13 Land Subsidence

R.J. de Glopper[1] and H.P. Ritzema[2]

13.1 Introduction

Subsidence is the downward movement of the ground surface. The term 'subsidence' includes one or more of the following processes:

- Compression/Compaction: Compression is the change in soil volume produced by the application of a static external load. Compaction is produced artificially by momentary load application such as rolling, tamping, or vibration (USDI 1974);
- Consolidation: The gradual, slow compression of a cohesive soil due to weight acting on it, which occurs as water, or water and air, are driven out of the voids in the soil (Scott 1981);
- Shrinkage: The change in soil volume produced by capillary stress during drying of the soil (USDI 1974);
- Oxidation: The process by which organic carbon is converted to carbon dioxide and lost to the atmosphere (Young 1980).

A prediction of possible subsidence and its magnitude is of great importance in a land reclamation or drainage project (Section 13.2). The effect of compression of clay and sandy subsoils, and their possible consolidation, can be calculated with standard equations of soil mechanics (Section 13.3). These equations, however, are not appropriate for predicting the topsoil shrinkage of newly reclaimed clay or peat soils. Instead, Section 13.4, after explaining the process of physical ripening, presents two methods by which this shrinkage can be predicted: an empirical method and a numerical simulation method. Section 13.5 treats the subsidence of organic soils. Finally, Section 13.6 concludes this chapter with the calculation of the total subsidence and a discussion of the applicability of the various methods.

13.2 Subsidence in relation to Drainage

Of the four processes recognized in the previous section, those that involve soil mechanics are compression/compaction and consolidation; they occur both naturally and by man's manipulation (Allen 1984). Consolidation only occurs in clays or other soils of low permeability. Consolidation is not the same as compaction, which is a mechanical, immediate process, which only occurs in soils with at least some sand. The amount of subsidence brought about by these processes is a function of the pore space in the original material, the effectiveness of the compacting mechanism, and the thickness of the deposit undergoing compaction.

Shrinkage is a process involving soil physics. Irreversible shrinkage can occur as the result of the physical ripening of a newly reclaimed soil. The subsidence that results

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[1] Retired from the Department of Public Works and Water Management, Flevoland Directorate, Lelystad

[2] International Institute for Land Reclamation and Improvement

from shrinkage is mainly a function of the moisture content of the soil and the abstraction of soil water by evapotranspiration.

Oxidation is a biochemical process that occurs in organic soils. It is caused by microorganisms utilizing organic compounds as sources of both energy and carbon. The process depends on the air and water conditions in the soil.

The subsidence of agricultural land can be caused by many processes, the most important of which are:

1) Compression – and consolidation if the material is clay or peat – as a result of a lowering of the watertable to improve the drainage conditions in waterlogged areas;
2) Compression – and consolidation if the material is clay or peat – of deep layers as a result of the extraction of gas, oil, or water (for irrigation or other purposes). The mechanisms involved are the same as in 1), but the effect can be much more severe if the watertable is lowered to extreme depths. In California, groundwater withdrawal has led to land subsidence of as much as 9 m (Poland 1984);
3) Compression – and consolidation if the material is clay or peat – of the subsoil by an overburden that has been placed on the soil (e.g. a canal embankment);
4) Irreversible shrinkage as a result of the physical ripening of soft sediments after an improvement in the drainage conditions;
5) Loss of soil particles as a result of the oxidation of organic matter;
6) Loss of soil particles as a result of the leaching of mineral components. This loss is generally so small that it can be neglected;
7) Hydrocompaction as a result of the moistening of very loose and dry fine-textured sediments in arid regions. Hydrocompaction is mainly associated with irrigation projects underlain by loess and mudflow deposits and is beyond the scope of this chapter. A review of subsidence caused by hydrocompaction is presented by Lofgren (1969);
8) Tectonic movements, the subsurface solution of rock salt, gypsum, or carbonate rocks, and activities like mining can all cause subsidence (Allen 1984), but these topics are also beyond the scope of this chapter.

