Components of Settlement

$$S_t = S_e + S_c + S_s$$

S_t = Total settlement

S_e = elastic (immediate) settlement

S_c = Primary consolidation settlement

S_s = Secondary consolidation settlement

CONSOLIDATION

A gradual reduction in volume change of a fully saturated soils of low permeability due to the drainage of pore water from soil voids

CONSOLIDATION SETTLEMENT

Time-dependent settlement in saturated fine-grained soils having a low coefficient of permeability.

Two components:

1. **Primary consolidation settlement**

   (extrusion of pore water from the void space)

2. **Secondary consolidation settlement**

   (readjustment of soil grains @ constant effective stress)

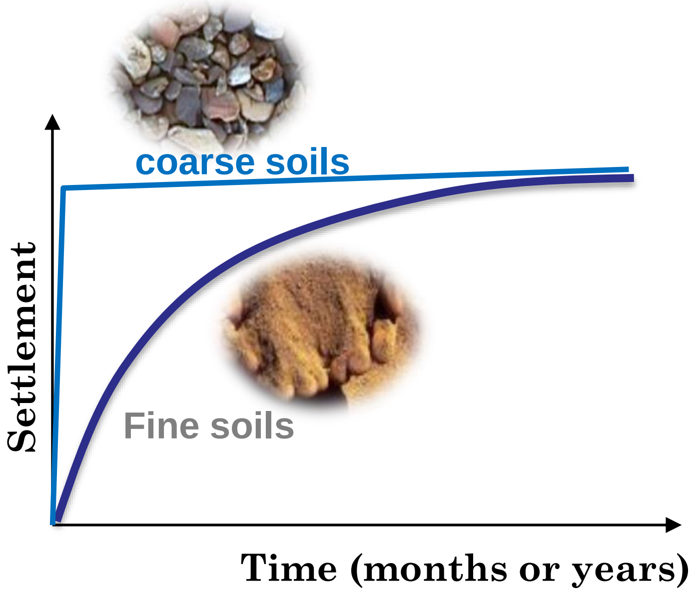
CONSOLIDATION SETTLEMENT

- **In coarse soils (sands & gravels) any volume change resulting from a change in loading occurs immediately; increases in pore pressures are dissipated rapidly due to high permeability. This is called drained loading.**

- **In fine soils (silts & clays) - with low permeability - the soil is undrained as the load is applied. Slow seepage occurs and the excess pore pressures dissipate slowly, and consolidation settlement occurs.**

- **In coarse soils (sand & gravel) the settlement takes place instantaneously.**
- **In fine soils (clay & silt): settlement takes far much more time to complete. Why?**

So, consolidation settlement: is decrease in voids volume as pore-water is squeezed out of the soil. It is only significant in fine soil (clays & silts).



CONSOLIDATION SETTLEMENT

In fine-grained soil the process requires along time interval for its completion and the nature of settlement is more difficult to analyze.

Gradual reduction in volume == gradual reduction in void ratio, e. Therefore we have to know the change in e in order to know settlement.

