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Chapter 14

Soils as particulate materials

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Soil is made up of countless particles of different shapes and sizes which are in frictional contact with each other and are acted on by gravity. This chapter illustrates the key features of mechanical behaviour that stem directly from the particulate nature of soils. A simple base friction apparatus is described that demonstrates some of these features. In particular the importance of self-weight and microfabric are illustrated, together with the phenomena of contractancy and dilatancy. The apparatus is used to study particle movements associated with active and passive earth pressures, settlement and bearing capacity. A simple mechanistic approach is presented to illustrate the importance of pore water pressure, leading to a demonstration of Terzaghi's effective stress principle. A similar mechanistic approach is used to introduce some key features of unsaturated soil behaviour.

CONTENTS

14.1	Introduction	153
14.2	Phase relationships	153
14.3	A simple base friction apparatus	154
14.4	Soil particles and their arrangements	156
14.5	The concept of effective stress in fully saturated soils	158
14.6	The mechanistic behaviour of unsaturated soils	160
14.7	Conclusions	161
14.8	References	161

14.1 Introduction

It was pointed out in the Introduction to Chapter 4 *The geotechnical triangle* that soil is a particulate material. Thus a sample of soil is made up of countless particles of a variety of shapes and sizes. The particles are in contact with each other, and the arrangement of particles is often referred to as the 'soil skeleton'. Loads are transmitted through this skeleton at points of contact between the particles. Frequently the contacts between the particles are essentially frictional. However, in many natural soils there is a small amount of bonding between the particles either due to cementation or physico-chemical effects (Mitchell, 1993). The presence of even a small amount of bonding between the particles can have an important influence on both the stiffness and strength of a soil.

The purpose of this chapter is to illustrate in a very simple mechanistic way the key principles governing the behaviour of particulate materials. In order to carry out calculations of ground displacement and stability it is necessary to idealise the soil as a continuum with certain stiffness and strength properties. The danger is that we get so used to thinking in terms of the stress–strain response of idealised continua (e.g. porous elastic materials or elastic–perfectly plastic materials) that we forget all too easily that the soil is actually particulate and its behaviour is controlled by this fact.

14.2 Phase relationships

Figure 14.1 illustrates an element of soil made up of a number of discrete particles. The spaces between the particles are referred to as the 'voids'. The voids may be filled with water or a mixture of water and air. Completely dry soils whose voids are filled with air are not often encountered in nature but can be reproduced in the laboratory.

The closeness of packing of the particles has a dominant influence on the mechanical behaviour of a soil. The more densely packed the particles the greater will be the stiffness and strength of the soil and the lower will be its permeability. A widely used measure of the 'closeness of packing' of the particles is the volume of the voids in an element of soil divided by the volume of all the particles (solids). This is termed the 'void ratio' of the soil and is denoted as e. Thus the void ratio e is the volume of the voids per unit volume of the solids – see **Figure 14.1**. Another less widely used measure of the closeness of packing of the particles is *porosity* (n), which is defined as the ratio of the volume of voids to the total volume of the soil element, so that, from **Figure 14.1**, $n = e/(1 + e)$. Because of its ease of determination, the closeness of pack of the particles in fully saturated soils (particularly clayey soils) is frequently specified in terms of the mass of water divided by the mass of the solids and is defined as the moisture content w. The various relationships between the volumes and masses of solids, voids, water and air are termed *phase relationships* and these can be found in any basic textbook on soil mechanics – e.g. Craig (2004) and Powrie (2004). These relationships are not complicated but remembering them can be tedious!

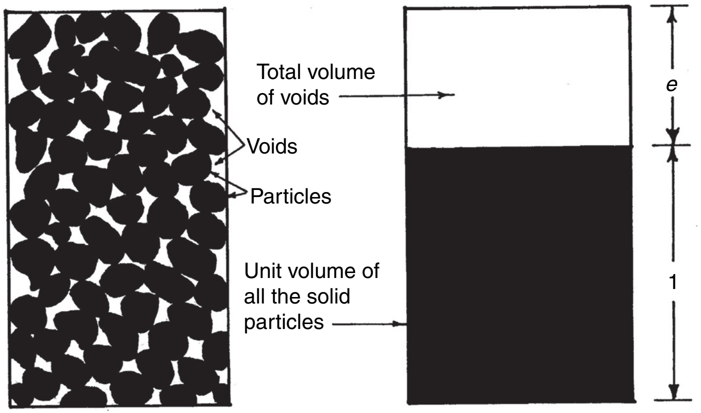

Figure 14.1 Soil is a particulate material. Void ratio e = volume of voids per unit/volume of solids

14.3 A simple base friction apparatus

It is possible to illustrate many of the basic mechanisms of behaviour of particulate materials using a simple physical model. **Figure 14.2** shows a photograph of what is termed a 'base friction apparatus'. It consists of a perspex base across which a standard acetate strip is drawn by means of a small variable speed electric motor. The arrow in **Figure 14.2** shows the direction of movement of the sheet. In this case the model particles consist of short lengths of copper tube of three different diameters. When the electric motor is switched on the acetate sheet carries the particles with it until they come up against a boundary, after which the acetate sheet 'drags' against each particle, simulating the force of gravity acting on it. The behaviour of the particles can be projected on to a vertical screen by means of an overhead projector so that they appear to be 'dragged' downwards under the action of gravity.