In the planning of agricultural land drainage projects, subsidence can have effects on land use, on drainage, and on buildings, structures, and embankments, as will be discussed below.

Land Use

Subsidence can be a major factor in assessing the potential for land reclamation. The reclamation of peat soils will always result in the oxidation of these layers; the rate at which this occurs will determine the feasibility of the project. The effect of oxidation can be seen in the western part of The Netherlands, where, since their reclamation in the Middle Ages, peat areas have gradually subsided from 0.5 m above mean sea level to 1 to 2 m below. So, over a period of 8 to 10 centuries, the surface has subsided about 2 m, in spite of a continuously shallow drainage. Some 85% of this subsidence can be ascribed to the oxidation of organic matter, which will continue at a rate of 2 mm/year (Schothorst 1982). Drainage has a direct effect on this rate of subsidence; for example, a 0.50 m deeper drainage, needed for a shift from pasture to grain crops, will increase the subsidence rate to 6 mm/year.

Subsidence also alters the soil conditions. Recently drained clay soils are soft and impassable. The process of physical ripening will result in a better workability and a higher load-bearing capacity, and will thus increase the number of workable days. On the other hand, shrinkage may reduce the water-holding capacity; soils may then become susceptible to drought and may require irrigation in the future.

Drainage

Subsidence will affect the future elevation of the reclaimed area. Consequently, it will affect the water levels in the drainage system, the possibility of drainage by gravity, and the lift and capacity of pumping stations. It will increase or decrease (or even reverse) the longitudinal slopes in the main drain system, the elevation of sills and sluices, and the crest heights of weirs and revetments. Unlike compaction, which is an immediate process, consolidation will continue for considerable time, so provisions have to be made in the design to guarantee the future use. Moreover, subsidence often varies over short distances, depending on variations in the thickness and softness of the subsiding layer. This may disarrange the drainage and irrigation systems.

The importance of a correct prediction of subsidence is demonstrated in the IJsselmeerpolders in The Netherlands. There, in the first century after reclamation, subsidence will vary between 0.50 and 1.50 m (De Glopper 1989). Compared with other areas (e.g. California, Mexico City), where subsidence of as much as 5 to 9 m has been observed, these values are relatively small, but the consequences are nevertheless far-reaching.

Buildings, Structures, and Embankments

In areas with low bearing capacities, buildings and structures have to be built on pile foundations. Subsidence will change the relative elevation of piled buildings and structures with respect to the surrounding area. The areas surrounding these buildings and structures will have to be raised from time to time by the addition of earth or other fill material; this, in its turn, will cause additional subsidence. Special measures have to be taken in connecting utilities (power lines, water mains, etc.).

On soils with soft clay or peat layers, the design height of embankments has to be corrected to take the future subsidence into account; otherwise, the safety requirements may not be met.

The factors that influence the rate and degree of subsidence are the following (Segeren and Smits 1980):

- Clay content: The water content in sediments is linearly related to their clay content; hence clayey sediments lose more water than sandy sediments. As a consequence, clay soils will subside more;
- Depth of the layer in the profile: The loss of water in the different soil layers decreases with depth. The number of roots and their water uptake similarly decrease with depth. Beside this, deeper layers are closer to the watertable and will thus be kept moist by capillary rise. So the subsidence caused by the shrinkage of the different soil layers at a given clay content decreases with depth;
- The thickness of compressible layers: The greater the thickness of the compressible layers, the greater will be the subsidence;
- Organic matter content: The water content depends to some extent on the organic

matter content. Mineral soils containing high contents of organic matter show greater degrees of subsidence. The oxidation of the organic matter not only results in the loss of the organic matter, but also in the loss of the water associated with it;