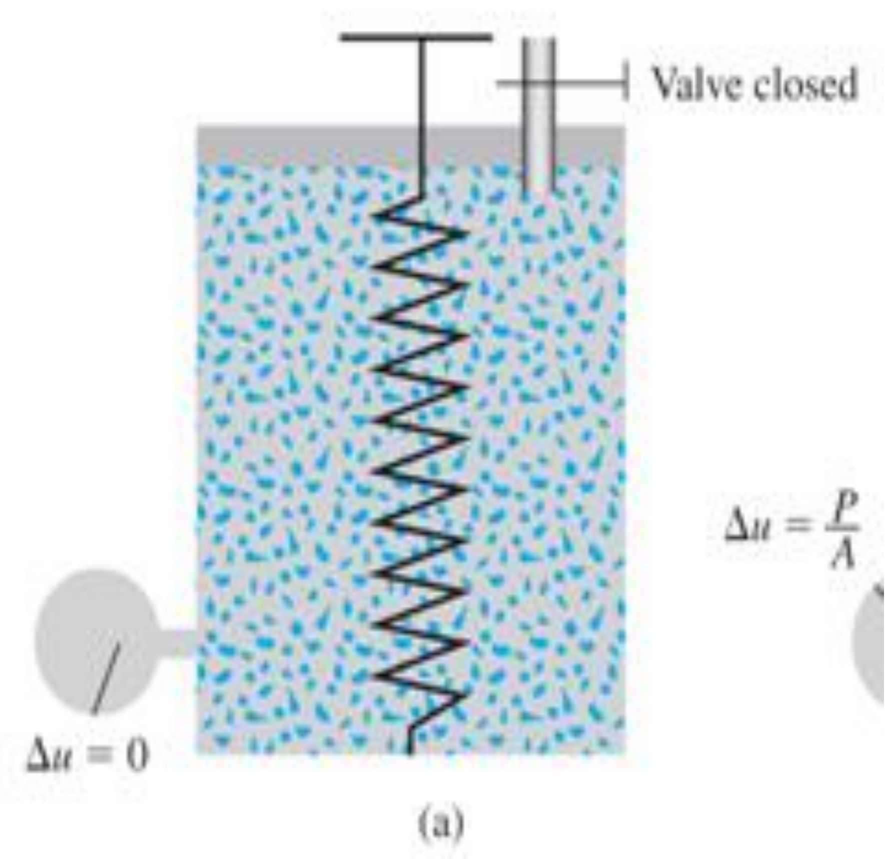
e is our internal variable that through it we can follow the change in soil volume.

Description of primary consolidation process

1. When a saturated soil layer is subjected to a stress increase, the external load is initially transferred to water causing sudden increase in the pore water pressure (excess pore water pressure).
2. Elastic settlement occurs immediately. However, due to the low coefficient of permeability of clay, the excess pore water pressure generated by loading gradually squeezes over a long period of time.
3. Eventually, excess pore pressure becomes zero and the pore water pressure is the same as hydrostatic pressure prior to loading.
4. The associated volume change (that is, the consolidation) in the clay may continue long after the elastic settlement.
5. The settlement caused by consolidation in clay may be several times greater than the elastic settlement.

Consolidation process – Spring analogy

i. At equilibrium under overburden stress



- System is analog to soil layer at equilibrium with weight of all soil layer (overburden) above it.
- In equilibrium, valve is closed.
- Piston is loaded, compresses a spring in chamber.
- Hydrostatic pressure = u_o

