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CONTENTS

Chapter 29

Arid soils

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Arid soil forms when more water evaporates than enters the ground from precipitation. It is this process that generates specific problematic soils occurring at specific locations on the Earth's surface. Arid soils present a number of challenges to engineers due to the highly variable nature of their engineering properties associated with active and ancient geomorphic processes; the considerable diurnal temperature ranges experienced, potentially resulting in accelerated disintegration of soil and rock formations as well as man-made structures; lithification processes can result in cementation of the soil particles, making excavation problematic; and various problematic behaviour occurs in arid conditions, such as soils with significant shrink–swell or collapsing potentials, or aggressive salt environments. Key to understanding how arid soils behave and how these soils can be engineered is achieved through an appreciation of the geomorphology of their formation. Associated with these processes are soils that can be cemented or uncemented, whilst being unsaturated. Once geomorphologic effects are understood, appropriate engineering assessment and mitigation can be applied. A number of other logistical challenges also occur with arid environments owing to the limited availability of suitable water sources for construction; only through careful planning can these problems be avoided.

29.1 Introduction

Arid soils can be described as those soils that are conditioned by an arid climate; such climates occur when the potential annual evaporation exceeds annual precipitation and a soil moisture deficit is the result (Atkinson, 1994). Overall, it is estimated that a third of the Earth's land mass currently experiences arid conditions (Warren, 1994a) yet only approximately 25% of the soils found in hyper-arid and arid regions comprises active sand dunes (see **Figure 29.1**) (Warren, 1994b). Arid conditions can be found in both hot and cold locations on the Earth, e.g. arid soils can comprise hot desert soils such as the Sahara, cold desert soils such as the Gobi, even locations within the polar regions are considered arid.

In addition, movements of the tectonic plates result in soils and rock previously formed in arid conditions being found in temperate climates (such as the dune-bedded sandstones, **Figure 29.2**, in the UK's midlands), and soils not commonly associated with arid conditions being found in modern-day arid environments.

Arid soils present a number of challenges to engineers owing to:

- the highly variable nature of their engineering properties associated with active and ancient geomorphic processes;
- the considerable diurnal temperature ranges experienced, potentially resulting in accelerated disintegration of soil and rock formations as well as man-made structures;
- lithification processes, which can result in cementation of the soil particles, making excavation problematic;

Figure 29.1 Sand dune in the Namib Desert, Namibia
Image courtesy of Mrs Jackson-Royal

Figure 29.2 Dune-bedded Permian sandstone, Shropshire, UK
Reproduced from Toghill (2006); Airlife Publishing

- various problematic soils, which occur in arid conditions, such as those with significant shrink–swell or collapse potentials (see Section 3 *Problematic soils and their issues* of this manual for related chapters).

Arid conditions can mean there is a limited availability of water for construction, potentially affecting the suitability of geotechnical processes during construction. This may necessitate the use of locally sourced water, which can contain high concentrations of dissolved salts and will affect construction activities such as the casting of concretes. Limited availability of water can create logistical problems, which must be surmounted if the project is to be completed on time, or it can raise the cost of the project.

The mechanics describing the behaviour of arid soils are not unique to these deposits; soils not currently experiencing arid conditions may still be unsaturated, cemented, prone to shrink-swell or be metastable, although the effects of these mechanisms can be pronounced in arid deposits. However, the climatic and geomorphologic processes that shape arid soils must be considered in order to understand the nature and engineering behaviour of soils in arid regions. This chapter will, therefore, give the key aspects of soil mechanics and geotechnical engineering associated with arid soils along with a description of climatic and geomorphologic processes that shape arid soil conditions (and are likely to continue affecting a site after the completion of a construction project).

29.2 Arid climates

Arid climates form when more water evaporates and transpirates than enters the ground from precipitation. It is this process that generates specific problematic soils occurring at specific locations on the Earth's surface, therefore this section briefly introduces:

- the development of arid conditions in hot and cold regions;
- the characterisation of arid regions into hyper-arid, arid and semi-arid zones.

29.2.1 Development of arid conditions

Arid conditions develop through the global circulation patterns (or macroclimate) of the atmosphere, the location of the land in relation to the sea and the prevailing winds. This is governed by a number of complex processes driven by differences in air temperature and pressure across the globe and the rotation of the Earth. The distribution of arid environments around the world is shown in **Figure 29.3**.