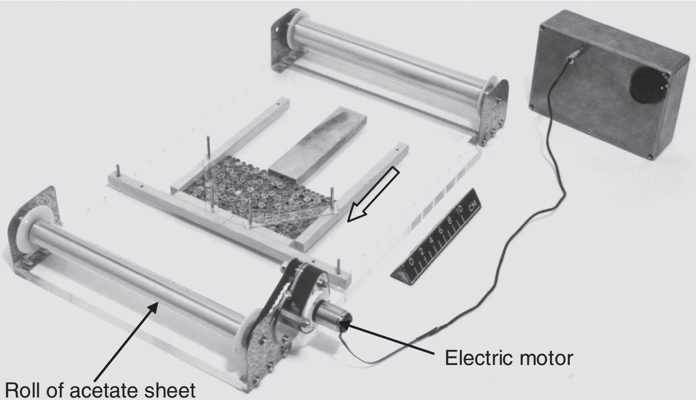

Figure 14.2 Base friction model (arrow shows direction of movement of acetate sheet)
Reproduced from Burland, 1987

The key feature of a base friction apparatus is that it simulates the forces of gravity which give rise to the all-important effects of self-weight. In soil mechanics, the self-weight of the material generates the confining pressures that govern its strength and stiffness, and it also provides the dominant stabilising and destabilising mechanisms for most stability problems.

14.3.1 The process of deposition

Figure 14.3 illustrates the process of vertical deposition of a dispersed suspension of particles acted on by gravity into a container with a horizontal base and vertical sides. **Figure 14.3(c)** shows the particle arrangements on completion of deposition and illustrates a number of important features. The small particles tend to form into clusters. There are a number of voids around which the particles tend to 'arch' so that beneath an arch the particles will not be transmitting much load. If a top plate is placed on the assemblage and gravity is 'switched off', then a gentle up and down movement of the whole assemblage shows that there are numerous 'loose' particles that are not transmitting any load, i.e. there are many more 'arches' than was at first apparent. The whole assemblage is clearly in a very loose state with a high void ratio.

Another key observation is that it is possible to trace numerous vertical and sub-vertical columns of particles showing well-defined preferred arrangements or 'structures'. Thus the particles have arranged themselves so as to resist the dominant vertical gravity forces and the assemblage is stiffer and stronger in the vertical direction than in the horizontal direction. In other words the assemblage has anisotropic properties which are inherent to the mode of deposition under the action of gravity.

The assemblage of particles shown in **Figure 14.3(c)** is termed 'normally consolidated' because the vertical stresses acting on it are those imposed as a result of deposition. If the vertical stresses are reduced subsequent to deposition the

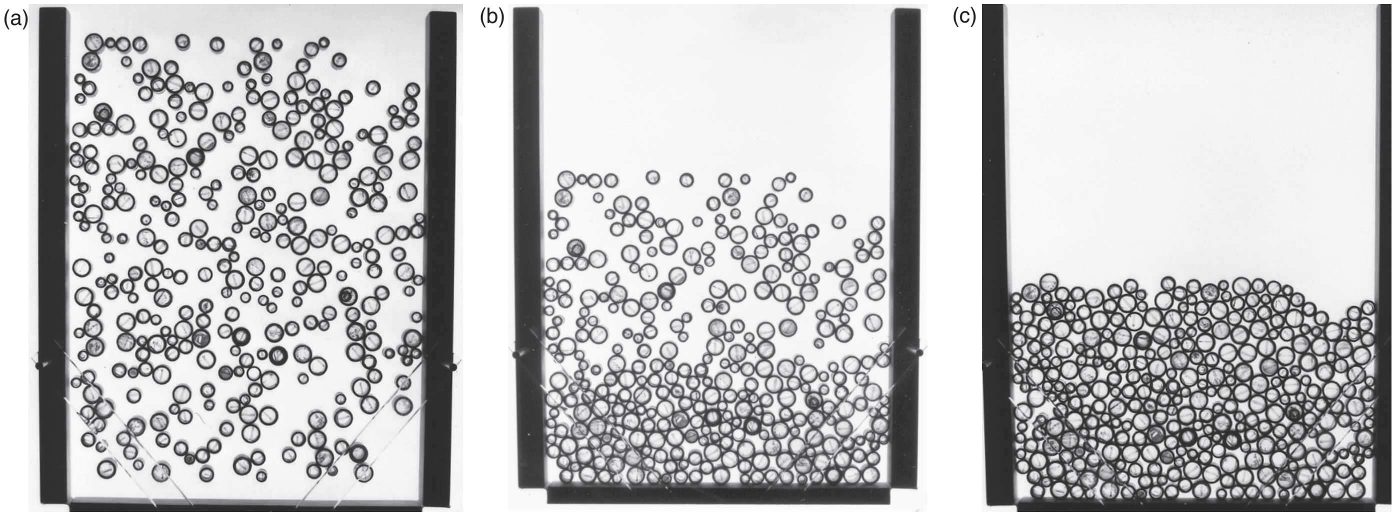

Figure 14.3 Successive stages of the deposition of an initially dispersed suspension of particles
Reproduced from Burland, 1987

material is defined as ‘overconsolidated’. The ‘overconsolidation ratio’ is the maximum previous vertical stress divided by the present vertical stress. Normally consolidated soils are invariably in a loose state.

14.3.2 Contractant and dilatant behaviour

If a top plate is placed on the surface of the assemblage of particles, gravity is ‘switched on’ and the sides of the container are then slowly rotated by equal amounts in the same sense, then the assemblage will be deformed under what is termed ‘simple shear’. During this process of shearing it will be observed that the various ‘arches’ of particles are broken down and the particles move to take on a closer packing, i.e. the void ratio *decreases*. This process of void ratio reduction during pure shearing is known as ‘contractancy’.

The assemblage of particles can be compacted to a closer pack by ‘switching on’ gravity and tamping the top plate. If after compaction the assemblage is again subjected to simple shear it can then be observed that the particles ride over one another and the overall volume *increases*. This process of void ratio increase during pure shearing is known as ‘dilatancy’.

The phenomenon of contractant and dilatant behaviour during shearing is almost unique to particulate materials and is an extremely important property having a profound influence on the shearing resistance of the material.