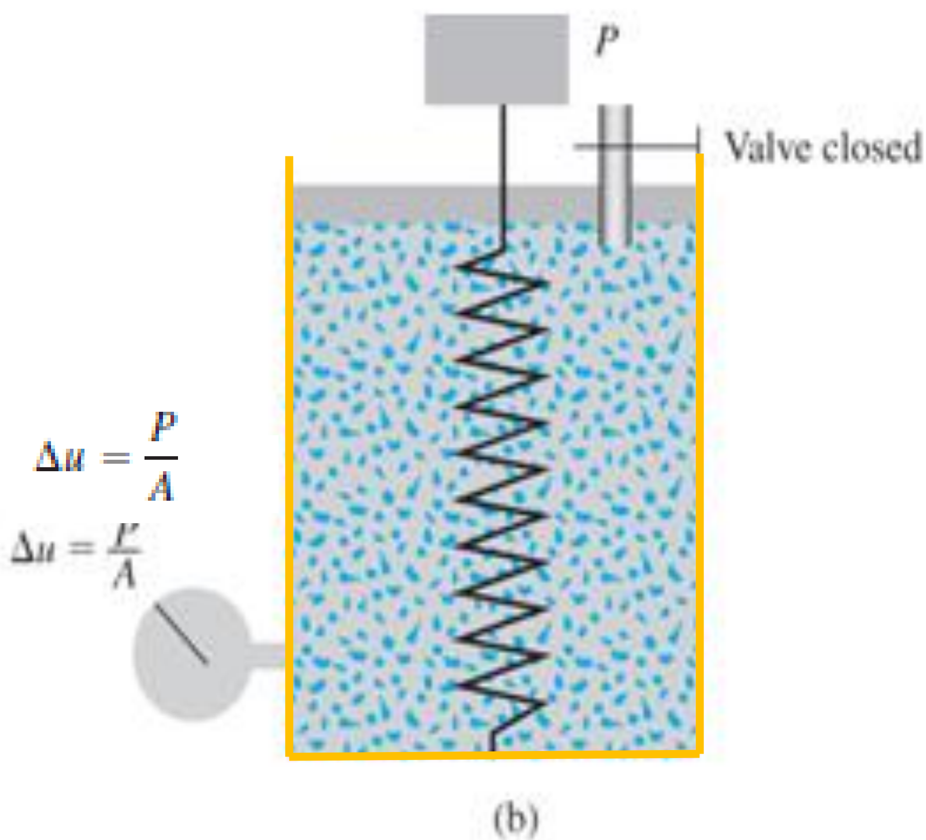
spring ≈ soil skeleton

water ≈ water in soil void

valve ≈ pore sizes in soil

Consolidation process- Spring analogy (cont.)

ii. Under Load (t = 0)



- **Soil is loaded by stress increment $\Delta\sigma$**
- **Valve is initially closed**
- **As water is incompressible and valve is closed, no water is out, no movement of piston.**
- **Stress is ($\Delta\sigma$) is transferred to water.**
- **Pressure gauge reads an excess pore pressure (Δu) such that:**

  $\Delta u = \Delta\sigma$

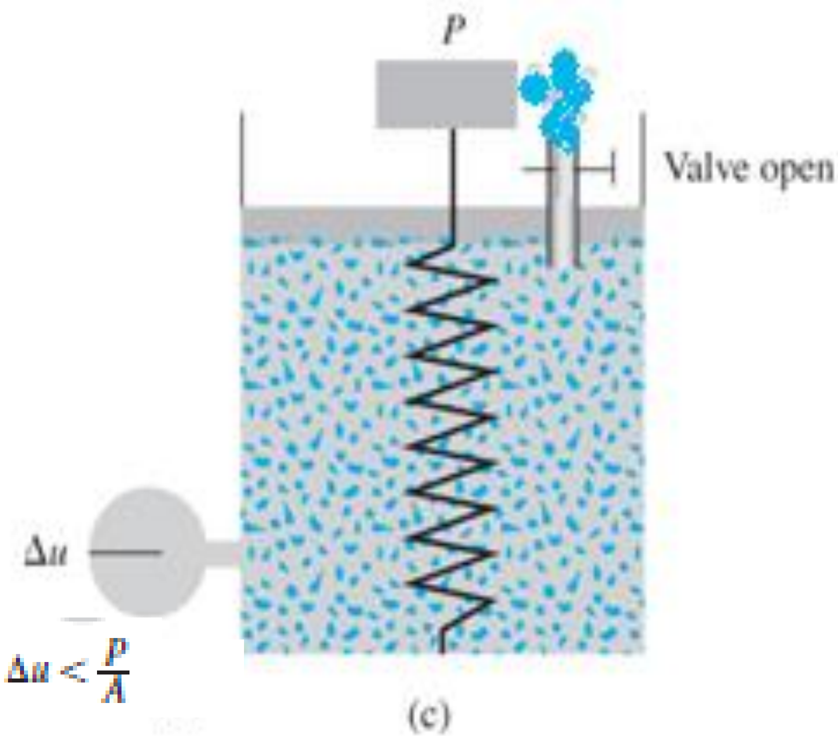
  $u = u_o + \Delta u$

From the principle of effective stresses:

$\Delta\sigma' = \Delta\sigma - \Delta u$ Then $\Delta\sigma' = 0$

Consolidation process- Spring analogy (cont.)