The equatorial regions of the Earth experience the greatest concentration of solar radiation and the poles the least; this imbalance creates a number of convection currents within the macroclimate on either side of the equator (see Wallen and Stockholm, 1966, for further details). The associated climate and atmospheric patterns are the principle reasons why the majority of hot arid conditions are located around the 30° line of latitude on either side of the equator (see **Figure 29.3**).

Cold arid landscapes tend to form because of their location within a land mass in relation to the sea and the prevailing winds (Bell, 1998; Wallen and Stockholm, 1966; **Figure 29.3**); the further from the sea the more likely the water transported in the atmosphere has already precipitated, leaving the air relatively dry (see Lee and Fookes, 2005a, for more details). Topographic structures, such as mountain ranges, can also interrupt the transport of water from sea to land by inducing precipitation

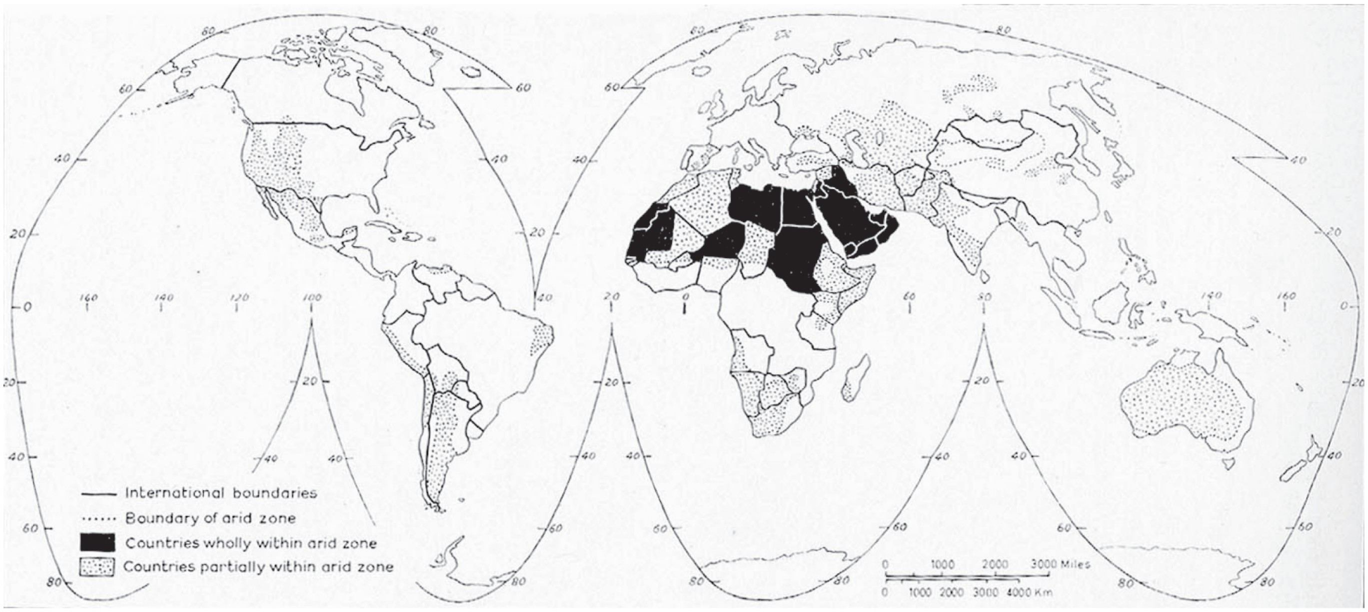

Figure 29.3 The distribution of arid environments
Reproduced from White (1966); Methuen and Co Ltd

on the topographic structure and leaving the air flowing into the lands behind relatively dry (Bell, 1998; Wallen and Stockholm, 1966).

Cold sea currents that approach the surface and flow near to land (such as the Humboldt Current, situated off Chile's coast) can exacerbate the effect of atmospheric circulation on an arid environment by creating stable and cool air conditions at sea, making precipitation unlikely to occur (although fog and clouds can still form) (Wallen and Stockholm, 1966). The Atacama Desert, Chile, is considered one of the driest places on Earth due to the combined effects of the atmospheric circulation, the presence of a topographical structure along the coastline and the Humboldt Current (Wallen and Stockholm, 1966; Lee and Fookes, 2005a); Lee and Fookes (2005a) give data indicating that the Atacama Desert receives a mean annual precipitation of less than 0.3 mm.

29.2.2 Precipitation in arid environments

Arid environments are not necessarily under constant drought conditions; although there are locations in hyper-arid regions that may be in drought for years, if precipitation occurs at all. However, by definition, arid environments do experience a moisture deficit. Regions can be classified as arid (or subdivided into hyper-arid and arid, depending on the classification system used), sub-humid (where the magnitude of the deficit is low) or semi-arid (transitional tracts of land between arid and sub-humid lands); see **Figure 29.4**.

