pressure

μ = Poisson’s ratio

E = Modulus of elasticity

B = Least lateral dimension

I_w = Influence factor

2.2.2 Primary settlement

There are different ways of calculating primary settlement. These methods are given below [8] [4]:

2.2.2.1 Compression index method

$$S_p = \sum_{i=1}^{i=n} \frac{c_c \Delta H_i}{1 + e_o} log_{10} \frac{p_2}{p_1} \quad (2.33)$$

Where:

c_c = Compression index

ΔH_i = Depth step

e_o = Initial void ratio

p_1 = Overburden pressure

$p_2 = p_1 + \Delta p$

Δp = Additional pressure due to applied load

2.2.2.2 Average modulus of compressibility method

$$S_p = \frac{A}{E_s} \quad (2.34)$$

Where:

A = Area of pressure distribution curve

E_s = Average modulus of compressibility

2.2.2.3 Coefficient of volume compressibility method

$$S_p = m_v pH \quad (2.35)$$

Where:

m_v = Coefficient of volume compressibility

p = Stress due to applied additional load

H = Thickness of soil

2.2.3 Secondary settlement

It is a settlement due to plastic deformation of soils. It is a time dependant settlement. Immediate settlement and primary settlement attain finite values while this is not the case in secondary settlement. [8]

Two methods of determining secondary settlement are given below:

2.2.3.1 Constant modulus of compressibility method

With this method secondary settlement is calculated as [6]:

$$S_s = \frac{A}{E_{ss}} \ln(\mathrm{t}_2/\mathrm{t}_1) \tag{2.36}$$

Where:

A = Area of pressure distribution curve

E_{ss} = Modulus of compressibility for secondary settlement

t_1 = Time for completion of primary settlement

t_2 = Time for which settlement is to be calculated

2.2.3.2 Variable modulus of compressibility method

Secondary settlement by this method is calculated as [6]:

$$S_s = \frac{F \ln(\mathrm{t}_2/\mathrm{t}_1)}{V_2} \tag{2.37}$$

Where:

$F = \frac{H}{6}(F_1 + 4F_2 + F_3)$

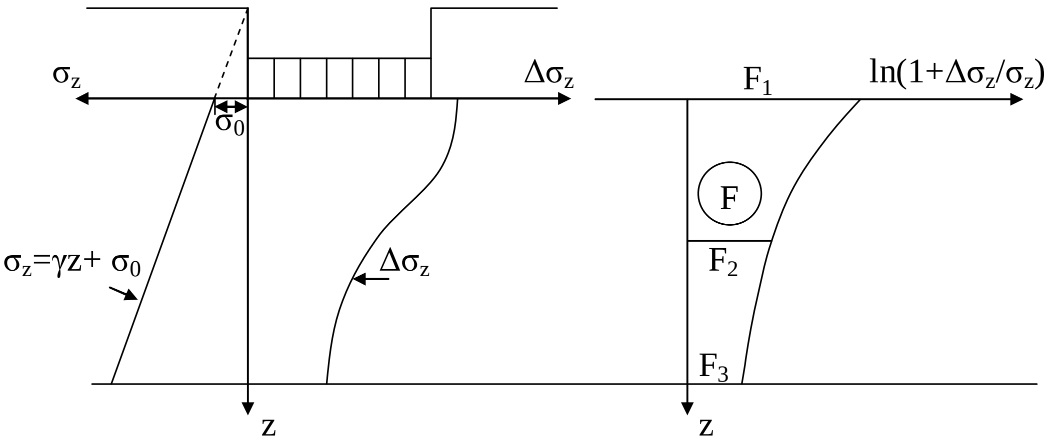
$F_1 = ln\left(1 + (\Delta\sigma_t/\sigma_t)\right)$

$F_2 = \ln\left(1 + (\Delta\sigma_m/\sigma_m)\right)$

$F_3 = ln\left(1 + (\Delta\sigma_b/\sigma_b)\right)$

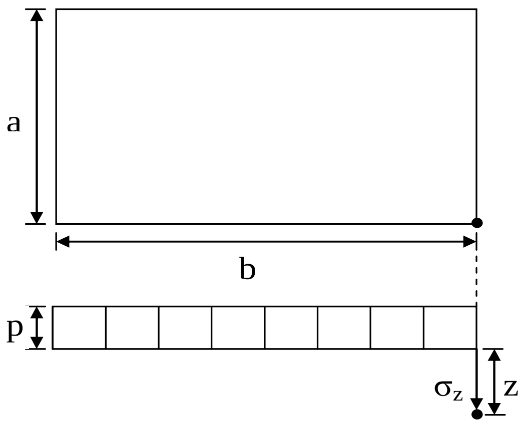
$\sigma_t, \sigma_m, \sigma_b$ = Initial overburden pressure at the top, middle and bottom respectively.

$\Delta\sigma_t, \Delta\sigma_m, \Delta\sigma_b$ = Additional pressure at the top, middle and bottom respectively.



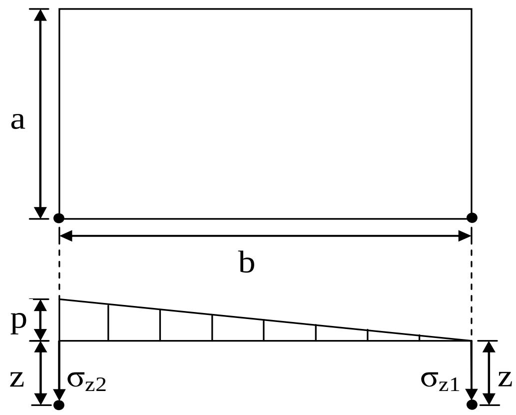
Pressure distribution due to a given load, for different loading types, can be calculated by using equations that are given below.

A. <u>*Vertical uniform load of rectangular plan area*</u> Pressure distribution under the corner of the load [7]:



$$\sigma_z = \frac{P}{2\pi}\left[arctan\left(\frac{ab}{zR}\right) + \frac{abz}{R}\left(\frac{1}{a^2 + z^2} + \frac{1}{b^2 + z^2}\right)\right] \qquad (2.38)$$

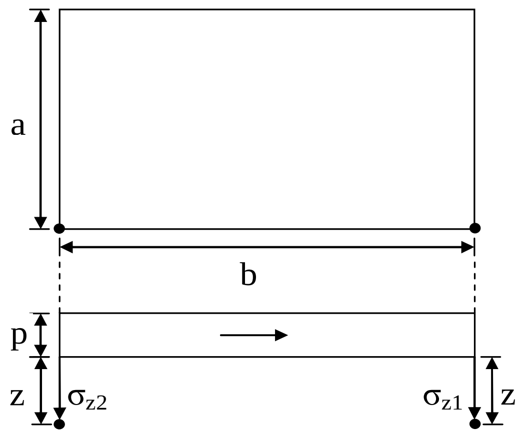
B. *Vertical triangular load of rectangular plan area with the triangular face parallel to b* Pressure distribution under the corner of the load [7]:



$$\sigma_{z1} = \frac{P}{2\pi}\left[\frac{abz}{R(z^2+b^2)} + \frac{az}{bR}\,\frac{R-\sqrt{(a^2+z^2)}}{\sqrt{(a^2+z^2)}}\right] \tag{2.39}$$

$$\sigma_{z2} = \frac{P}{2\pi}\left[arctan\left(\frac{ab}{zR}\right) + \frac{az}{a^2+z^2}\,\frac{R-\sqrt{(a^2+z^2)}}{b}\right] \tag{2.40}$$

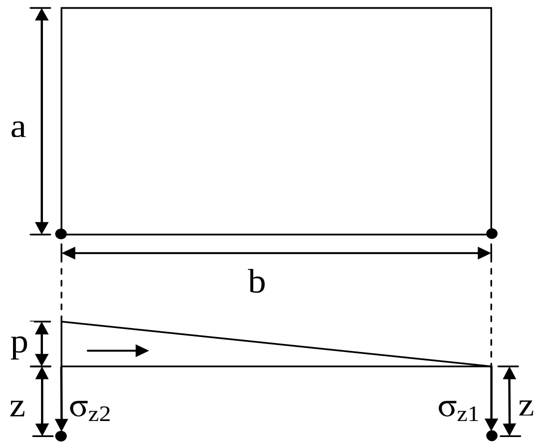
C. *Horizontal uniform load of rectangular plan area* Pressure distribution under the corner of the load [7]:



$$\sigma_{z1} = \frac{P}{2\pi}\left[\frac{a}{\sqrt{(z^2+a^2)}} - \frac{z^2}{z^2+b^2}\,\frac{a}{R}\right] \tag{2.41}$$

$$\sigma_{z2} = -\frac{P}{2\pi}\left[\frac{a}{\sqrt{(z^2+a^2)}} - \frac{z^2}{z^2+b^2}\,\frac{a}{R}\right] \tag{2.42}$$

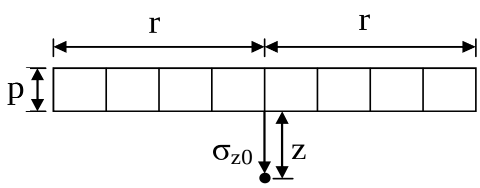
D. *Horizontal triangular load of rectangular plan area with the triangular face parallel to b* Pressure distribution under the corner of the load [7]:



$$\sigma_{z1} = \frac{P}{2\pi}\left[\frac{\pi}{2}\,\frac{z}{b} - \frac{z^2}{z^2+b^2}\,\frac{a}{R} - \frac{z}{b} arctan\left(\frac{zR}{ab}\right)\right] \tag{2.43}$$

σ_{z2} is taken from table.

E. *Vertical uniform load of Circular plan area* Pressure distribution under the center of the load [7]:



For $\mu \neq 0$

$$\sigma = P\left\{1 - \frac{k}{\sqrt{\left[k^2 + \left(\frac{r}{z}\right)^2\right]}}\right\} \tag{2.44}$$

For μ = 0

$$\sigma = P\left\{1 - \frac{1}{\sqrt{\left[1 + 2\left(\frac{r}{z}\right)^2\right]}}\right\} \tag{2.45}$$

Where:

a , b = Dimensions of a rectangular foundation.

r = Radius of a circular foundation

z = Depth

$R = \sqrt{(a^2 + b^2 + z^2)}$

$k = \sqrt{\frac{1-2\mu}{2(1-\mu)}}$

CHAPTER THREE

Methodology

3.1 General

As stated in chapter one, the aim of this thesis is to develop software for analysis of consolidation and settlement. A software is developed using visual basic.net 2008 programming language. Flowchart is first prepared before going to designing the interface of the software and writing the code. The next work performed is preparing interface, writing the code and debugging.

The prepared flowchart describes the flow of the work which includes the inputs required, the way of arriving to the output and the output of the software. The flowchart is presented in the appendix part of the thesis. The software has a multi-form user interface. These forms communicate to each other through globally declared variables in a module. Debugging is done repeatedly during the coding time.

The software performs consolidation and settlement analysis for different loading conditions, different drainage conditions and different soil conditions. The analyses done by the software for these conditions are given in the next sections of this chapter.

3.2 Consolidation Analysis

As stated in chapter two, consolidation analysis can be done by using Fourier series solution of the consolidation equation or by using finite difference solution. The developed software can analyze consolidation by the two methods.

3.2.1 Consolidation analysis using Fourier series solution

Consolidation analysis using Fourier series solution of consolidation equation is done using equations (2.2) to (2.15) in chapter two. Inputs required, conditions considered and the outputs of the software for this case are given below.

3.2.1.1 Input

Inputs required for this case include initial excess pore water pressure distribution, drainage condition, thickness of consolidating layer and coefficient of consolidation of the soil. In addition to this inputs, time, depth and degree of consolidation values may be needed depending on the required output.

3.2.1.2 Conditions considered

For consolidation analysis using Fourier series solution, one assumes that the soil is saturated. It is also assumed that soil layer is homogeneous. Single and double drainage conditions are treated.

Initial excess pore water pressure distribution can be given or it can be calculated from contact pressure due to given surface loading. The initial excess pore water pressure distributions considered are trapezoidal and special triangular (Fig. 3.1). Rectangular and triangular initial excess pore water pressure distributions can be handled using the trapezoidal case. Special triangular initial excess pore water pressure distribution is considered for double drainage only. For initial excess pore water pressure distribution from contact pressure case, the contact pressures considered are rectangular uniform contact pressure and circular uniform contact pressure. Here the initial excess pore water pressure distribution is taken as the calculated pressure distribution by approximating it to a trapezoidal shape. For rectangular uniform contact pressure case, pressure distributions, in turn initial excess pore water pressure distributions, under the center and at the characteristic point of the load area are considered whereas for circular uniform contact pressure case, initial excess pore water pressure distribution only under the center of the load area is considered.

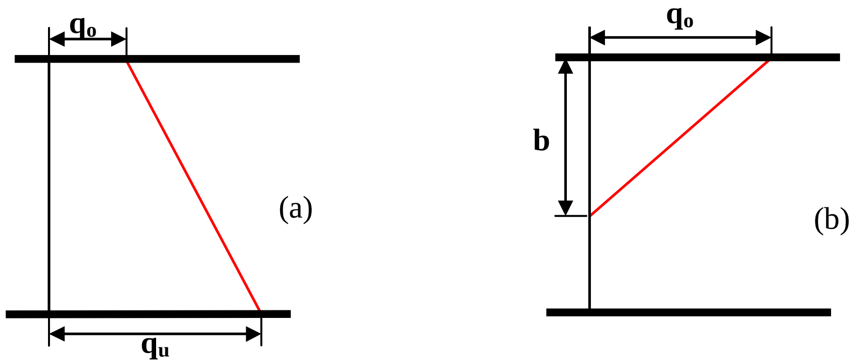


Figure 3.1: Initial excess pore water pressure distribution. (a) Trapezoidal initial excess pore water pressure distribution; (b) Special triangular initial excess pore water pressure distribution.

3.2.1.3 Output

The output is presented numerically and graphically. The Numerical outputs are degree of consolidation for given time, time required for given degree of consolidation and pore water pressure at a given depth and time. The graphical outputs are isochrones for given time and time versus degree of consolidation graph.

3.2.2 Consolidation analysis by finite difference method

3.2.2.1 Saturated soils

A. <u>Input</u>

Inputs required for this case include initial excess pore water pressure distribution, drainage condition, number of soil layers, thickness, coefficient of consolidation, change in coefficient of consolidation and coefficient of permeability of each soil layer, time, depth step and time step. Inputting coefficient of permeability is not required if the analysis is for single soil layer.

B. <u>Conditions considered</u>

By this method of analysis, a single layer and multi-layered soil profile can be handled. Drainage can be single or double drainage.

Initial excess pore water pressure distribution can be given or it can be calculated from contact pressure due to given surface loading. Trapezoidal and special triangular initial excess pore water pressure distributions can be given. Rectangular and triangular initial excess pore water pressures can be handled by the trapezoidal case. For initial excess pore water pressure from contact pressure case, rectangular uniform contact pressure and circular uniform contact pressure distributions are considered. Initial excess pore water pressure distributions at the center and at the characteristic point of the load area are considered for rectangular uniform contact pressure distribution case whereas initial excess pore water pressure distribution only at the center is considered for circular uniform contact pressure distribution case.

In addition to the above conditions, this case also includes different load scenarios. These scenarios are constant load scenario, variable load scenario and abrupt change of load scenario. For constant load scenario, Eq. (2.16), Eq. (2.17), Eq. (2.18) and Eq. (2.19) are used to calculate pore water pressure and degree of consolidation. However, for variable load and abrupt change of load scenarios, these equations are modified as given below [4].

- Variable load scenario

Excess pore water pressure at interior nodes is calculated as:

$$u_{i,j+1} = du_{i,j} + u_{i,j} + \frac{c_v t}{z^2}\left(u_{i-1,j} - 2u_{i,j} + u_{i+1,j}\right) \tag{3.1}$$

Excess pore water pressure at boundary nodes is calculated as:

$$u_{i,j+1} = du_{i,j} + u_{i,j} + \frac{c_v t}{z^2}\left(2u_{i-1,j} - 2u_{i,j}\right) \tag{3.2}$$

Excess pore water pressure at the interface for layered soils is calculated as:

$$u_{i,j+1} = du_{i,j} + u_{i,j} + \frac{c_{v1}\Delta t}{(\Delta z)^2}\frac{1 + k_2/k_1}{1 + (k_2/k_1)(c_{v1}/c_{v2})} \times \left(\frac{2k_1}{k_1 + k_2}u_{i-1,j} - 2u_{i,j} + \frac{2k_2}{k_1 + k_2}u_{i+1,j}\right) \tag{3.3}$$

Where:

- $du_{i,j}$ = Change in excess pore water pressure per each time step due to the change in load

Degree of consolidation is calculated as:

$$U = \frac{\left[\left(\frac{u_o + u_n}{2}\right) + \sum_{i=1}^{n-1} u_i\right]_t}{\left[\left(\frac{u_o + u_n}{2}\right) + \sum_{i=1}^{n-1} u_i\right]_o} \tag{3.4}$$

Where:

- $\left[\left(\frac{u_o+u_n}{2}\right) + \sum_{i=1}^{n-1} u_i\right]_t$ = Term calculated using pore water pressure at time t.
- $\left[\left(\frac{u_o+u_n}{2}\right) + \sum_{i=1}^{n-1} u_i\right]_o$ = Term calculated using unconsolidated pressure at time t.

- <u>Abrupt change of load scenario</u>

For calculations at the times different from the time of abrupt change of load, excess pore water pressure is calculated using equations (2.16), (2.17) and (2.18). For calculations at the time of abrupt change of load, the following equations are used.

Excess pore water pressure at interior nodes is calculated as:

$$u_{i,j+1} = du_{i,j} + u_{i,j} + \frac{c_v t}{z^2}\left(u_{i-1,j} - 2u_{i,j} + u_{i+1,j}\right) \tag{3.5}$$

Excess pore water pressure at boundary nodes is calculated as:

$$u_{i,j+1} = du_{i,j} + u_{i,j} + \frac{c_v t}{z^2}\left(2u_{i-1,j} - 2u_{i,j}\right) \tag{3.6}$$

Excess pore water pressure at the interface for layered soils is calculated as:

$$u_{i,j+1} = du_{i,j} + u_{i,j} + \frac{c_{v1}\Delta t}{(\Delta z)^2}\frac{1 + k_2/k_1}{1 + (k_2/k_1)(c_{v1}/c_{v2})} \times \left(\frac{2k_1}{k_1 + k_2}u_{i-1,j} - 2u_{i,j} + \frac{2k_2}{k_1 + k_2}u_{i+1,j}\right) \tag{3.7}$$

Where:

- $du_{i,j}$ = Change in excess pore water pressure due to the abrupt change in load

Calculation of degree of consolidation will be done by Eq. (3.4).

C. Output

The outputs of this case are given in tabular and graphical form. The outputs obtained in tabular form are pore water pressure for each depth step and time step and degree of consolidation for each time step. Graphical outputs are isochrones for given time and time versus degree of consolidation graph. Isochrones are plotted in two options. One option is plotting isochrones for each time step up to the given time. The second option is plotting isochrone for a selected time step in the range of the given time.

3.2.2.2 Unsaturated soils

Consolidation analysis for unsaturated soils includes analysis with respect to both water and air.

A. Input

Inputs related to the water phase are initial excess pore water pressure distribution, drainage condition for water, coefficient of permeability with respect to water, density of water, coefficient of water volume change with respect to change in net normal stress and coefficient of water volume change with respect to change in matric suction.

Inputs related to the air phase are initial excess pore air pressure distribution, drainage condition for air, molecular mass of air, coefficient of transmission, coefficient of air volume change with respect to change in net normal stress and coefficient of air volume change with respect to change in matric suction.

In addition to the above inputs other inputs required are thickness of soil, degree of saturation, porosity, temperature, time, depth step and time step.

B. Conditions considered

Consolidation analysis for unsaturated soils by finite difference method is done for only single soil layer. Single or double drainage can be considered.

Initial excess pore air and pore water pressure distributions considered in this analysis case are trapezoidal initial excess pore air and pore water pressure distributions and special triangular initial excess pore air and pore water pressure distributions. Here also rectangular and triangular initial excess pore air and pore water pressure distributions can be handled by the trapezoidal case.

Excess pore water pressure and excess pore air pressure calculation at interior nodes is done using equations (2.30) and (2.31). For excess pore water pressure and excess pore air pressure calculation at boundary nodes, equations (2.30) and (2.31) are modified to the following form.

Equation for calculating pore water pressure:

$$u_{w(i,j+1)} = u_{w(i,j)} + \frac{\beta_w g_1^w}{(1 - C_a C_w)} - \frac{C_w}{(1 - C_a C_w)} \beta_a f_1^a \tag{3.9}$$

Equation for calculating pore air pressure:

$$u_{a(i,j+1)} = u_{a(i,j)} + \frac{\beta_a f_1^a}{(1 - C_a C_w)} - \frac{C_a}{(1 - C_a C_w)} \beta_w g_1^w \tag{3.8}$$

Where:

$$\beta_w = c_v^w \frac{\Delta t}{\Delta y^2}$$

$$\beta_a = c_v^a \frac{\Delta t}{\Delta y^2}$$

$$g_1^w = 2u_{w(i-1,j)} - 2u_{w(i,j)}$$

$$f_1^a = 2u_{a(i-1,j)} - 2u_{a(i,j)}$$

Degree of consolidation calculation is done using Eq. (2.19) for the air and water phases.

C. Output

The outputs of this case are also obtained in tabular and graphical form. The outputs obtained in tabular form are pore air pressure and pore water pressure for each depth step and time step and degree of consolidation for air and water phases for each time step. Graphical outputs are isochrones for given time and time versus degree of consolidation graph for both phases.

Isochrones for each time step to the given time or isochrone for a selected time step in the range of the given time can be obtained.

3.3 Settlement Analysis

Settlement analysis part of the software contains calculation of immediate settlement, primary settlement and secondary settlement. Immediate settlement is a settlement independent of time whereas primary settlement and secondary settlement are time dependant settlements. Primary settlement can be calculated as primary settlement for given time or final primary settlement. Secondary settlement is calculated for times after the completion of primary settlement. Time of completion of primary settlement for given loading is an input required from the user.

Immediate settlement is calculated by using equation (2.32). Final primary settlement is calculated using equations (2.33), (2.34) or (2.35) depending on the selected calculation method. Primary settlement for given time is calculated from the final primary settlement and degree of consolidation. Degree of consolidation is calculated by Fourier series method using equations (2.3), (2.5), (2.7), (2.9), (2.11) and (2.13). Secondary settlement is calculated using equations (2.36) and (2.37) depending on the selected calculation method.

3.3.1 Input

Inputs required for settlement analysis part of the software include load, type and dimension of the footing for which settlement is to be calculated, surcharge above the base of the footing, thickness of the soil layer, unit weight, influence factor (for immediate settlement calculation), Poisson's ratio, modulus of elasticity, modulus of compressibility, compression index, initial void ratio, coefficient of volume compressibility, parameters related to secondary settlement (i.e. modulus of compressibility for secondary settlement and V_2), coefficient of consolidation, drainage condition, time for one hundred percent consolidation and time. All the above inputs are not necessary for any settlement analysis. The inputs required from the user depend on the type of analysis.

3.3.2 Conditions considered

The conditions considered depend upon parameters like the type of settlement to be calculated and point at which the settlement is to be calculated. Generally, settlement analysis is done for single soil layer. The overburden pressure from the soil above the base of the footing for which settlement is to be calculated and other loads above the base of the footing are considered as surcharge. The foundation types considered are rectangular foundation and circular foundation.

For rectangular foundation, vertical loads and horizontal loads will be accepted by the software. Vertical loads accepted include point load with eccentricity in both directions, line load with eccentricity, distributed load with a trapezoidal shape. Any other distribution that does not comply with the standard flexure formula is not accepted by the software. Horizontal loads accepted include uniformly distributed load and triangularly distributed load. Fig. 3.2 shows some selected loading geometries for vertical and horizontal loads.

For circular foundation case, point load at the center, line load at the centerlines and vertical uniformly distributed load will be accepted.

Thickness of the settling layer can be given by the user or can be determined by the software. The thickness determined by the software is taken as the depth from the base of the foundation to a depth at which the pressure due to the load coming from the foundation becomes ten percent of the over burden pressure at that depth.

Immediate settlement calculation is carried out for only vertical loading. The given load will be averaged to uniformly distributed load to use it for immediate settlement calculation. Immediate settlement calculation is done at the center, at the corners and at the characteristic points for rectangular foundation and at the center for circular foundation.

Primary settlement and secondary settlement calculation is done at the center, at the corners and at the characteristic points for rectangular foundation and at the center for circular foundation. For a rectangular foundation, calculation for vertical load is done at the center, at the corners and at the characteristic points while calculation for horizontal load is done at the center and at the corners only.

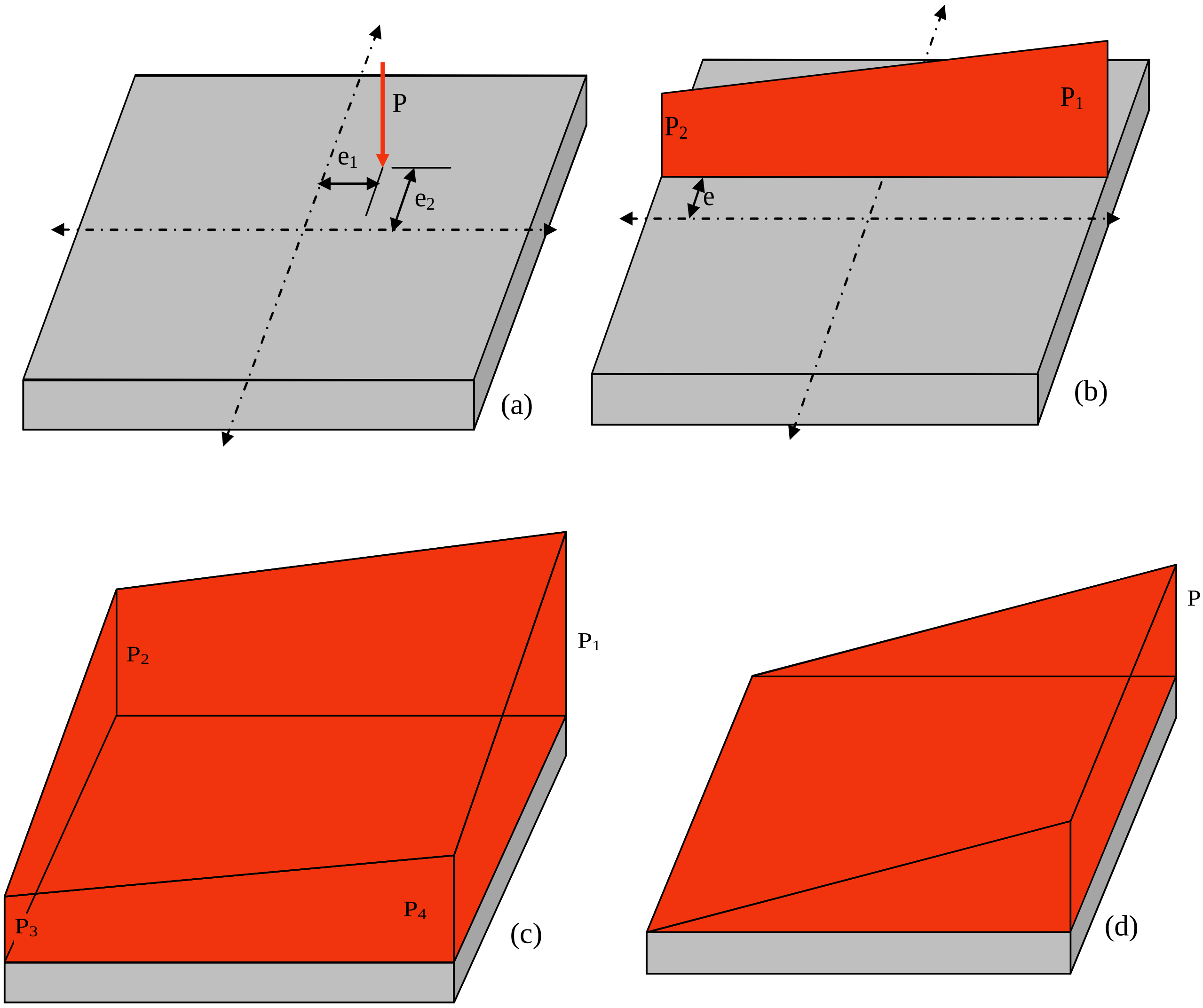


Figure 3.2: Loads. (a) Point load; (b) Line load; (c) Trapezoidal load; (d) Triangular load.

3.3.3 Output

The outputs of the settlement analysis are presented numerically and graphically. The numerical outputs include immediate settlement, final primary settlement, primary settlement for given time, secondary settlement, final total settlement and total settlement for given time. Graphical outputs are pressure distribution and time versus total settlement graph.

CHAPTER FOUR

Application of the Software

In this chapter, the contents of the developed software and the procedures that will be followed to use the software are presented.

4.1 General

When the software is started, the window in Figure 4.1 will appear.

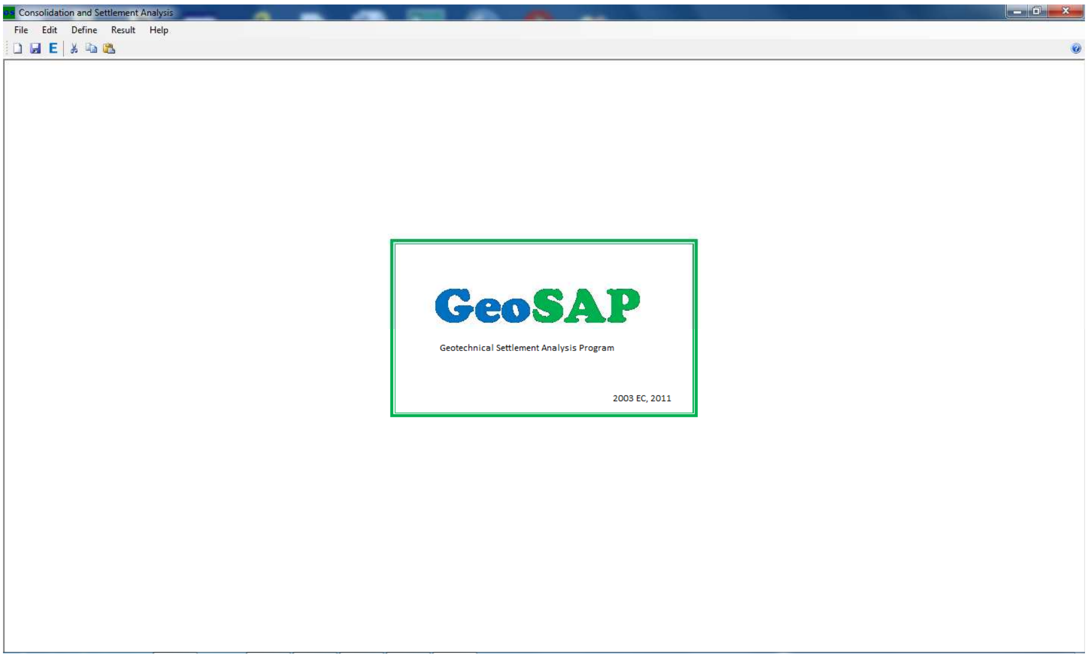


Figure 4.1: Main window

The window given in Figure 4.1 contains menus in its upper left corner. These are the File, Edit, Define, Result and Help menus (Figure 4.2). The contents of these menus are given below.

Figure 4.2: Menus

4.1.1 File menu

This menu contains the New, Save As and Export commands. The New command lets the user to select the type of analysis. The Save As command allows the user to save the inputs used for analysis. The Export command is used to export finite difference calculation table to excel in the case of consolidation analysis by finite difference method. These commands can also be accessed by using the shortcut keys given there or by the buttons provided in the toolbar.