14.3.3 Active and passive earth pressures

The base friction apparatus can be used to illustrate the development of active and passive regions behind and in front of retaining walls. Refer to Chapter 20 *Earth pressure theory* which discusses active and passive earth pressures. **Figure 14.4(a)** shows what happens if gravity is ‘switched on’ and one of the sides is then rotated away from the retained assemblage of particles. It can be seen that the movement of the particles is confined to a relatively narrow wedge-shaped region close to the wall. This is known as the ‘active’ wedge. At a relatively small rotation the earth pressure reaches a steady minimum value termed the ‘active earth pressure’.

Figure 14.4(b) illustrates the movement of the particles when the wall is rotated inwards towards the retained material. It can be seen that the region of movement of the particles extends much further than for the active wedge; it is known as the ‘passive’ region – in this case it is still wedge-shaped. Much larger rotations are required to fully mobilise full ‘passive earth pressure’ than for active conditions.

14.3.4 Foundation settlement and bearing capacity

The mechanisms involved in foundation settlement and bearing capacity can be studied by placing a thin rectangular strip of wood on the acetate sheet of the apparatus and then ‘switching on’ gravity. The foundation moves slowly down until it is in contact with the ground surface. By placing a relatively light weight on the wooden strip the frictional drag on the strip is increased (simulating a small increase in foundation loading) and the foundation settles due to the compaction of some of the particles immediately beneath the foundation. The zone of compaction is confined to a depth equal to about half the width of the foundation.

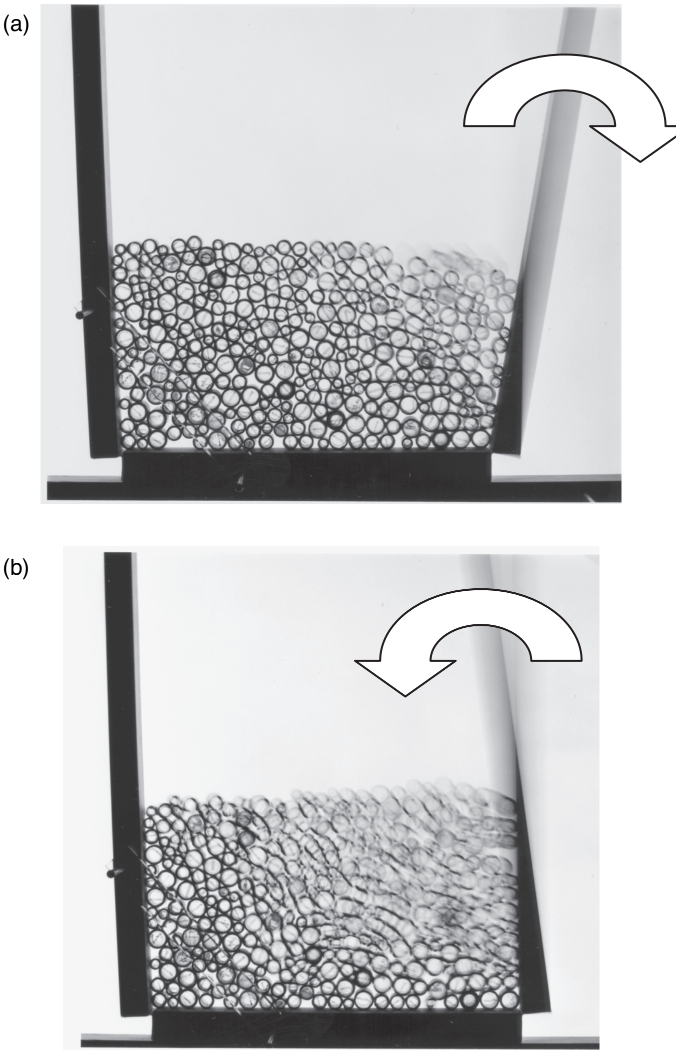

Figure 14.4 (a) Development of an active earth pressure region. (b) Development of a passive earth pressure region
Reproduced from Burland, 1987

The load can be increased further by replacing the wooden strip with a brass strip. When gravity is ‘switched on’ the foundation settles significantly and the zone of particle movement extends further beneath the foundation and outwards on either side as shown in **Figure 14.5**. The foundation has reached bearing-capacity failure and the shearing resistance of the assemblage of particles has been fully mobilised within the observed zone of movement. Further loading of the brass strip causes it to plunge and the zone of particle movement extends around the base and upwards to the surface alongside the strip. This behaviour is modelling the driving of a pile into granular material, and it is possible to visualise the development of high end resistances and also frictional resistance along the shaft of the pile.

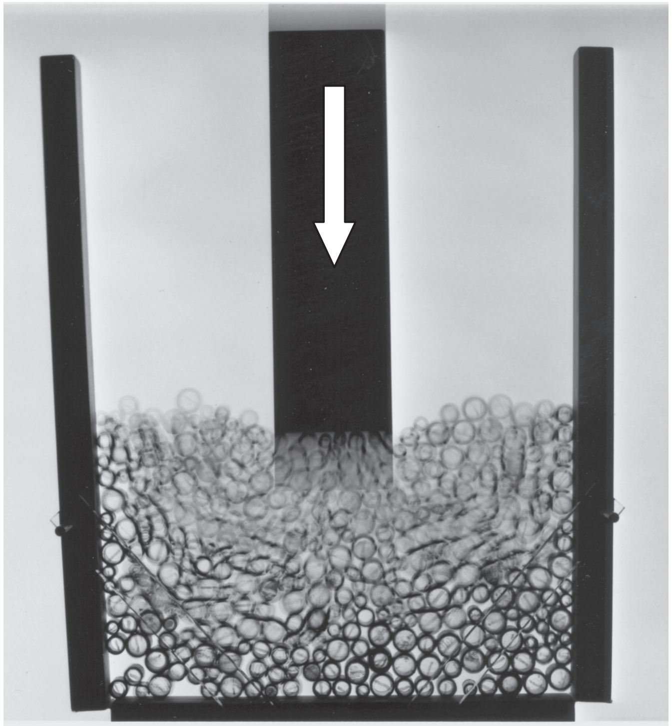

Figure 14.5 Development of bearing-capacity failure
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The base friction apparatus can be used to illustrate mechanisms of ground behaviour for other geotechnical problems as well. For example it can be used to illustrate subsidence above tunnels and arching around them as they are excavated. Also it is possible to illustrate the mechanisms of deep-seated movement around propped excavations.