- Type of crop: As different crops are characterized by different evapotranspiration rates, their influence on subsidence also differs. The difference may be due to the depth of the rooting system; compare, for instance, alfalfa with its deep rooting system and grass with its shallow rooting system. The length of the growing period is another important factor: spring-sown cereals harvested in midsummer have a lower total evapotranspiration than perennial crops like grass or alfalfa;
- Density of the soil: Sediments with different pore volumes (and different water contents) show different water losses and hence different degrees of subsidence. Sea- and lake-bottom soils have a lower density than sea-shore deposits exposed at each low tide. During the formation of such sea-shore deposits, shrinkage already occurs and thus also subsidence;
- Field drainage conditions: Under poor drainage conditions, which often prevail in the first years after reclamation, the shrinkage may be limited because the watertable is still high and consequently the capillary stresses are low. Thus, under these conditions, the rate of subsidence will be less than in well-drained soils;
- Climatic conditions: The drier the climate, the more water will be lost, and hence the greater will be the subsidence;
- Time: Subsidence, both that caused by consolidation and that by shrinkage, is a function of time. As shrinkage is caused by the physical ripening of the soil, the rate of subsidence will decrease with time.

The influence of the above-mentioned factors on each of the processes involved in subsidence will be discussed in the following sections.

13.3 Compression and Consolidation

In the theory of both compression and consolidation, which are the soil mechanical components of subsidence, the crucial factor is the intergranular pressure or effective stress in the soil (Section 13.3.1). The factor time is not considered in the compression of sandy soils; each change in pressure, brought about by an increased load or a lowering of the watertable, results in an instantaneous subsidence. For clay or peat soils, however, the process is much more complicated, and the factor time becomes important. The subsidence in such soils can be calculated with Terzaghi's consolidation theory (Section 13.3.2). The problems one faces in using the consolidation equations are discussed in Section 13.3.3.

13.3.1 Intergranular Pressure

Soil consists of three components: solids or granules, air, and water (Chapter 11). In this section, we consider a fully saturated soil profile; thus all pores are completely filled with water.

The intergranular pressure or effective stress is defined as the pressure transmitted through the contact points of the individual solids (Bouwer 1978). If we increase the intergranular pressure (e.g. by placing a load on top of the soil or by lowering the watertable), the individual solids move relative to each other to produce a lower void ratio; hence the material is compressed.

The void ratio is defined as the volume occupied by the voids (pores), divided by the volume of the solids.

The intergranular pressure at a given depth can be calculated as the difference between the total ground pressure and the hydraulic pressure at that depth (Terzaghi and Peck 1967)

$$p_i = p_t - p_h \tag{13.1}$$

in which

p_i = intergranular pressure or effective stress (kPa)
p_t = total ground pressure (kPa)
p_h = hydraulic or water pressure (kPa)

This equation becomes clear if we consider the vertical forces acting on an imaginary horizontal plane. The downward force on the plane is equal to the weight of the soil and the groundwater above it. But, because of hydraulic pressure, there is also an upward force against the bottom of the plane. The difference between the downward and the upward forces is the net load on the plane, which acts on the individual solids at their contact points. The total pressure at a given depth is calculated as the weight per unit area of all solids and groundwater above that point.

How the different soil pressures are calculated is demonstrated in Example 13.1.

Example 13.1

The watertable in a soft clay layer (6 m thick) on top of a non-subsiding dense sand layer reaches the ground surface (Figure 13.1). The porosity of the clay layer (ε), which is defined as the ratio between the volume of voids V_v and the total volume V (Chapter 3.4.2), is 0.75. The density of the solids (ρ_s) is 2660 kg/m³. What will happen to the intergranular pressure if the watertable is lowered 1 m and if we assume that the soil in the top 1.0 m will continue to be saturated?