4.1.2 Edit menu

The commands in this menu are the Cut, Copy and Paste commands. These commands are used to cut, copy and paste a text respectively. These commands can also be accessed by using the shortcut keys given or by the buttons provided in the toolbar.

4.1.3 Define menu

This menu contains commands used to insert input values. For consolidation analysis, the first command is the Load command which is used to input parameters related to load. For settlement analysis, the first command is the Structure and Load command. This is used to input parameters related to foundation and load. The next command for both consolidation and settlement analysis is the Soil Property command. This command allows the user to input parameters related to soil.

4.1.4 Result menu

The result menu contains commands that provide the user with the results of the analysis. For consolidation analysis, the commands in this menu are the Consolidation, Isochrones and Time Vs Degree of Consolidation Graph commands. The Consolidation command is used to display numerical outputs of consolidation analysis. The Isochrones command and the Time Vs Degree of Consolidation command are used to display isochrones and time versus degree of consolidation graph respectively. For settlement analysis, the menu contains the Settlement, Pressure Distribution and Time Vs Settlement graph commands. The Settlement command is used to display numerical outputs of settlement analysis. The Pressure Distribution command and the Time Vs Settlement Graph command are used to display pressure distribution and time versus settlement graphs respectively.

4.1.5 Help menu

The Help menu contains the GeoSAP Help and About GeoSAP commands. The GeoSAP Help command can also be accessed by using the shortcut key given or the Help button in the toolbar.

In starting both consolidation and settlement analysis, the first step is to click New in the File menu to display the New dialog box (Figure 4.3). The New dialog box allows the user to select the type of analysis to be done.

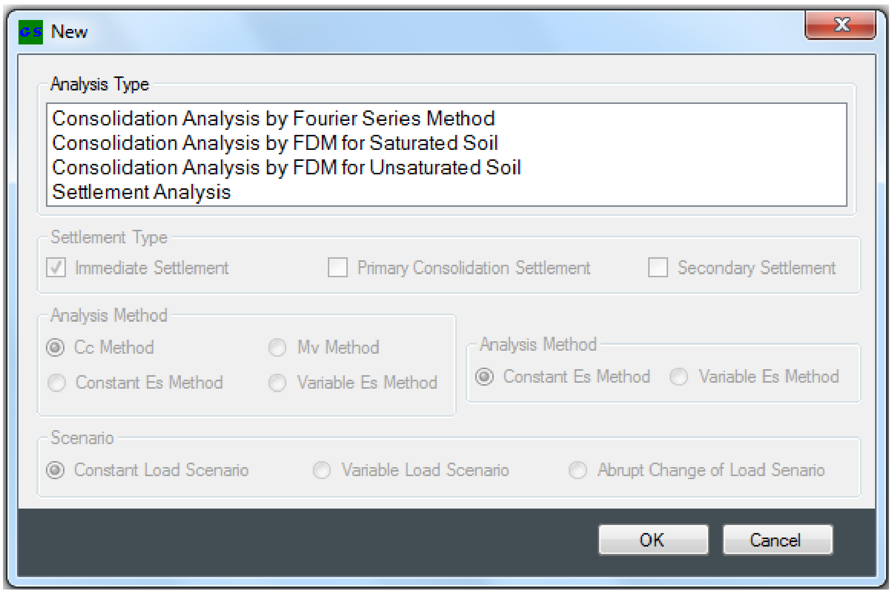


Figure 4.3: New dialog box

4.2 Consolidation Analysis by Fourier Series Method

To start this analysis, select Consolidation Analysis by Fourier Series Method in the Analysis Type list box in the New dialog box and click OK. Then click Load in the Define menu. The Load dialog box will appear (Figure 4.4).

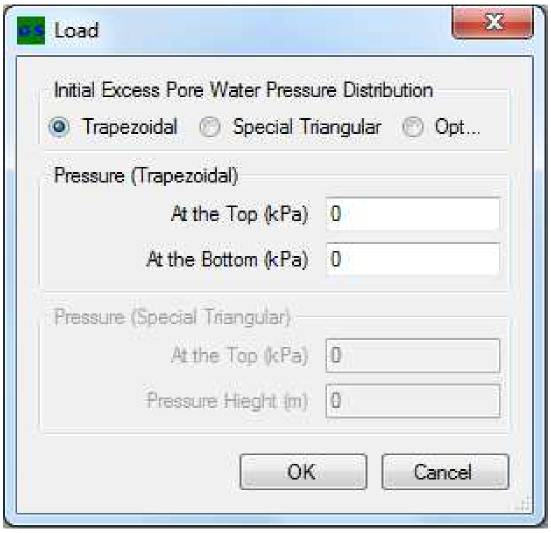


Figure 4.4: Load dialog box

In the Initial Excess Pore Water Pressure Distribution group box, select the given initial excess pore water pressure distribution. If the Trapezoidal or Special Triangular radio button is selected, give the loads and click OK. If the Opt... radio button is selected, another Load dialog box will appear (Figure 4.5).

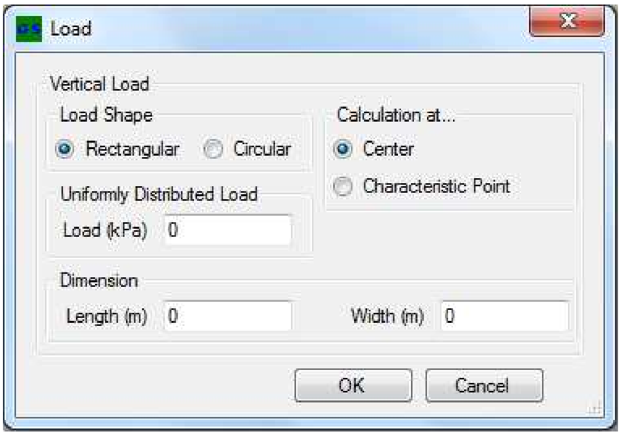


Figure 4.5: Load dialog box

In the Load Shape group box, select the shape of the given load and in the Calculation at… group box, select the point of calculation at which consolidation analysis is to be done. Then give the required values in the Distributed Load and Dimension group boxes and click OK. For circular load shape case, calculation will be done at the center only. Then click Soil Property in the Define menu. The Soil Property dialog box will appear (Figure 4.6).

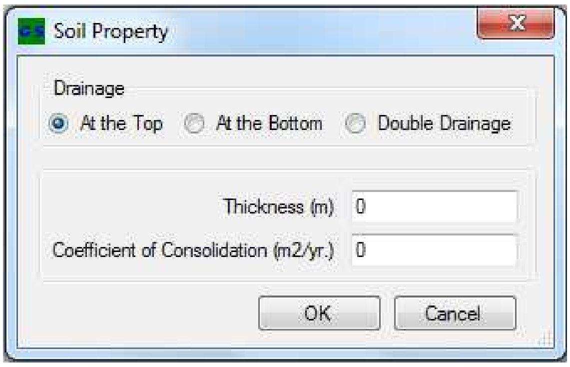


Figure 4.6: Soil Property dialog box

Insert the given values required in Soil Property dialog box and click OK. Then click Consolidation in the Result menu. The Consolidation dialog box will appear (Figure 4.7).

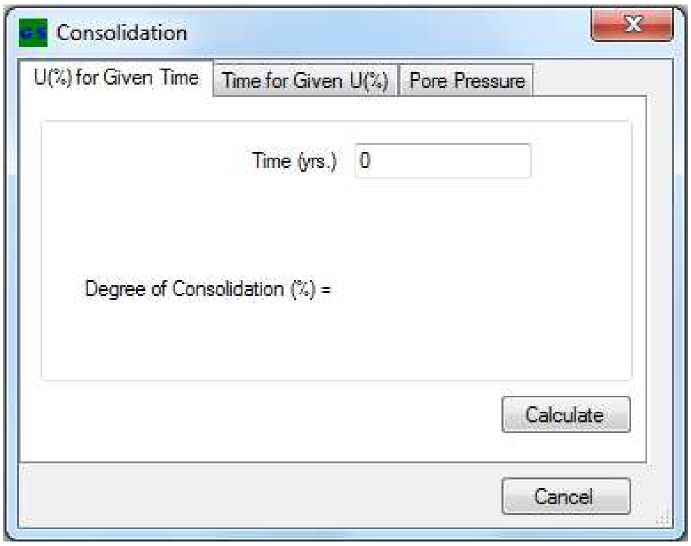


Figure 4.7: Consolidation dialog box

Select the tab with the required value, from the three tabs. Insert the given values and click Calculate. Click Cancel in the Consolidation dialog box. Then click Isochrones in the Result menu under Graphs submenu. The Isochrone dialog box will appear (Figure 4.8).

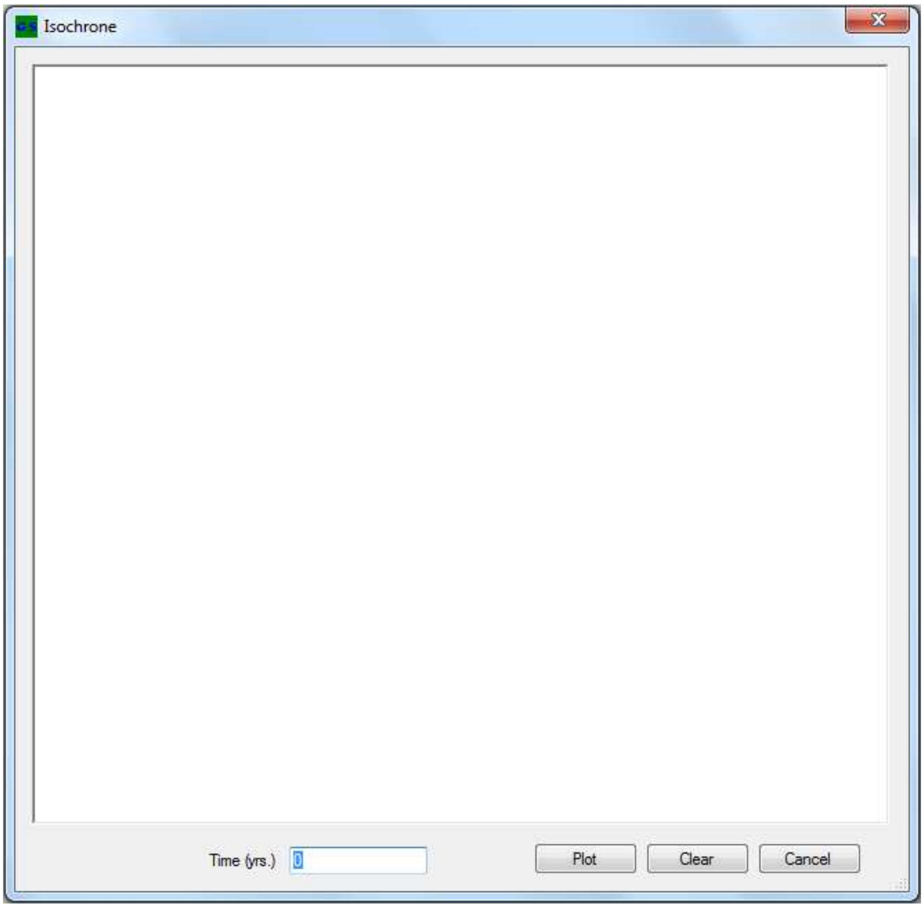


Figure 4.8: Isochrone dialog box

Give the time and click Plot. Click Cancel in the Isochrone dialog box. Then click Time Vs Degree of Consolidation Graph in the Result menu under Graphs submenu. A plotting area will appear. Give the time and click Plot. Click Cancel to end.

4.3 Consolidation Analysis by FDM for Saturated Soil

4.3.1 Constant load scenario

To start this analysis, select Consolidation Analysis by FDM for Saturated Soil in the Analysis Type list box and select Constant Load Scenario in the Scenario group box both in the New dialog box and click OK. Then click Load in the Define menu. The Load dialog box will appear (Figure 4.9).

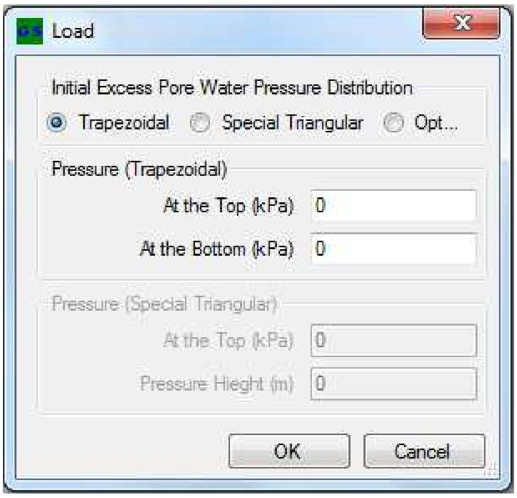


Figure 4.9: Load dialog box

In the Initial Excess Pore Water Pressure Distribution group box, select the given initial excess pore water pressure distribution. If the Trapezoidal or Special Triangular radio button is selected, give the loads and click OK. If the Opt... radio button is selected, another Load dialog box will appear (Figure 4.10).

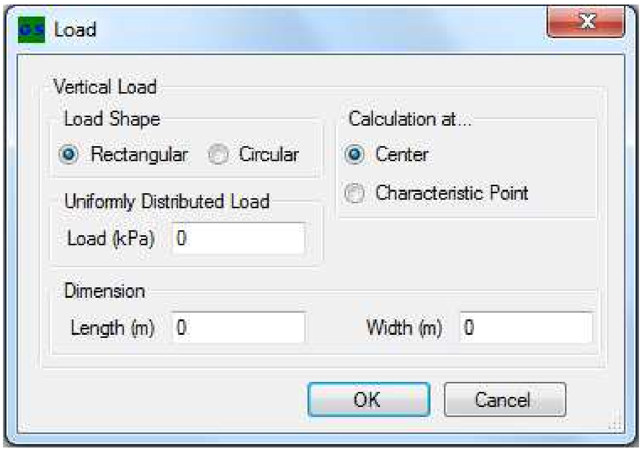


Figure 4.10: Load dialog box

In the load shape group box, select the shape of the given load and in the Calculation at… group box, select the point of calculation at which consolidation analysis is to be done. Then give the required values in the Uniformly Distributed Load and Dimension group boxes and click OK. For circular load shape case, calculation will be done at the center only. Then click Soil Property in the Define menu. The Soil Property dialog box will appear (Figure 4.11).

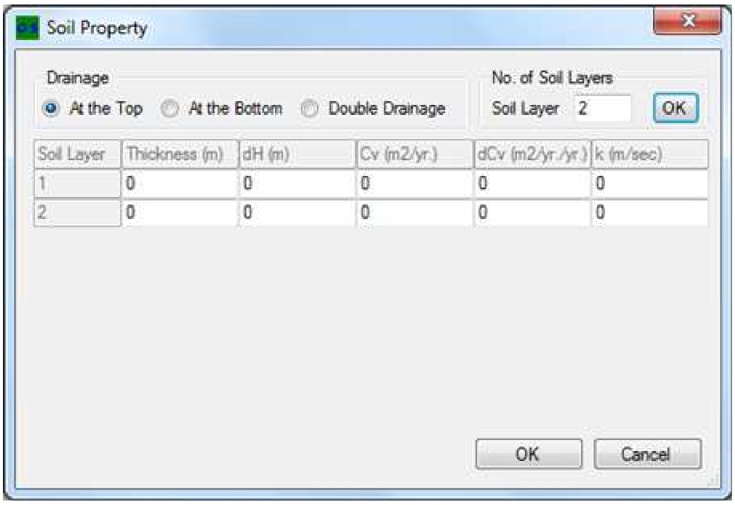


Figure 4.11: Soil Property dialog box

In the No. of Soil Layers group box, give the number of soil layers and click the OK button in the same group box. Insert other given values required in Soil Property dialog box and click OK. Then click Consolidation in the Result menu. The Consolidation dialog box will appear (Figure 4.12).

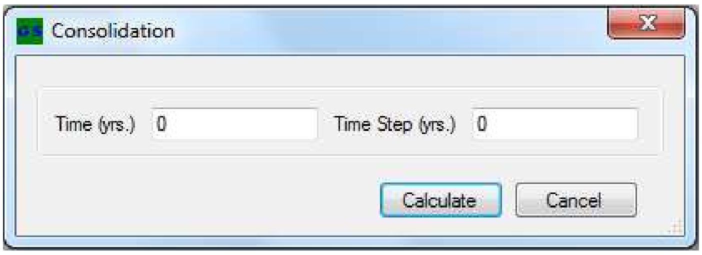


Figure 4.12: Consolidation dialog box

Insert the given values required in Consolidation dialog box and click Calculate. Then click Isochrones in the Result menu under Graphs submenu. The Isochrone dialog box will appear (Figure 4.13).

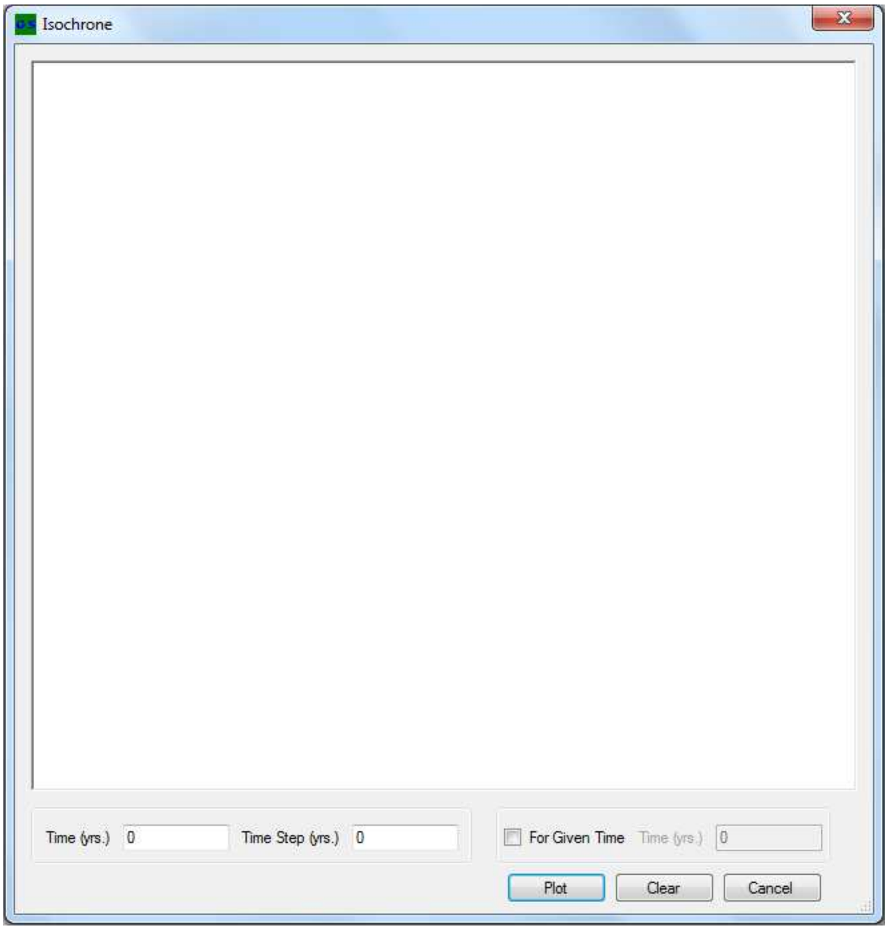


Figure 4.13: Isochrone dialog box

Give the time and time step and click Plot. This will result in isochrones at each time step. If isochrone at specific time is required, check the For Given Time checkbox, give the time and click Plot. The time should be within the total time given above. Click Cancel in the Isochrone dialog box. Then click Time Vs Degree of Consolidation Graph in the Result menu under Graphs. A plotting area will appear. Give the time and time step and click Plot. Then click Export in the File menu. The Export dialog box will appear (Figure 4.14).

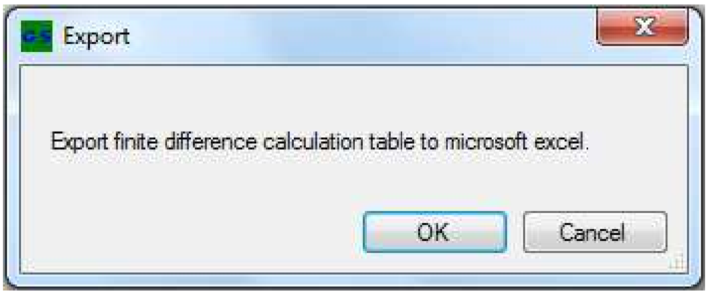


Figure 4.14: Export dialog box

Click OK and the finite difference calculation table will be exported to Microsoft excel.

4.3.2 Variable load scenario

To start this analysis, select Consolidation Analysis by FDM for Saturated Soil in the Analysis Type list box and select Variable Load Scenario in the Scenario group box both in the New dialog box and click OK. Other procedures of this analysis are similar to the procedures of constant load scenario except the dialog boxes in Figure 4.9 and Figure 4.10 will be changed to dialog boxes shown in Figure 4.15 and Figure 4.16 respectively.

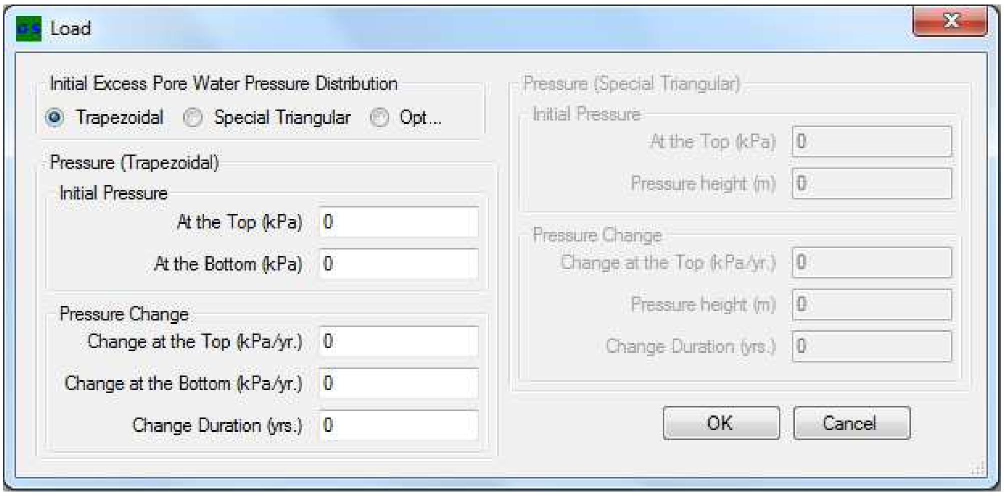


Figure 4.15: Load dialog box

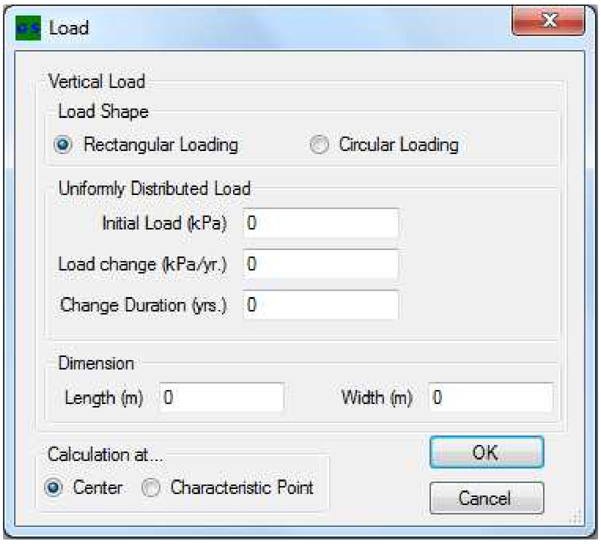


Figure 4.16: Load dialog box

4.3.3 Abrupt change of load scenario

To start this analysis, select Consolidation Analysis by FDM for Saturated Soil in the Analysis Type list box and select Abrupt Change of Load Scenario in the Scenario group box both in the New dialog box and click OK. Other procedures of this analysis are also similar to the procedures of constant load scenario except the dialog boxes in Figure 4.9 and Figure 4.10 will be changed to dialog boxes shown in Figure 4.17 and Figure 4.18 respectively.

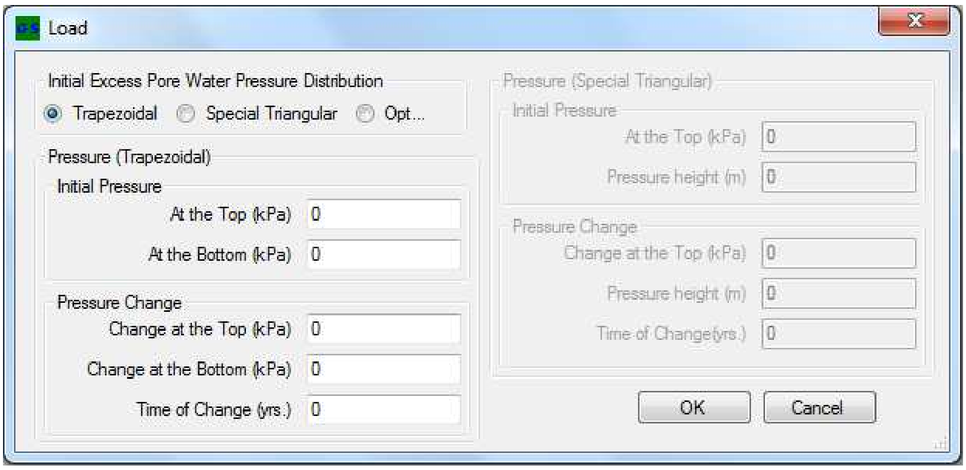


Figure 4.17: Load dialog box

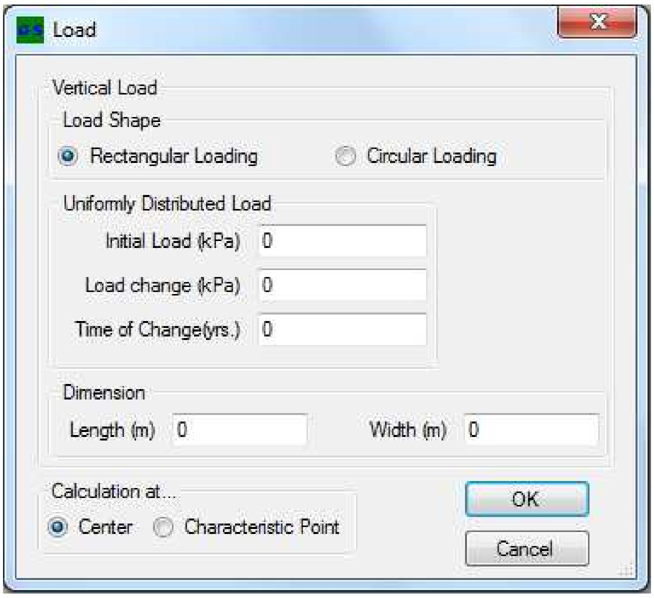


Figure 4.18: Load dialog box

4.4 Consolidation Analysis by FDM for Unsaturated Soil

To start this analysis, select Consolidation Analysis by FDM for Unsaturated Soil in the Analysis Type list box in the New dialog box and click OK. Then click Load in the Define menu. The Load dialog box will appear (Figure 4.19).

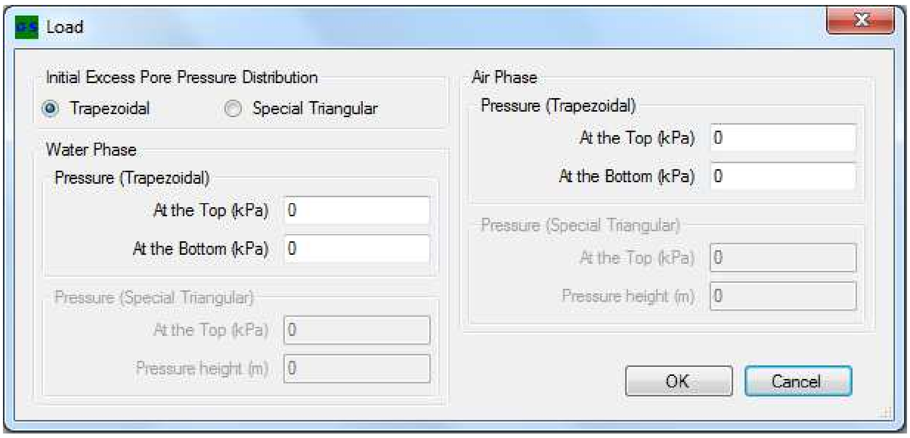


Figure 4.19: Load dialog box

In the Initial Excess Pore Pressure Distribution group box, select the given initial excess pore pressure distribution. Give the loads and click OK. Then click Soil Property in the Define menu. The Soil Property dialog box will appear (Figure 4.20).

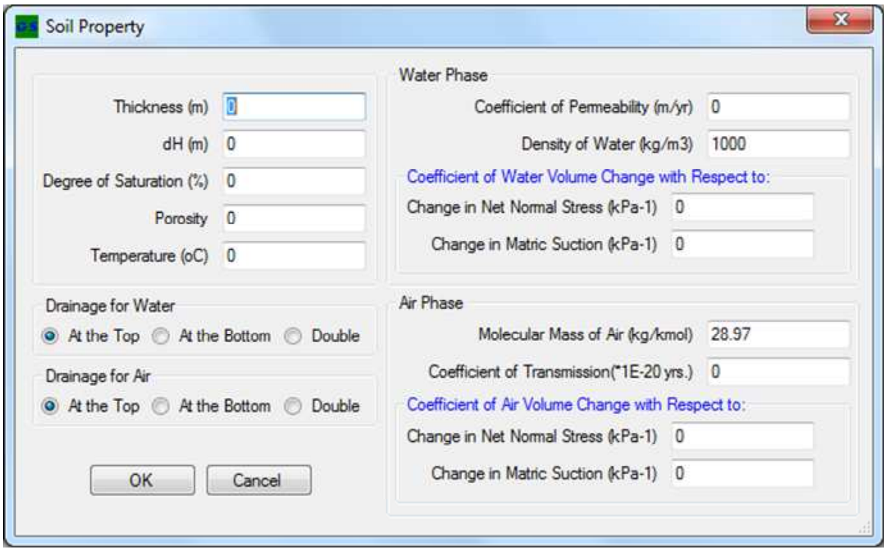


Figure 4.20: Soil Property dialog box

Insert the given values required in Soil Property dialog box and click OK. Then click Consolidation in the Result menu. The Consolidation dialog box will appear (Figure 4.21).

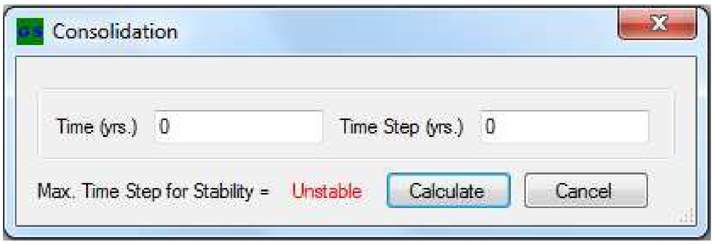


Figure 4.21: Consolidation dialog box

Give the time and time step and click Calculate. Then click Isochrones in the Result menu under Graphs submenu. The Isochrone dialog box will appear (Figure 4.22).