14.4 Soil particles and their arrangements

In the previous section we examined the mechanical response of a relatively simple assemblage of round particles of three different sizes. It was evident that, even with an assemblage composed of uniformly shaped and sized particles, relatively complex arrangements can occur. Most natural soils are made up of much more complex arrangements of particles.

14.4.1 Particle size

The range of sizes of particles that make up a soil is huge, varying from boulders, through gravels, sands and silts down to clay sizes. **Table 14.1** shows the approximate sizes of these particles and some important visual and tactile descriptions. **Table 14.2** illustrates the amazing range of sizes, numbers and surface areas of typical grains in a gram of soil. **Table 14.3** describes dimensions of three typical clay minerals. The engineering importance of grain size lies primarily in the drainage characteristics of the soil thereby influencing the permeability and rate at which the volume change and strength respond to changes in loading.

Very few soils in nature fall entirely within one grain size classification. Mostly soils are mixtures (e.g. silty clay; very sandy, fine to coarse gravel). The distribution of grain size in a soil is termed its ‘grading’. Thus the ‘soil type’ is primarily based on grain size and grading. There is an unfortunate tendency in practice to refer to ‘cohesive’ and ‘non-cohesive’ soils to distinguish between soils with a high or a low clay content. This can be very misleading as many normally consolidated

Soil type		Size (mm)	Visual or tactile description
Boulders			**Visible to the naked eye**
Gravel	Coarse	>60	**Particle shape:**
	Medium	20	Angular; subangular; rounded; flat; elongated
	Fine	6	
Sand	Coarse	2	**Texture**: Rough; smooth; polished
	Medium	0.6	**Grading**: Well graded (wide range of sizes)
	Fine	0.2	
			Poorly (uniformly) graded
			Gap graded
Silt		0.01	**Not visible to naked eye**
			Gritty to hand or teeth
			Disintegrates quickly in water
			Exhibits dilatancy when squeezed in hand
Clay		0.002	Feels soapy when rubbed with water in hand
			Sticks to fingers and dries slowly
			When spread with knife leaves shiny surface
Organic soils			Contains substantial amounts of organic matter
Peats			Predominantly plant remains, dark brown or black
			Low bulk density

Table 14.1 Soil types

Particle	Diameter (mm)	Mass (g)	No. per gram	Surface area m²/g
Boulder	75	590	1.7×10^{-3}	3×10^{-5}
Coarse sand	1	1.4×10^{-3}	720	2.3×10^{-3}
Fine sand	0.1	1.4×10^{-6}	7.2×10^{5}	2.3×10^{-2}
Medium silt	0.01	1.4×10^{-9}	7.2×10^{8}	0.23
Fine silt	0.002	5.6×10^{-12}	9×10^{11}	1.1

Table 14.2 Typical grain dimensions (assumed spherical)

Mineral	Width (mm)	Width/thickness	Surface area (m²/gr)
Kaolinite	0.1–4.0	10:1	10
Illite	0.1–0.5	20:1	100
Smectite	0.1–0.5	100:1	1000

Table 14.3 Typical clay mineral dimension

clay soils do not exhibit cohesion and many granular soils can be bonded. Moreover, all soils that are sheared without allowing drainage exhibit undrained strength which is often treated as an equivalent cohesion in analysis. True cohesion in a soil is a very difficult property to determine and its precise definition is far from clear. It is much better simply to refer to ‘clayey soils’ and ‘granular soils’ without implying anything about their cohesion (sometimes the terms ‘fine-grained’ and ‘coarse-grained’ are used).

14.4.2 Particle shape

The particles used in the simple base friction model illustrated in section 14.3 of this chapter are circular in shape. Soil particles vary in shape. For granular soils (boulders down to silt-size particles) the variety of shapes may be embraced by the following descriptors: angular, sub-angular, rounded, flat, elongated – see **Table 14.1**. The texture of the particle surfaces also varies ranging from rough, through smooth, to polished. The shape and angularity of the particles have a profound influence on its shearing resistance. This was impressed firmly on the author when he went for a walk on Chesil Beach in Dorset. The beach is made up of smooth rounded gravel-sized particles – see **Figure 14.6**. As a consequence it is extremely difficult to walk on the beach because the grains move around so much underfoot!

Clay particles are generally much smaller than their granular counterparts and are usually plate-like in shape with plan dimensions much greater than the thickness. **Table 14.3** gives some typical dimensions of three common clay minerals: kaolinite, illite and smectite (montmorillonite). The clay content in a soil, together with stress history, has a dominant influence on its compressibility.