The mass of the solids in 1 m³ of the clay layer is

$$m_s = (1 - \varepsilon)\,\rho_s = (1 - 0.75) \times 2660 = 665\ \text{kg}$$

and the mass of the water ($\rho_w = 1000\ \text{kg/m}^3$) filling the pores between the solids is

$$m_w = \varepsilon \times \rho_w = 0.75 \times 1000 = 750\ \text{kg}$$

Thus the wet bulk density of the clay layer is

$$\rho_{wb} = 665 + 750 = 1415\ \text{kg/m}^3$$

At 4.0 m below the ground surface, the total pressure equals

$$p_t = \rho_{wb}\,g\,h = 1415 \times 10 \times 4.0 = 56\,600\ \text{Pa} = 56.6\ \text{kPa}$$

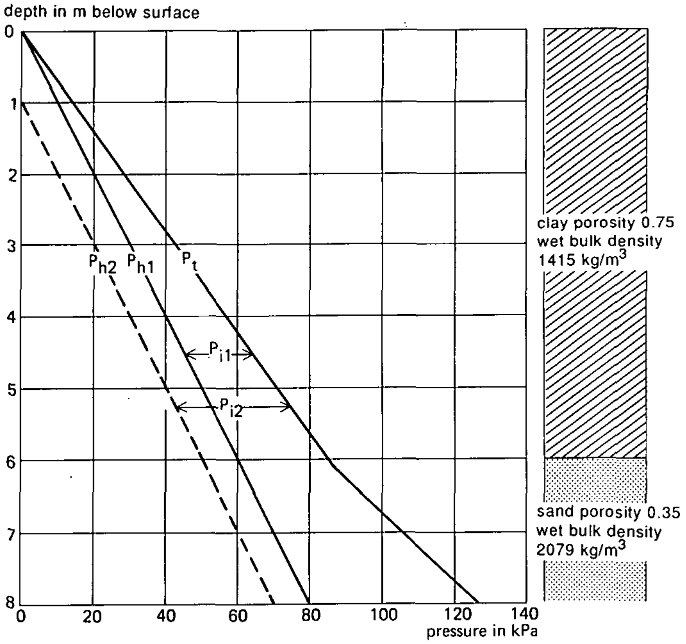


Figure 13.1 The relationship between the total pressure (p_t), the hydraulic pressure before (p_{h1}) and after (p_{h2}) the watertable is lowered, and the matching intergranular pressures (p_{i1} and p_{i2}) in a soft clay overlying a dense sand (Example 13.1)

in which

g = acceleration due to gravity ($\approx$ 10 m/s^2)
h = hydraulic head (m)

The water or hydraulic pressure at this level is

$$p_h = \rho_w g h = 1000 \times 10 \times 4.0 = 40.0 \text{ kPa}$$

Hence the intergranular pressure is (Equation 13.1)

$$p_i = p_t - p_h = 56.6 - 40.0 = 16.6 \text{ kPa}$$

Lowering the watertable by 1.0 m reduces the hydraulic pressure by 10.0 kPa. This lower value of p_h is indicated by the dotted line in Figure 13.1. Because we have assumed that the soil in the top 1.0 m remains saturated, the total pressure will not change and thus the intergranular pressure will increase. At the depth of 4.0 m, for example, the total ground pressure is still 56.6 kPa, but the hydraulic pressure has decreased to

$$P_h = 1000 \times (4-1) \times 10.0 = 30.0 \text{ kPa}$$

and thus the intergranular pressure becomes

$$P_i = 56.6 - 30.0 = 26.6 \text{ kPa}$$

An increase in the intergranular pressure results in a decrease in the void ratio, and hence a compression of the soil layer, and consequently a subsidence of the ground surface, as discussed below.

13.3.2 Terzaghi's Consolidation Theory

If the watertable is lowered or a load (e.g. an embankment) is placed on the soil surface, the intergranular pressure in the soil profile will increase. The subsidence resulting from this increase in soil pressure can be described by the classical theory of soil mechanics developed by Terzaghi in 1925 (Terzaghi and Peck 1967). This theory is based on the following assumptions:

- The soil is homogeneous and completely saturated with water;
- The solids and the water are incompressible;
- The hydraulic conductivity is constant during the consolidation process.