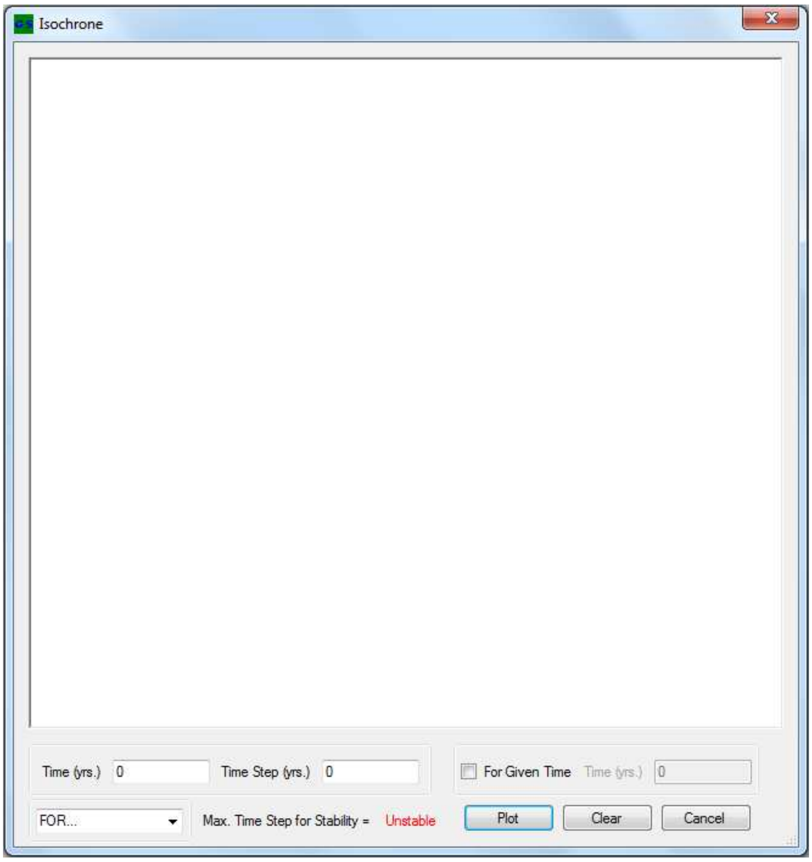


Figure 4.22: Isochrone dialog box

Select the case for which isochrone is to be plotted from the For… combo box. Give the time and time step and click plot. This will result in isochrones at each time step. If isochrone at specific time is required, check the For Given Time check box, give the time and click Plot. The time should be within the total time given. Click Cancel in the Isochrone dialog box. Then click Time Vs Degree of Consolidation Graph in the Result menu under Graphs submenu. A plotting area will appear. Select the case for which isochrone is to be plotted from the For… combo box. Give the time and time step and click Plot. Then click Export in the File menu. The Export dialog box will appear (Figure 4.14). Click OK and the finite difference calculation table will be exported to Microsoft excel.

4.5 Settlement Analysis

To start this analysis, select Settlement Analysis in the Analysis Type list box, the required settlement types in the Settlement Type group box and the methods of analysis for primary settlement and secondary settlement in the Analysis Method group boxes all in the New dialog box and click OK. Then click Structure and Load in the Define menu. The Structure dialog box will appear (Figure 4.23).

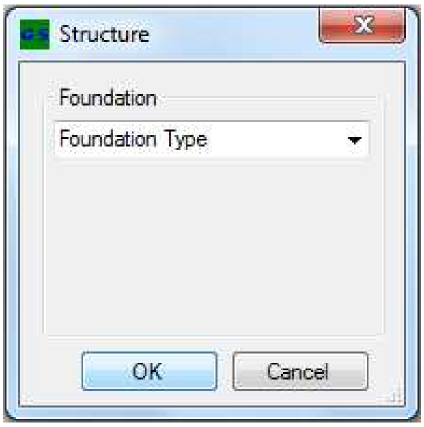


Figure 4.23: Structure dialog box

Analysis can be done for rectangular foundation and circular foundation. The procedures for these two cases are given in the next sections.

4.5.1 Rectangular foundation

In the Structure dialog box, in the Foundation Type combo box, select Rectangular. Give other given values required in Structure dialog box and click OK. The Load dialog box will appear (Figure 4.24).

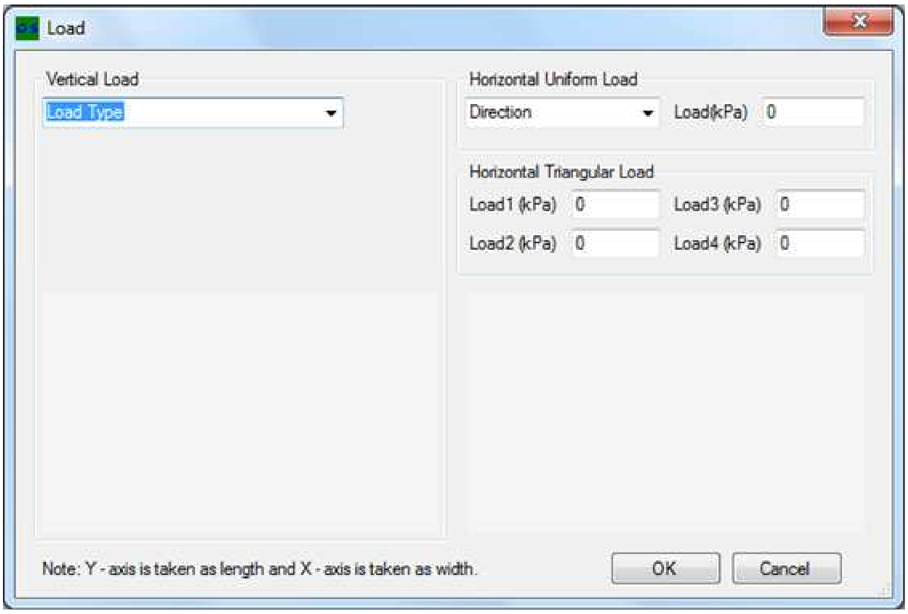


Figure 4.24: Load dialog box

In the Vertical Load group box, in the Load Type combo box, select the type of load. Insert the load and other given values required in Vertical Load group box. In the Horizontal Uniform Load group box, in the Direction combo box, select the direction. Insert the load value in the Horizontal Uniform Load group box. In the Horizontal Triangular Load group box, insert the load values and click OK. Then click Soil Property in the Define menu. The Soil property dialog box will appear (Figure 4.25).

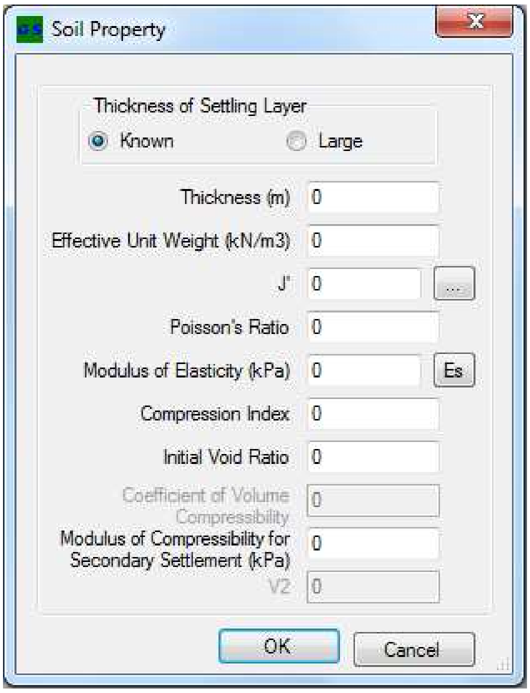


Figure 4.25: Soil Property dialog box

If the thickness of the soil layer is known, check the Known radio button in the Thickness of Settling Layer group box and insert the thickness value. Else if the thickness of the soil layer is required to be calculated by the software, check the Large radio button in the Thickness of Settling Layer group box. If the value of J’ to be given is the same at the center, corners and characteristic points, insert the value. Else if the value of J’ to be given is different, click the button near the J’ text box and the J’ dialog box will appear (Figure 4.26).

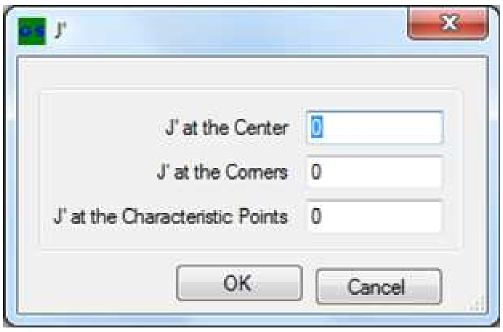


Figure 4.26: J’ dialog box

Insert the values of J’ at the center, corners and characteristic points and click OK. If the modulus of elasticity is to be given, insert the value and the value of modulus of compressibility will be calculated from it. Else if the modulus of compressibility is to be given, click the Es button and the Modulus of Compressibility dialog box will appear (Figure 4.27).

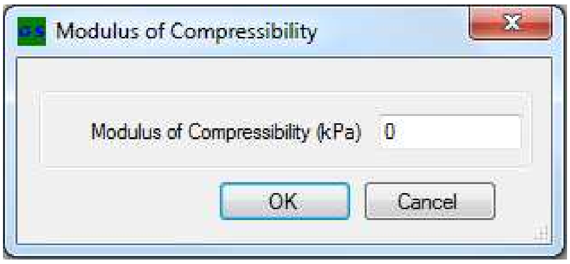


Figure 4.27: Modulus of Compressibility dialog box

Insert the value of modulus of compressibility and click OK. The modulus of elasticity will be calculated from the given modulus of compressibility. Insert other given values required in Soil Property dialog box and click OK. Then click Settlement in the Result menu. The Settlement dialog box will appear (Figure 4.28).

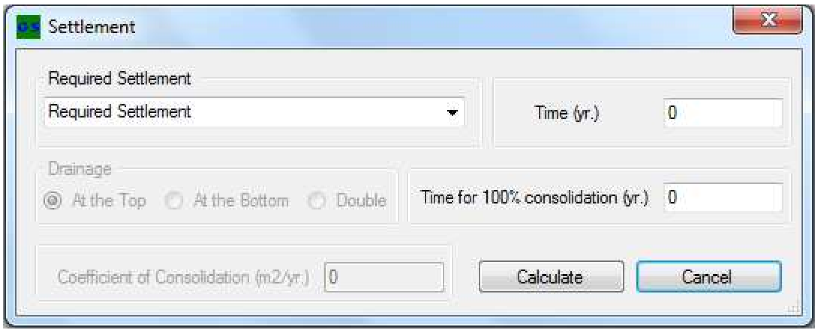


Figure 4.28: Settlement dialog box

In the Settlement dialog box, in the Required Settlement combo box, select the type of settlement required. Insert other inputs required in the dialog box and click Calculate. Another Settlement dialog box will appear (Figure 4.29).

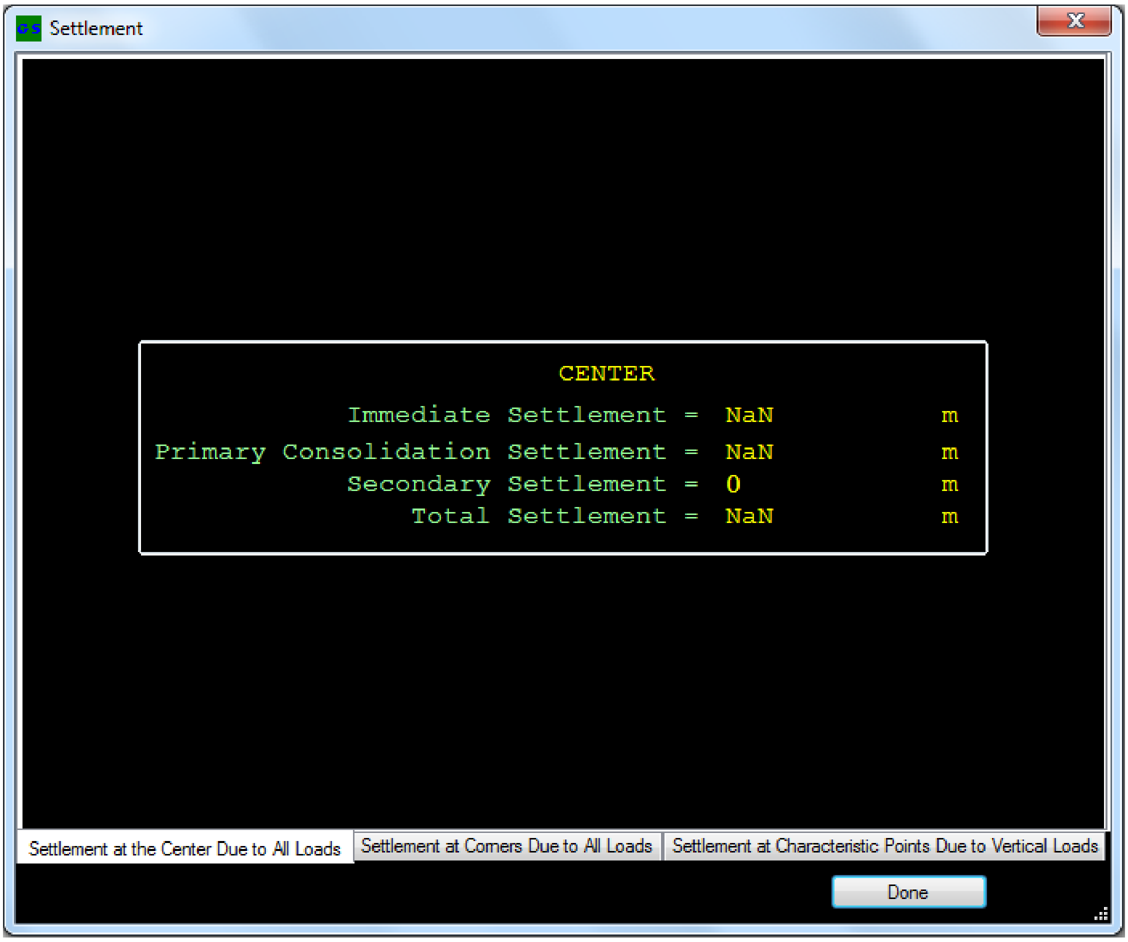


Figure 4.29: Settlement dialog box

Click the three tabs to see the settlement values at different locations of the foundation and click Done. Then click Pressure Distribution in the Result menu under Graphs submenu. The Pressure Distribution dialog box will appear (Figure 4.30).

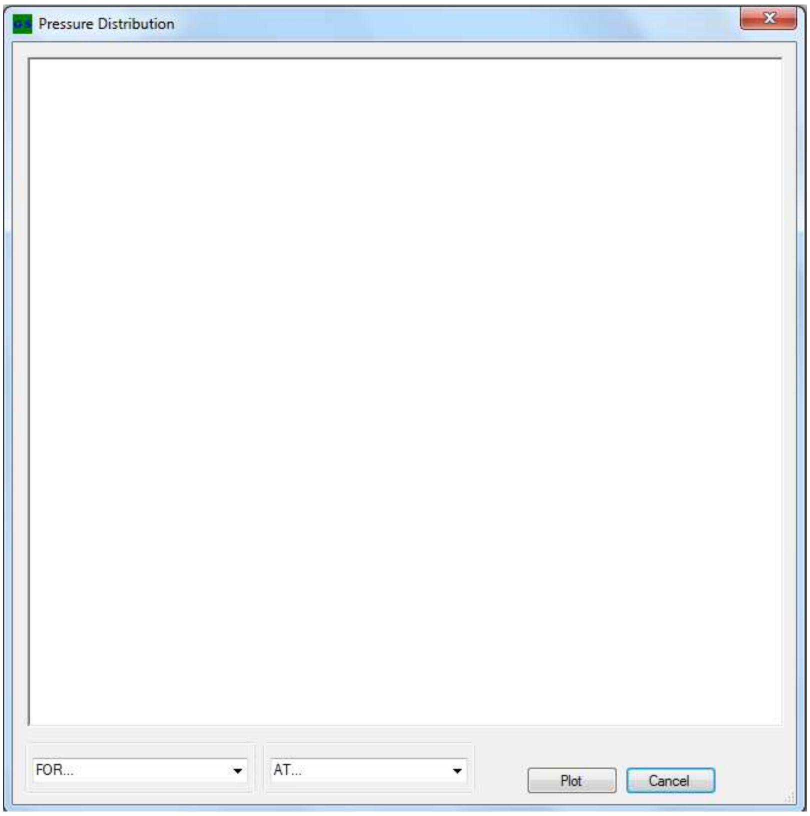


Figure 4.30: Pressure Distribution dialog box

Select the load type for which pressure distribution is to be plotted and the location of the foundation at which pressure distribution is to be plotted from the FOR… and AT… combo boxes respectively and click Plot. Click Cancel and then click Time Vs Settlement Graph in the Result menu under Graphs submenu. The Time-Settlement Graph dialog box will appear (Figure 4.31).

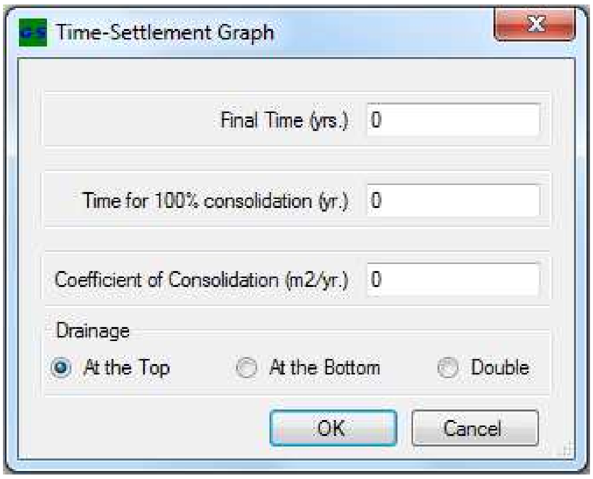


Figure 4.31: Time-Settlement Graph dialog box

Insert the required inputs and click OK. A plotting area will appear. Give the location of the foundation at which time versus settlement graph is to be plotted and click Plot. Click Cancel to end.

4.5.2 Circular foundation

In the Structure dialog box, in the Foundation Type combo box, select Circular. Give other given values required in Structure dialog box and click OK. The Load dialog box will appear (Figure 4.32).

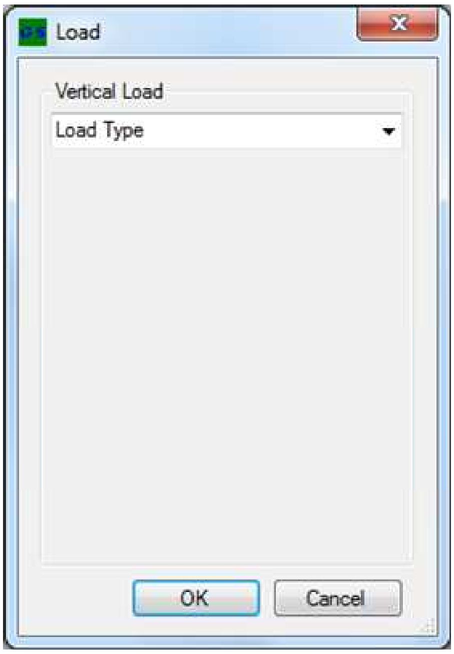


Figure 4.32: Load dialog box

In the Vertical Load group box, in the Load Type combo box, select the type of load. Insert the load value and click OK. Then click Soil Property in the Define menu. The Soil property dialog box will appear (Figure 4.25).

If the thickness of the soil layer is known, check the Known radio button in the Thickness of Settling Layer group box and insert the thickness value. Else if the thickness of the soil layer is required to be calculated by the software, check the Large radio button in the Thickness of Settling Layer group box. If the modulus of elasticity is to be given, insert the value and the value of modulus of compressibility will be calculated from it. Else if the modulus of compressibility is to be given, click the Es button and the Modulus of Compressibility dialog box will appear (Figure 4.27).

Insert the value of modulus of compressibility and click OK. The modulus of elasticity will be calculated from the given modulus of compressibility. Insert other given values required in Soil Property dialog box and click OK. Then click Settlement in the Result menu. The Settlement dialog box will appear (Figure 4.28).

In the Required Settlement combo box, select the type of settlement required. Insert other inputs required in the dialog box and click Calculate. Another Settlement dialog box will appear (Figure 4.33).

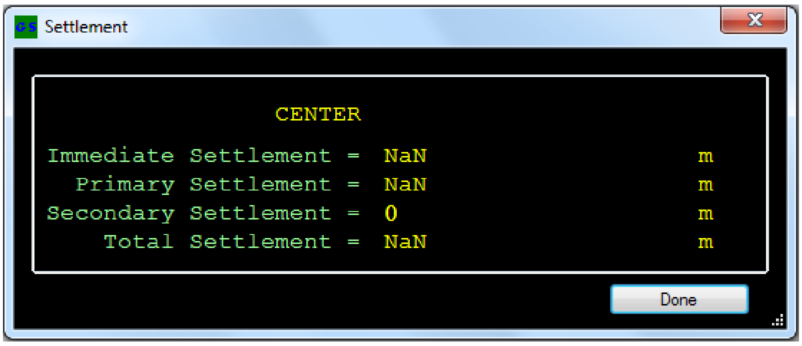


Figure 4.33: Settlement dialog box

Click Done and click Pressure Distribution in the Result menu under Graphs submenu. The Pressure Distribution dialog box will appear (Figure 4.34).

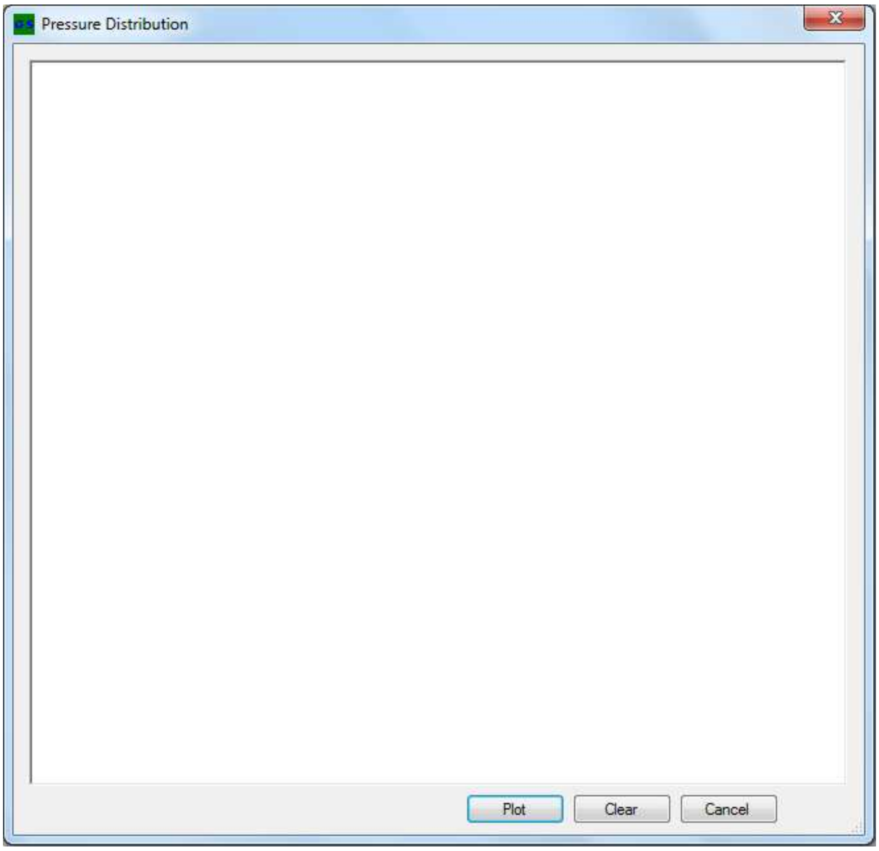


Figure 4.34: Pressure Distribution dialog box

Click Plot. Click Cancel to cancel the dialog box. Then click Time Vs Settlement Graph in the Result menu under Graphs submenu. The Time-Settlement Graph dialog box will appear (Figure 4.31). Insert the required inputs and click OK. A plotting area will appear. Click Plot. And click Cancel to end.

CHAPTER FIVE

Validation of the Software

To validate the software developed, examples have been worked out as presented in Appendix B. From the examples, the following observation is made.

- The result obtained from the common calculation methods and the results of the software are more or less similar in all analyses.
- The result of consolidation analysis by Fourier series method and finite difference method give approximately similar result. The value of pore water pressure obtained from the two methods is more or less the same. And the value of degree of consolidation from the methods is also similar even if it is not as similar as the pore water pressure.
- The developed software is simpler, faster and more accurate.

CHAPTER SIX

Conclusion and Recommendation

6.1 Conclusion

Conclusions from the study include:

1. The result of consolidation analysis by Fourier series method and finite difference method give approximately similar result.
2. For the consolidation analysis by finite difference method, the stability of the calculation is very sensitive to the beta value. The result may not be reliable for inappropriate beta values.
3. The developed software can be used to analyze consolidation and settlement simply, quickly and accurately. Comparison of results obtained from different analysis methods of consolidation and settlement can be also made with the software. The developed software is also important to study the properties of the results for different values of input parameters.

6.2 Recommendation

There are additional cases to be considered which are important for the practice and open for further studies. These include settlement analysis for unsaturated soils, consolidation and settlement analysis for two dimensional and three dimensional consolidation processes.

References

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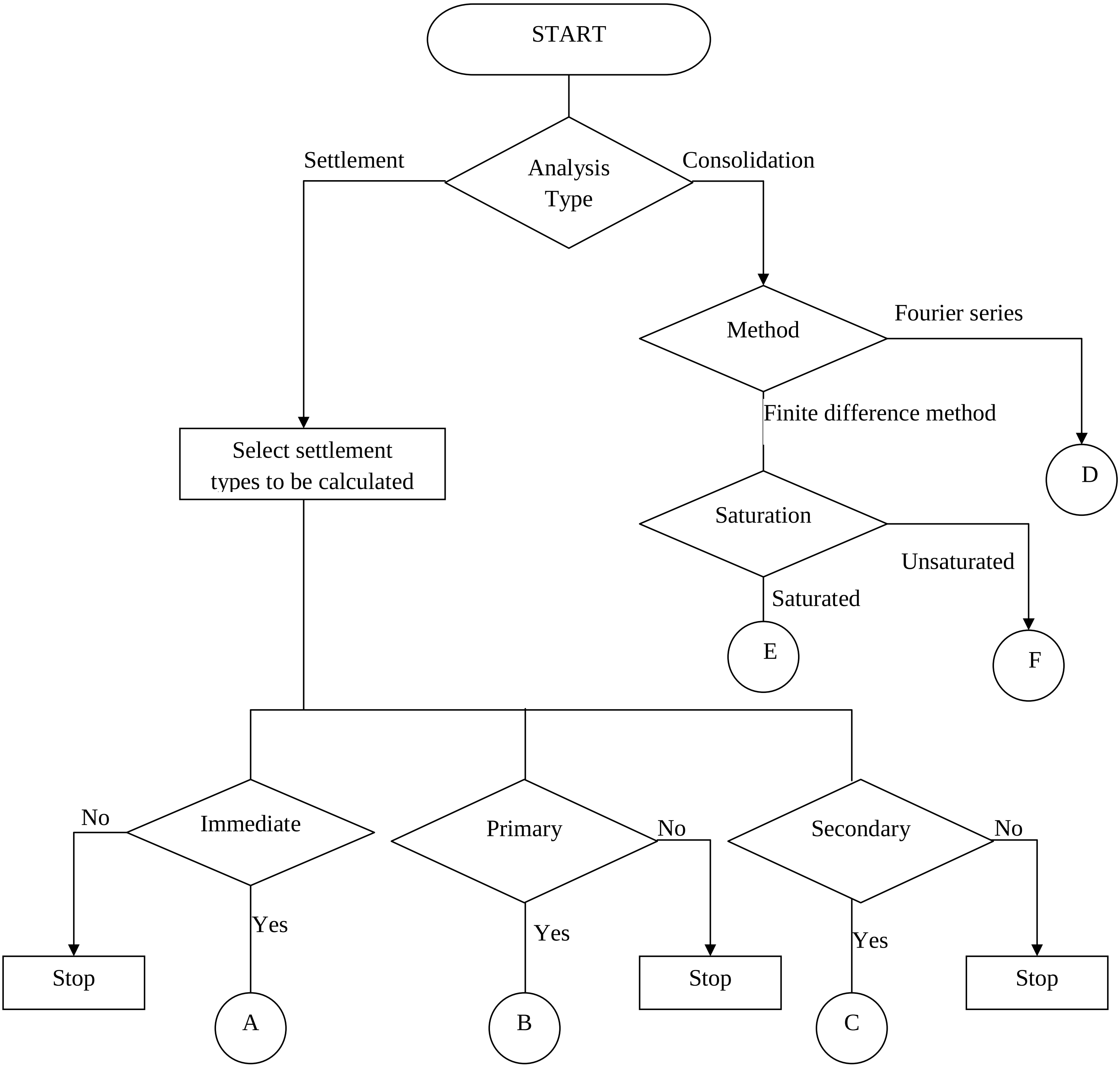
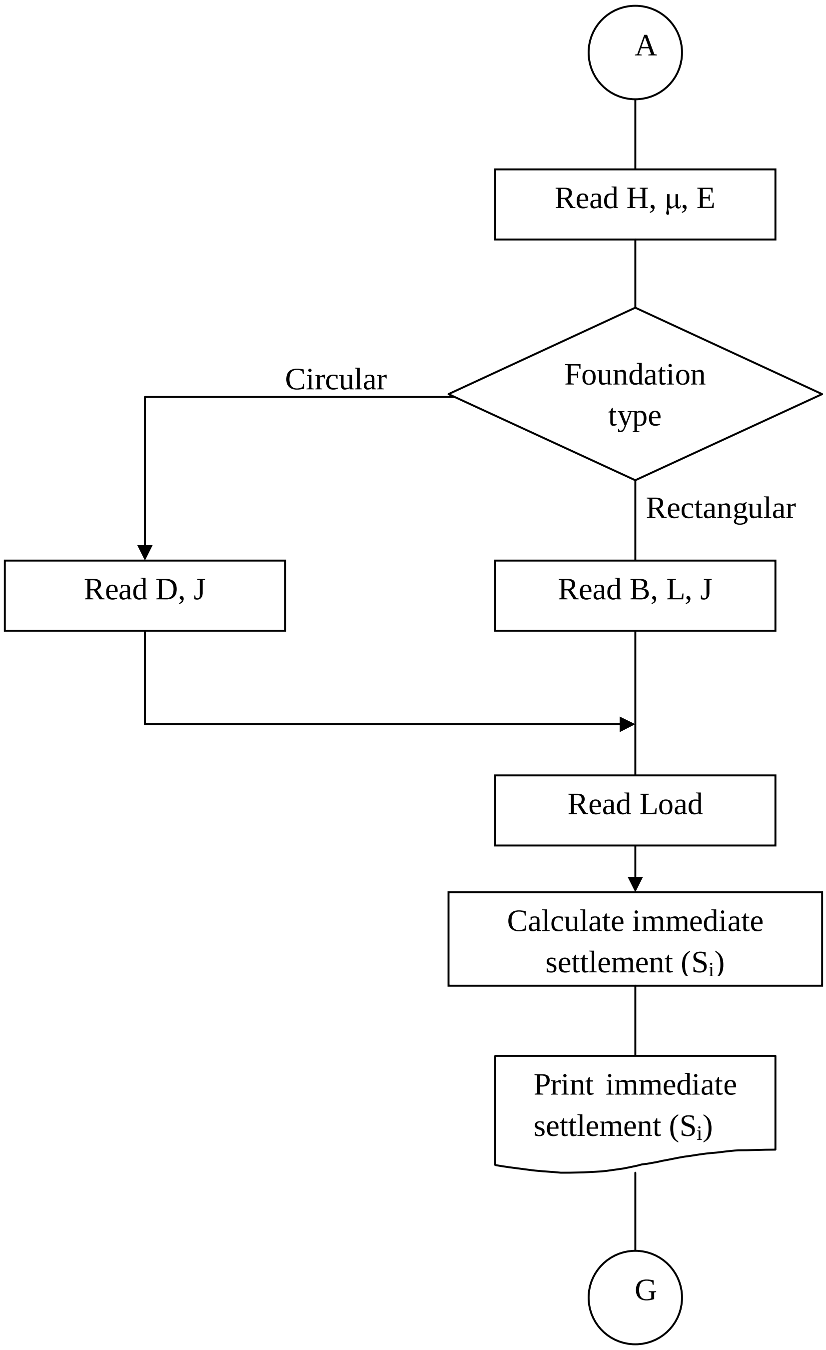
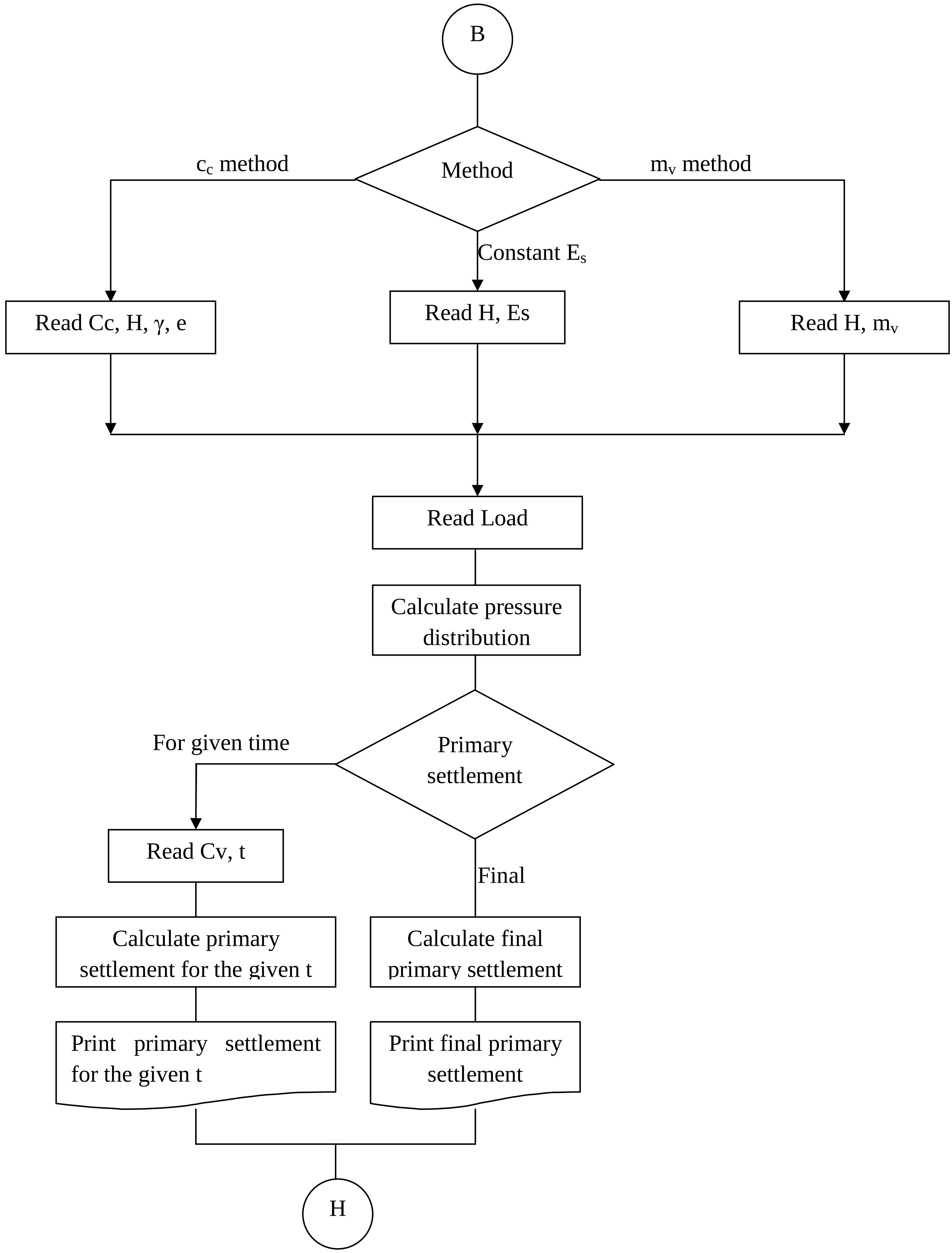
4. Seged, H., 2010. Finite Difference Method. Lecture Notes, CENG 6202 Advanced Computational Methods in Geotechnical Engineering, Addis Ababa Institute of Technology.
5. Teferra, A., 2008. Principles of Foundation Engineering. AAU – Press. Addis Ababa.
6. Teferra, A., 2010. Theory of Consolidation and Settlement Analysis. Lecture Notes, CENG 6207 Advanced Soil Mechanics, Addis Ababa Institute of Technology.
7. Teferra, A. and E. Schultze, 1988. Formulae, Charts and Tables in the area of soil Mechanics and Foundation Engineering. A.A.BALKEMA. Rotterdam.
8. Teferra, A. and M. Leikun, 1999. Soil Mechanics. AAU – Press. Addis Ababa.
9. Terzaghi, K., 1943. Theoretical Soil Mechanics. JOHN WILEY AND SONS, INC. New York.