14.4.3 Fabric and micro-structure

The above sizes and shapes of particles combine to form a bewildering array of particle arrangements – termed the ‘fabric’ of the soil. **Figures 14.7** and **14.8** show, respectively, some typical

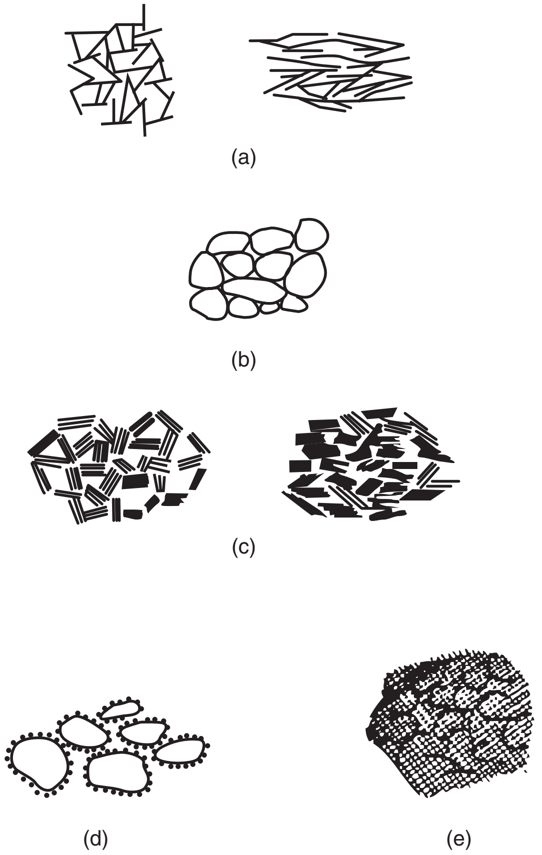

Figure 14.7 Schematic representation of elementary particle arrangements. (a) Individual clay platelet interaction. (b) Individual silt or sand particle interaction. (c) Clay platelet group interaction. (d) Clothed silt or sand particle interaction. (e) Partly discernible particle interaction

Reproduced from Collins and McGown (1974)

