Settlement of Foundations

INTRODUCTION

- Structures are built on soils. They transfer loads to the subsoil through the foundations.
- The effect of the loads is felt by the soil normally up to a depth of about two to three times the width of the foundation. The soil within this depth gets compressed due to the imposed stresses.
- The compression of the soil mass leads to the decrease in the volume of the mass which results in the settlement of the structure.
- The displacements that develop at any given boundary of the soil mass can be determined on a rational basis by summing up the displacements of small elements of the mass resulting from the strains produced by a change in the stress system.
- The compression of the soil mass due to the imposed stresses may be almost immediate or time dependent according to the permeability characteristics of the soil.
- Cohesion less soils which are highly permeable are compressed in a relatively short period of time as compared to cohesive soils which are less permeable.

The compressibility characteristics of a soil mass might be due to any or a combination of the following factors:

I. **Compression of the solid matter.**
II. **Compression of water and air within the voids.**
III. **Escape of water and air from the voids.**

- **It is quite reasonable and rational to assume that the solid matter and the pore water are relatively incompressible under the loads usually encountered in soil masses.**
- **The change in volume of a mass under imposed stresses must be due to the escape of water if the soil is saturated.**
- **But if the soil is partially saturated, the change in volume of the mass is partly due to the compression and escape of air from the voids and partly due to the dissolution of air in the pore water.**
- **The compressibility of a soil mass is mostly dependent on the rigidity of the soil skeleton. The rigidity, in turn, is dependent on the structural arrangement of particles and, in fine grained soils, on the degree to which adjacent particles are bonded together.**
- **Soils which possess a honeycombed structure possess high porosity and as such are more compressible.**
- **A soil composed predominantly of flat grains is more compressible than one containing mostly spherical grains.**

- A soil in an undisturbed state is less compressible than the same soil in a remolded state. Soils are neither truly elastic nor plastic.
- When a soil mass is under compression, the volume change is predominantly due to the slipping of grains one relative to another. The grains do not spring back to their original positions upon removal of the stress. However, a small elastic rebound under low pressures could be attributed to the elastic compression of the adsorbed water surrounding the grains.

Soil engineering problems are of two types.

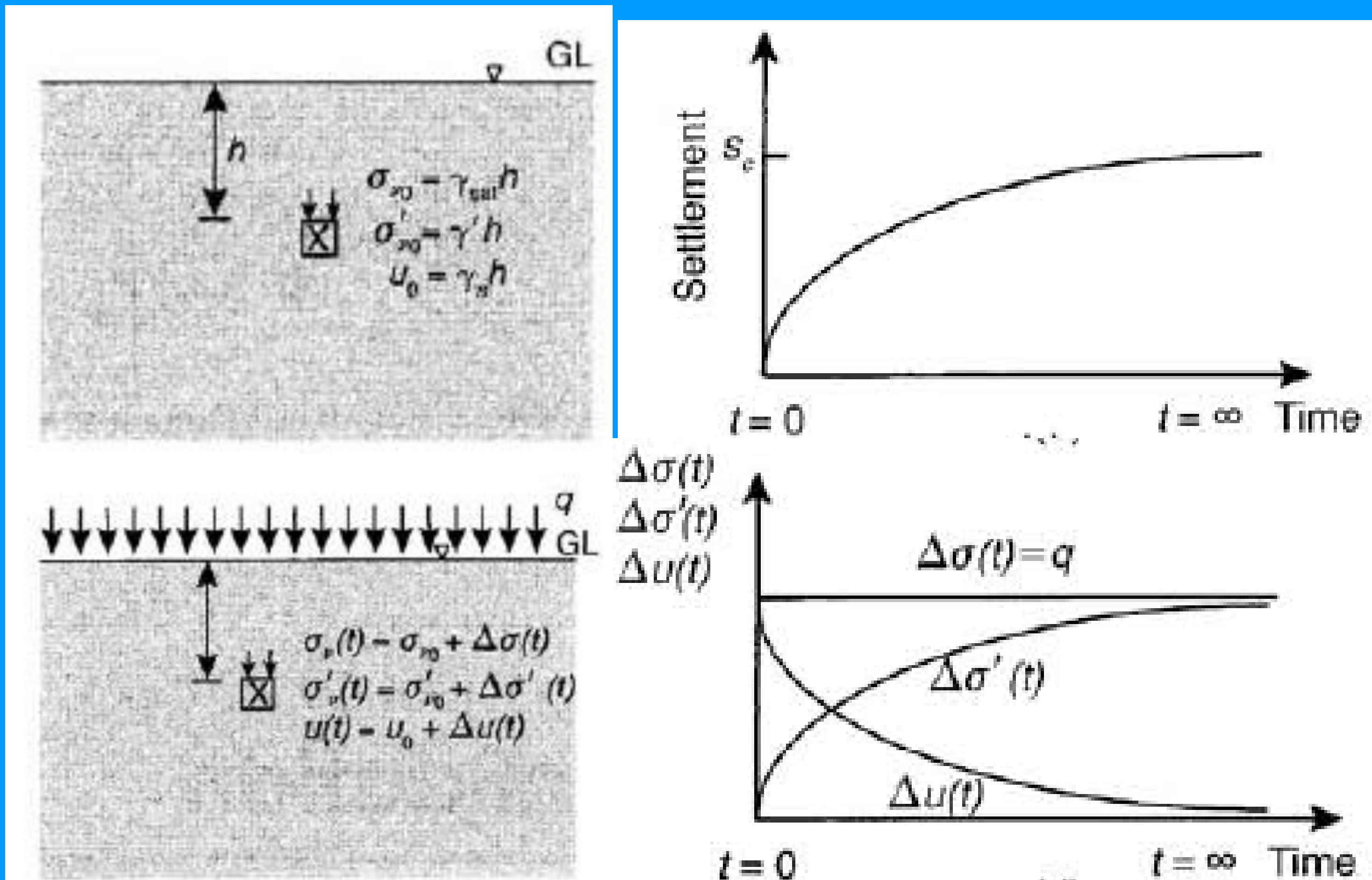
A. The first type includes all cases wherein there is no possibility of the stress being sufficiently large to exceed the shear strength of the soil, but wherein the strains lead to what may be a serious magnitude of displacement of individual grains leading to settlements within the soil mass.