iii. Under Load ($0 < t < \infty$)



- **To simulate fine grained cohesive soil, where permeability is slow, valve is <u>slightly</u> opened.**
- **Water slowly leave the chamber.**
- **As water flows out excess pore pressure (Δu) decreases, and load is transferred to the spring.**
- **Settlement is observed.**

$\Delta u < \Delta\sigma$

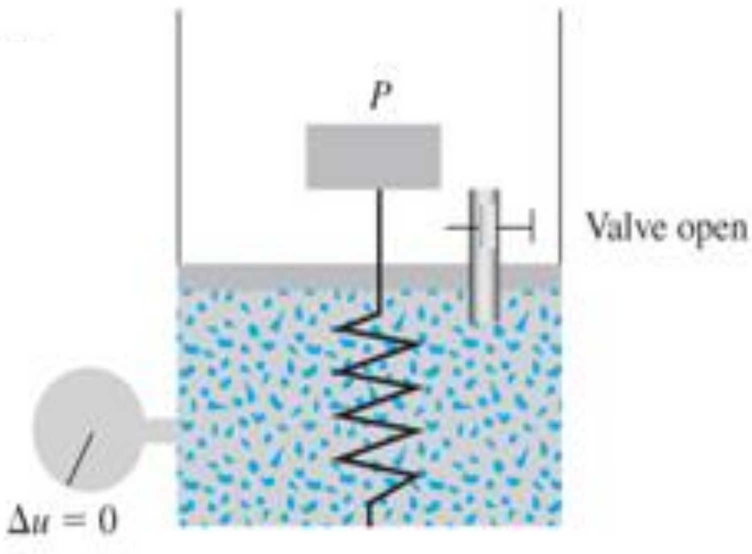
$u = u_o + \Delta u$

From the principle of effective stresses:

$\Delta\sigma' = \Delta\sigma - \Delta u$ $\quad \Delta u < \Delta\sigma$ $\quad$ Then $\Delta\sigma' > 0$

Consolidation process- Spring analogy (cont.)

iv. End of consolidation (t = ∞)



(d)

- At the end of consolidation, no further water is squeezed out, excess pore pressure is **zero.**
- Pore water pressure is back to hydrostatic.

$$\Delta u = 0$$

$$u = u_o$$

- The spring (soil) is in equilibrium with applied stress.
- **Final** (ultimate) settlement is reached.

All stresses are transferred to soil

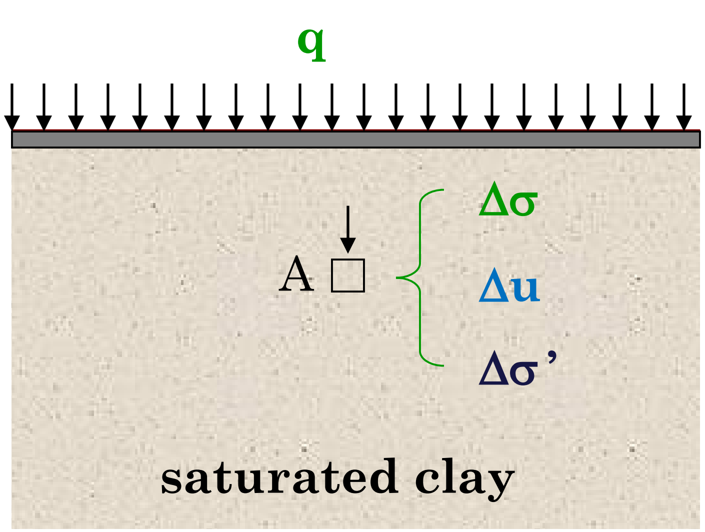
From the principle of effective stresses:

$\Delta\sigma' = \Delta\sigma - \Delta u$ $\quad \Delta u = 0$ $\quad$ Then $\Delta\sigma' = \Delta\sigma$

Short-term and long-term stresses

- With the spring analogy in mind, consider the case where a layer of saturated clay of thickness **H** that is confined between two layers of sand is being subjected to an instantaneous increase of total stress of **Δσ.**

- Due to a surcharge **q** applied at the **GL**, the stresses and pore pressures are increased at point **A** and, they vary with time.