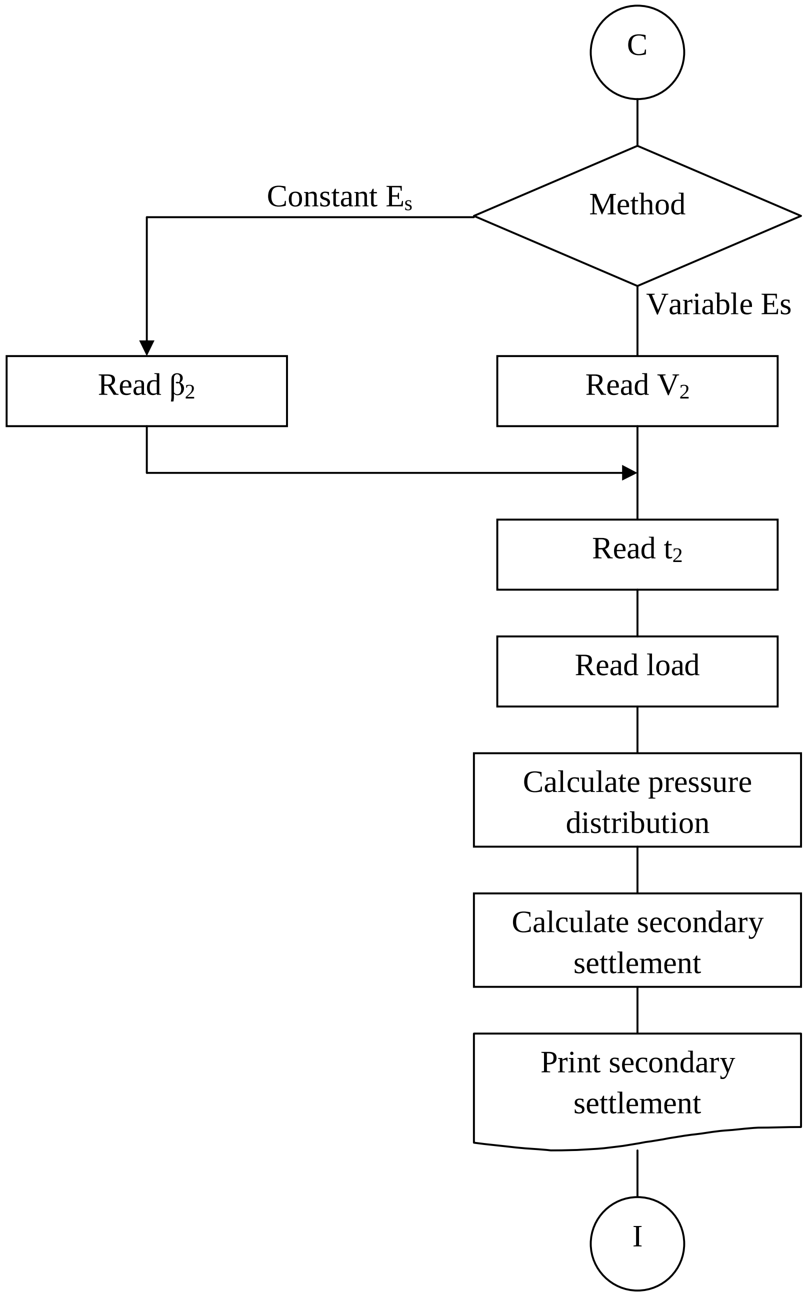
APPENDIX A

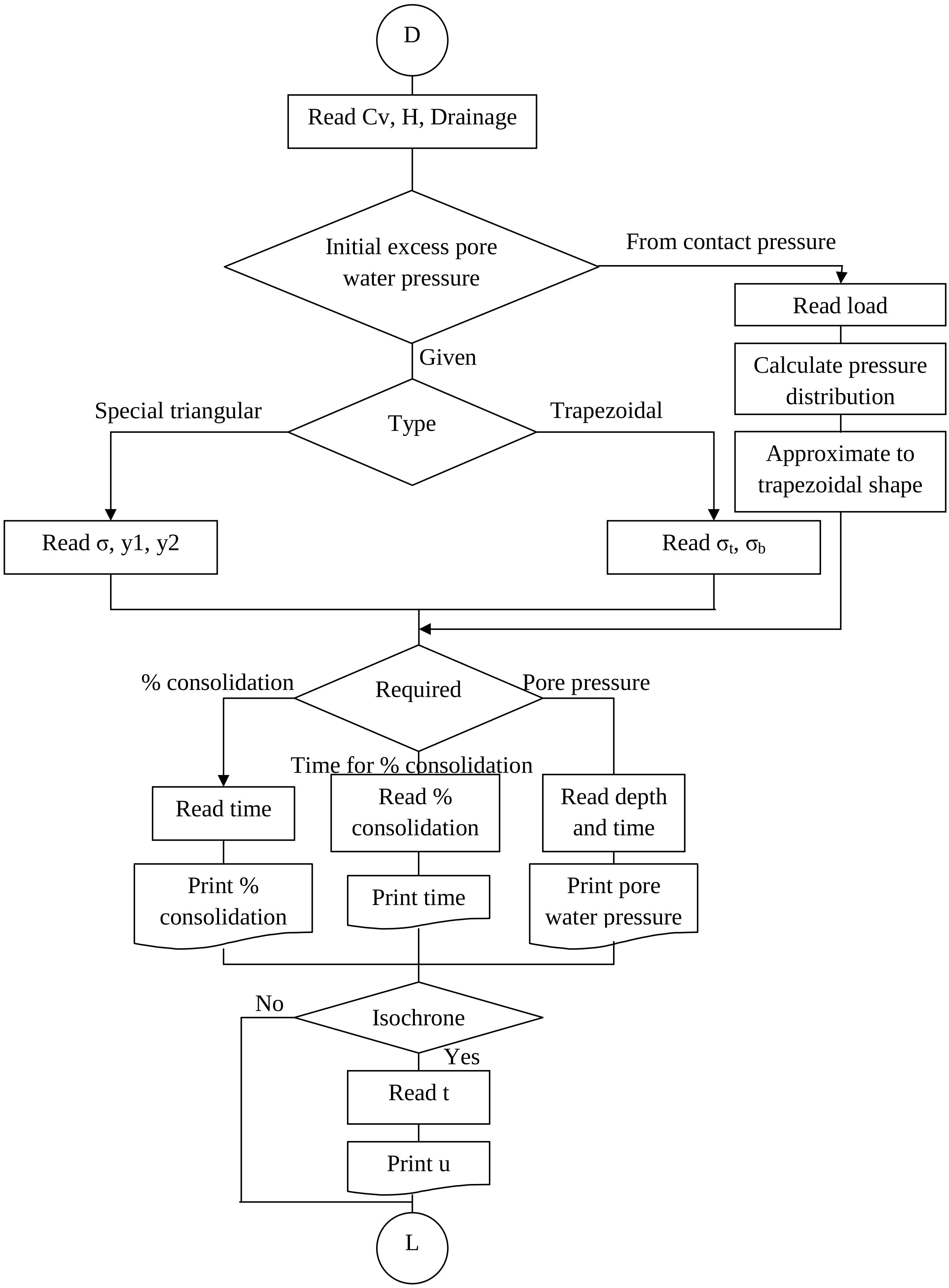
Flowchart


START
Analysis Type
Settlement
Consolidation
Method
Fourier series
Finite difference method
D
Select settlement types to be calculated
Saturation
Unsaturated
Saturated
E
F
Immediate
No
Yes
Primary
No
Yes
Secondary
No
Yes
Stop
Stop
Stop
A
B
C

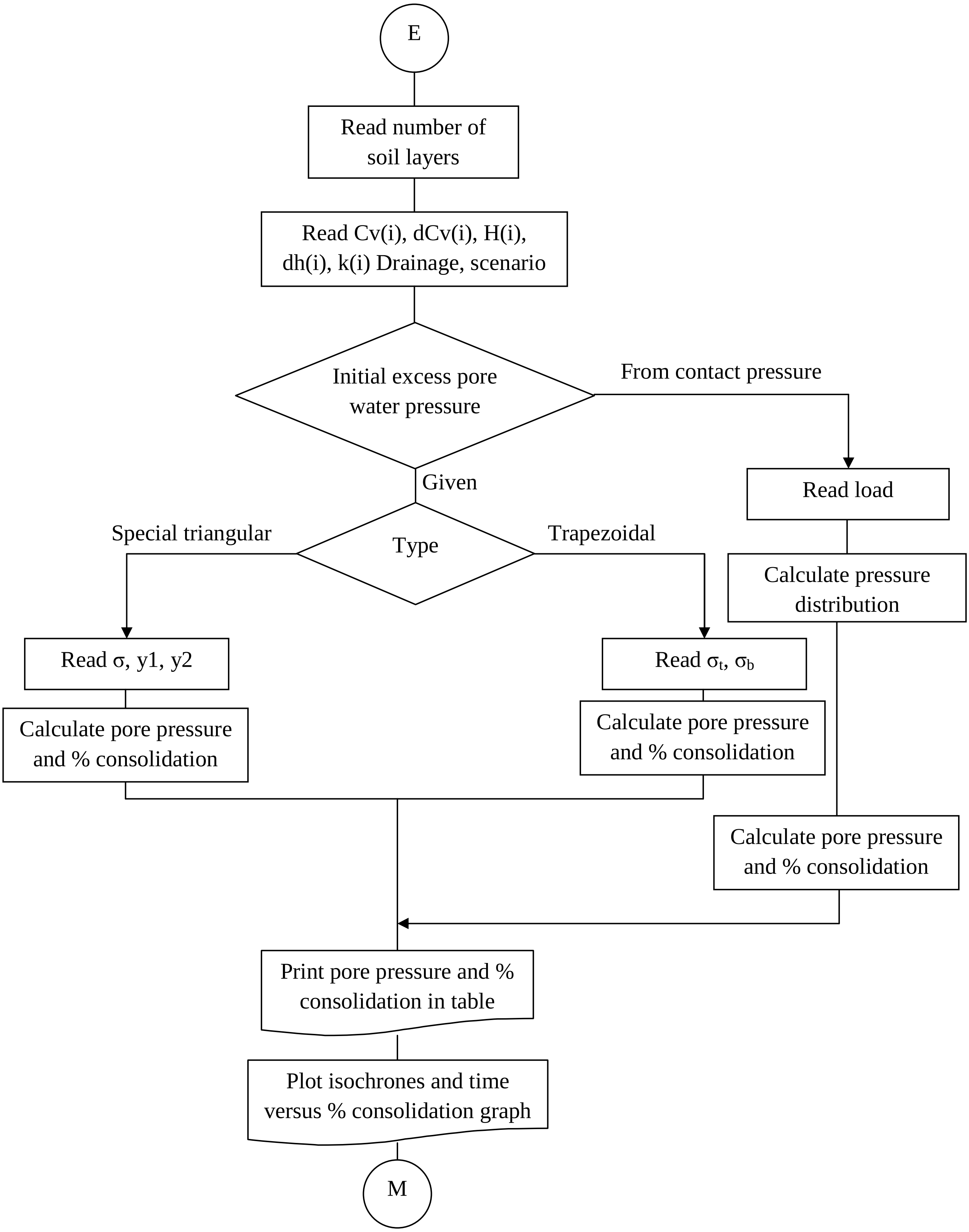

A
Read H, μ, E
Circular
Foundation type
Rectangular
Read D, J
Read B, L, J
Read Load
Calculate immediate settlement (Si)
Print immediate settlement (Si)
G

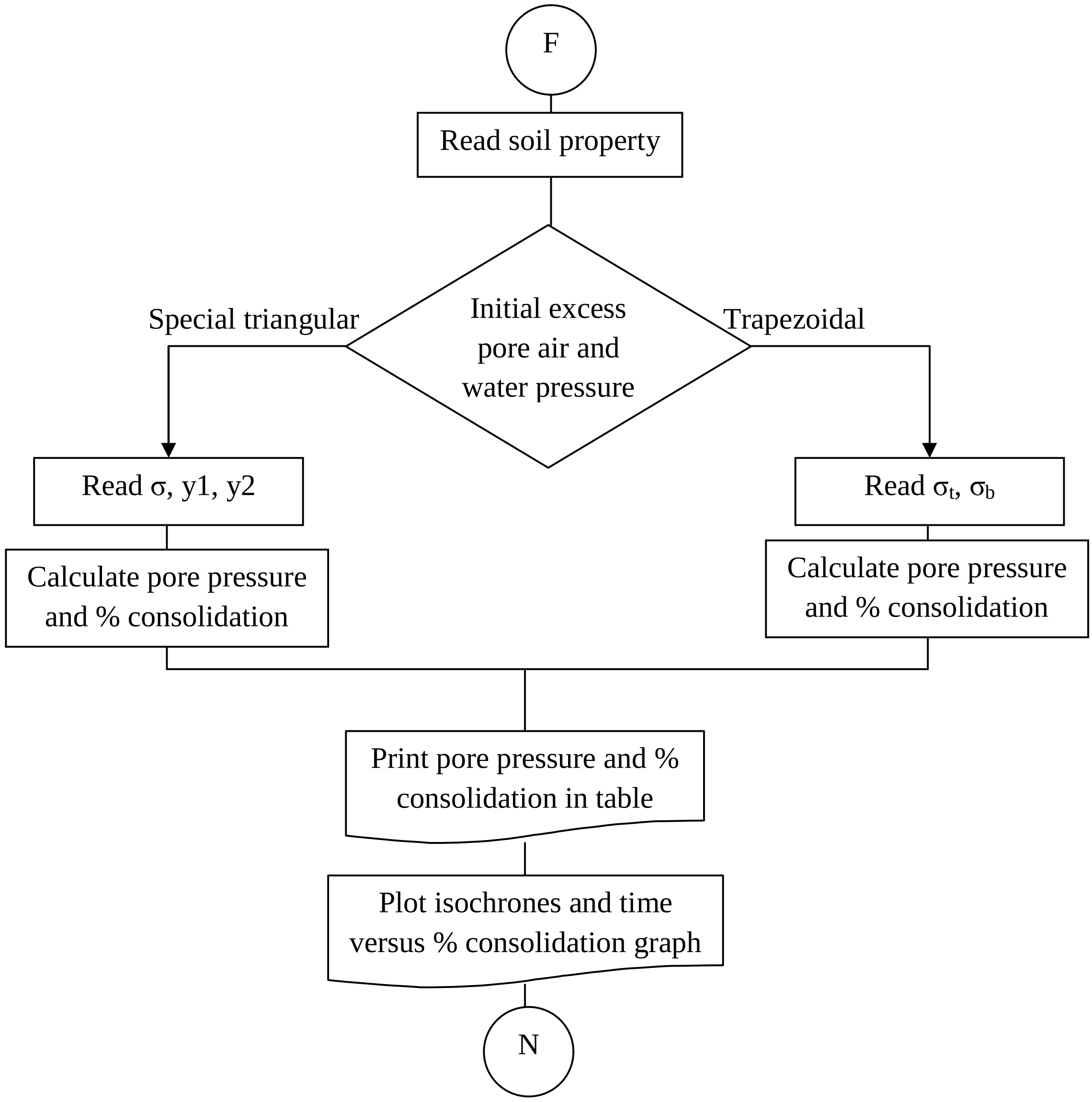

B
Method
cc method
mv method
Constant Es
Read Cc, H, γ, e
Read H, Es
Read H, mv
Read Load
Calculate pressure distribution
Primary settlement
For given time
Final
Read Cv, t
Calculate primary settlement for the given t
Calculate final primary settlement
Print primary settlement for the given t
Print final primary settlement
H

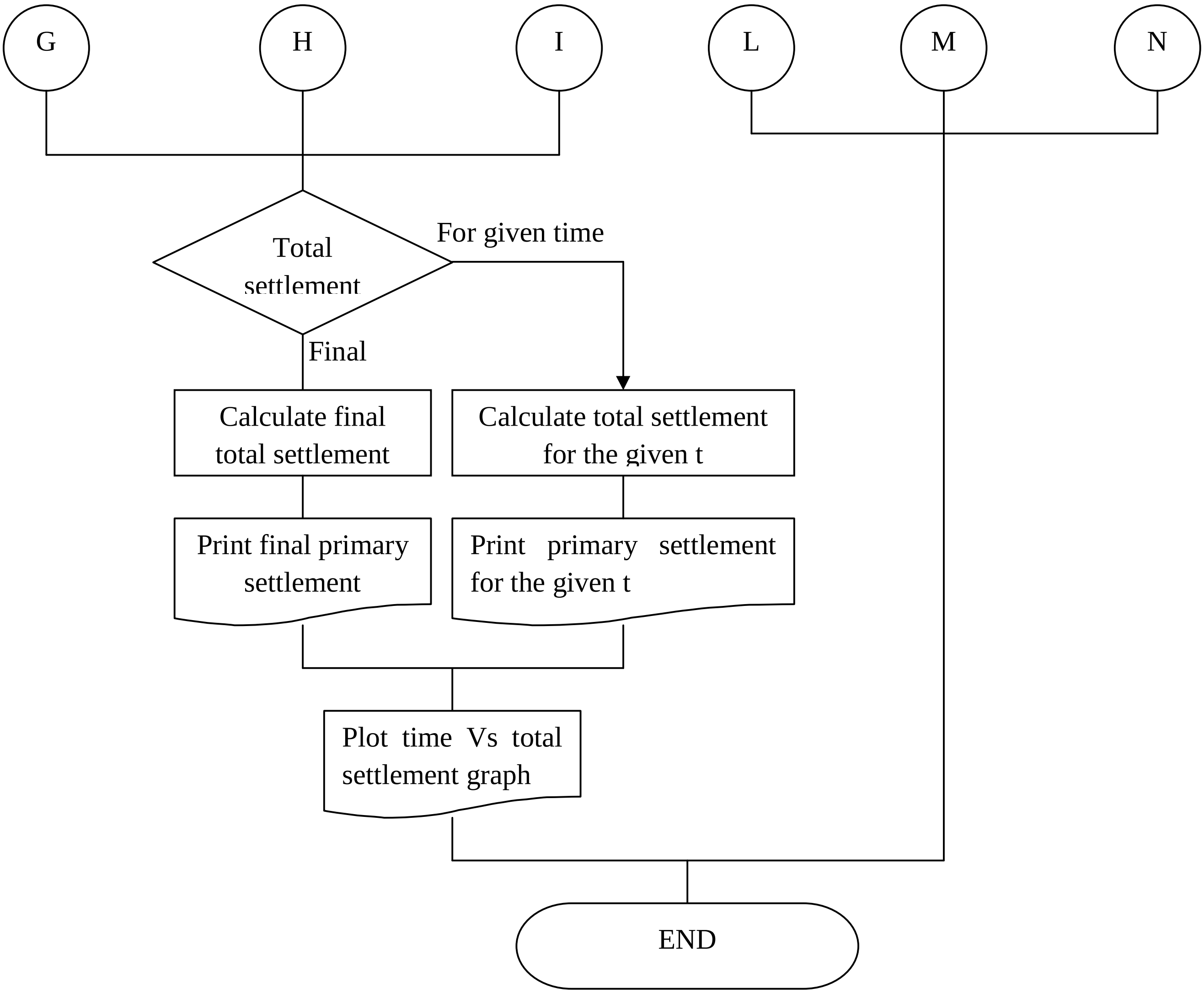

C
Method
Constant Es
Variable Es
Read β2
Read V2
Read t2
Read load
Calculate pressure distribution
Calculate secondary settlement
Print secondary settlement
I



D
Read Cv, H, Drainage
Initial excess pore water pressure
From contact pressure
Read load
Calculate pressure distribution
Approximate to trapezoidal shape
Given
Type
Special triangular
Trapezoidal
Read σ, y1, y2
Read σ_t, σ_b
Required
% consolidation
Pore pressure
Time for % consolidation
Read time
Read % consolidation
Read depth and time
Print % consolidation
Print time
Print pore water pressure
Isochrone
No
Yes
Read t
Print u
L


E
Read number of soil layers
Read Cv(i), dCv(i), H(i), dh(i), k(i) Drainage, scenario
Initial excess pore water pressure
From contact pressure
Given
Read load
Type
Special triangular
Trapezoidal
Calculate pressure distribution
Read σ, y1, y2
Read σt, σb
Calculate pore pressure and % consolidation
Calculate pore pressure and % consolidation
Calculate pore pressure and % consolidation
Print pore pressure and % consolidation in table
Plot isochrones and time versus % consolidation graph
M


F
Read soil property
Initial excess pore air and water pressure
Special triangular
Trapezoidal
Read σ, y1, y2
Read σ_t, σ_b
Calculate pore pressure and % consolidation
Calculate pore pressure and % consolidation
Print pore pressure and % consolidation in table
Plot isochrones and time versus % consolidation graph
N


G
H
I
L
M
N
Total settlement
For given time
Final
Calculate final total settlement
Calculate total settlement for the given t
Print final primary settlement
Print primary settlement for the given t
Plot time Vs total settlement graph
END

APPENDIX B

Example Problems

This chapter contains analysis of example problems by the common computation methods and by the developed software. Finally the results obtained from the two methods will be compared. Three example problems will be analyzed here; one on consolidation analysis for a saturated soil, one on consolidation analysis for an unsaturated soil and the other on settlement analysis.

5.1 Consolidation Analysis for a Saturated Soil

A 5 m thick saturated caly soil is given. It is required to calculate degree of consolidation for three years, time for 50% degree of consolidation and isochrone after two years all for single and double drainage cases. The analysis will be done by the two methods, i.e. by Fourier series method and by finite difference method. The coefficient of consolidation is 1.5m^2/sec.

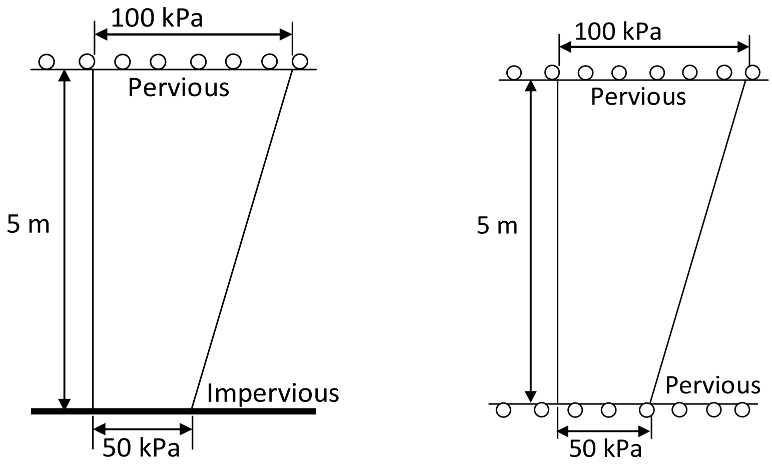


Figure B.1: Initial excess pore water pressure distributions

5.1.1 Result from common calculation methods

5.1.1.1 Fourier series method

A. Degree of consolidation for three years

Degree of consolidation for trapezoidal initial stress is calculated as:

- Single drainage case

$$\mu_{TRP} = \frac{2\mu_R q_o + \mu_T (q_u - q_o)}{q_u + q_o}$$

Where:

$$\mu_R = 1 - \frac{8}{\pi^2} \sum_{m=1,3,5}^{m=\infty} \frac{1}{m^2} e^{-m^2 Mt}$$

$$\mu_T = 1 - \frac{32}{\pi^3} \sum_{m=1,2,3}^{m=\infty} \frac{(-1)^{m+1}}{(2m-1)^3} e^{-(2m-1)^2 Mt}$$

The calculation is done using excel and given below:

Table B.1: Degree of consolidation for three years for single drainage case

Rectangular						
m=1	m=3	m=5	m=7	m=9	m=11	**μ_R**
0.51988	0.00165	4.9E-07	5.9E-12	2.4E-18	3.1E-26	47.8462
Triangular						
m=1	m=2	m=3	m=4	m=5	m=6	**μ_T**
0.66194	-0.0007	1.2E-07	-1E-12	3.4E-19	-4E-27	33.8766
Trapezoidal						
μ_{TRP}=52.5027						

- Double drainage case

$$\mu_{TRP} = \frac{2\mu_R q_o + \mu_T (q_u - q_o)}{q_u + q_o}$$

Where:

$$\mu_R = 1 - \frac{8}{\pi^2} \sum_{m=1,3,5}^{m=\infty} \frac{1}{(2m-1)^2} e^{-(2m-1)^2 Mt}$$

$$\mu_T = 1 - \frac{8}{\pi^2} \sum_{m=1,3,5}^{m=\infty} \frac{1}{m^2} e^{-m^2 Mt}$$

The calculation is done using excel and given below:

Table B.2: Degree of consolidation for three years for double drainage case

Rectangular						
m=1	m=3	m=5	m=7	m=9	m=11	**μ_R**
0.13717	1.7E-21	3.2E-65	2E-133	3E-226	0	86.2832
Triangular						
m=1	m=3	m=5	m=7	m=9	m=11	**μ_T**
0.13717	1E-08	1.7E-21	2.6E-40	3.2E-65	3E-96	86.2832
Trapezoidal						
μ_{TRP}=86.2832						

B. *Time for 50% degree of consolidation*

The time for the given degree of consolidation will be obtained by calculating degree of consolidation for different times until 50% consolidation is obtained. The calculation is done using excel and given below.