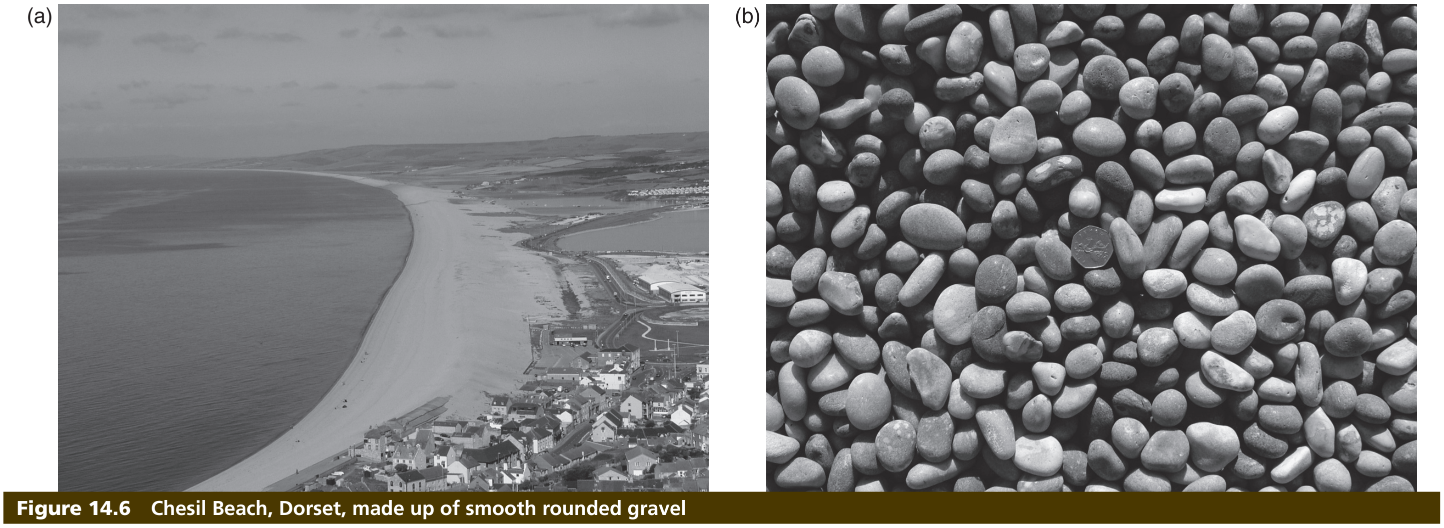

Figure 14.6 Chesil Beach, Dorset, made up of smooth rounded gravel

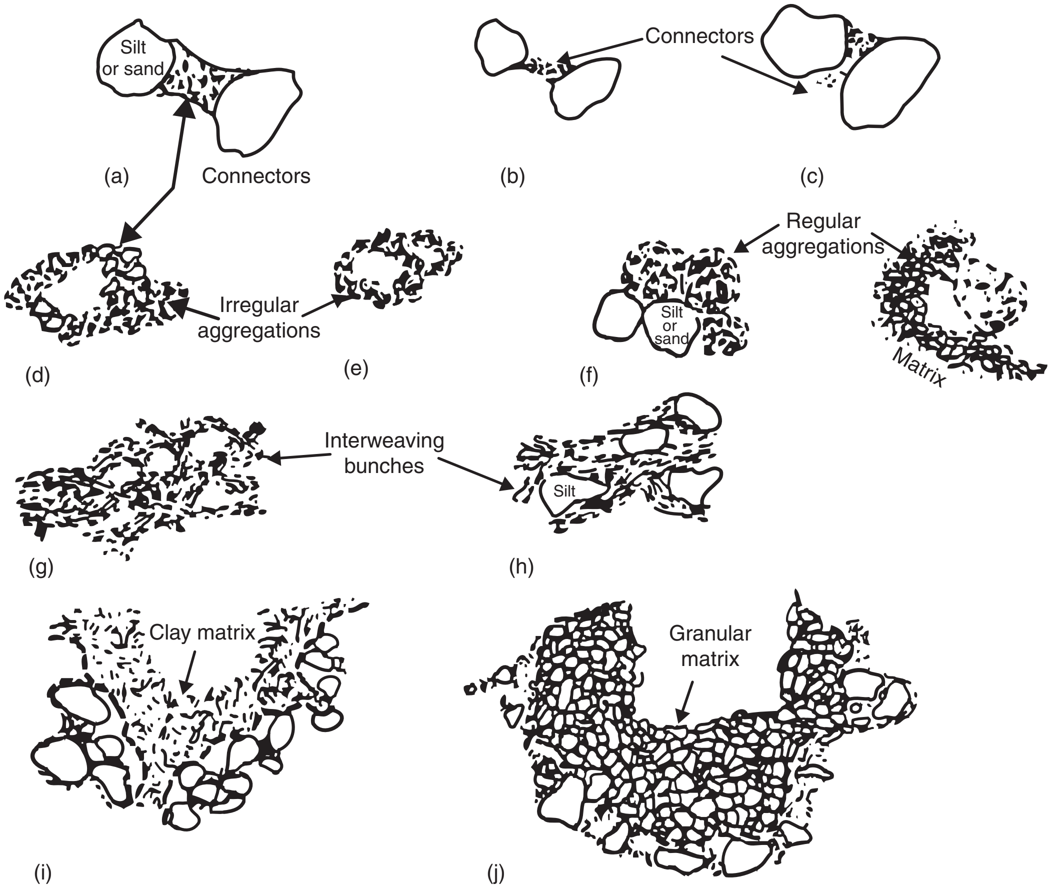

Figure 14.8 Schematic representation of particle assemblages. (a), (b) and (c) Connectors. (d) and (e) Irregular aggregations. (f) Regular aggregations interacting with particle matrix. (g) and (h) Interweaving bunches of clay. (i) Clay particle matrix. (j) Granular particle matrix
Reproduced from Collins and McGown (1974)

schematic representations of elementary particle arrangements and particle assemblages (Collins and McGown, 1974).

As mentioned previously, the particles of soil are usually in mechanical contact with each other, and resistance to sliding at the contact results from friction and interlocking. Frequently in natural soils the particles are lightly bonded at their grain contact points due to cementation or physico-chemical effects.

The term 'micro-structure' means the combination of 'fabric' (the arrangement of the particles) and interparticle 'bonding' (Mitchell, 1993).

14.4.4 Macro-structure

It is important to appreciate that many soils have discontinuities through the mass of the soil as a result of geological or man-made processes. For example joints and fissures can form due to deformations during deposition or tectonic activity. These give rise to important planes of weakness, particularly if clay particles on the joint surface have realigned themselves to give very low frictional resistance. Similarly, pre-existing shear planes can exist in clayey soils due to previous landslipping or geological processes. The weathering of rocks containing relic joints can also lead to important planes of weakness in the soil mass. The presence of such discontinuities can have a dominant influence on the strength of the ground.

Varying depositional environments can lead to alternating layers of clays and granular materials. These more permeable layers usually need to be taken into account in the design and construction of excavations, slopes and embankments. An example of this is given in Chapter 4 *The geotechnical triangle* where it is shown that the design of the underground car park at the Palace of Westminster was dominated by the discovery of thin silt and sand partings in the clay just beneath excavation level. It is also important to note that the presence of joints and fissures can profoundly influence the mass permeability of the ground, particularly if any bonding or cementation is present in the soil mass, because there will be a tendency for these discontinuities to remain open.

14.5 The concept of effective stress in fully saturated soils

Appreciation that soils are essentially particulate materials, albeit very complicated ones, leads to a simple mechanistic understanding of the underlying factors that govern the behaviour of fully saturated soils. **Figure 14.9** shows an element of soil containing an aggregation of particles where the voids between the particles are full of water. The sides of the element are acted on by the stresses σ_v, σ_h and τ_{vh} as shown, and there is a positive pressure u acting in the water. The stresses acting on the boundaries of the element (called total stresses) are made up of two parts: (i) the water pressure u, which acts in the water and in the solids in every direction with equal intensity as shown, and (ii) the balances $(\sigma_v - u)$, $(\sigma_v - u)$, and τ_h which are carried by the soil skeleton. Terzaghi (1936) defined these balances $(\sigma - u)$ and τ as 'effective' stresses. He then stated his *effective stress principle*, which is that 'all measurable effects of a change of stress, such as compression, distortion and a change of shearing resistance, are exclusively due to changes in effective stress'. Thus the two variables, the total normal stress σ, and the pore pressure u, have been replaced by a single variable $\sigma' = (\sigma - u)$. This is a tremendous advantage when measuring the mechanical properties of a soil, as only the relevant effective stresses have to be applied and not the absolute values of the total stress and pore pressure. On the other hand the effective stress principle requires that, in carrying out a soil investigation, it is essential to know the *in situ* pore pressures as well as the total stresses acting on the soil.

It is important to note that the effective stress principle says nothing about the way that the effective stresses are transmitted through the soil skeleton, i.e. it gives no information about the stresses at the particle contact points. Thus an effective stress is *not* an inter-granular stress even though it is sometimes called that. The effective stress is simply that part of the total stress that is carried by the soil skeleton. Note that a shear stress is always an effective stress because water cannot carry shear.

The validity of Terzaghi's effective stress principle can be demonstrated mechanistically as follows. **Figure 14.10(a)** schematically illustrates an element of loose granular material which in **Figure 14.10(b)** is compressed by the application of an all-round stress σ with the pore pressure u held constant. At each grain contact point is acting a normal force P and a shear force T as illustrated in **Figure 14.10(b)**. In view of the large number of grain contact points for each grain, relative displacement between grains can only take place as a result of slip at the contact points. For a grain to be in equilibrium under its contact forces the ratio T/P must be less than or equal to μ at every contact point, where μ is the coefficient of friction of the material composing the grains.