The load q applied on the saturated soil mass, is **carried by pore water** in the beginning.

As the water starts escaping from the voids, the excess water pressure gets gradually **dissipated** and the load is shifted to the **soil solids** which increases the effective stress.

Short-term and long-term stresses

- $\Delta\sigma$, the increase in total stress remains the same during consolidation, while effective stress $\Delta\sigma'$ increases.

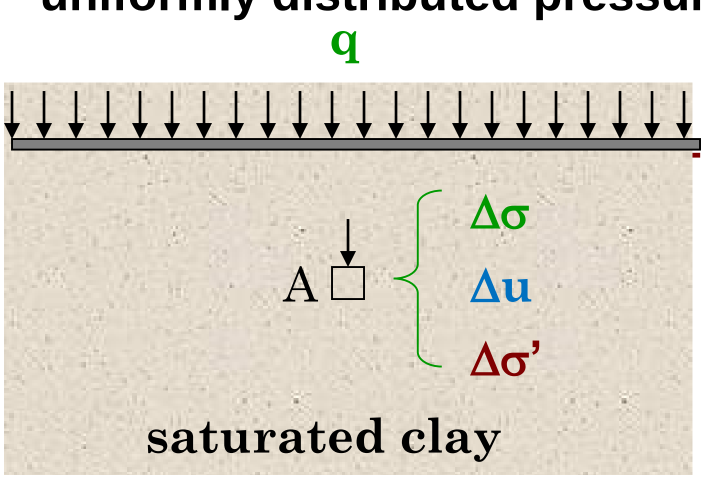
- Δu the excess pore-water pressure decreases (due to drainage) transferring the load from water to the soil.

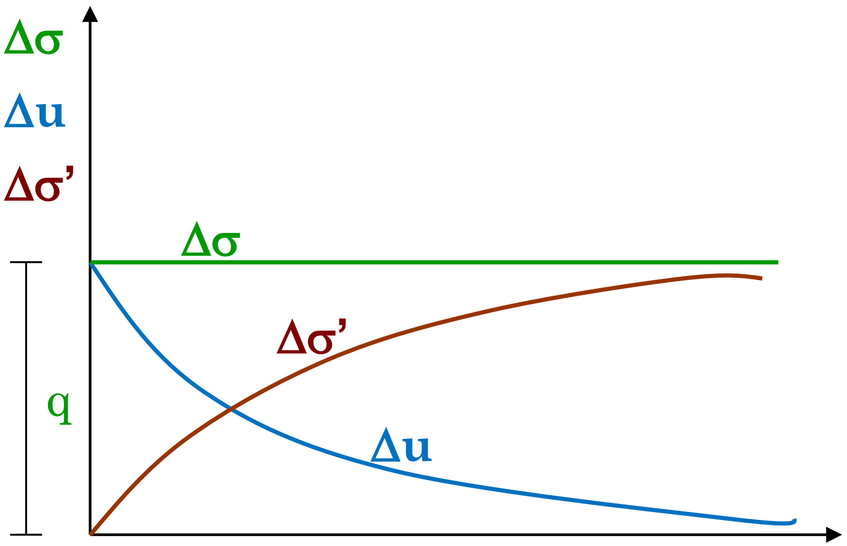
Excess pore pressure (Δu)

is the difference between the current pore pressure (u) and the steady state pore pressure (u_o).