Terzaghi found a relation between the increase in intergranular pressure and the void ratio

$$e_u = e_i - C_c \ln \frac{p_i + \Delta p_i}{p_i} \tag{13.2}$$

in which

e_u = ultimate void ratio (= ratio between the ultimate volume of pores and the volume of solids; –)
e_i = initial void ratio (= ratio between the initial volume of pores and the volume of solids; –)
C_c = compression index (–)
p_i = average intergranular pressure in the considered soil layer before the loading and/or the lowering of the watertable (kPa)
Δp_i = increase in the average intergranular pressure after loading and/or lowering the watertable (kPa)

The increase in pressure can be caused by an external load on the surface or by a lowering of the watertable. As the solids are incompressible and no solids are lost, the subsidence can be solely attributed to a decrease in the volume of voids (Figure 13.2).

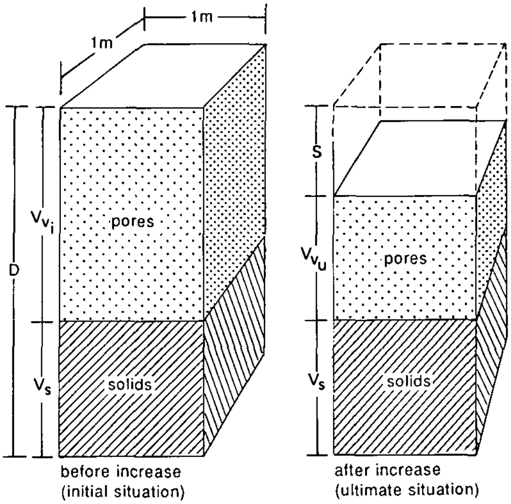
$$S = \frac{e_i - e_u}{e_i + 1} \times D \tag{13.3}$$

in which

S = subsidence (m)
D = thickness of the original soil layer (m)

We can express the subsidence as a function of the intergranular pressure by substituting Equation 13.2 into Equation 13.3

$$S = \frac{1}{c} \ln \left(\frac{p_i + \Delta p_i}{p_i} \right) \times D \tag{13.4}$$



initial void ratio:

$$e_i = \frac{V_{v_i}}{V_s} \left(= \frac{\text{initial volume of voids}}{\text{volume of solids}} \right) \longrightarrow V_{v_i} = e_i V_s$$

ultimate void ratio:

$$e_u = \frac{V_{v_u}}{V_s} \left(= \frac{\text{ultimate volume of voids}}{\text{volume of solids}} \right) \longrightarrow V_{v_u} = e_u V_s$$

$$\frac{S}{D} = \frac{V_{v_i} - V_{v_u}}{V_{v_i} + V_s} = \frac{e_i V_s - e_u V_s}{e_i V_s + V_s} = \frac{e_i - e_u}{e_i + 1}$$

Figure 13.2 Subsidence as the difference between the initial and ultimate volume of voids before and after the increase in intergranular pressure

in which

$$c = \text{compression constant} \left(= \frac{C_c}{e_i + 1} \right)$$

The value of the compression constant c depends on the soil type. An indication of magnitudes is given in Table 13.1.

The exact value for a specific soil is difficult to establish, as will be discussed in Section 13.3.3. If the compression constant is known, the subsidence can be calculated, as will be demonstrated in Example 13.2.

Table 13.1 Indication of values of the compression constant c (after Euroconsult 1989)

Soil type	Range
Sand, densely packed	100 - 200
Sand, loosely packed	20 - 100
Clay loam	20 - 30
Clay	10 - 25
Peat	2 - 10

Example 13.2

Considering the same soil profile as in Example 13.1, we shall calculate the subsidence of the ground surface caused by the compression of the clay layer. The compression constant has been determined in a laboratory and equals 12. The calculation is based on the averages of the hydraulic and intergranular pressure before and after the watertable is lowered. Before the watertable is lowered, the pressures at 6.0 m depth are

Total pressure: $p_t = \rho_{wb}\, g\, h = 1415 \times 10 \times 6.0 = 84.9\,\text{kPa}$

Hydraulic pressure: $p_h = \rho_w\, g\, h = 1000 \times 10 \times 6.0 = 60.0\,\text{kPa}$