B. The second type includes cases in which there is danger of shearing stresses exceeding the shear strength of the soil. Problems of this type are called *Stability Problems* which are dealt with under the chapters of earth pressure, stability of slopes, and foundations.

Soil in nature may be found in any of the following states

I. **Dry state.**
II. **Partially saturated state.**
III. **Saturated state.**

- **Settlements of structures built on granular soils are generally considered only under two states, that is, either dry or saturated. The stress-strain characteristics of dry sand, depend primarily on the relative density of the sand, and to a much smaller degree on the shape and size of grains. Saturation does not alter the relationship significantly provided the water content of the sand can change freely.**
- **However, in very fine-grained or silty sands the water content may remain almost unchanged during a rapid change in stress. Under this condition, the compression is time-dependent. Suitable hypotheses relating displacement and stress changes in granular soils have not yet been formulated. However, the settlements may be determined by semi-empirical methods (Terzaghi, Peck and Mesri, 1996).**
- **In the case of cohesive soils, the dry state of the soils is not considered as this state is only of a temporary nature. When the soil becomes saturated during the rainy season, the soil becomes more compressible under the same imposed load.**


GL
h
σv0 = γsat h
σ'v0 = γ'h
u0 = γw h
Settlement
sc
t = 0
t = ∞
Time
q
GL
σv(t) = σv0 + Δσ(t)
σ'v(t) = σ'v0 + Δσ' (t)
u(t) = u0 + Δu(t)
Δσ(t)
Δσ'(t)
Δu(t)
Δσ(t)=q
Δσ' (t)
Δu(t)
t = 0
t = ∞
Time

- **Settlement characteristics of cohesive soils are, therefore, considered only under completely saturated conditions. It is quite possible that there are situations where the cohesive soils may remain partially saturated due to the confinement of air bubbles, gases etc.**
- **Current knowledge on the behavior of partially saturated cohesive soils under external loads is not sufficient to evolve a workable theory to estimate settlements of structures built on such soils.**

TYPES OF SETTLEMENT

Based on degree & mode of settlement

1. **Uniform settlement**
2. **Non-uniform/Differential settlement**

Based on settlement process

1. **Immediate settlement**
2. **Consolidation settlement**

TOLERABLE AND NON-TOLERABLE SETTLEMENT

Depends mainly on the amount of settlement and type of structure

- **Due to structural loads, settlement small or large is inevitable.**
- **Some settlements are tolerable.**
- **Tolerable settlement depends on the amount and mode of settlement and the type of structure.**
- **Small uniform settlement of a building may be tolerable where as non-uniform settlement of the same magnitude for the same building may not be tolerable.**
- **Large uniform settlement may not be tolerable due to some reasons.**
- **Settlement of garage or warehouse may be tolerable whereas same amount of settlement (specially non-uniform) of a luxury hotel may not be allowed.**

CAUSES OF SETTLEMENT

1) **Static loads of structures.**
2) **Dynamic forces by machinery, traffic, piling operations, explosions, earthquakes. These factors loose the structural strength of soil, particularly for non-cohesive soil.**

3) Fluctuation of ground water table.

a. Natural lowering of GWT due to drought.
b. Artificial lowering of GWT due to de-watering for lying foundations in surrounding areas.
c. Rising of GWT by impounding water in reservoirs, floods, leakage through water or sewerage pipes.