$\Delta u = u - u_o$

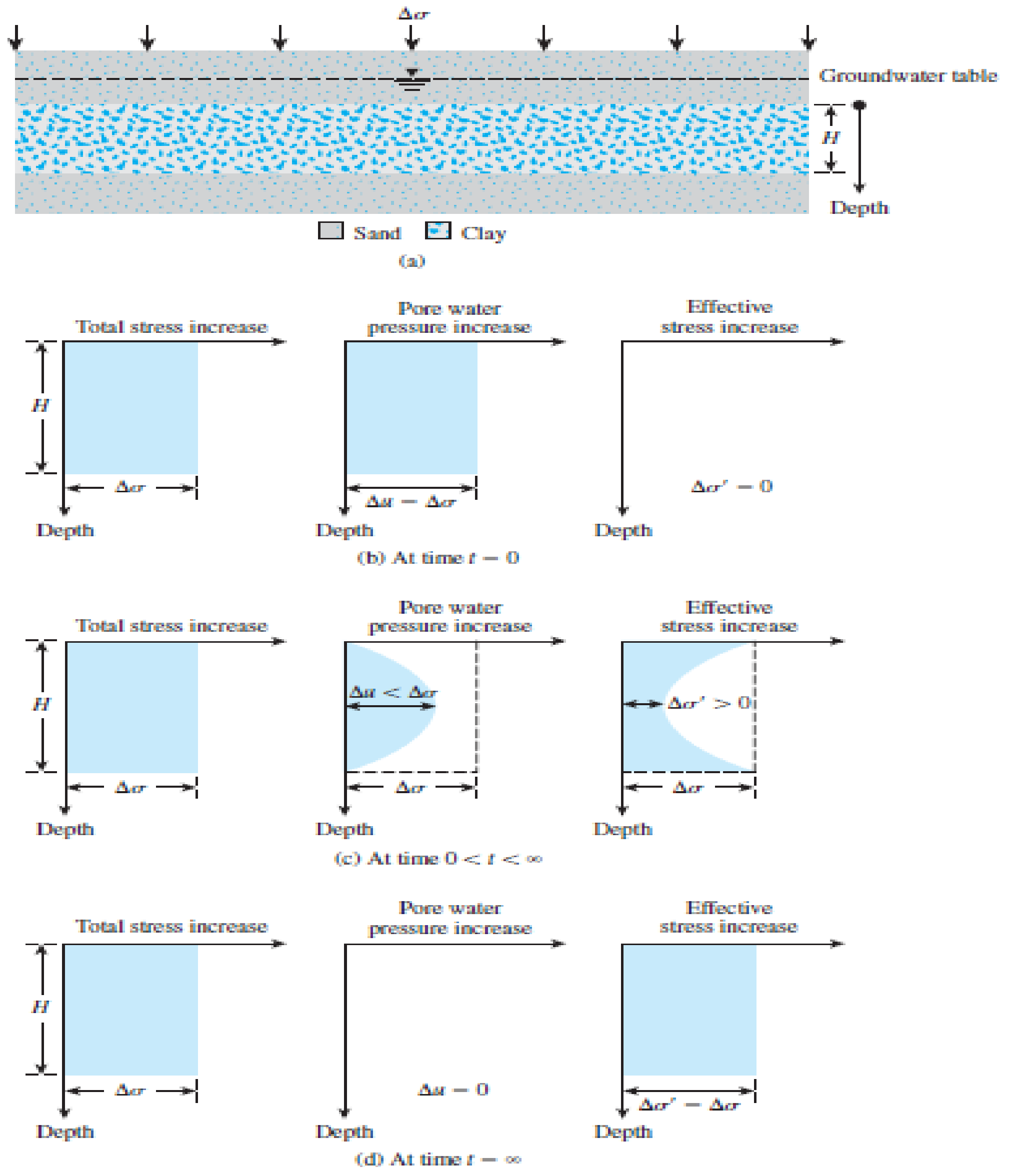
uniformly distributed pressure





Short-term and long-term stresses

- Variation of total stress [σ], pore water pressure [*u*], and effective stress [σ′] in a clay layer drained at top and bottom as a result of an added stress, Δσ.



Remark:

If an additional load is applied, the cycle just described will be repeated and further settlement will develop.

This is noticed in the consolidation test where for each load increment we get a t vs. e curve.