Thus the intergranular pressure at this depth is (Equation 13.1)

$$p_i = p_t - p_h = 84.9 - 60.0 = 24.9\,\text{kPa}$$

After the watertable is lowered, the total pressure remains the same (because we have assumed that the soil profile remains saturated up to the surface). However, the hydraulic pressure decreases and, consequently, the intergranular pressure increases. At 6.0 m depth, these pressures become respectively

$$p_h = 1000 \times 10 \times 5.0 = 50.0\,\text{kPa}$$

$$p_i = p_t - p_h = 84.9 - 50.0 = 34.9\,\text{kPa}$$

To calculate the compression of the clay layer, we first have to calculate the average pressures in this layer, both before and after the watertable is lowered. Before the watertable is lowered the average intergranular pressure is 42.45 − 30.0 = 12.45 KPa and after the watertable is lowered this has become 42.45 − 25.0 = 17.45 KPa. The increase in the average intergranular pressure is

$$\Delta p_i = 17.45 - 12.45 = 5.0\,\text{kPa}$$

We can now calculate the total compression with Equation 13.4

$$S = \frac{1}{c} \ln \left(\frac{p_i + \Delta p_i}{p_i}\right) \times D = \frac{1}{12} \ln \left(\frac{12.45 + 5.0}{12.45}\right) \times 6.0 = 0.17\,\text{m}$$

The problem is more complicated if we do not assume that the soil above the watertable remains saturated. In that case, the unsaturated top layer will have a different wet bulk density and we have to divide the clay profile into two layers: one layer above the watertable and one below it. We can now calculate the compression of each layer in the same way as we did in Example 13.2.

The above equations do not take the factor time into consideration. In them, it is assumed that an increase in intergranular pressure results in an instantaneous subsidence. As stated earlier, this assumption is valid for sandy soils, but, for clay or peat soils, subsidence will continue for a long time. Keverlingh Buisman (1940) showed that, for these soils, the subsidence proceeds proportionally with the logarithm of time. Koppejan (1948) combined the relations found by Terzaghi and Keverlingh Buisman into one equation, which reads

$$S(t) = \left[\left(\frac{1}{c_p} + \frac{1}{c_s} \log t\right) \ln \left(\frac{p_i + \Delta p_i}{p_i}\right)\right] \times D \qquad (13.5)$$

in which

$S(t)$ = subsidence as a function of time (m)
c_p = consolidation constant (direct effect; –)
c_s = consolidation constant (secular effect; –)
t = time since loading or lowering the watertable (days)

The consolidation constants stand for, respectively, the direct and the secular effect of the subsidence. The direct effect is that part of the subsidence that occurs the first day after the load increase. The secular effect stands for that part of the subsidence that occurs as the excess water is drained out of the soil profile. This is a very slow process, especially in clay soils, because of their low hydraulic conductivity. The secular effect will cause the subsidence to continue indefinitely.

Equation 13.5 is based on the assumption that c_p and c_s are independent of the size of the load, but c_p depends on the selected time period (one day).

13.3.3 Application of the Consolidation Equations

In applying the consolidation theory, we face a number of problems. Difficulties arise in determining not only the consolidation constants but also the total and the hydraulic pressures.

Determining the Consolidation Constants

Small undisturbed soil samples are used to determine the consolidation constants. The samples are contained in a ring (height 20 mm, diameter 64 mm) and placed in a consolidometer. In this apparatus, the top and bottom of the sample are confined by porous plates to allow the excess water to drain from the sample after it is loaded and consequently compressed. The load applied is increased step by step, and the subsidence is measured after each step (Figure 13.3). From the relation between the subsidence, the applied load, and the time, we can derive the consolidation constants. A similar test is described in The Earth Manual (USDI 1974).

The small samples (64 cm^3) used to determine the consolidation constants are not very representative because soil is a highly heterogeneous medium, especially if such samples are supposed to be representative of vast areas. Collecting the samples with soil-drilling equipment and testing them in the laboratory are both costly affairs. There is therefore a tendency to restrict the number of samples taken, which reduces their reliability even further.