4) Adjacent excavations.

5) Subsidence of soil caused by mining/tunneling

6) Settlement of frost-heaved soil.

a. Natural – from thawing
b. Artificial – under refrigeration houses

7) Lateral expulsion of soil underneath a foundation. This mode of settlement is noticeable when load is applied at the ground surface (particularly in sandy soil) over small area.

CONSOLIDATION

- **When a saturated clay-water system is subjected to an external pressure, the pressure applied is initially taken by the water in the pores resulting thereby in an excess pore water pressure. If drainage is permitted, the resulting hydraulic gradients initiate a flow of water out of the clay mass and the mass begins to compress. A portion of the applied stress is transferred to the soil skeleton, which in turn causes a reduction in the excess pore pressure. This process, involving a gradual compression occurring simultaneously with a flow of water out of the mass and with a gradual transfer of the applied pressure from the pore water to the mineral skeleton is called *consolidation.***
- **The process opposite to consolidation is called *swelling,* which involves an increase in the water content due to an increase in the volume of the voids.**

Consolidation may be due to one or more of the following factors:

1) **External static loads from structures.**
2) **Self-weight of the soil such as recently placed fills.**
3) **Lowering of the ground water table.**
4) **Desiccation.**

The total compression of a saturated clay strata under excess effective pressure may be considered as the sum of

1) **Immediate compression,**
2) **Primary consolidation, and**
3) **Secondary compression.**

- **The portion of the settlement of a structure which occurs more or less simultaneously with the applied loads is referred to as the *initial* or *immediate settlement.* This settlement is due to the immediate compression of the soil layer under undrained condition and is calculated by assuming the soil mass to behave as an elastic soil.**
- **If the rate of compression of the soil layer is controlled solely by the resistance of the flow of water under the induced hydraulic gradients, the process is referred to as *primary consolidation.* The portion of the settlement that is due to the primary consolidation is called *primary consolidation settlement* or *compression.* At the present time the only theory of practical value for estimating time-dependent settlement due to volume changes, that is under primary consolidation is *the one-dimensional theory.***

The third part of the settlement is due to secondary consolidation or compression of the clay layer. This compression is supposed to start after the primary consolidation ceases, that is after the excess pore water pressure approaches zero. It is often assumed that secondary compression proceeds linearly with the logarithm of time. However, a satisfactory treatment of this phenomenon has not been formulated for computing settlement under this category.

The Process Of Consolidation

The process of consolidation of a clay-soil-water system may be explained with the help of a mechanical model as described by Terzaghi and Frohlich (1936). The model consists of a cylinder with a frictionless piston as shown in Figure below. The piston is supported on one or more helical metallic springs. The space underneath the piston is completely filled with water. The springs represent the mineral skeleton in the actual soil mass and the water below the piston is the pore water under saturated conditions in the soil mass.