Example

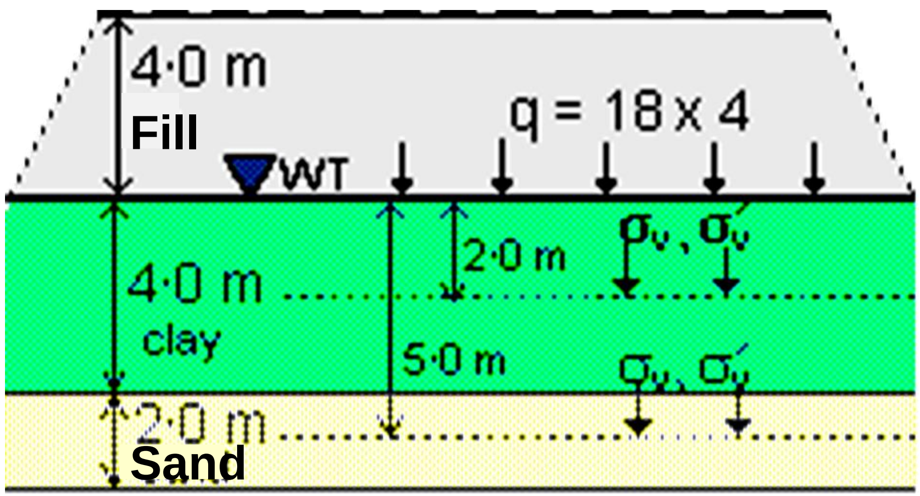
The figure below shows how an extensive layer of fill will be placed on a certain site.
The unit weights are:

Clay and sand = 20 kN/m³
Rolled fill =18 kN/m³
Water = 10 kN/m³

Calculate the total and effective stress at the mid-depth of the sand and the mid-depth of the clay for the following conditions:

(i) **Initially, before construction**
(ii) **Immediately after construction**
(iii) **Many years after construction**

Note: You know how to handle these cases from your background in CE382.
(we consider here the extreme cases with respect to loading time and the p.w.p is taken equal to the extended load).



Solution

(i) **Initially, before construction**

Initial stresses at mid-depth of clay (z = 2.0m)

Vertical total stress σ_v = 20.0 x 2.0 = 40.0kPa

Pore pressure u = 10 x 2.0 = 20.0 kPa

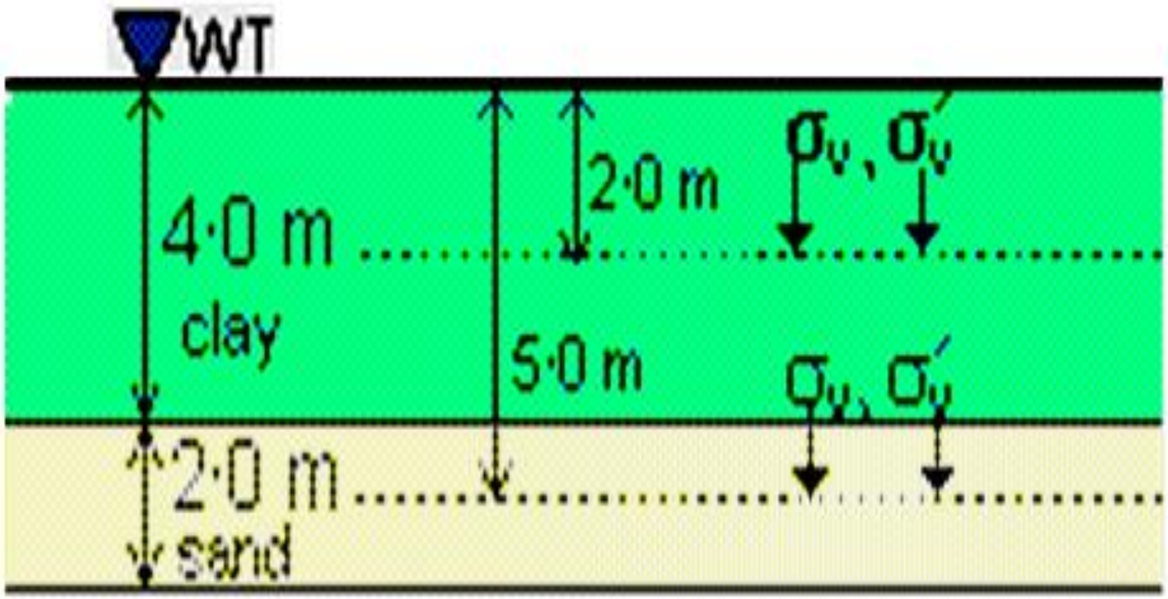
Vertical effective stress $\sigma'_v = \sigma_v$ - u = 20.0kPa