An alternative way of calculating the consolidation constants has proved successful in The Netherlands. With this method, consolidation constants are estimated from the initial porosity, because clear correlations were established (Figure 13.4). The advantages of this method are:

- The same data can be used as are needed to calculate the wet bulk density (required for calculating the total pressure);
- The sampling is less complicated because disturbed samples can be used. In soft soil layers, a simple hand-auger set can take samples to a depth of 10 m;
- The volume of the samples is much larger, about 1500 to 2000 cm^3, which is some 25 to 30 times larger than those used in a consolidometer. They are thus more

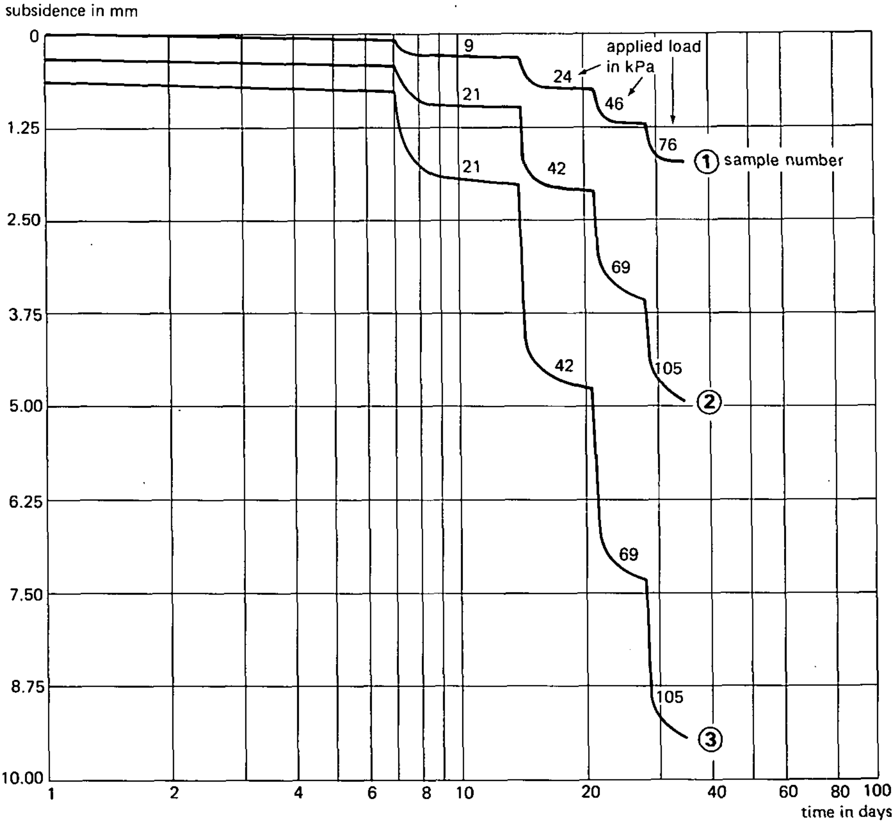


Figure 13.3 Results of consolidometer tests for a loamy (Sample 1), a clay (Sample 2) and a peat (Sample 3) soil

representative. As a rule of thumb, it is recommended to take at least five borings, 2 to 4 m apart, and to combine these for each soil-layer into one sample;

- The cost of collecting and analyzing the samples is remarkably lower; it is estimated to be only 10 to 25% of the cost of the conventional method (De Glopper 1977).

Determining the Total and the Hydraulic Pressure

To determine the total pressure, we have to know the wet bulk density (Section 13.3.1), and to obtain the wet bulk density, we have to collect soil samples from the subsiding soil layers. These samples can be difficult to collect because the area may not be easily accessible, and collecting samples from deeper layers may require heavy soil-sampling equipment. However, as explained earlier, obtaining the wet bulk density is a lot easier than obtaining representative values of the consolidation constants. (The calculation of the wet bulk density is treated in Chapter 11.)