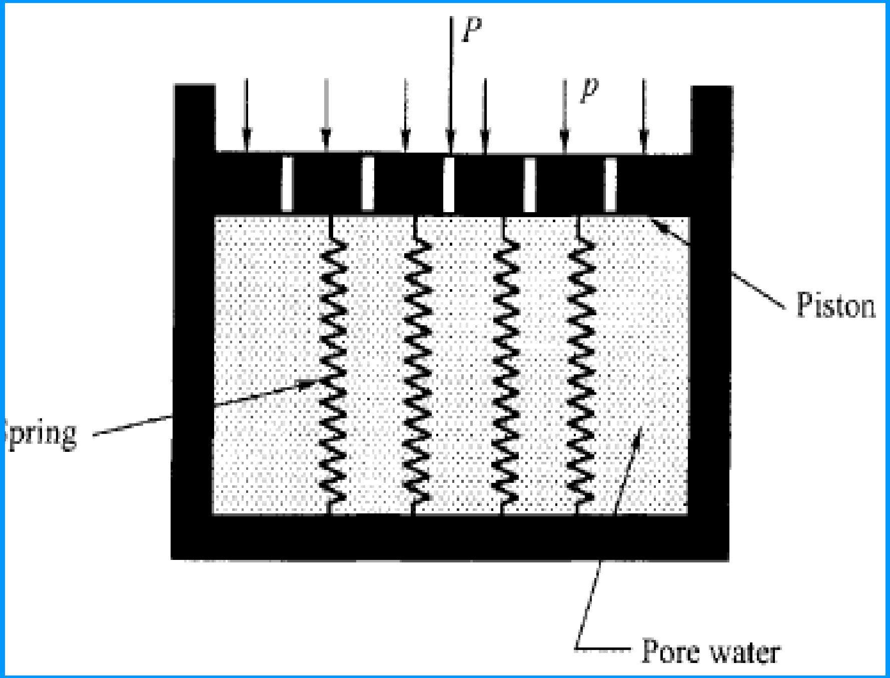


Figure : Mechanical model to explain the process of consolidation

When a load of *p* is placed on the piston, this stress is fully transferred to the water (as water is assumed to be incompressible) and the water pressure increases. The pressure in the water is

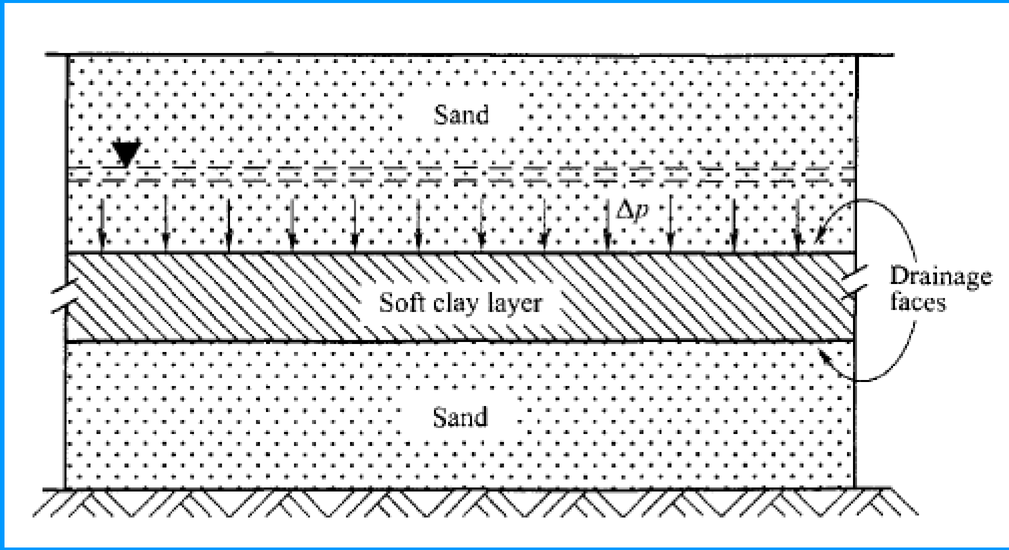
$$u = p$$

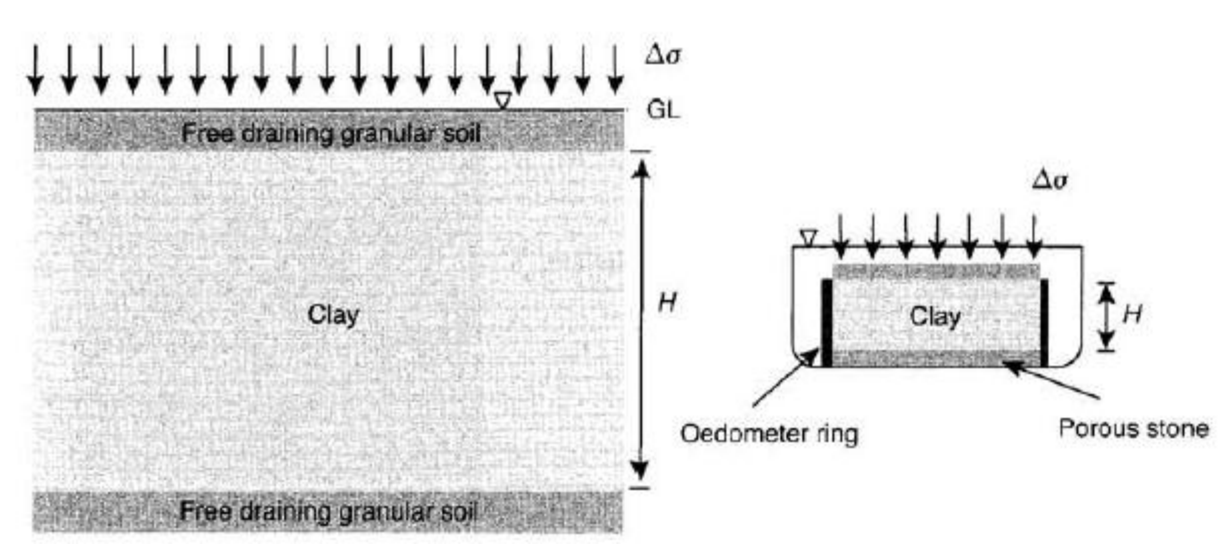
This is analogous to pore water pressure, *u,* that would be developed in a clay-water system under external pressures. If the whole model is leakproof without any holes in the piston, there is no chance for the water to escape. Such a condition represents a highly impermeable clay-water system in which there is a very high resistance for the flow of water.