Initial stresses at mid-depth of sand (z = 5.0 m)

Vertical total stress σ_v = 20.0 x 5.0 = 100.0 kPa

Pore pressure u = 10 x 5.0 = 50.0 kPa

Vertical effective stress $\sigma'_v = \sigma_v$ - u = 50.0 kPa



Solution

(ii) **Immediately after construction**

The construction of the embankment applies a surface surcharge:

$q = 18 \times 4 = 72.0$ kPa.

The sand is drained (either horizontally or into the rock below) and so there is no increase in pore pressure.

The clay is undrained and the pore pressure increases by 72 kPa.

Initial stresses at mid-depth of clay (z = 2.0m)

Vertical total stress $\sigma_v = 20.0 \times 2.0 + 72.0 = 112.0$kPa

Pore pressure $u = 10 \times 2.0 + 72.0 = 92.0$ kPa

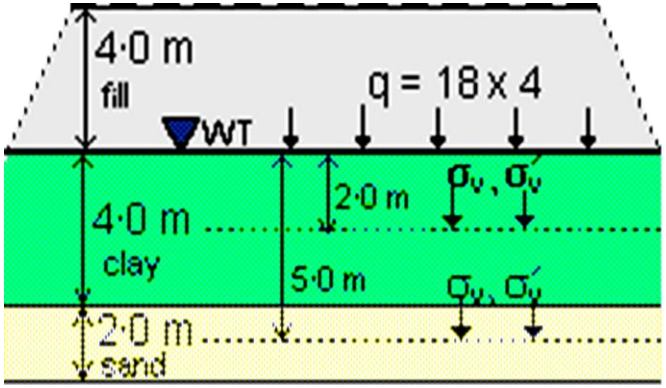
Vertical effective stress $\sigma'_v = \sigma_v - u = 20.0$kPa (i.e. no change immediately)

Initial stresses at mid-depth of sand (z = 5.0m)

Vertical total stress $\sigma_v = 20.0 \times 5.0 + 72.0 = 172.0$kPa

Pore pressure $u = 10 \times 5.0 = 50.0$ kPa

Vertical effective stress $\sigma'_v = \sigma_v - u = 122.0$kPa (i.e. an immediate increase)



Solution

(iii) **Many years after construction**

After many years, the excess pore pressures in the clay will have dissipated. The pore pressures will now be the same as they were initially.

Initial stresses at mid-depth of clay (z = 2.0 m)

Vertical total stress σ_v = 20.0 x 2.0 + 72.0 = 112.0 kPa

Pore pressure u = 10 x 2.0 = 20.0 kPa

Vertical effective stress $\sigma'_v = \sigma_v$ - u = 92.0 kPa (i.e. a long-term increase)

Initial stresses at mid-depth of sand (z = 5.0 m)

Vertical total stress σ_v = 20.0 x 5.0 + 72.0 = 172.0 kPa

Pore pressure u = 10 x 5.0 = 50.0 kPa

Vertical effective stress $\sigma'_v = \sigma_v$ - u = 122.0 kPa (i.e. no further change)

This gradual process of drainage under an additional load application and the associated transfer of excess pore water pressure to effective stress cause the time-dependent settlement in the clay soil layer. This is called consolidation.