Table B.3: Time for 50% degree of consolidation for single drainage case

	Rectangular				Triangular				Trapezoidal
Time (yrs.)	m=1	m=3	m=5	μ_R	m=1	m=2	m=3	μ_T	μ_{TRP}
1	0.699	0.0238	1E-08	27.721	0.89	-0.01	0.0002	11.985	32.96606
2	0.6028	0.0063	4E-15	39.089	0.7676	-0.003	5E-06	23.51	44.28233
2.1	0.594	0.0055	1E-15	40.053	0.7563	-0.002	3E-06	24.605	45.20283
2.2	0.5853	0.0048	2E-16	40.995	0.7452	-0.002	2E-06	25.687	46.09713
2.3	0.5767	0.0042	5E-17	41.915	0.7342	-0.002	2E-06	26.757	46.96718
2.4	0.5682	0.0037	1E-17	42.814	0.7234	-0.002	1E-06	27.814	47.81473
2.5	0.5598	0.0032	3E-18	43.695	0.7128	-0.001	8E-07	28.857	48.64132
2.6	0.5516	0.0028	6E-19	44.558	0.7023	-0.001	5E-07	29.888	49.44831
2.61	0.5508	0.0028	5E-19	44.643	0.7013	-0.001	5E-07	29.99	49.52798
2.62	0.55	0.0027	5E-19	44.729	0.7002	-0.001	5E-07	30.092	49.60747
2.63	0.5492	0.0027	4E-19	44.814	0.6992	-0.001	5E-07	30.194	49.68677
2.64	0.5483	0.0027	3E-19	44.898	0.6982	-0.001	5E-07	30.296	49.7659
2.65	0.5475	0.0026	3E-19	44.983	0.6971	-0.001	5E-07	30.398	49.84485
2.66	0.5467	0.0026	3E-19	45.068	0.6961	-0.001	4E-07	30.5	49.92361
2.661	0.5466	0.0026	3E-19	45.076	0.696	-0.001	4E-07	30.51	49.93148
2.662	0.5466	0.0026	2E-19	45.084	0.6959	-0.001	4E-07	30.52	49.93935
2.663	0.5465	0.0026	2E-19	45.093	0.6958	-0.001	4E-07	30.53	49.94721
2.664	0.5464	0.0026	2E-19	45.101	0.6957	-0.001	4E-07	30.54	49.95507
2.665	0.5463	0.0026	2E-19	45.11	0.6956	-0.001	4E-07	30.55	49.96293
2.666	0.5462	0.0026	2E-19	45.118	0.6955	-0.001	4E-07	30.561	49.97079
2.667	0.5462	0.0026	2E-19	45.127	0.6954	-0.001	4E-07	30.571	49.97865
2.668	0.5461	0.0026	2E-19	45.135	0.6953	-0.001	4E-07	30.581	49.9865
2.669	0.546	0.0026	2E-19	45.144	0.6952	-0.001	4E-07	30.591	49.99435
2.6691	0.546	0.0026	2E-19	45.144	0.6952	-0.001	4E-07	30.592	49.99514
2.6692	0.546	0.0026	2E-19	45.145	0.6952	-0.001	4E-07	30.593	49.99593
2.6693	0.546	0.0026	2E-19	45.146	0.6951	-0.001	4E-07	30.594	49.99671
2.6694	0.546	0.0026	2E-19	45.147	0.6951	-0.001	4E-07	30.595	49.9975
2.6695	0.546	0.0026	2E-19	45.148	0.6951	-0.001	4E-07	30.596	49.99828
2.6696	0.5459	0.0026	2E-19	45.149	0.6951	-0.001	4E-07	30.597	49.99907
2.6697	0.5459	0.0026	2E-19	45.149	0.6951	-0.001	4E-07	30.598	49.99985
2.6698	0.5459	0.0026	2E-19	45.15	0.6951	-0.001	4E-07	30.599	50.00064
2.6699	0.5459	0.0026	2E-19	45.151	0.6951	-0.001	4E-07	30.6	50.00142
2.67	0.5459	0.0026	2E-19	45.152	0.6951	-0.001	4E-07	30.601	50.00221

Table B.4: Time for 50% degree of consolidation for double drainage case

	Rectangular				Triangular				Trapezoidal
Time (yrs.)	m=1	m=3	m=5	μ_R	m=1	m=3	m=5	μ_T	μ_{TRP}
0.1	0.764	0.0074	8E-05	22.858	0.764	0.0529	0.0074	17.58	24.616774
0.2	0.72	0.0017	7E-07	27.828	0.72	0.031	0.0017	24.727	28.862365
0.3	0.6786	0.0004	6E-09	32.098	0.6786	0.0182	0.0004	30.278	32.705051
0.4	0.6396	9E-05	5E-11	36.03	0.6396	0.0107	9E-05	34.961	36.385911
0.5	0.6028	2E-05	4E-13	39.714	0.6028	0.0063	2E-05	39.087	39.923186
0.6	0.5682	4E-06	3E-15	43.182	0.5682	0.0037	4E-06	42.814	43.304595
0.7	0.5355	1E-06	3E-17	46.449	0.5355	0.0022	1E-06	46.233	46.521192
0.8	0.5047	2E-07	2E-19	49.528	0.5047	0.0013	2E-07	49.402	49.570611
0.81	0.5017	2E-07	1E-19	49.826	0.5017	0.0012	2E-07	49.706	49.866419
0.811	0.5014	2E-07	1E-19	49.856	0.5014	0.0012	2E-07	49.737	49.89591
0.812	0.5011	2E-07	1E-19	49.886	0.5011	0.0012	2E-07	49.767	49.925383
0.813	0.5008	2E-07	1E-19	49.915	0.5008	0.0012	2E-07	49.797	49.954841
0.814	0.5005	2E-07	1E-19	49.945	0.5005	0.0012	2E-07	49.827	49.984282
0.8141	0.5005	2E-07	1E-19	49.948	0.5005	0.0012	2E-07	49.83	49.987225
0.8142	0.5005	2E-07	1E-19	49.951	0.5005	0.0012	2E-07	49.834	49.990168
0.8143	0.5005	2E-07	1E-19	49.954	0.5005	0.0012	2E-07	49.837	49.993111
0.8144	0.5004	2E-07	1E-19	49.957	0.5004	0.0012	2E-07	49.84	49.996053
0.8145	0.5004	2E-07	1E-19	49.96	0.5004	0.0012	2E-07	49.843	49.998996
0.8146	0.5004	2E-07	1E-19	49.963	0.5004	0.0012	2E-07	49.846	50.001938
0.8147	0.5003	2E-07	1E-19	49.966	0.5003	0.0012	2E-07	49.849	50.004881
0.8148	0.5003	2E-07	1E-19	49.969	0.5003	0.0012	2E-07	49.852	50.007823

As it can be seen from Table B.3 and Table B.4, the time to attain 50% degree of consolidation is 2.6697 years for single drainage case and 0.8145 years for double drainage case.

C. *Isochrone after two years*

The isochrones for the given time for single drainage and double drainage cases will be plotted by first calculating pore water pressure at different depths for the given time. The calculation is done by using excel and given in Table B.5 and Table B.6. And the isochrones are given in Figure B.2 and Figure B.3.

- Single drainage case

Pore water pressure will be calculated as:

$$u(z,t) = u_R(z,t) + u_T(z,t)$$

Where:

$$u_R(z,t) = \frac{4}{\pi} q_o \sum_{m=1,3,5}^{m=\infty} \frac{1}{m} e^{-m^2 Mt} \sin\frac{m\pi z}{2h}$$

$$u_T(z,t) = \frac{8}{\pi^2}(q_u - q_o) \sum_{m=1,2,3}^{m=\infty} \frac{(-1)^{m+1}}{(2m-1)^2} e^{-(2m-1)^2 Mt} \sin\frac{(2m-1)\pi z}{2h}$$

Table B.5: Pore water pressure at different depths for single drainage case

	Rectangular				Triangular				Trapezoidal
Depth (m)	m=1	m=3	m=5	m=7	m=1	m=2	m=3	m=4	**u(z,t)**
0	0	0	0	0	0	0	0	0	0
0.5	14.813	1.3413	0.011	8E-06	-4.715	0.1423	-7E-04	4E-07	11.59203
1	29.262	2.3902	0.0155	7E-06	-9.314	0.2536	-1E-03	3E-07	22.60597
1.5	42.99	2.9181	0.011	-1E-06	-13.68	0.3096	-7E-04	-6E-08	32.54389
2	55.66	2.8099	2E-18	-9E-06	-17.72	0.2981	-1E-19	-4E-07	41.05056
2.5	66.958	2.0891	-0.011	-6E-06	-21.31	0.2217	0.0007	-3E-07	47.94547
3	76.609	0.913	-0.016	3E-06	-24.39	0.0969	0.001	1E-07	53.21874
3.5	84.373	-0.462	-0.011	9E-06	-26.86	-0.049	0.0007	4E-07	56.99449
4	90.059	-1.737	-4E-18	5E-06	-28.67	-0.184	2E-19	2E-07	59.47145
4.5	93.528	-2.632	0.011	-4E-06	-29.77	-0.279	-7E-04	-2E-07	60.85545
5	94.694	-2.954	0.0155	-9E-06	-30.14	-0.313	-1E-03	-4E-07	61.29825

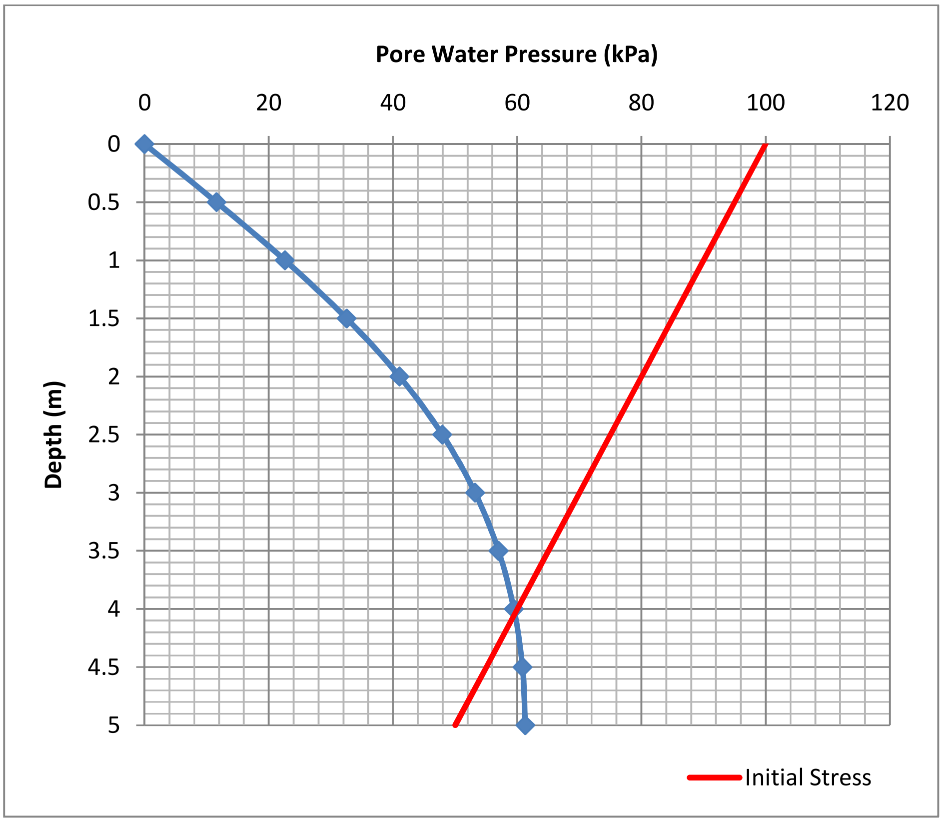


Figure B.2: Isochrone after two years for single drainage case

- <u>Double drainage case</u>

Pore water pressure will be calculated as:

$$u(z,t) = u_R(z,t) + u_T(z,t)$$

Where:

$$u_R(z,t) = \frac{4}{\pi} q_o \sum_{m=1,2,3}^{m=\infty} \frac{1}{2m-1}\; e^{-(2m-1)^2 Mt}\; sin \frac{(2m-1)\pi z}{2h}$$

$$u_T(z,t) = \frac{2}{\pi}(q_u - q_o) \sum_{m=1,2,3}^{m=\infty} \frac{(-1)^{m+1}}{m}\; e^{-m^2 Mt}\; sin \frac{m\pi z}{2h}$$

Table B.6: Pore water pressure at different depths for double drainage case

	Rectangular				Triangular				Trapezoidal
Depth (m)	m=1	m=2	m=3	m=4	m=1	m=2	m=3	m=4	**u(z,t)**
0	0	0	0	0	0	0	0	0	0
0.5	12.037	0.0008	4E-12	9E-25	-3.009	0.082	-2E-04	4E-19	9.110658
1	22.897	0.0009	4E-28	-1E-24	-5.724	0.1326	-2E-04	5E-35	17.30578
1.5	31.514	0.0003	-4E-12	4E-25	-7.879	0.1326	-8E-05	-4E-19	23.7687
2	37.047	-6E-04	-9E-28	7E-25	-9.262	0.082	0.0001	-1E-34	27.86713
2.5	38.954	-1E-03	4E-12	-1E-24	-9.739	2E-17	0.0002	4E-19	29.21477
3	37.047	-6E-04	1E-27	7E-25	-9.262	-0.082	0.0001	2E-34	27.70321
3.5	31.514	0.0003	-4E-12	4E-25	-7.879	-0.133	-8E-05	-4E-19	23.50347
4	22.897	0.0009	-2E-27	-1E-24	-5.724	-0.133	-2E-04	-2E-34	17.04055
4.5	12.037	0.0008	4E-12	9E-25	-3.009	-0.082	-2E-04	4E-19	8.946736
5	5E-15	4E-19	2E-27	1E-39	-1E-15	-3E-17	-9E-20	3E-34	3.55E-15

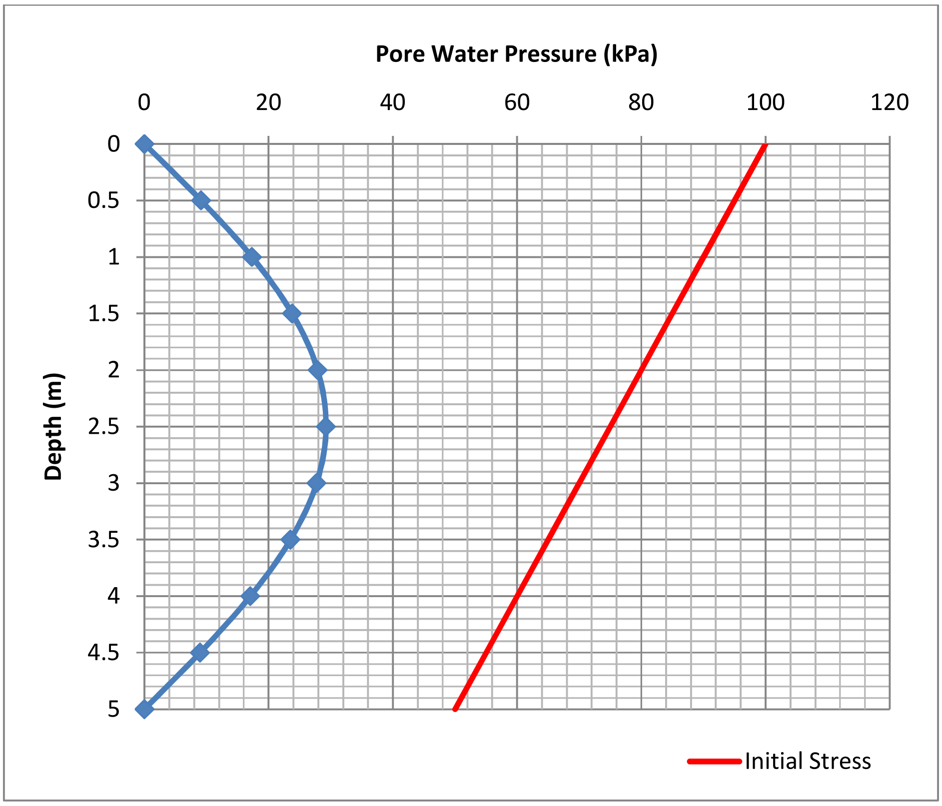


Figure B.3: Isochrone after two years for double drainage case

B.1.1.2 Finite difference method

By this method, all the required values will be calculated from the finite difference calculation tables for single drainage and double drainage cases (Table B.7 and Table B.8). A depth step of 1m and a time step of 0.2 year are taken. For these values the value of beta will be:

$$\beta = \frac{c_v \Delta t}{\Delta z^2} = \frac{1.5 * 0.2}{(1)^2} = 0.3$$

The value of beta is less than 0.5. So, the depth step and time step values taken fulfill the stability requirement.

Table B.7: Finite difference calculation table for single drainage case

Time	0	0.2	0.4	0.6	0.8	1	1.2	1.4
Depth=0 m	0	0	0	0	0	0	0	0
Depth=1 m	90	60	48	40.5	35.34	31.543	28.633	26.336
Depth=2 m	80	80	71	63.8	58.022	53.385	49.609	46.490
Depth=3 m	70	70	70	67.84	65.248	62.640	60.188	57.923
Depth=4 m	60	60	61.8	63.24	63.78	63.722	63.216	62.387
Depth=5 m	50	56	58.4	60.44	62.12	63.116	63.480	63.321
Consolidation (%)	0	20.533	25.333	29.173	32.413	35.240	37.764	40.054

… continued

1.6	1.8	2	2.2	2.4	2.6	2.8	3	3.2	3.4	3.6
0	0	0	0	0	0	0	0	0	0	0
24.481	22.954	21.675	20.583	19.637	18.803	18.057	17.381	16.761	16.187	15.649
43.873	41.643	39.712	38.012	36.494	35.120	33.861	32.696	31.607	30.582	29.611
55.832	53.893	52.083	50.381	48.772	47.241	45.780	44.380	43.035	41.740	40.490
61.328	60.109	58.782	57.385	55.948	54.492	53.032	51.581	50.146	48.733	47.347
62.761	61.901	60.826	59.599	58.271	56.877	55.446	53.998	52.548	51.107	49.683
42.161	44.12	45.956	47.69	49.337	50.908	52.412	53.857	55.247	56.588	57.883

Table B.8: Finite difference calculation table for double drainage case

Time (yrs.)	0	0.2	0.4	0.6	0.8	1	1.2	1.4
Depth=0 m	0	0	0	0	0	0	0	0
Depth=1 m	90	60	48	40.5	34.935	30.441	26.676	23.460
Depth=2 m	80	80	71	62.45	54.89	48.334	42.632	37.650
Depth=3 m	70	70	65.5	59.2	52.99	47.221	41.981	37.269
Depth=4 m	60	45	39	35.25	31.86	28.641	25.623	22.843
Depth=5 m	0	0	0	0	0	0	0	0
Consolidation (%)	0	32	40.4	47.36	53.42	58.764	63.49	67.674

… continued

1.6	1.8	2	2.2	2.4	2.6	2.8	3
0	0	0	0	0	0	0	0
20.679	18.255	16.132	14.265	12.619	11.167	9.883	8.749
33.279	29.432	26.040	23.044	20.397	18.056	15.984	14.151
33.055	29.301	25.963	23.000	20.371	18.040	15.975	14.146
20.318	18.044	16.008	14.192	12.577	11.142	9.869	8.740
0	0	0	0	0	0	0	0
71.37837	74.65813	77.56205	80.13321	82.40974	84.42541	86.2101	87.79028

A. *Degree of consolidation for three years*

- Single drainage case

The degree of consolidation for three years can be taken from Table B.7. The value is **46.758 %**.

- Double drainage case

The degree of consolidation for three years can be taken from Table B.8. The value is **84.738 %**.

B. *Time for 50% degree of consolidation*

- Single drainage case

From Table B.7, it can be seen that the degree of consolidation is approximately 50% at **3.4** years. So, this time will be taken as the time for 50% degree of consolidation.

- Double drainage case

From Table B.8, it can be seen that the degree of consolidation is approximately 50% at **1** year. So, this time will be taken as the time for 50% degree of consolidation.

C. *Isochrone after two years*

- Single drainage case

Using the pore water pressure for two years in Table B.7 the isochrone is plotted and given in Figure B.4.

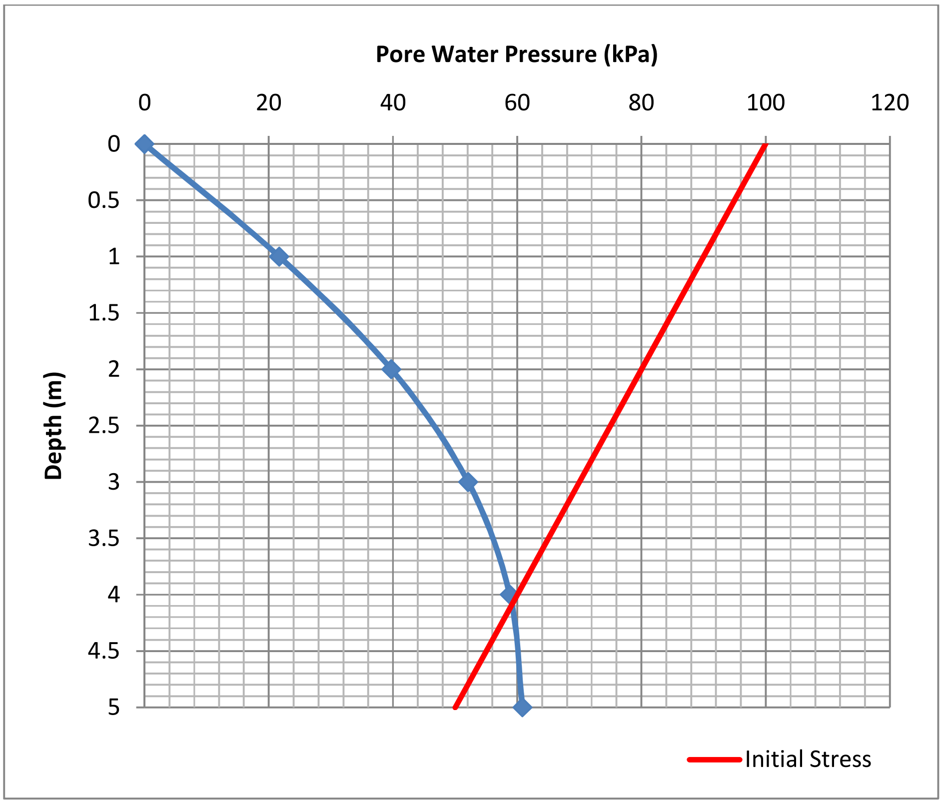


Figure B.4: Isochrone after two years for single drainage case

- Double drainage case

Using the pore water pressure for two years in Table B.8 the isochrone is plotted and given in Figure B.5.

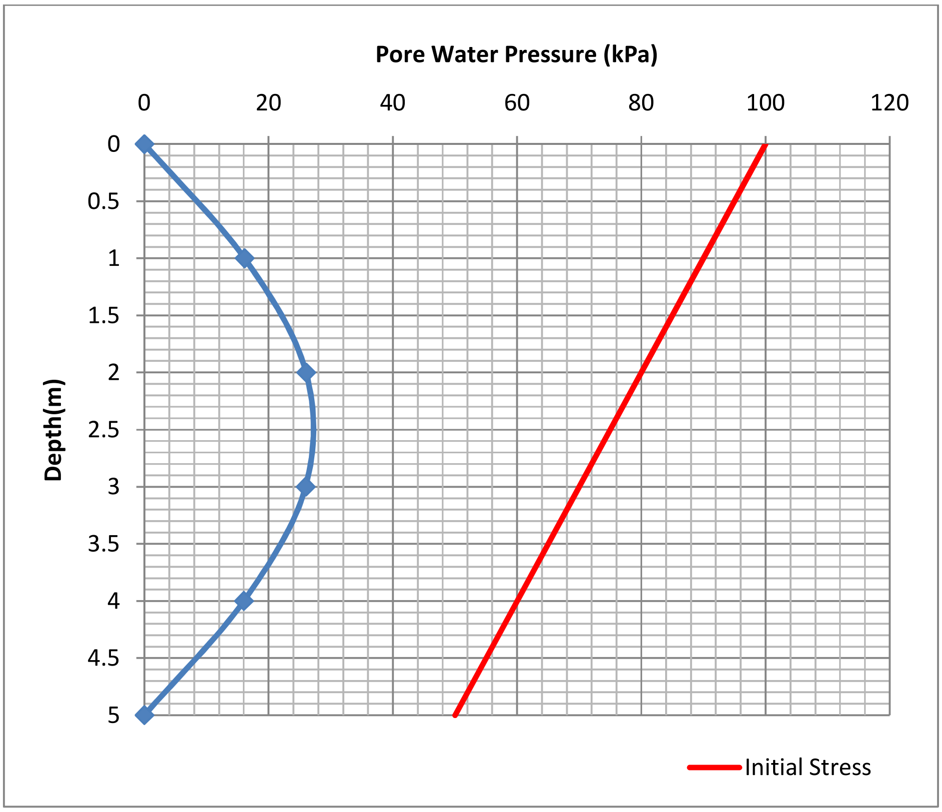


Figure B.5: Isochrone after two years for double drainage case

B.1.2 Result from the developed software

The required results in the above example problem are calculated using the developed software by inputting the given values to the software.

B.1.2.1 Fourier series method

A. *Degree of consolidation for three years*

- Single drainage case

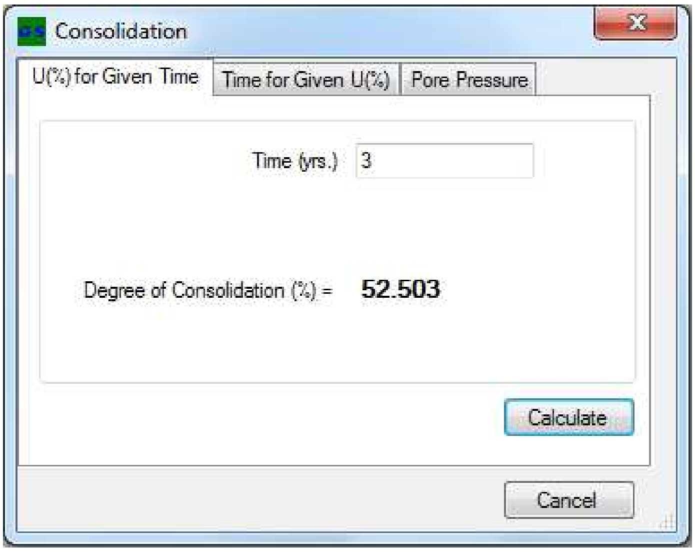


Figure B.6: Degree of consolidation for three years for single drainage case

- Double drainage case

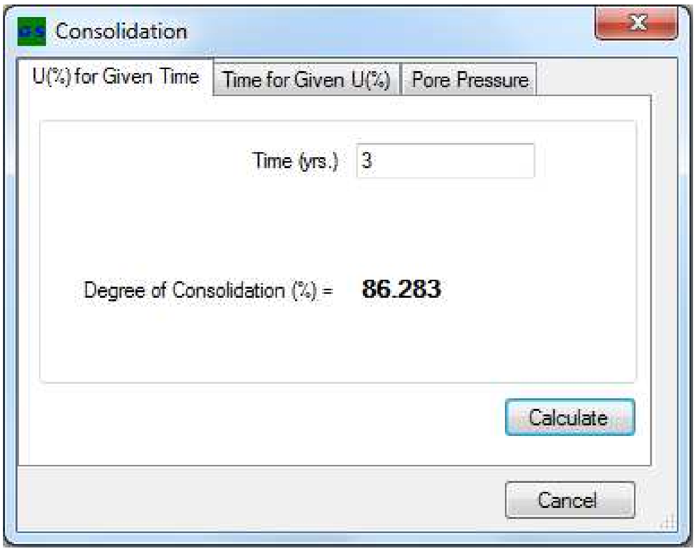


Figure B.7: Degree of consolidation for three years for double drainage case

B. *Time for 50% degree of consolidation*

- Single drainage case

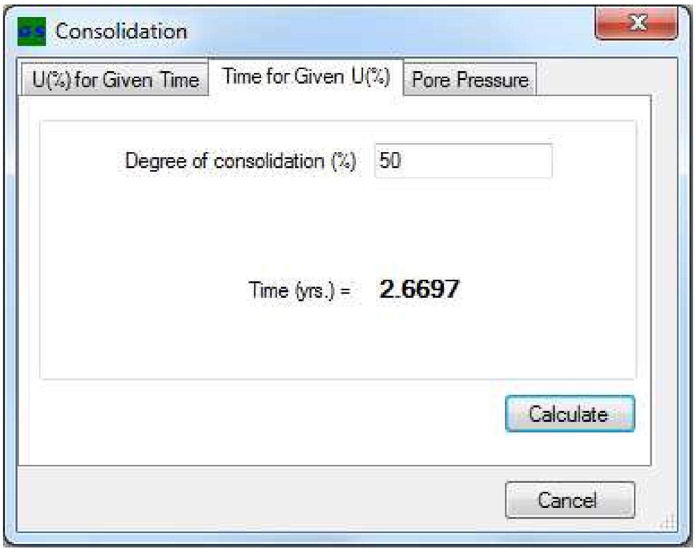


Figure B.8: Time for 50% degree of consolidation for single drainage case

- Double drainage case

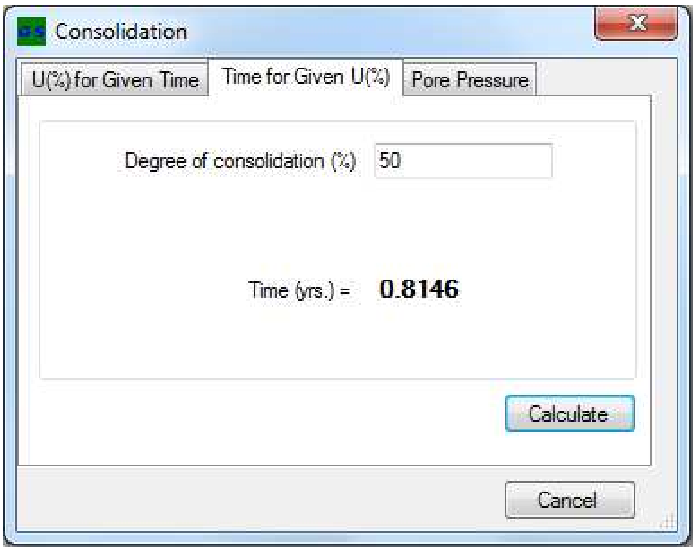


Figure B.9: Time for 50% degree of consolidation for double drainage case

C. Isochrone after two years

- Single drainage case

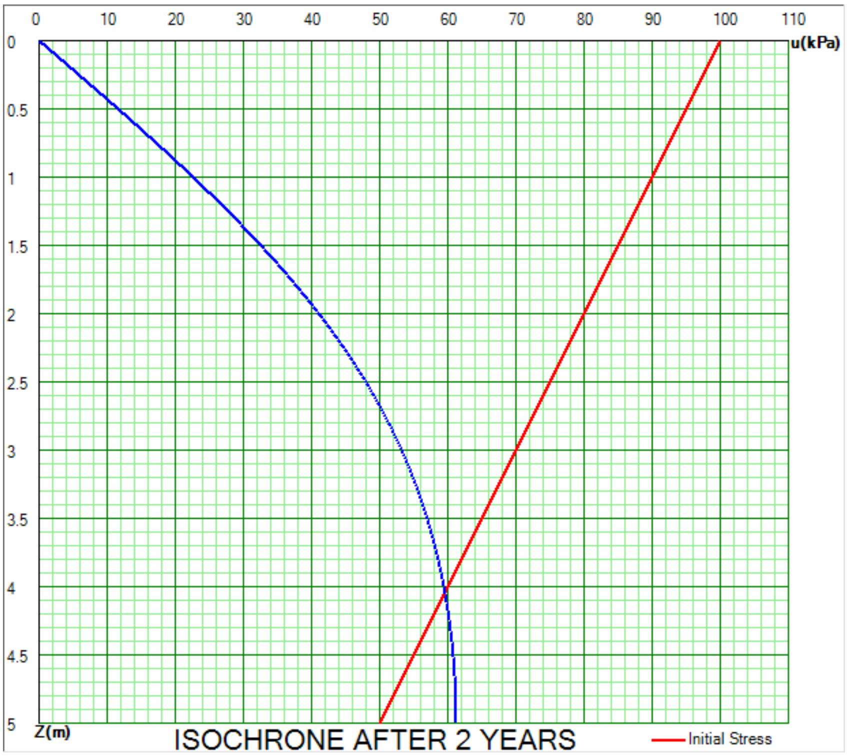


Figure B.10: Isochrone after two years for single drainage case

- <u>Double drainage case</u>

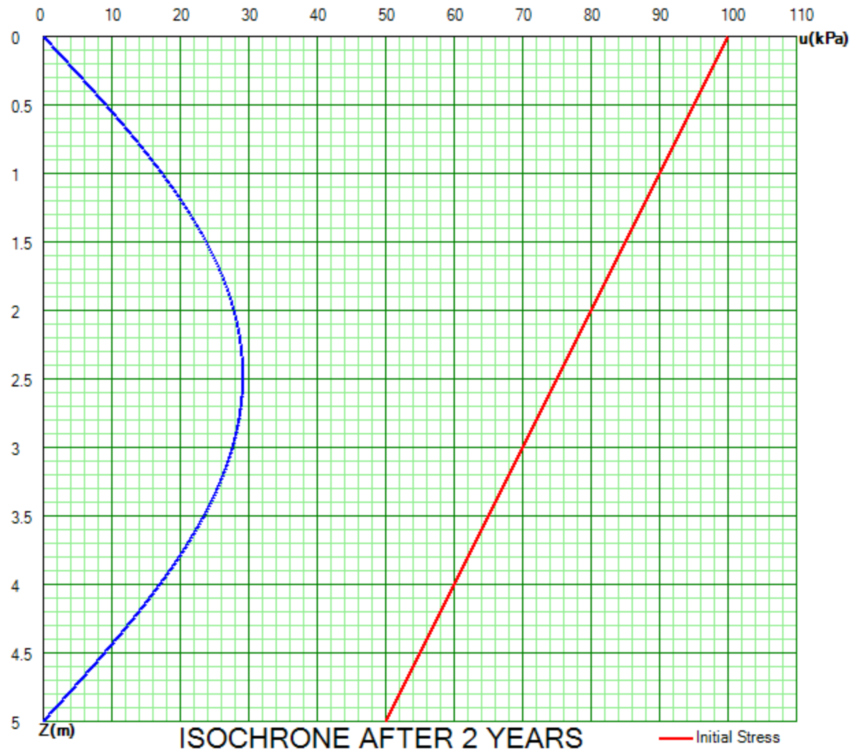


Figure B.11: Isochrone after two years for double drainage case

B.1.2.2 Finite difference method

Here also, the required values will be calculated from the finite difference calculation tables for single drainage and double drainage cases (Table B.9 and Table B.10). As in the case of manual calculation, a depth step of 1m and a time step of 0.2 year are taken. The stability is checked in the manual calculation case.