Determining the hydraulic pressure can also be problematical: often, the distribution of the hydraulic pressure is not hydrostatic because of differences in the hydraulic conductivity of the successive soil layers (Figure 13.5). Although most newly reclaimed soils have a high porosity, their hydraulic conductivity is often extremely

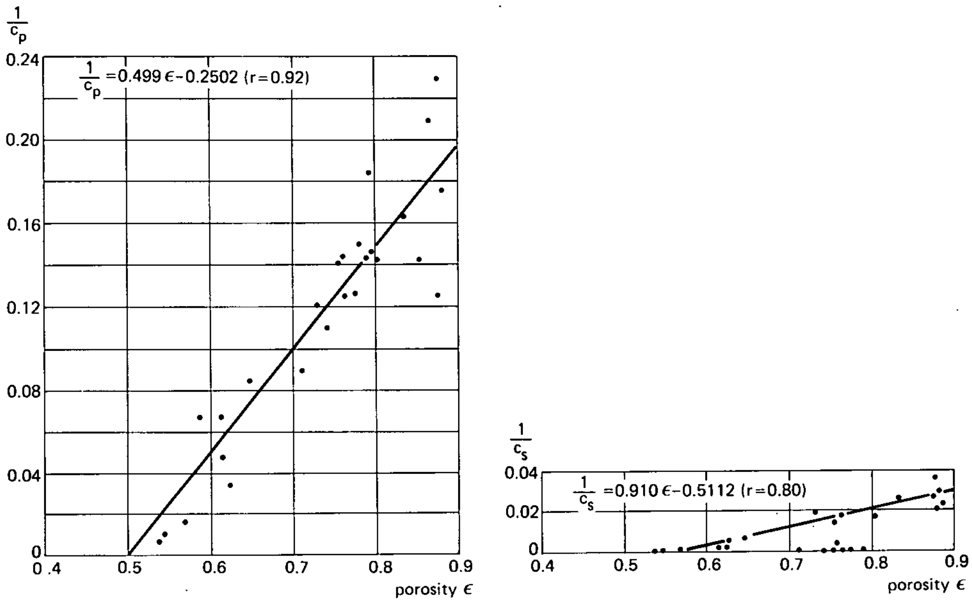


Figure 13.4 The relationship between the consolidation constants (c_p and c_s) and the porosity (ε) of some soils in the IJsselmeerpolders (De Glopper 1977)

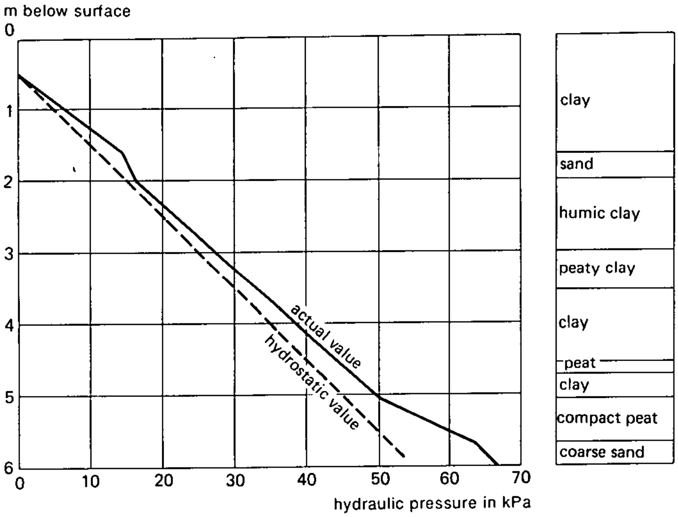


Figure 13.5 An example of a non-hydrostatic relationship between the hydraulic pressure and the depth below surface in a profile consisting of soft layers with varying hydraulic conductivities, overlying a permeable sandy subsoil under overpressure (De Glopper 1973)

low (in the range of 0.1 to 10 mm/d) because of the small diameter of the pores (a few microns). To obtain the distribution of the hydraulic pressure in the soil profile, one has to install piezometers at various depths and record their readings over a long period (Chapter 2).