- It has been found in the case of compact plastic clays that the minimum initial gradient required to cause flow may be as high as 20 to 30.
- If a few holes are made in the piston, the water will immediately escape through the holes. With the escape of water through the holes a part of the load carried by the water is transferred to the springs.
- This process of transference of load from water to spring goes on until the flow stops when all the load will be carried by the spring and none by the water.
- The time required to attain this condition depends upon the number and size of the holes made in the piston. A few small holes represents a clay soil with poor drainage characteristics.
- When the spring-water system attains equilibrium condition under the imposed load, the settlement of the piston is analogous to the compression of the clay-water system under external pressures.

One-Dimensional Consolidation

- In many instances the settlement of a structure is due to the presence of one or more layers of soft clay located between layers of sand or stiffer clay as shown below.
- The adhesion between the soft and stiff layers almost completely prevents the lateral movement of the soft layers. The theory that was developed by Terzaghi (1925) on the basis of this assumption is called the *one-dimensional consolidation theory.*
- In the laboratory this condition is simulated most closely by the *confined compression* or *consolidation test.*





Δσ
GL
Free draining granular soil
Clay
H
Free draining granular soil
Δσ
Clay
H
Oedometer ring
Porous stone

- The process of consolidation as explained with reference to a mechanical model may now be applied to a saturated clay layer in the field.
- If the clay strata shown in Figure is subjected to an excess pressure ▲***p*** due to a uniformly distributed load ***P*** on the surface, the clay layer is compressed over time and excess pore water drains out of it to the sandy layer.
- This constitutes the process of ***consolidation.*** At the instant of application of the excess load ▲***p***, the load is carried entirely by water in the voids of the soil.
- As time goes on the excess pore water pressure decreases, and the effective vertical pressure in the layer correspondingly increases.
- At any point within the consolidating layer, the value ***u*** of the excess pore water pressure at a given time may be determined from

$$u = u_i - \Delta p_z$$

where, u = excess pore water pressure at depth z at any time t

u_i = initial total pore water pressure at time $t = 0$

Δp_z = effective pressure transferred to the soil grains at depth z and time t

- At the end of primary consolidation, the excess pore water pressure ***u*** becomes equal to zero. This happens when ***u*** = 0 at all depths.
- The time taken for full consolidation depends upon the drainage conditions, the thickness of the clay strata, the excess load at the top of the clay strata etc.

The Standard One-Dimensional Consolidation Test

- **The main purpose of the consolidation test on soil samples is to obtain the necessary information about the compressibility properties of a saturated soil for use in determining the magnitude and rate of settlement of structures. The following test procedure is applied to any type of soil in the standard consolidation test.**
- **Loads are applied in steps in such a way that the successive load intensity, *p, is twice the* preceding one. The load intensities commonly used being 1/4, 1/2,1, 2,4, 8, and 16 tons/ft^2 (25, 50, 100,200,400, 800 and 1600 kN/m^2). Each load is allowed to stand until compression has practically ceased (no longer than 24 hours). The dial readings are taken at elapsed times of 1/4, 1/2, *1,2,4, 8,* 15, 30, 60, 120, 240, 480 and 1440 minutes from the time the new increment of load is put on the sample (or at elapsed times as per requirements). Sandy samples are compressed in a relatively short time as compared to clay samples and the use of one day duration is common for the latter.**
- **After the greatest load required for the test has been applied to the soil sample, the load is removed in decrements to provide data for plotting the expansion curve of the soil in order to learn its elastic properties and magnitudes of plastic or permanent deformations.**

The following data should also be obtained:

1) Moisture content and weight of the soil sample before the commencement of the test.
2) Moisture content and weight of the sample after completion of the test.
3) The specific gravity of the solids.
4) The temperature of the room where the test is conducted.