Table B.9: Finite difference calculation table for single drainage case

Time (yrs.)	0	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
Depth= 0 m	0	0	0	0	0	0	0	0	0
Depth= 1 m	90	60	48	40.5	35.34	31.543	28.633	26.336	24.481
Depth= 2 m	80	80	71	63.8	58.022	53.385	49.609	46.49	43.873
Depth= 3 m	70	70	70	67.84	65.248	62.64	60.188	57.923	55.832
Depth= 4 m	60	60	61.8	63.24	63.78	63.722	63.216	62.387	61.328
Depth= 5 m	50	56	58.4	60.44	62.12	63.116	63.48	63.321	62.761
Consolidation (%)	0	20.533	25.333	29.173	32.413	35.241	37.764	40.055	42.161

… continued

1.8	2	2.2	2.4	2.6	2.8	3	3.2	3.4	3.6
0	0	0	0	0	0	0	0	0	0
22.954	21.675	20.583	19.637	18.803	18.057	17.381	16.761	16.187	15.649
41.643	39.712	38.012	36.494	35.12	33.861	32.696	31.607	30.582	29.611
53.893	52.083	50.381	48.772	47.241	45.78	44.38	43.035	41.74	40.49
60.109	58.782	57.385	55.948	54.492	53.032	51.581	50.146	48.733	47.347
61.901	60.826	59.599	58.271	56.877	55.446	53.998	52.548	51.107	49.683
44.12	45.956	47.69	49.337	50.908	52.412	53.857	55.247	56.588	57.883

Table B.10: Finite difference calculation table for double drainage case

Time (yrs.)	0	0.2	0.4	0.6	0.8	1	1.2	1.4
Depth= 0 m	0	0	0	0	0	0	0	0
Depth= 1 m	90	60	48	40.5	34.935	30.441	26.676	23.46
Depth= 2 m	80	80	71	62.45	54.89	48.334	42.632	37.65
Depth= 3 m	70	70	65.5	59.2	52.99	47.221	41.981	37.269
Depth= 4 m	60	45	39	35.25	31.86	28.641	25.623	22.843
Depth= 5 m	0	0	0	0	0	0	0	0
Consolidation (%)	0	32	40.4	47.36	53.42	58.764	63.49	67.674

… continued

1.6	1.8	2	2.2	2.4	2.6	2.8	3
0	0	0	0	0	0	0	0
20.679	18.255	16.132	14.265	12.619	11.167	9.883	8.749
33.279	29.432	26.04	23.044	20.397	18.056	15.984	14.151
33.055	29.301	25.963	23	20.371	18.04	15.975	14.146
20.318	18.044	16.008	14.192	12.577	11.142	9.869	8.74
0	0	0	0	0	0	0	0
71.378	74.658	77.562	80.133	82.41	84.425	86.21	87.79

A. Degree of consolidation for three years

- Single drainage case

From the finite difference table for single drainage case (Table B.9), degree of consolidation for three years is **46.758 %**.

- Double drainage case

From the finite difference table for double drainage case (Table B.10), degree of consolidation for three years is **84.738 %**.

B. Time for 50% degree of consolidation

- Single drainage case

From Table B.9, the time for approximately 50% degree of consolidation is **3.4** years.

- Double drainage case

From Table B.10, the time for approximately 50% degree of consolidation is **1** year.

C. Isochrone after two years

- Single drainage case

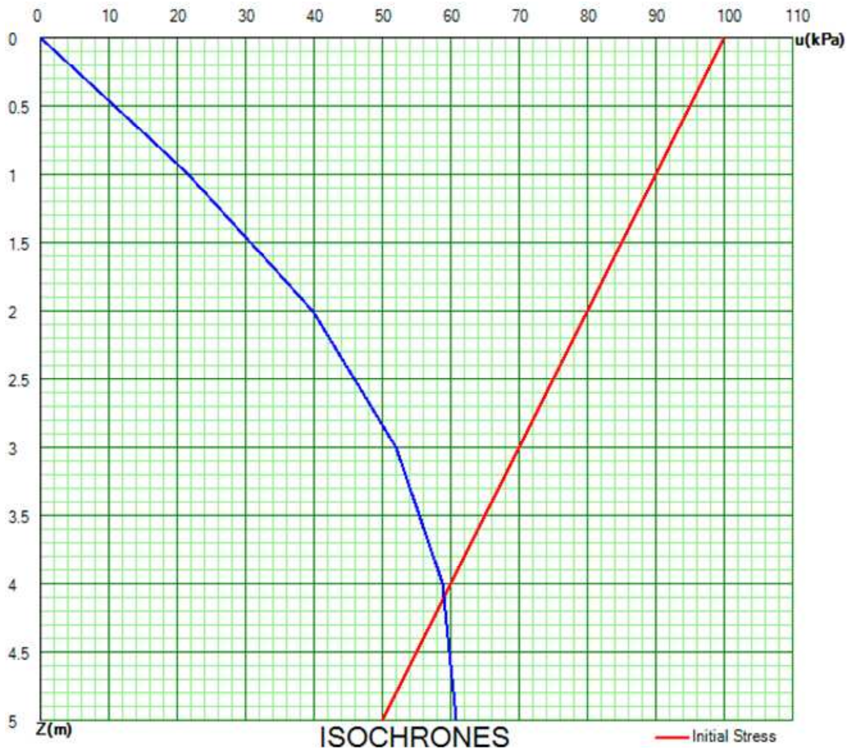


Figure B.12: Isochrone after two years for single drainage case

- <u>Double drainage case</u>

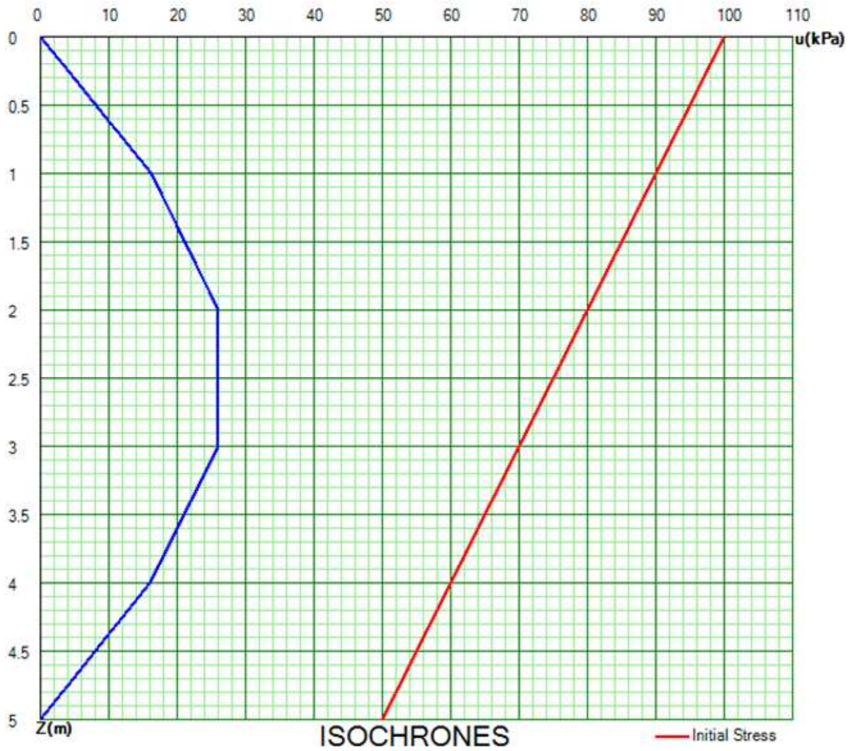


Figure B.13: Isochrone after two years for double drainage case

B.2 Consolidation Analysis for an Unsaturated soil

This section contains an example problem on consolidation analysis for an unsaturated soil. The required results are degree of consolidation and isochrone for one year.

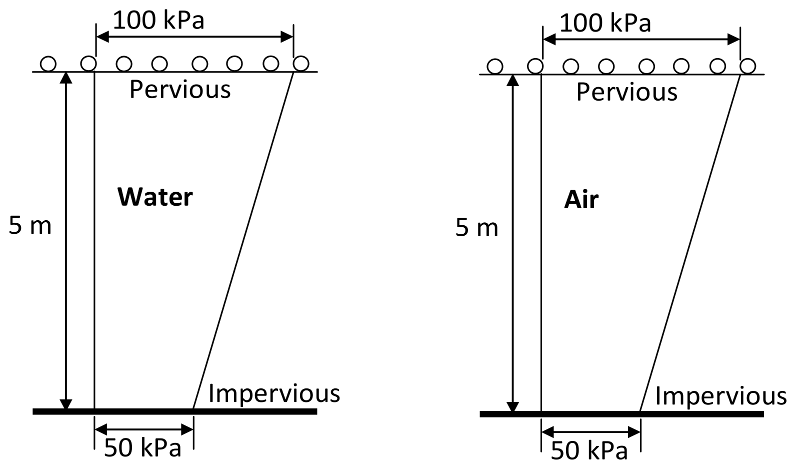


Figure B.14: Initial excess pore water pressure distributions

- Degree of saturation = 80 %
- Porosity = 0.4
- Temperature = 20 ^{0}c
- Coefficient of permeability with respect to the water phase = 0.005 m/yr
- Coefficient of water volume change with respect to change in net normal stress = 0.00015
- Coefficient of water volume change with respect to change in matric suction = 0.0001
- Coefficient of transmission = 0.2 * 10^{-20} year
- Coefficient of air volume change with respect to change in net normal stress = 0.001
- Coefficient of air volume change with respect to change in matric suction = 0.0001

The density of water is taken as 1000 kg/m^3 and the molecular mass of air is taken as 28.97 kg/kmol.

B.2.1 Result from common calculation methods

B.2.1.1 Degree of consolidation for one year

The required values will be calculated from the finite difference calculation tables for the water phase and air phases (Table B.11 and Table B.12). A depth step of 1.25m and a time step of 0.05 year are taken. For these values the value of beta will be:

$$c_v^w = k_w/\rho_w g m_2^w$$

$$= 0.005/1 * 9.81 * 0.0001 = 5.1\ m^2/yr$$

$$c_v^a = \frac{D_a^*}{(\omega_a/RT)} \frac{1}{\bar{u}_a m_{1k}^a (1 - m_2^a/m_{1k}^a) - (1 - S)n}$$

$$= \frac{0.2 * 10^{-20}}{(0.02897/((8.31432 * (3600 * 24 * 365.25)^2) * (20 + 273.16)))}$$

$$* \frac{1}{101 * 0.001 * (1 - 0.0001/0.001) - (1 - 0.8) * 0.4}$$

$$= 15.37\ m^2/yr$$

$$\beta_w = c_v^w \frac{\Delta t}{\Delta y^2} = \frac{5 * 0.05}{(1.25)^2} = 0.163$$

$$\beta_a = c_v^a \frac{\Delta t}{\Delta y^2} = \frac{15.37 * 0.05}{(1.25)^2} = 0.492$$

The value of beta is less than 0.5. So, the depth step and time step values taken fulfills the stability requirement. Here the c_v^a is for a gauge pore air pressure value of zero. Consequently, the calculated β_a value is the maximum for non-negative gauge pore air pressure values and so for gauge pressure values greater than zero, the value of β_a will be less than the calculated value.

Table B.11: Finite difference calculation table for water phase

Time (yrs.)	0	0.05	0.1	0.15	0.2	0.25	0.3
Depth=0 m	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Depth=1.25 m	87.500	72.616	63.044	56.320	51.297	47.372	44.199
Depth=2.5 m	75.000	75.000	72.375	69.233	66.208	63.473	61.048
Depth=3.75 m	62.500	62.500	63.050	63.243	63.068	62.631	62.018
Depth=5 m	50.000	53.328	55.591	57.388	58.708	59.561	60.009
Consolidation (%)	0.000	21.073	24.578	27.503	30.024	32.248	34.243

… continued

0.35	0.4	0.45	0.5	0.55	0.6	0.65
0.000	0.000	0.000	0.000	0.000	0.000	0.000
41.562	39.322	37.381	35.670	34.142	32.760	31.498
58.900	56.986	55.262	53.691	52.242	50.892	49.621
61.293	60.497	59.658	58.796	57.922	57.045	56.171
60.131	60.004	59.690	59.242	58.698	58.088	57.432
36.059	37.731	39.285	40.741	42.115	43.420	44.665

… continued

0.7	0.75	0.8	0.85	0.9	0.95	1
0.000	0.000	0.000	0.000	0.000	0.000	0.000
30.337	29.263	28.264	27.331	26.459	25.641	24.872
48.416	47.266	46.163	45.101	44.077	43.087	42.131
55.303	54.442	53.591	52.750	51.918	51.096	50.284
56.748	56.044	55.330	54.609	53.886	53.163	52.441
45.857	47.002	48.106	49.171	50.201	51.198	52.164

Table B.12: Finite difference calculation table for air phase

Time (yrs.)	0	0.05	0.1	0.15	0.2	0.25	0.3
Depth=0 m	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Depth=1.25 m	87.500	84.648	80.882	76.809	72.697	68.678	64.824
Depth=2.5 m	75.000	75.000	75.394	75.593	75.477	75.058	74.382
Depth=3.75 m	62.500	62.500	62.486	62.709	63.102	63.579	64.077
Depth=5 m	50.000	51.499	52.957	54.230	55.410	56.548	57.654
Consolidation (%)	0.000	17.367	18.253	19.258	20.340	21.470	22.630

… continued

0.35	0.4	0.45	0.5	0.55	0.6	0.65
0.000	0.000	0.000	0.000	0.000	0.000	0.000
61.175	57.754	54.572	51.632	48.932	46.463	44.216
73.497	72.451	71.282	70.026	68.710	67.359	65.993
64.555	64.988	65.359	65.661	65.889	66.043	66.124
58.720	59.734	60.683	61.559	62.356	63.070	63.700
23.804	24.980	26.148	27.300	28.430	29.533	30.606

… continued

0.7	0.75	0.8	0.85	0.9	0.95	1
0.000	0.000	0.000	0.000	0.000	0.000	0.000
42.174	40.325	38.650	37.133	35.759	34.511	33.376
64.628	63.277	61.952	60.660	59.406	58.196	57.031
66.136	66.081	65.965	65.793	65.568	65.296	64.982
64.247	64.711	65.095	65.401	65.634	65.796	65.891
31.646	32.654	33.629	34.571	35.483	36.366	37.222

The degree of consolidation for one year for the water phase can be taken from Table B.11 which is **42.597%**. And the degree of consolidation for one year for the air phase can be taken from Table B.12 which is **24.666%**.

B.2.1.2 Isochrone after one year

Using the pore water pressure and pore air pressure values for one year in Table B.11 and Table B.12 the isochrones for the water phase and the air phase are plotted and given in Figure B.15 and Figure B.16 respectively.

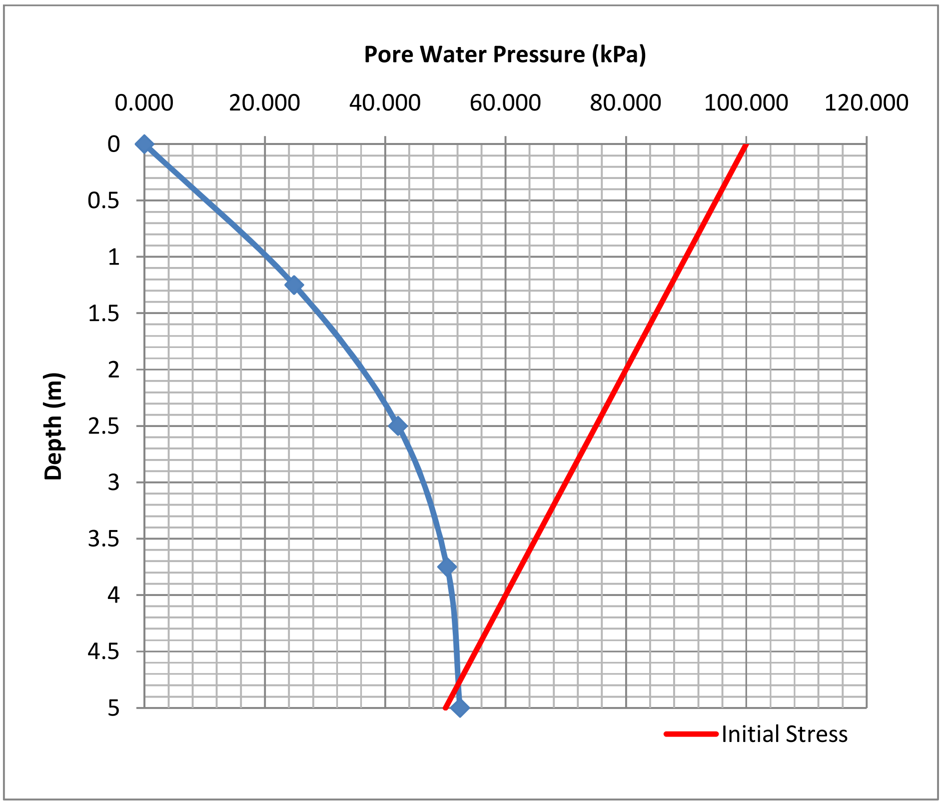


Figure B.15: Isochrone after one year for water phase

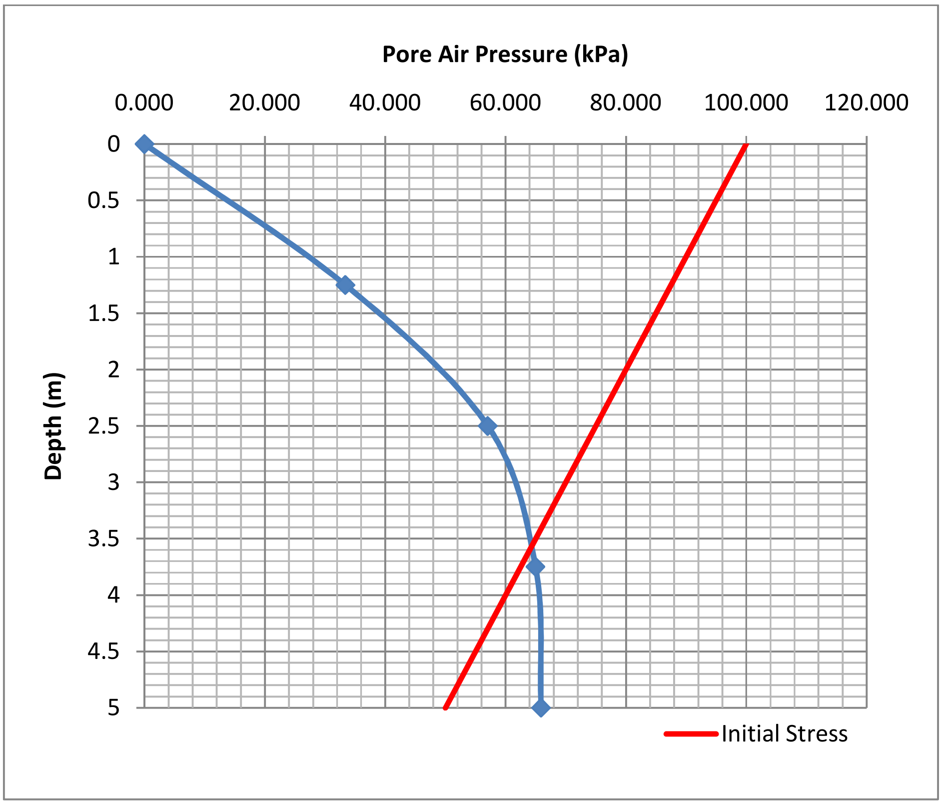


Figure B.16: Isochrone after one year for air phase

B.2.2 Result from the developed software

B.2.2.1 Degree of consolidation for one year

The degree of consolidation for one year is taken from the finite difference calculation tables given in Table B.13 and Table B.14 which are obtained from the software. The stability is checked in the case of calculation by common methods.

Table B.13: Finite difference calculation table for water phase

Time (yrs.)	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
Depth= 0 m	0	0	0	0	0	0	0	0	0	0	0
Depth= 1.25 m	87.5	72.616	63.044	56.32	51.297	47.372	44.199	41.562	39.322	37.381	35.67
Depth= 2.5 m	75	75	72.375	69.233	66.208	63.473	61.048	58.9	56.986	55.262	53.691
Depth= 3.75 m	62.5	62.5	63.05	63.243	63.068	62.631	62.018	61.293	60.497	59.658	58.796
Depth= 5 m	50	53.328	55.591	57.388	58.708	59.561	60.009	60.131	60.004	59.69	59.242
Consolidation (%)	0	21.073	24.578	27.503	30.024	32.248	34.243	36.059	37.731	39.285	40.741

… continued

0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1
0	0	0	0	0	0	0	0	0	0
34.142	32.76	31.498	30.337	29.263	28.264	27.331	26.459	25.641	24.872
52.242	50.892	49.621	48.416	47.266	46.163	45.101	44.077	43.087	42.131
57.922	57.045	56.171	55.303	54.442	53.591	52.75	51.918	51.096	50.284
58.698	58.088	57.432	56.748	56.044	55.33	54.609	53.886	53.163	52.441
42.115	43.42	44.665	45.857	47.002	48.106	49.171	50.201	51.198	52.164

Table B.14: Finite difference calculation table for air phase

Time (yrs.)	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
Depth= 0 m	0	0	0	0	0	0	0	0	0	0	0
Depth= 1.25 m	87.5	84.648	80.882	76.809	72.697	68.678	64.824	61.175	57.754	54.572	51.632
Depth= 2.5 m	75	75	75.394	75.593	75.477	75.058	74.382	73.497	72.451	71.282	70.026
Depth= 3.75 m	62.5	62.5	62.486	62.709	63.102	63.579	64.077	64.555	64.988	65.359	65.661
Depth= 5 m	50	51.499	52.957	54.23	55.41	56.548	57.654	58.72	59.734	60.683	61.559
Consolidation (%)	0	17.367	18.253	19.258	20.34	21.47	22.63	23.804	24.98	26.148	27.3

… continued

0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1
0	0	0	0	0	0	0	0	0	0
48.932	46.463	44.216	42.174	40.325	38.65	37.133	35.759	34.511	33.376
68.71	67.359	65.993	64.628	63.277	61.952	60.66	59.406	58.196	57.031
65.889	66.043	66.124	66.136	66.081	65.965	65.793	65.568	65.296	64.982
62.356	63.07	63.7	64.247	64.711	65.095	65.401	65.634	65.796	65.891
28.43	29.533	30.606	31.646	32.654	33.629	34.571	35.483	36.366	37.222

The degree of consolidation for one year for the water phase can be taken from Table B.13 which is **42.597%**. And the degree of consolidation for one year for the air phase can be taken from Table B.14 which is **24.666%**.

B.2.2.2 Isochrone after one year

Figure B.17: Isochrone after one year for water phase

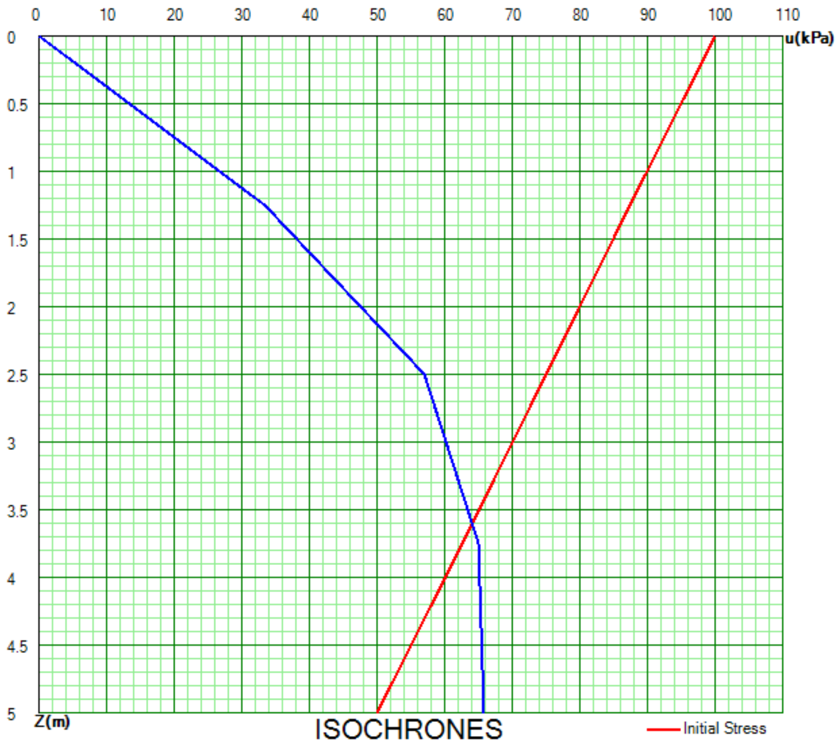
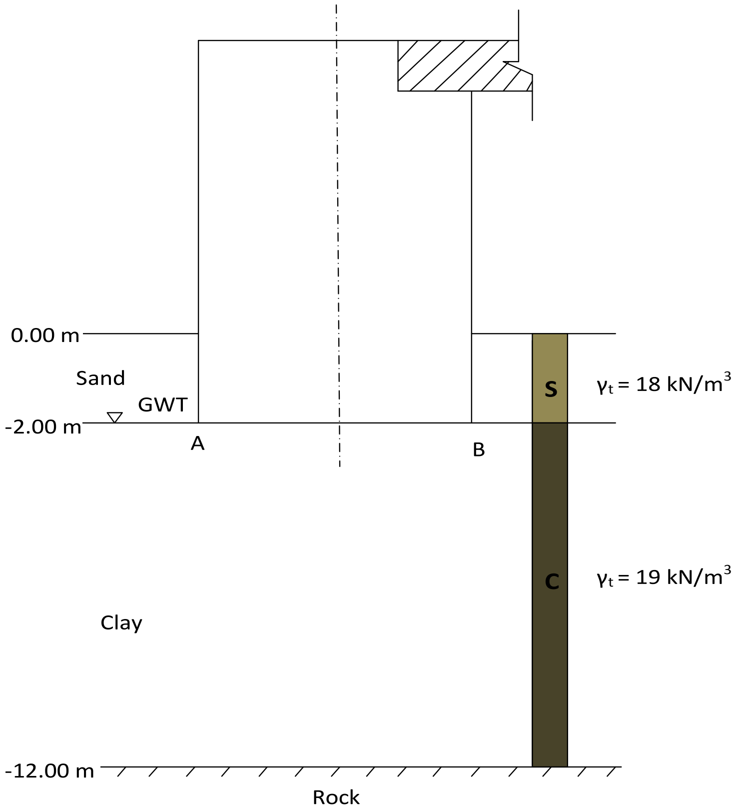


Figure B.18: Isochrone after one year for air phase

B.3 Settlement Analysis

Settlement analysis is done by hand calculation and spreadsheet and compared with the result of the software for the foundation given below:



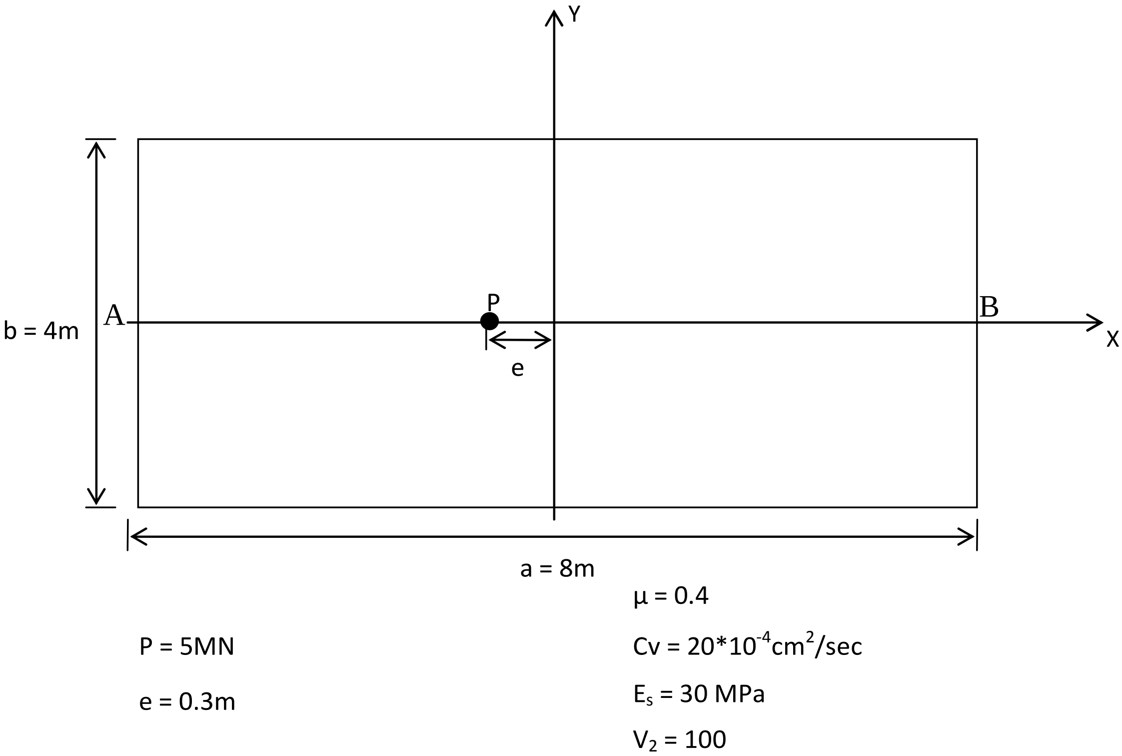


Figure B.19: Elevation and plan of an abutment

The required values are immediate (elastic) settlement, final primary settlement, primary settlement after two years and secondary settlement after 35 years taking time for completion of primary consolidation to be 25 years.

B.3.1 Result from common calculation methods

B.3.1.1 Immediate (elastic) settlement

The immediate settlement is calculated as:

$$S_i = qB\frac{1-\mu^2}{E}I_w$$

Where:

- S = Immediate settlement
- q = Contact pressure
- μ = Poisson's ratio
- E = Modulus of elasticity
- B = Least lateral dimension

- I_w = Influence factor

- I_w is determined by first calculating height to width and length to width ratios and by reading the value from table for the calculated ratios. So;

$$H/B = 10/4 = 2.5$$

$$L/B = 8/4 = 2.0$$

For these values, I_w will be taken from table as:

$$I_w = 1.22 \; [6]$$

- The stress distribution due to the vertical load with the given eccentricity shall be calculated by flexure formula [5].

$$\sigma_{max,min} = \frac{P}{a * b}\left[1 \pm \frac{6e_b}{b} \pm \frac{6e_a}{a}\right]; e_b = 0$$

- Checking whether the given eccentricity is within the kern or not:

$$a/6 = 8/6 = 1.33m > e_a = 0.3m$$

$$\sigma_{max,min} = \frac{P}{a * b}\left[1 \pm \frac{6e_a}{a}\right]$$

$$= \frac{5000}{8 * 4}\left[1 \pm \frac{6 * 0.3}{8}\right]$$

$$\sigma_{max} = 191.41 \; kN/m^2 \text{ and } \sigma_{min} = 121.09 \; kN/m^2$$

- The average pressure will be taken for the calculation of immediate settlement. So;

$$\sigma_{avg} = \frac{\sigma_{max} + \sigma_{min}}{2}$$

$$\sigma_{avg} = \frac{191.41 + 121.09}{2}$$

$$= 156.25 \; kN/m^2$$

$$E = E_s\left[\frac{1 - \mu - 2\mu^2}{1 - \mu}\right]$$

$$= 30 * \left[\frac{1 - 0.4 - 2 * (0.4)^2}{1 - 0.4}\right]$$

$$= 14 \; MPa = 14000 \; kPa$$

- So, the immediate settlement will be:

$$S_i = qB\frac{1-\mu^2}{E}I_w$$

$$= 156.25 * 4 * \frac{1-(0.4)^2}{14000} * 1.22$$

$$= 0.04575\ m$$

B.3.1.2 Final primary settlement

- Primary settlement will be calculated at the center, edge A, edge B, characteristic points near edge A and characteristic points near edge A. Constant E_s method is used for the calculation.