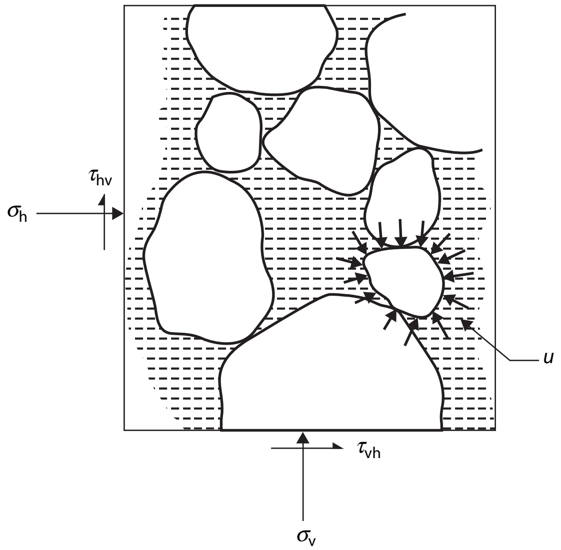

Figure 14.9 Mechanistic model of a loose granular material
Reproduced from Burland and Ridley, 1996

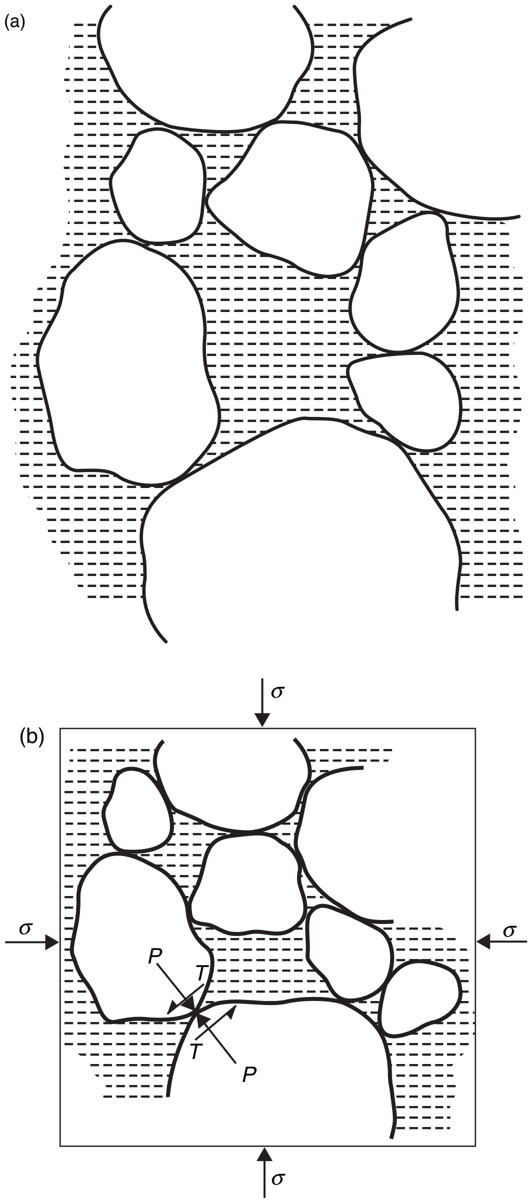

Figure 14.10 Mechanistic model of a loose granular material compressing under equal all-round effective stress. (a) uncompressed. (b) compressed
Reproduced from Burland and Ridley, 1996

An increase in all-round stress $\Delta\sigma$ at constant u will cause a small decrease in volume. This occurs as a result of grain slip at some contact points at which $T/P = \mu$ giving rise to a closer pack of the particles. Therefore an increment in all-round stress induces increases in shear force as well as normal force at the grain contact points. If, instead of an *increase* in total all-round stress σ, the pore pressure u is *decreased* by the same amount, the assemblage of grains would behave in exactly the same way. Clearly a decrease in u is equivalent to an increase in σ in its effects on the grain contact forces. This is a simple mechanistic demonstration of Terzaghi's principle of effective stress for fully saturated soils. It provides a clear demonstration that knowledge of the pore pressure in a soil is just as important as a knowledge of the applied stresses.

14.6 The mechanistic behaviour of unsaturated soils

When a soil is unsaturated the voids contain both air and water. If the air voids are continuous then the water tends to migrate towards the grain contact points due to surface tension effects. **Figure 14.11** shows two spherical particles in contact, with a lens of water around the contact point. It can be shown that surface tension within the curved surface of the water, called the meniscus, generates a compressive force F between the particles. This phenomenon is of profound importance to the behaviour of an unsaturated assemblage of particles. The pressure within the lens of water is less than atmospheric, i.e. the water pressure is negative and is often termed 'suction'.

14.6.1 The process of drying a soil

Figure 14.12 illustrates mechanistically the process of drying for a loose granular soil. In **Figure 14.12(a)** the assemblage of grains is fully saturated and the pore pressure is positive. Evaporation, or drying, then starts to take place, reducing the pore pressure. In **Figure 14.12(b)** the assemblage is still fully saturated but menisci have formed at the boundary. In this situation the pore pressure is less than atmospheric and the tension in the boundary menisci induces compression of the assemblage, resulting in some grain slip and a small reduction of volume.

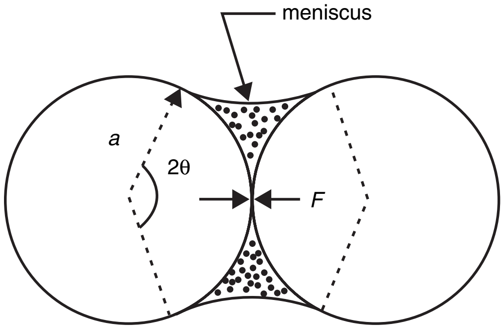

Figure 14.11 Inter-particle force due to surface tension
Reproduced from Burland and Ridley, 1996

At a limiting value of suction (known as the 'air entry value') air will enter the pores of the assemblage and the pore water will form lenses around the grain contact points as illustrated in **Figure 14.12(c)**. These water lenses will generate inter-particle contact forces which are essentially normal to the planes of contact. It is evident that the inter-particle forces generated in this way will tend to inhibit grain slip, thereby stabilising the aggregation of grains. We may think of the water at the grain contact points as acting rather like blobs of glue or bonds which increase both the stiffness and the strength of the soil. This is why a sand-castle constructed from damp sand is so much more stable than one constructed from either perfectly dry sand or very wet sand.