A. <u>*Calculation of contact pressure due to given loads*</u>

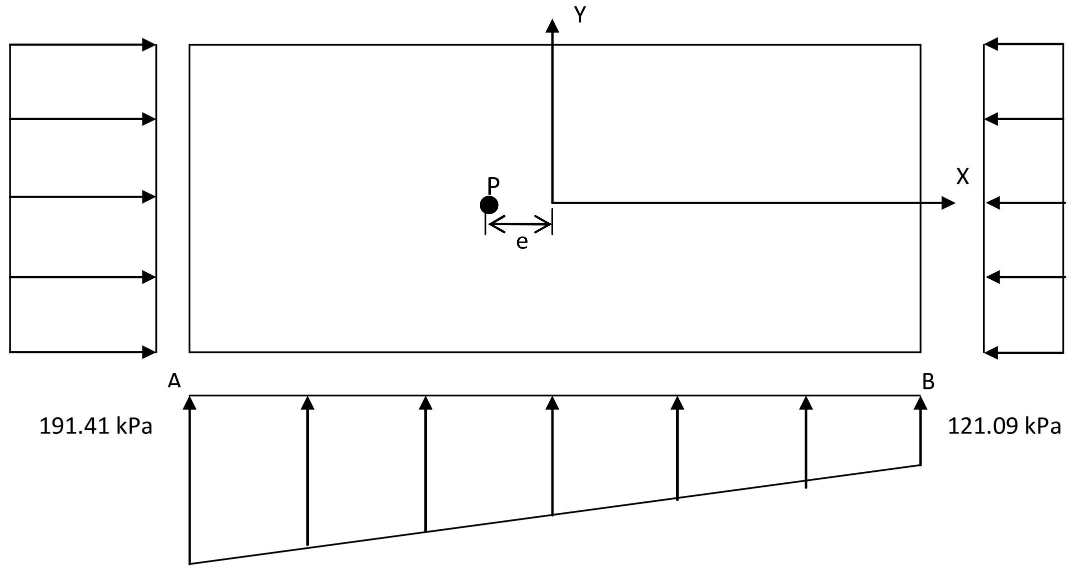


Figure B.20: Contact pressure distribution

- <u>At the center</u>

The trapezoidal contact pressure in Figure 4.20 is divided into different uniform and triangular parts (Figure 4.21). Pressure distribution for each part is calculated and then added to get the pressure distribution due to the trapezoidal contact pressure in Figure 4.20.

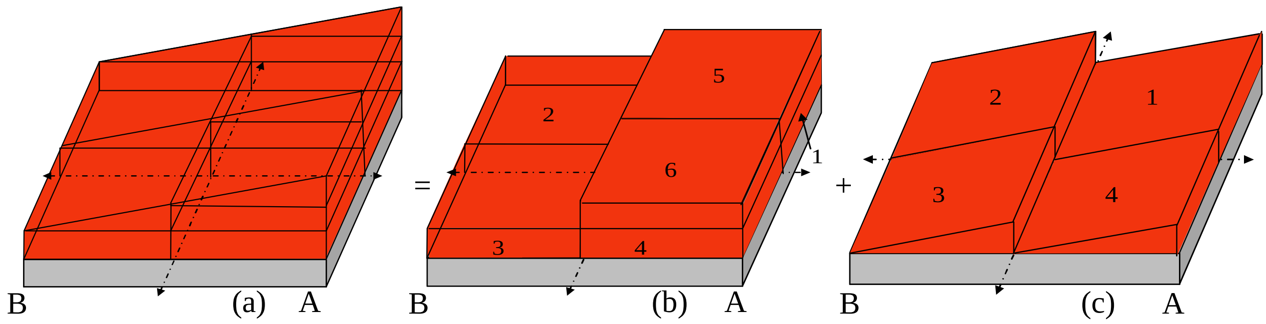


Figure B.21: Contact pressure distribution

- For uniform parts:

The pressure distribution is calculated using Boussinesq's equation of pressure distribution at a corner of a rectangular area loaded with a uniformly distributed load.

$$\sigma_z = 4P_1 i + 2P_2 i$$

Where:

- $P_1 = 121.09\ kPa$
- $P_2 = (191.41 - 121.09)/2 = 35.16\ kPa$
- i = influence coefficient as a function of (length/depth) and (width/depth) which is taken from table [7].

Table B.15: Pressure due to uniform parts (Figure B.21 (b))

Elevation (m)	Depth (m)	Width/Depth	Length/Depth	i	σ_z (kPa)
-2	0	Infinity	Infinity	0.25	138.670
-4.5	2.5	0.8	1.6	0.17739	98.395
-7	5	0.4	0.8	0.09314	51.663
-9.5	7.5	0.267	0.533	0.05231	29.015
-12	10	0.2	0.4	0.0328	18.194

- For triangular parts:

The pressure distribution is calculated using Boussinesq's equation of pressure distribution at different corners of a rectangular area loaded with a triangularly distributed load.

$$\sigma_z = 2Pi_1 + 2Pi_2$$

Where:

- $P = 35.16\ kPa$
- i_1 = influence coefficient as a function of (Width/Length) and (Depth/Width) for parts 1 and 4 in Figure 4.3 (c) [7].
- i_2 = influence coefficient as a function of (Width/Length) and (Depth/Width) for parts 2 and 3 in Figure 4.3 (c) [7].

Table B.16: Pressure due to triangular parts (Figure B.21 (c))

Elevation (m)	Depth (m)	Width/Length	Depth/Width	i_1	i_2	σ_z (kPa)
-2	0	0.5	0	0	0.25	17.580
-4.5	2.5	0.5	1.25	0.04995	0.12805	12.517
-7	5	0.5	2.5	0.038	0.0587	6.800
-9.5	7.5	0.5	3.75	0.02402	0.0299	3.792
-12	10	0.5	5	0.0154	0.0174	2.306

Table B.17: Summary of pressure distributions (uniform + triangular)

Elevation (m)	Depth (m)	Pressure due to uniform loading (kPa)	Pressure due to triangular loading (kPa)	Total (kPa)
-2	0	138.670	17.580	156.250
-4.5	2.5	98.395	12.517	110.912
-7	5	51.663	6.800	58.463
-9.5	7.5	29.015	3.792	32.807
-12	10	18.194	2.306	20.500

- <u>At the edges</u>

The trapezoidal contact pressure in Figure B.20 is divided into rectangular part with a value of 121.09kPa and triangular part with a magnitude of 70.32kPa (i.e. 191.41kPa- 121.09kPa =70.32kPa). The pressure distribution for each part is given below.

- For uniform part:

The pressure distribution is calculated using Boussinesq's equation of pressure distribution at a corner of a rectangular area loaded with a uniformly distributed load.

$$\sigma_z = Pi$$

Where: P = uniformly distributed load (kPa)

i = influence coefficient as a function of (length/depth) and (width/depth). It is taken from table [7].

Table B.18: Pressure due to uniform part under point A and B

Elevation (m)	Depth (m)	Width/Depth	Length/Depth	i	σ_z (kPa)
-2	0	Infinity	Infinity	0.25	30.273
-4.5	2.5	1.6	3.2	0.2311	27.984
-7	5	0.8	1.6	0.17739	21.480
-9.5	7.5	0.533	1.067	0.12756	15.446
-12	10	0.4	0.8	0.09314	11.278

- For triangular part (Under edge A):

The pressure distribution is calculated using Boussinesq's equation of pressure distribution at different corners of a rectangular area loaded with a triangularly distributed load.

$$\sigma_{zA} = Pi_A$$

Where: P = uniformly distributed load (kPa)

i_A = influence coefficient as a function of (Width/Length) and (Depth/Width) [7].

Table B.19: Pressure due to triangular part under point A

Elevation (m)	Depth (m)	Width/Length	Depth/Width	i_A	σ_{zA} (kPa)
-2	0	0.5	0	0.25	17.580
-4.5	2.5	0.5	0.625	0.1907	13.410
-7	5	0.5	1.25	0.12805	9.004
-9.5	7.5	0.5	1.875	0.0831	5.844
-12	10	0.5	2.5	0.0587	4.128

- For triangular part (Under edge B):

$$\sigma_{zB} = Pi_B$$

Where: P = uniformly distributed load (kPa)

i_B = influence coefficient as a function of (Width/Length) and (Depth/Width) [7].

Table B.20: Pressure due to triangular part under point B

Elevation (m)	Depth (m)	Width/Length	Depth/Width	i_B	σ_{zB} (kPa)
-2	0	0.5	0	0	0.000
-4.5	2.5	0.5	0.625	0.0397	2.792
-7	5	0.5	1.25	0.04995	3.512
-9.5	7.5	0.5	1.875	0.046075	3.240
-12	10	0.5	2.5	0.038	2.672

Table B.21: Summary of pressure distributions (rectangular + triangular)

Elevation (m)	Depth (m)	Pressure due to rectangular loading (kPa)		Pressure due to triangular loading (kPa)		Total (kPa)	
		At Point A	At Point B	At Point A	At Point B	At Point A	At Point B
-2	0	30.273	30.273	17.580	0.000	47.853	30.273
-4.5	2.5	27.984	27.984	13.410	2.792	41.394	30.776
-7	5	21.480	21.480	9.004	3.512	30.485	24.993
-9.5	7.5	15.446	15.446	5.844	3.240	21.290	18.686
-12	10	11.278	11.278	4.128	2.672	15.406	13.950

- At the characteristic points

The trapezoidal contact pressure in Figure B.20 is divided into different uniform and triangular parts. The way of the division is similar to the one as shown in Figure B.21, but the point of division will be shifted from the center to the characteristic points. Pressure distribution for each part is calculated and then added to get the pressure distribution due to the trapezoidal contact pressure.

- For uniform parts (Under characteristic points near edge A):

The pressure distribution is calculated using Boussinesq's equation of pressure distribution at the corner of a rectangular area loaded with a uniformly distributed load.

$$\sigma_z = P_1 i_1 + P_1 i_2 + P_1 i_3 + P_1 i_4 + P_2 i_1 + P_2 i_4$$

Where:

- $P_1 = 121.09\ kPa$
- $P_2 = (191.41 - 121.09) * 0.87 = 61.18\ kPa$
- i_1, i_2, i_3, i_4 = influence coefficients as a function of (length/depth) and (width/depth) which is taken from table [7].

Table B.22: Pressure due to uniform parts

Elevation (m)	Depth (m)	i_1	i_2	i_3	i_4	σ_z (kPa)
-2	0	0.25	0.25	0.25	0.25	151.680
-4.5	2.5	0.03494	0.06392	0.22406	0.11258	61.761
-7	5	0.00986	0.03202	0.16121	0.04889	34.106
-9.5	7.5	0.00446	0.01889	0.11045	0.0256	21.141
-12	10	0.00254	0.01451	0.07733	0.0155	14.409

- For uniform parts (Under characteristic points near edge B):

The pressure distribution is calculated using Boussinesq's equation of pressure distribution at the corner of a rectangular area loaded with a uniformly distributed load.

$$\sigma_z = P_1 i_1 + P_1 i_2 + P_1 i_3 + P_1 i_4 + P_2 i_2 + P_2 i_3$$

Where:

- $P_1 = 121.09\ kPa$
- $P_2 = (191.41 - 121.09) * 0.87 = 9.14\ kPa$
- i_1, i_2, i_3, i_4 = influence coefficients as a function of (length/depth) and (width/depth) which is taken from table [7].

Table B.23: Pressure due to uniform parts

Elevation (m)	Depth (m)	i_1	i_2	i_3	i_4	σ_z (kPa)
-2	0	0.25	0.25	0.25	0.25	125.660
-4.5	2.5	0.22406	0.11258	0.03494	0.06392	54.084
-7	5	0.16121	0.04889	0.00986	0.03202	31.048
-9.5	7.5	0.11045	0.0256	0.00446	0.01889	19.577
-12	10	0.07733	0.0155	0.00254	0.01451	13.470

- For triangular parts (Under characteristic points near edge A):

The pressure distribution is calculated using Boussinesq's equation of pressure distribution at different corners of a rectangular area loaded with a triangularly distributed load.

$$\sigma_z = P_1 i_1 + P_2 i_2 + P_2 i_3 + P_1 i_4$$

Where:

- $P_1 = 9.14\ kPa$
- $P_2 = 61.18\ kPa$
- i_1, i_2, i_3, i_4 = influence coefficient as a function of (Width/Length) and (Depth/Width) [7].

Table B.24: Pressure due to triangular parts

Elevation (m)	Depth (m)	i_1	i_2	i_3	i_4	σ_z (kPa)
-2	0	0	0.25	0.25	0	30.590
-4.5	2.5	0.01659	0.10025	0.18054	0.05128	17.799
-7	5	0.00502	0.07746	0.1115	0.02239	11.811
-9.5	7.5	0.00458	0.07638	0.07029	0.01242	9.129
-12	10	0.00456	0.07632	0.04615	0.00757	7.603

- For triangular parts (Under characteristic points near edge B):

The pressure distribution is calculated using Boussinesq's equation of pressure distribution at different corners of a rectangular area loaded with a triangularly distributed load.

$$\sigma_z = P_1 i_1 + P_2 i_2 + P_2 i_3 + P_1 i_4$$

Where:

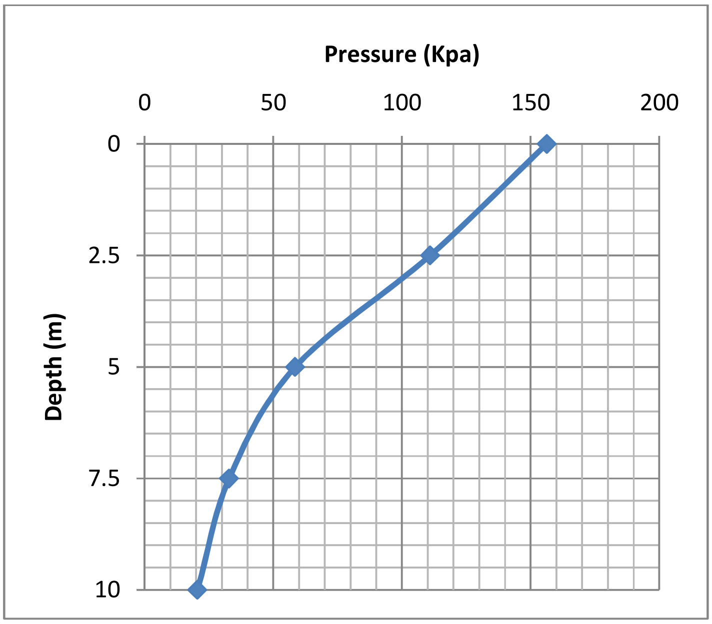
- $P_1 = 61.18\ kPa$
- $P_2 = 9.14\ kPa$
- i_1, i_2, i_3, i_4 = influence coefficient as a function of (Width/Length) and (Depth/Width) [7].

Table B.25: Pressure due to triangular parts

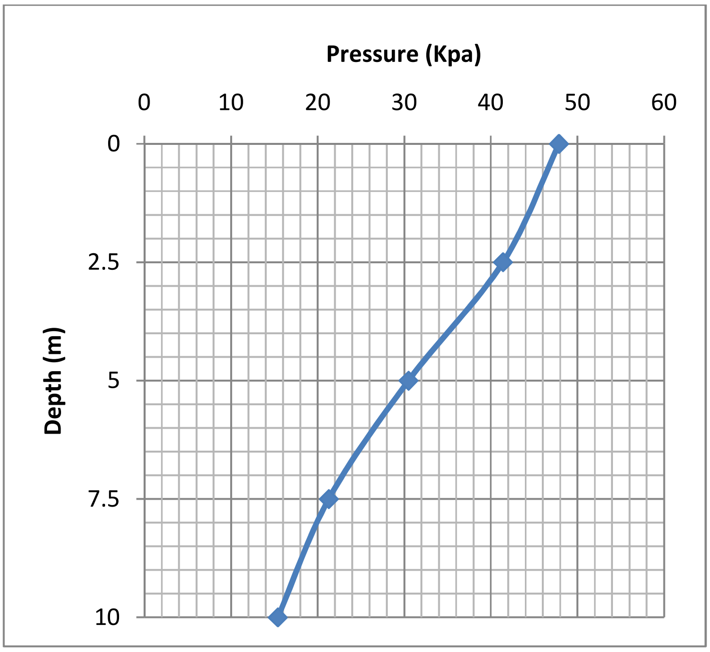
Elevation (m)	Depth (m)	i_1	i_2	i_3	i_4	σ_z (kPa)
-2	0	0	0.25	0.25	0	4.570
-4.5	2.5	0.04336	0.05834	0.01903	0.01067	4.013
-7	5	0.05014	0.02257	0.0051	0.00786	3.801
-9.5	7.5	0.04262	0.01263	0.00458	0.00759	3.229
-12	10	0.03299	0.0076	0.00456	0.00755	2.592

Table B.26: Summary of pressure distributions (uniform + triangular)

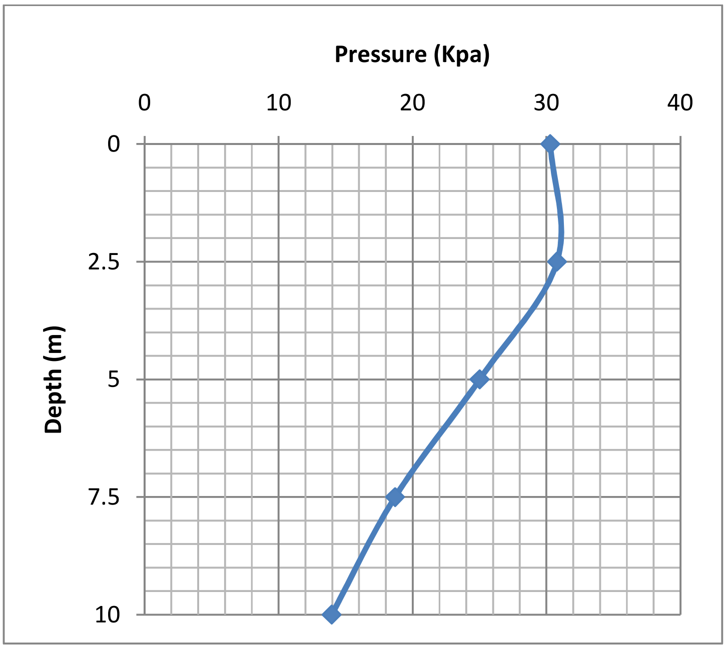
Elevation (m)	Depth (m)	Pressure due to rectangular loading (kPa)		Pressure due to triangular loading (kPa)		Total (kPa)	
		At CHR.A	At CHR.B	At CHR.A	At CHR.B	At CHR.A	At CHR.B
-2	0	151.68	125.66	30.59	4.57	182.27	130.23
-4.5	2.5	61.761	54.084	17.799	4.013	79.56	58.097
-7	5	34.106	31.048	11.811	3.801	45.917	34.849
-9.5	7.5	21.141	19.577	9.129	3.229	30.27	22.806
-12	10	14.409	13.47	7.603	2.592	22.012	16.062


Pressure (Kpa)
0
50
100
150
200
0
2.5
5
7.5
10
Depth (m)

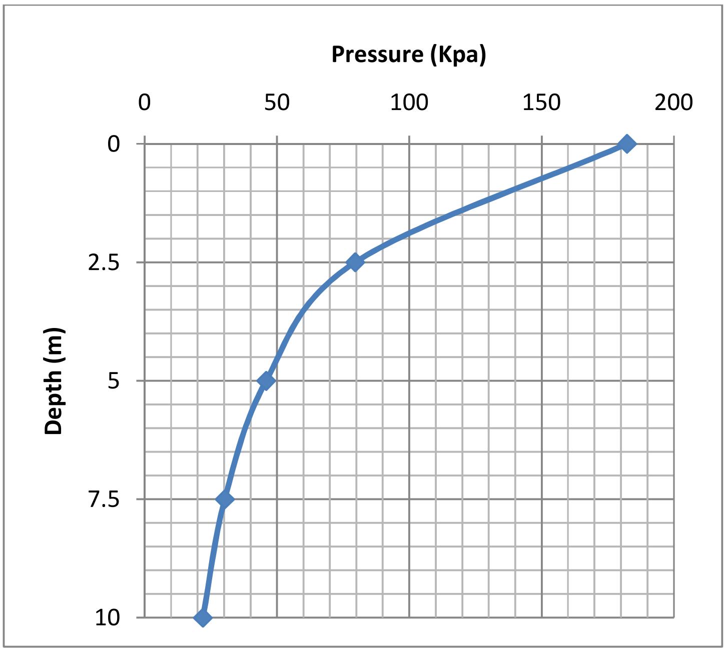
(a)


Pressure (Kpa)
0
10
20
30
40
50
60
0
2.5
5
7.5
10
Depth (m)

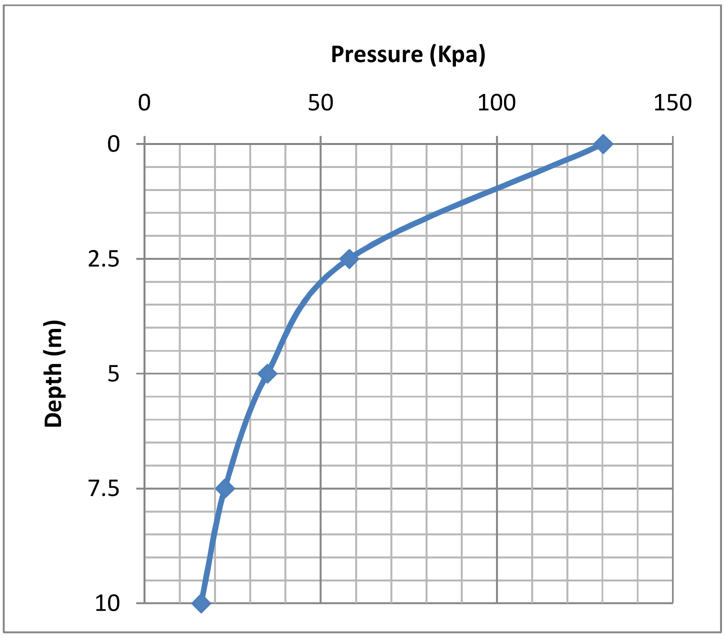
(b)


Pressure (Kpa)
0
10
20
30
40
0
2.5
5
7.5
10
Depth (m)

(c)


Pressure (Kpa)
0
50
100
150
200
0
2.5
5
7.5
10
Depth (m)

(d)



(e)

Fig B.22: Pressure distribution with depth. (a) At edge A; (b) At edge B; (c) At center; (d) At characteristic points near edge A; (e) At characteristic points near edge B.

B. Calculation of settlement

Using constant modulus of compressibility method, the final primary settlement is calculated by dividing the area of the pressure distribution curve by the modulus of compressibility. The area is approximately calculated by Simpson's formula as [8]:

$$A = \frac{Z_{(b)} - Z_{(t)}}{6}(\sigma_t + 4\sigma_m + \sigma_b)$$

Where:

- $Z_{(t)}$ and $Z_{(b)}$ are the depths at the top and at the bottom respectively.
- σ_t, σ_m and σ_b are stresses at the top, middle and bottom respectively.

$$A_C = \frac{Z_{(b)} - Z_{(t)}}{6}(\sigma_t + 4\sigma_m + \sigma_b)$$

$$= \frac{10}{6}(156.25 + 4 * 58.463 + 20.5) = 684.337\ kPa/m$$

$$A_A = \frac{Z_{(b)} - Z_{(t)}}{6}(\sigma_t + 4\sigma_m + \sigma_b)$$

$$= \frac{10}{6}(47.853 + 4 * 30.485 + 15.406) = 308.665\ kPa/m$$

$$A_B = \frac{Z_{(b)} - Z_{(t)}}{6}(\sigma_t + 4\sigma_m + \sigma_b)$$

$$= \frac{10}{6}(30.273 + 4 * 24.993 + 13.95) = 240.325\ kPa/m$$

$$A_{crA} = \frac{Z_{(b)} - Z_{(t)}}{6}(\sigma_t + 4\sigma_m + \sigma_b)$$

$$= \frac{10}{6}(47.853 + 4 * 30.485 + 15.406) = 646.583\ kPa/m$$

$$A_{crB} = \frac{Z_{(b)} - Z_{(t)}}{6}(\sigma_t + 4\sigma_m + \sigma_b)$$

$$= \frac{10}{6}(30.273 + 4 * 24.993 + 13.95) = 476.147\ kPa/m$$

The settlement will be:

$$S_{pC} = \frac{A_C}{E_s} = \frac{684.337}{30000} = 0.0228m$$

$$S_{pA} = \frac{A_A}{E_s} = \frac{308.665}{30000} = 0.0103m$$

$$S_{pB} = \frac{A_B}{E_s} = \frac{240.325}{30000} = 0.0080m$$

$$S_{pcrA} = \frac{A_{crA}}{E_s} = \frac{646.583}{30000} = 0.0216m$$

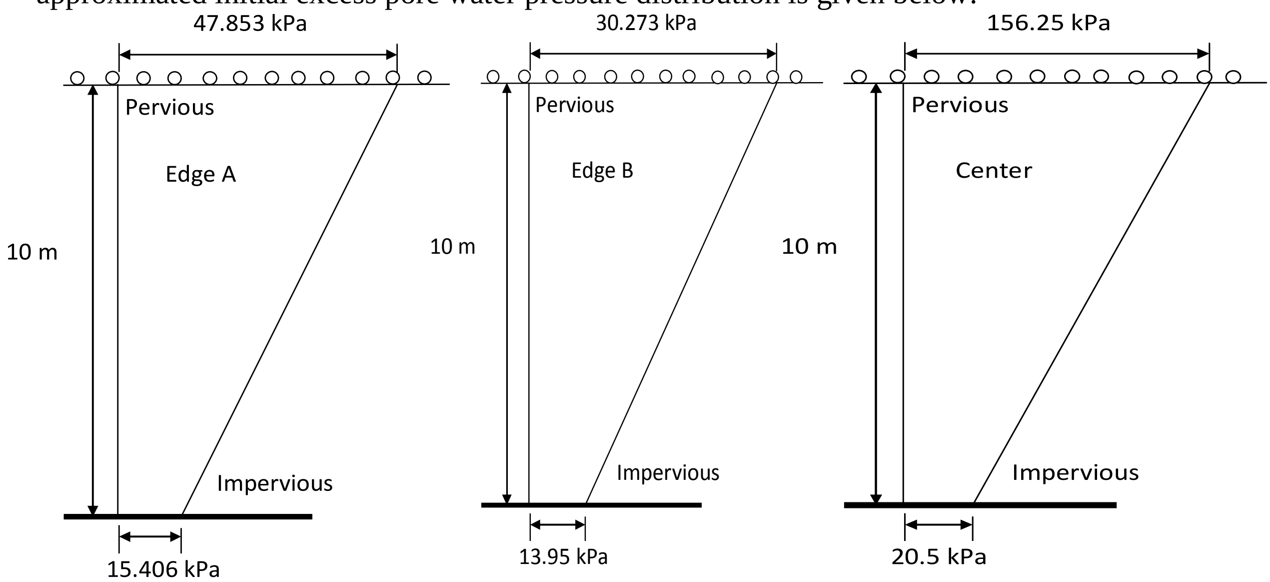
$$S_{pcrB} = \frac{A_{crB}}{E_s} = \frac{476.147}{30000} = 0.0159m$$

Where:

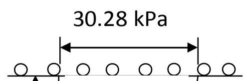
- $A_C, A_A, A_B, A_{crA}, A_{crB}$ = Area of pressure distribution curve at the center, at edge A, at edge B, at the characteristic points near edge A, the characteristic points near edge B respectively.
- $S_{pC}, S_{pA}, S_{pB}, S_{pcrA}, S_{pcrB}$ = Final primary settlement at the center, at edge A, at edge B, at the characteristic points near edge A, the characteristic points near edge B respectively.

B.3.1.3 Primary settlement after two years

To calculate the primary settlement after two years, the degree of consolidation for two years should first be determined. And to get the degree of consolidation for the given time, one should know the initial excess pore water pressure distribution first. The initial excess pore water pressure distribution is approximated from the pressure distribution diagrams. The approximated initial excess pore water pressure distribution is given below:



(a) (b) (c)



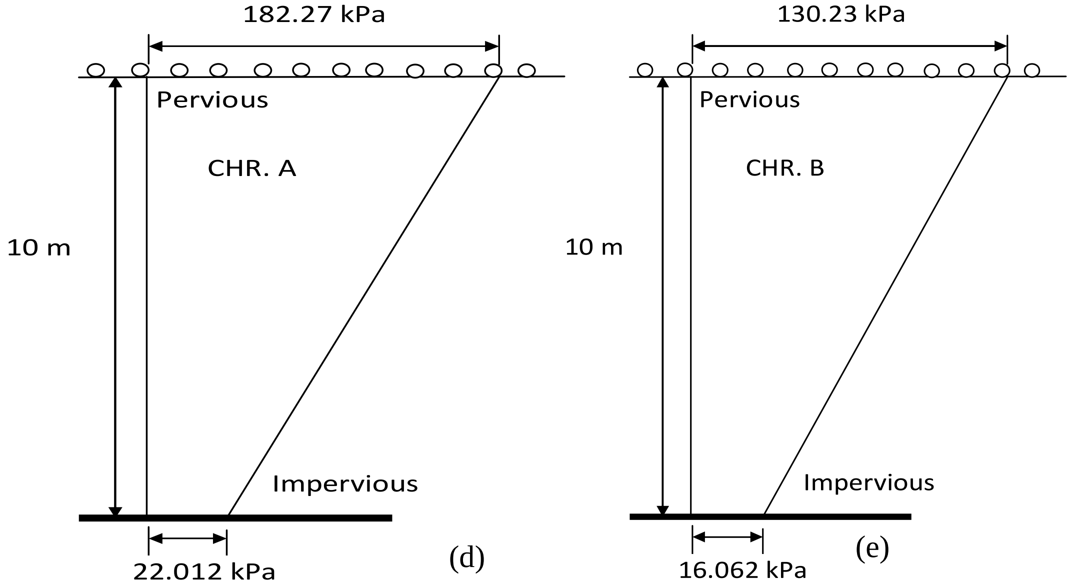


Figure B.23: Approximate initial excess pore water pressure distribution. (a) At edge A; (b) At edge B; (c) At center; (d) At characteristic points near edge A; (e) At characteristic points near edge B.

A. Calculation of degree of consolidation

The calculation of degree of consolidation is done using excel and given below.

Table B.27: Degree of consolidation for two years

	Rectangular				Triangular				Trapezoidal
Location	m=1	m=3	m=5	μ_R	m=1	m=3	m=5	μ_T	μ_{TRP}
Center	0.5936	0.0055	1E-05	40.089	0.7558	-0.002	3E-06	24.647	51.948485
Edge A	0.5936	0.0055	1E-05	40.089	0.7558	-0.002	3E-06	24.647	48.00907
Edge B	0.5936	0.0055	1E-05	40.089	0.7558	-0.002	3E-06	24.647	45.788259
CHR. A	0.5936	0.0055	1E-05	40.089	0.7558	-0.002	3E-06	24.647	52.202661
CHR. B	0.5936	0.0055	1E-05	40.089	0.7558	-0.002	3E-06	24.647	52.139623
Where: CHR A and CHR B are characteristic points near edge A and edge B respectively.									