In clayey soils the process of drying can give rise to considerable shrinkage of the soil, often resulting in the formation of shrinkage cracks and fissures. Tree roots are a prime cause of drying out of soils in periods of drought, and in clayey soils the resulting shrinkage, and consequent subsidence of the foundations, can be very damaging to buildings.

14.6.2 The process of wetting up of a dry soil

In the previous section we saw that the process of drying an initially saturated granular soil stabilises the grain contact points and increases both the stiffness and strength. The converse is that if an initially dry soil is wetted up, the stabilising forces at the grain contact points are removed, resulting in a loss of strength and, for loose soils, a rapid reduction in volume. This process of rapid volume reduction during wetting

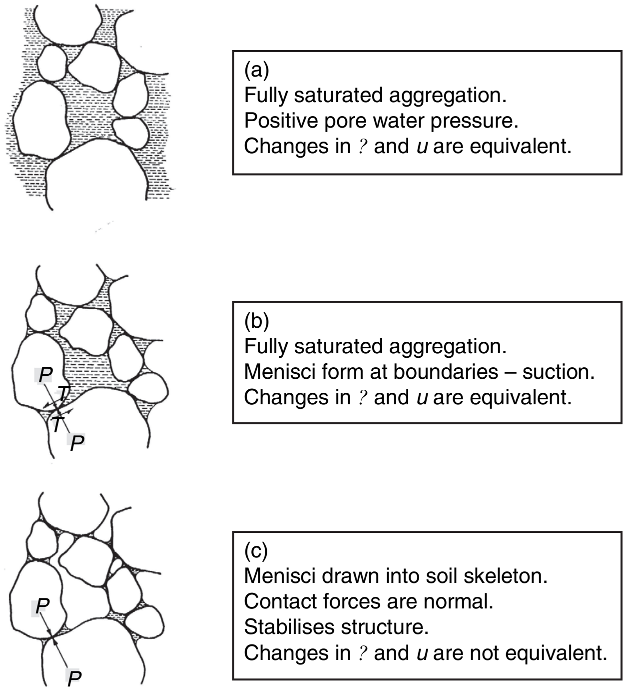

Figure 14.12 Mechanistic model showing the drying of a loose granular material
Reproduced from Burland and Ridley, 1996

is known as 'collapse of grain structure' or simply 'collapse'. The phenomenon of 'collapse' on wetting is well known for dry loose sandy soils in arid climates. This phenomenon is also well known for fill materials which have been inadequately compacted during placement and which subsequently wet up, often due to a rising groundwater table.

The wetting up of initially dry clay soils can also give rise to serious problems. Such soils are often fissured and cracked due to shrinkage. If water becomes available it can penetrate the clay rapidly through the cracks and cause the clay to swell, which can be very damaging to buildings founded on such soils. Also an excavation with steep sides in a dry clay soil may become unstable during heavy rain due to the rapid penetration of surface water down shrinkage cracks.

See Burland (1965) and Burland and Ridley (1996) for a detailed discussion of the mechanistic behaviour of unsaturated soils.

14.7 Conclusions

The key conclusions that can be drawn from this chapter are listed below. Some of them are oversimplified but they form a good basis for gaining an understanding of the complex behaviour of soils.

- All soils, even high plasticity clays, consist of countless particles of a variety of shapes and size. The spaces between the particles are referred to as the 'voids'. The void ratio is a measure of the closeness of pack of the particles and is an important parameter in determining the stiffness, strength and permeability of a soil.
- The particles are in contact with each other and may be thought of as forming the soil 'skeleton'. The arrangement of the particles is referred to as the 'microfabric'.
- The contacts between the particles are largely frictional but in most natural soils there is frequently a certain amount of bonding between the particles as well.
- A fundamental feature of the ground is that it has weight. The self-weight of the soil generates the confining pressures that govern its strength and stiffness. Moreover, the self-weight provides the dominant stabilising and destabilising mechanisms that operate in most stability problems.
- A simple base friction apparatus is described which simulates that action of gravity on the soil particles. The apparatus is used to introduce the formation of soil fabric during deposition. It is demonstrated that deposition under vertical gravity leads to preferred orientation of the particle arrangements and this leads to inherent anisotropy of the soil skeleton.
- When sheared, loosely packed particulate materials contract and densely packed particulate materials dilate. The base friction apparatus is used to illustrate these important phenomena.
- A number of standard soil mechanics problems are simulated in the base friction apparatus to illustrate the behaviour of particulate materials under gravity, including active and passive pressures, settlement and bearing capacity.
- The importance of particle grading, shape and fabric are discussed as well as the dominant influence that macro-structure can exert on the behaviour of a mass of soil.
- A simple mechanistic approach is presented to illustrate the importance of pore water pressure leading to the demonstration of Terzaghi's effective stress principle.
- This mechanistic approach is then used to illustrate some of the basic features that control the behaviour of unsaturated soils during the process of drying and wetting. In unsaturated soils the pore water forms lenses at particle contact points which provide an important stabilising effect on the aggregation of particles. During wetting up, this stabilising effect is reduced, leading to collapse of grain structure and reduction in strength.

14.8 References

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All chapters within Sections 1 *Context* and 2 *Fundamental principles* together provide a complete introduction to the Manual and no individual chapter should be read in isolation from the rest.