B. Calculation of settlement

The primary settlement after two years will be calculated by multiplying the final primary settlement by the degree of consolidation for two years. The calculation at the five locations is given below.

$$S_{pC} = 0.5195 * 0.0228 = 0.0118m$$

$$S_{pA} = 0.4801 * 0.0103 = 0.0049m$$

$$S_{pB} = 0.4579 * 0.0080 = 0.0037m$$

$$S_{pcrA} = 0.5220 * 0.0216 = 0.0113m$$

$$S_{pcrB} = 0.5214 * 0.0159 = 0.0083m$$

Where:

- $S_{pC}, S_{pA}, S_{pB}, S_{pcrA}, S_{pcrB}$ = Primary settlement after two years at the center, at edge A, at edge B, at the characteristic points near edge A, the characteristic points near edge B respectively.

B.3.1.4 Secondary settlement

Secondary settlement is calculated as:

$$S_s = \frac{F\ln(t_2/t_1)}{V_2}$$

Where:

- $F = \frac{H}{6}(F_1 + 4F_2 + F_3)$
- $F_1 = ln\left(1 + (\Delta\sigma_t/\sigma_t)\right)$
- $F_2 = \ln\left(1 + (\Delta\sigma_m/\sigma_m)\right)$
- $F_3 = ln\left(1 + (\Delta\sigma_b/\sigma_b)\right)$

The calculation is given in Table B.28. For the calculation t_1, t_2 and V_2 are given to be 25 years, 35 years and 100 respectively.

Table B.28: Secondary settlement at different locations

Location		Δσ (kPa)	σ_o (kPa)	ln (1+(Δσ/σ_o))	F	Ss (m)
Center	At the top	156.25	36	1.67527767	6.629759	0.0223
	At the middle	58.463	81.95	0.538478775		
	At the bottom	20.5	127.9	0.148662622		
Edge A	At the top	47.853	36	0.845546327	3.7072395	0.0125
	At the middle	30.485	81.95	0.316265972		
	At the bottom	15.406	127.9	0.113733496		
Edge B	At the top	30.273	36	0.610263636	2.9642197	0.0100
	At the middle	24.993	81.95	0.266186677		
	At the bottom	13.95	127.9	0.103521453		
CHR. A	At the top	182.27	36	1.80221389	6.2342318	0.0210
	At the middle	45.917	81.95	0.444881356		
	At the bottom	22.012	127.9	0.158799747		
CHR. B	At the top	130.23	36	1.529853433	5.1092249	0.0172
	At the middle	34.849	81.95	0.354345204		
	At the bottom	16.062	127.9	0.118300667		

Where: CHR A and CHR B are characteristic points near edge A and edge B respectively.

B.3.2 Result from the developed software

The analysis is done with the developed software and the following result is obtained.

B.3.2.1 Final settlement

A. Settlement at the center

The settlement at the center of the foundation is given in Figure B.24.

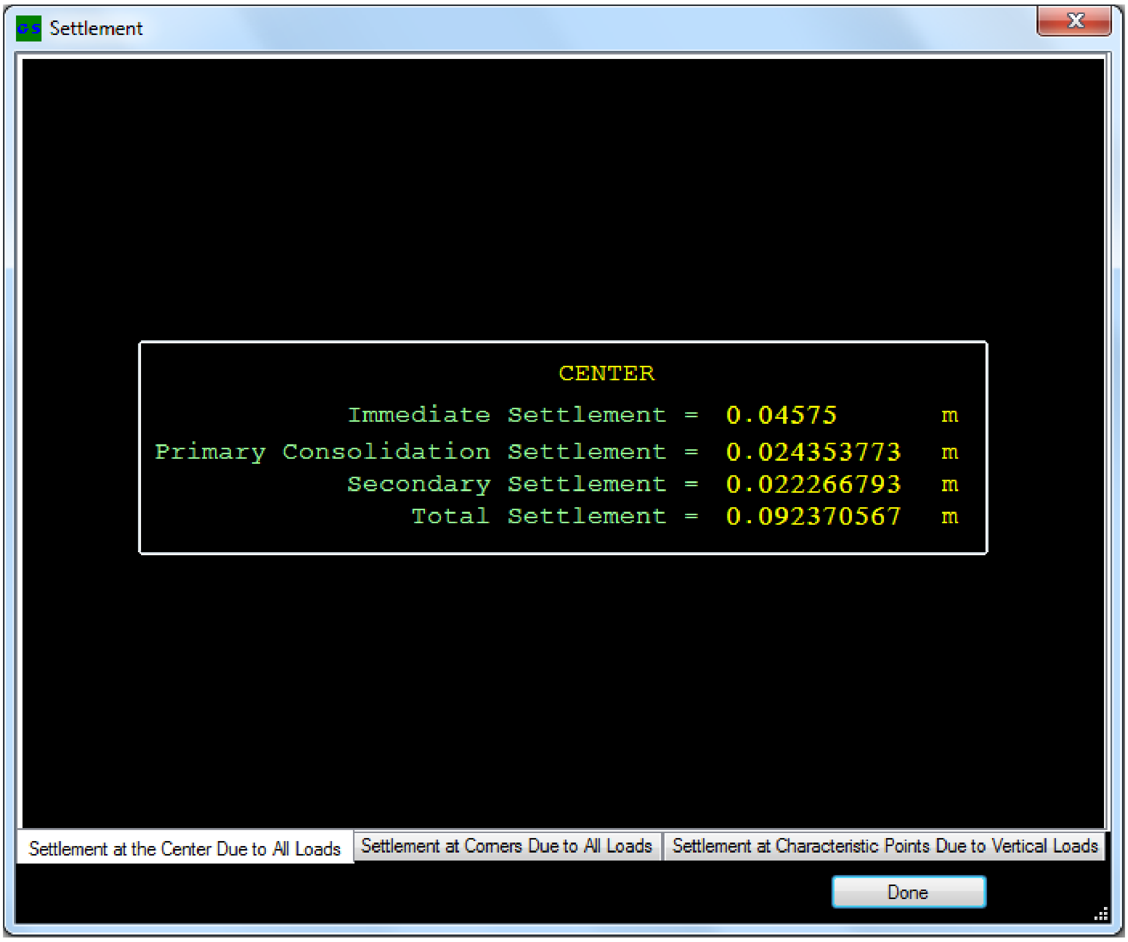


Figure B.24: Settlement at the center.

B. Settlement at the edges

The settlement at the edges is given in Figure B.25. Corner 1 and corner 2 are corners at edge A whereas corner 3 and corner 4 are corners at edge B.

Figure B.25: Settlement at the edges.

C. Settlement at the characteristic points

The settlement at the characteristic points is given in Figure B.26. Characteristic point 1 and characteristic point 2 are characteristic points at edge A whereas characteristic point 3 and characteristic point 4 are characteristic points at edge B.

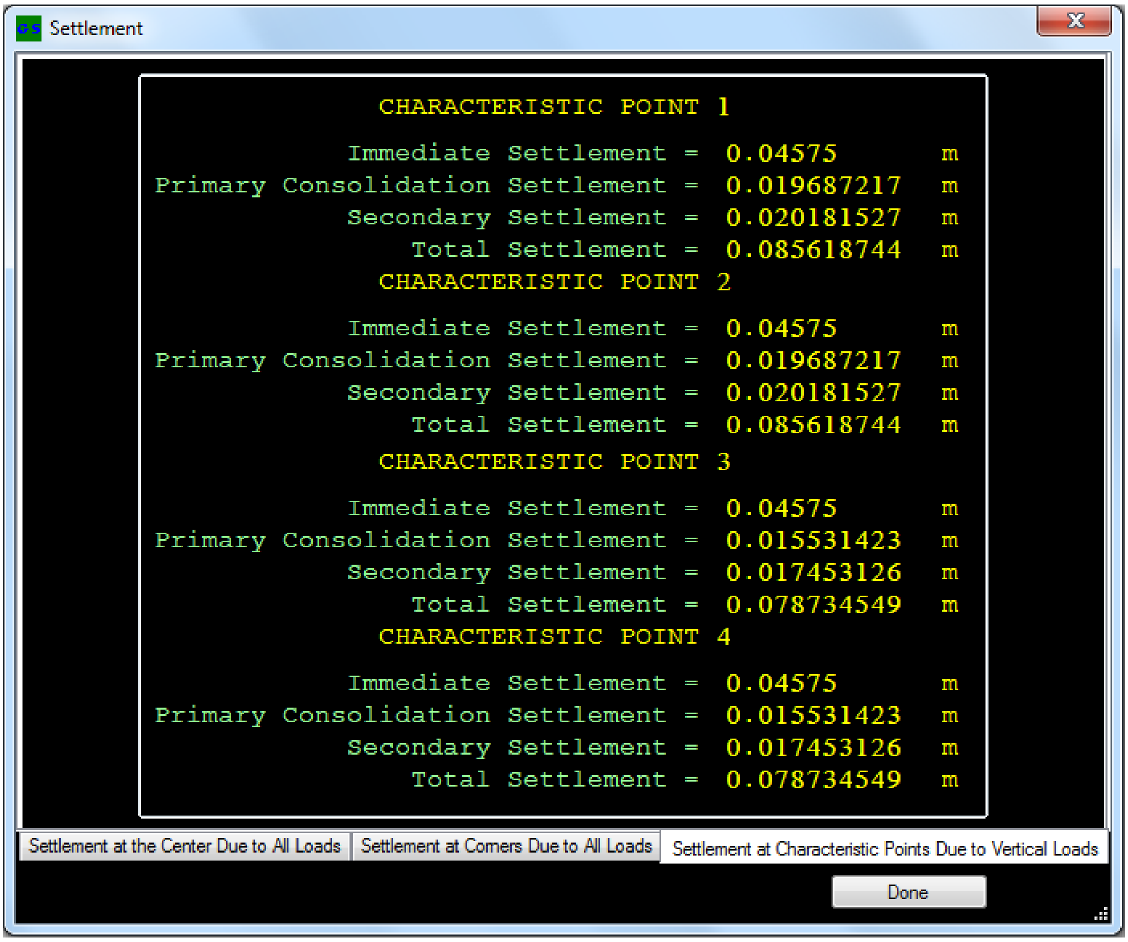


Figure B.26: Settlement at the characteristic points.

B.3.2.2 Settlement after two years

A. Settlement at the center

The settlement at the center of the foundation is given in Figure B.27.

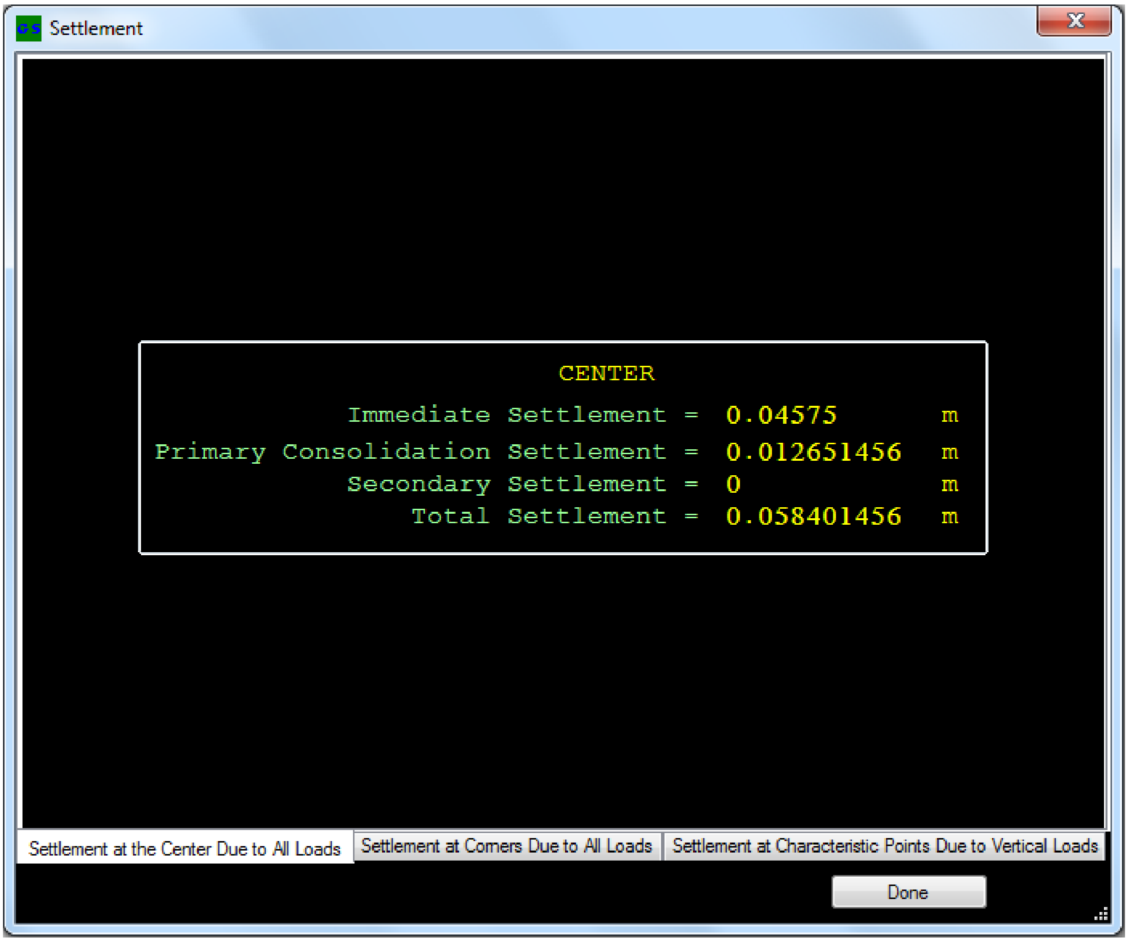


Figure B.27: Settlement at the center.

B. Settlement at the edges

The settlement at the edges is given in Figure B.28. Corner 1 and corner 2 are corners at edge A whereas corner 3 and corner 4 are corners at edge B.

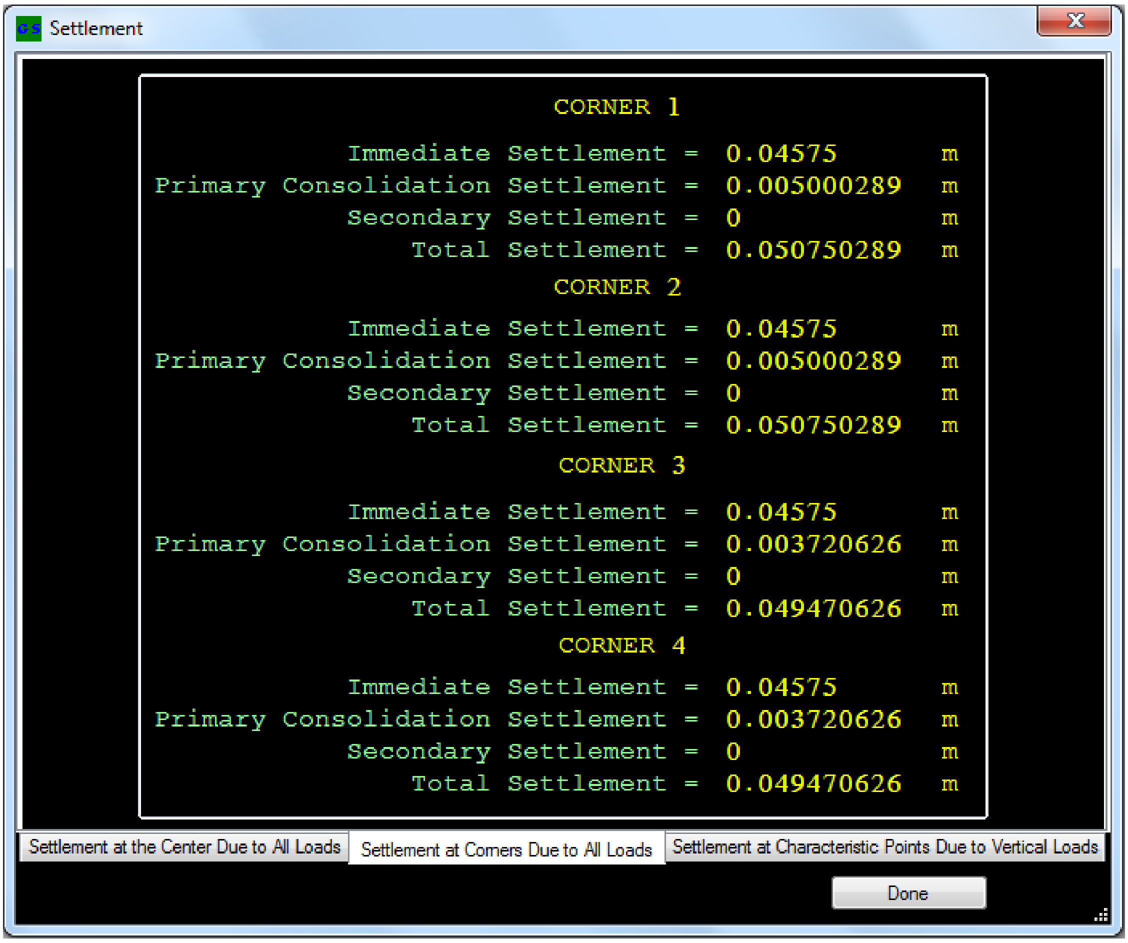


Figure B.28: Settlement at the edges.

C. Settlement at the characteristic points

The settlement at the characteristic points is given in Figure B.29. Characteristic point 1 and characteristic point 2 are characteristic points at edge A whereas characteristic point 3 and characteristic point 4 are characteristic points at edge B.

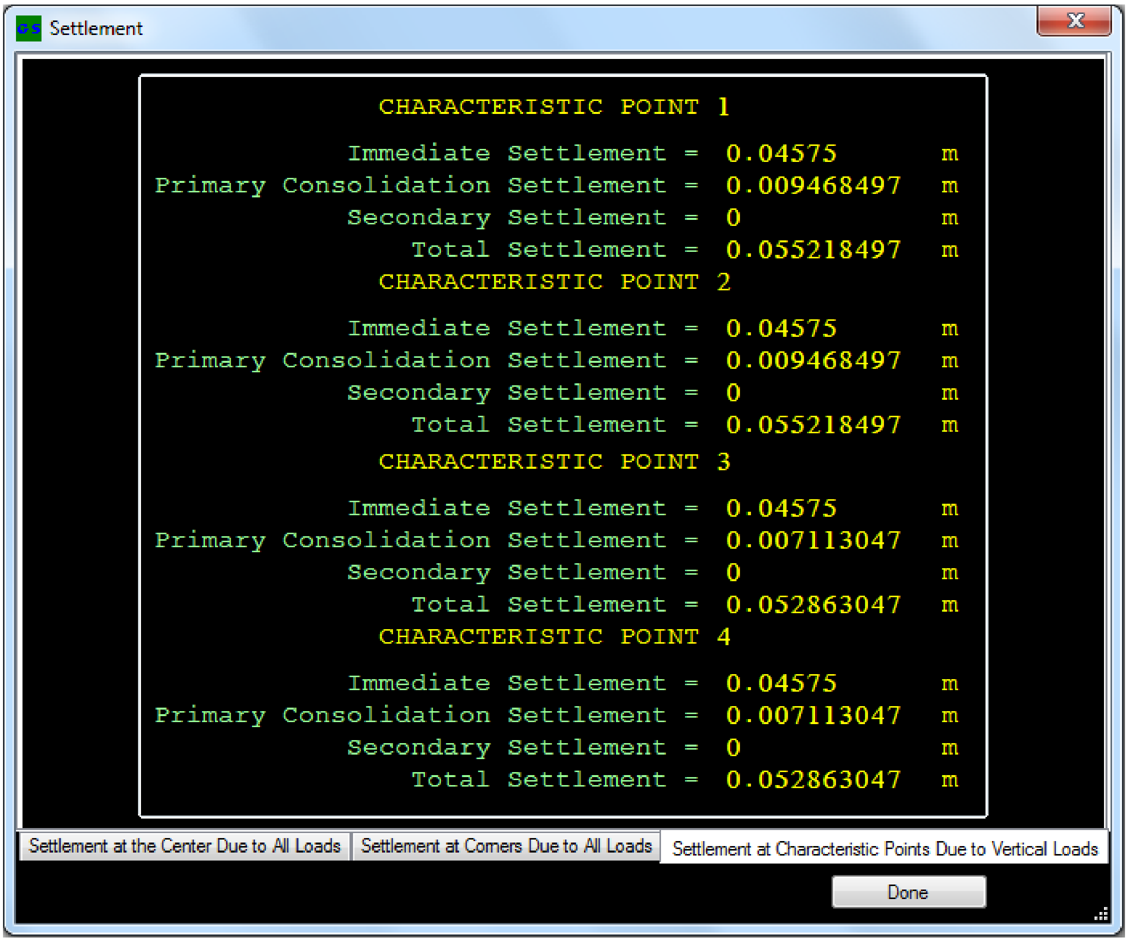


Figure B.29: Settlement at the characteristic points.

Pressure distributions under the center, corners and characteristic points are given in figures Figure B.30 to Figure B.34.

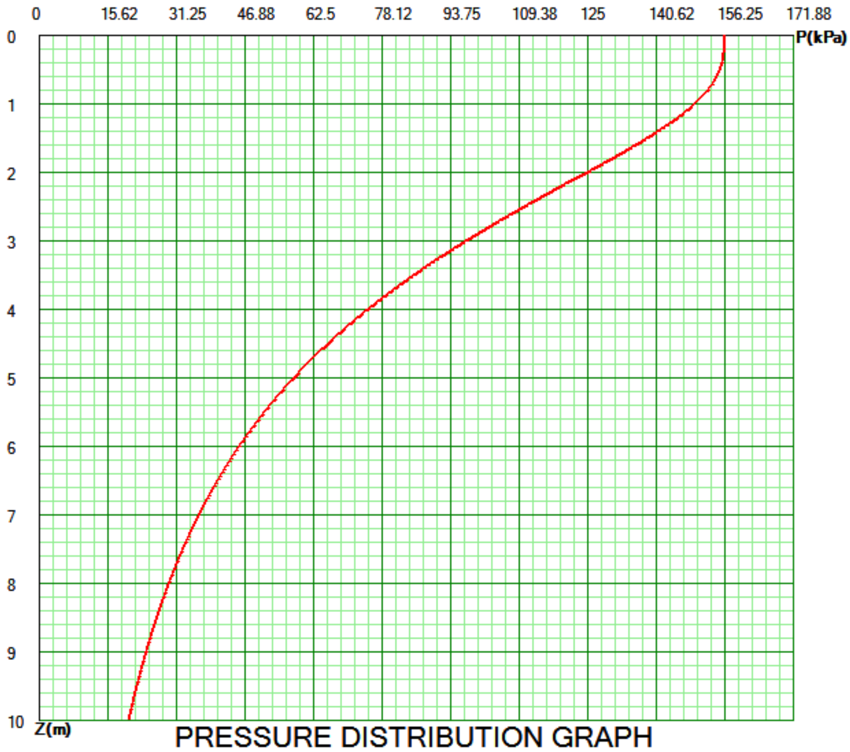


Figure B.30: Pressure distribution under the center.

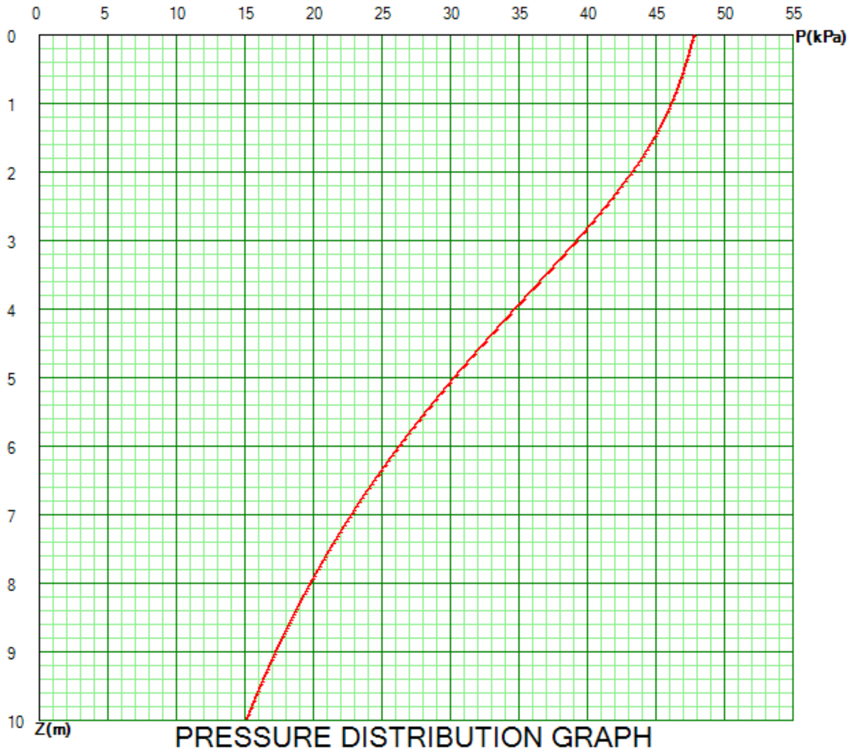


Figure B.31: Pressure distribution under edge A.

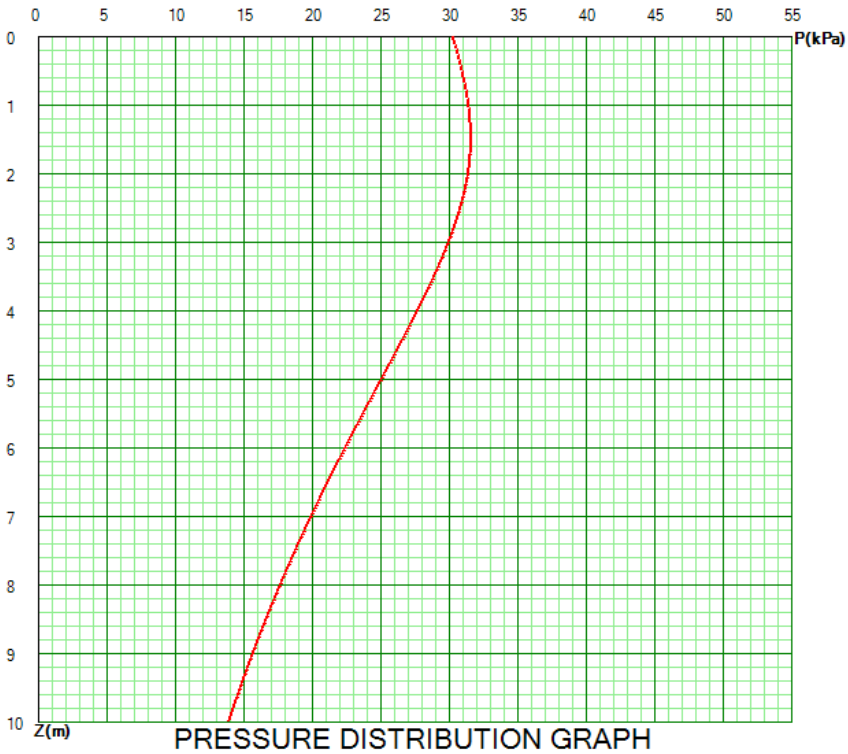


Figure B.32: Pressure distribution under edge B.

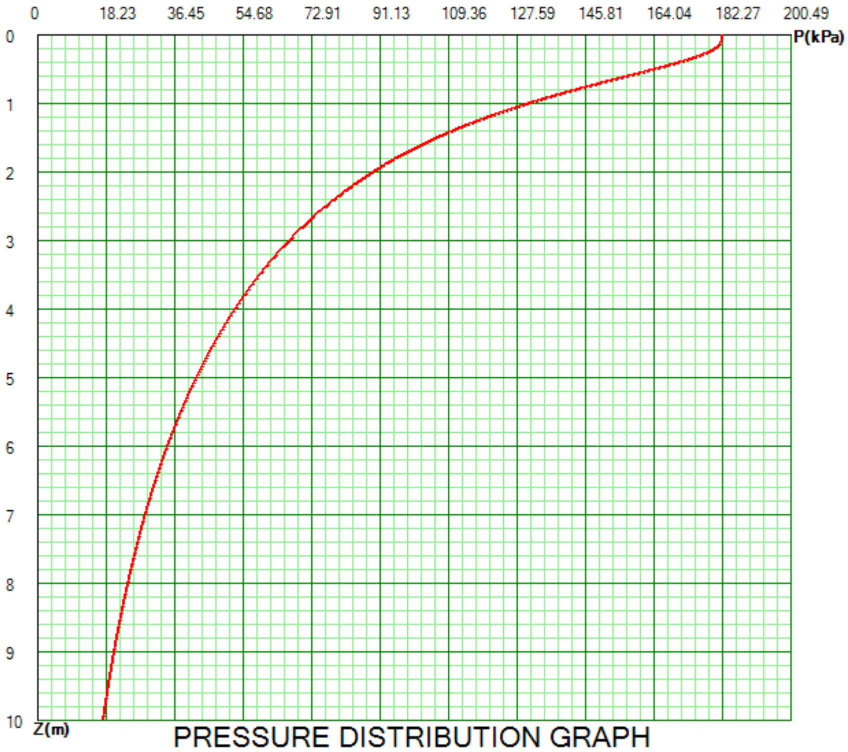


Figure B.33: Pressure distribution under characteristic points near edge A.

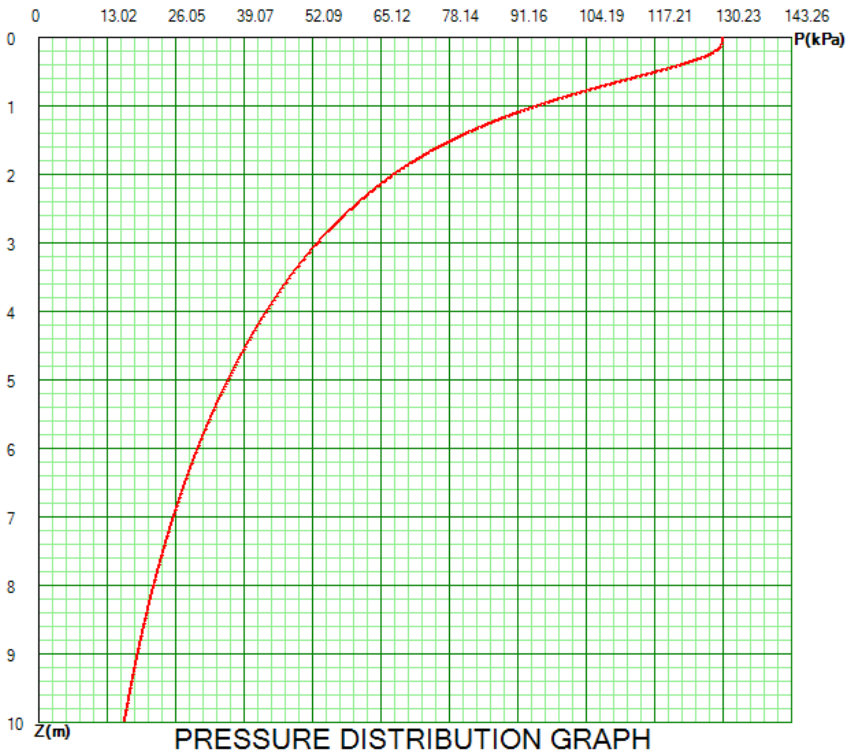


Figure B.34: Pressure distribution under characteristic points near edge B.

Declaration

This thesis is my original work and has not been presented for a degree in any other university, and that all sources of marerial used for the thesis have been duly acknowledged.

Name: Ayenew Yihune

Signature: ______________________

Advisor: Professor Alemayehu Teferra

Signature: ______________________