Lee and Fookes (2005a) give a simple relationship between mean annual precipitation and annual potential evapotranspiration (the combination of water vapour entering the atmosphere via evaporation and transpiration, Fetter, 2001), see **Table 29.1**, to determine the aridity of a region. Calculation of the annual potential evapotranspiration for a region can be determined using a number of approaches, although the Penman equation (not considered here) is considered the most suitable (see Lee and Fookes, 2005b, and Wallen and Stockholm, 1966, for further details). Deriving the annual potential evapotranspiration requires the quantification of a number of environmental parameters and Wallen and Stockholm (1966) give an alternative method (developed by Köppen) that relates aridity to mean annual precipitation and mean annual temperature (for a winter, summer or undefined season); see **Table 29.1**.

Figure 29.4 Semi-arid desert conditions in Botswana during the summer 'wet season'; note the profusion of green vegetation indicating the occurrence of recent rains
Image courtesy of Mrs Jackson-Royal

Arid regions can be described as having wet and dry seasons, although such an approach is more applicable to semi-arid regions than arid or hyper-arid regions. The duration of the wet season can be very short. Predicting actual precipitation patterns in hyper-arid and arid conditions can be very difficult as the annual precipitation can vary considerably, whereas semi-arid regions can experience more predictable conditions (Bell, 1998; Lee and Fookes, 2005b). Taking the mean precipitation over a reasonable time frame will result in the values quoted in the literature, though the annual precipitation will vary considerably throughout this period; some years very little precipitation, if any, will occur whilst in other years far greater amounts will be recorded (Lee and Fookes, 2005b). Lee and Fookes (2005b) give further details of the distribution of arid regions, including indications of aridity, periods of drought and associated temperature and the occurrence of wet and dry seasons.

Precipitation, when it occurs, can take the form of short-lived very heavy storms known as convection-cell cloudbursts. These storms can occur as infrequently as once in a decade or even once in a century in certain arid environments (Hills *et al*., 1966). However, they are very intense events and they can cause significant changes to localised topography and can damage earthworks (as illustrated in the subsequent sections of this chapter).

29.3 Geomorphology of arid soils and the effect of geomorphic processes on the geotechnical properties of arid soils

An overview of the geomorphology of arid soils has been included in this chapter as the geomorphic processes active in arid regions are fundamentally related to the geotechnical properties of the soils found within those areas. Failure to understand the geomorphic processes, which have acted upon, and will continue to act upon, the arid soils found on site, will limit the ability to successfully engineer those soils. Therefore, this section of the chapter considers:

- the commonly encountered types of arid regions and the associated ground conditions;
- erosion and deposition processes within arid regions (alluvial, chemical, fluvial and mechanical) and the potential effect these process have upon construction processes;

Humidity province	Characteristic vegetation[1]	P/ETP[2]	Summer[3]	Winter[3]	Undefined season[3]
Sub-humid zone	Grassland	0.50–0.75	-	-	-
Semi-arid zone	Steppe	0.20–0.50	$P \leq 20T$	$P \leq 20(T + 14)$	$P \leq 20(T + 7)$
Arid zone	Desert	0.03–0.20	$P \leq 10T$	$P \leq 10(T + 14)$	$P \leq 10(T + 7)$
Hyper-arid zone	Desert	<0.03	-	-	-

Where P is the annual precipitation (mm), ETP is the annual potential evapotranspiration and T is the annual mean temperature (°C)
1. Lee and Fookes (2005a)
2. Lee and Fookes (2005b)
3. Hills *et al.* (1966)

Table 29.1 Methods to determine if arid conditions apply for a given region
Data taken from Lee and Fookes (2005a, b) and Hills *et al.* (1966)

- landforms that are found in arid regions and their potential for use as aggregates;
- the formation of duricrusts and cemented soils and the problems these present to construction;
- the formation of hammada, dunes and other aeolian features, the conditions associated with these landforms and the geohazards these landforms present when undertaking construction;
- the formation of fans, wadis and other fluvial landforms, the conditions associated with these landforms and the geohazards these landforms present when undertaking construction;
- the formation of salinas, sabkhas and playas, the conditions associated with these landforms and the geohazards these landforms present when undertaking construction;
- considerations when undertaking site investigations in arid environments and potential sources of aggregates.

The geomorphic processes affecting arid environments are similar to those affecting other regions; arid environments are not governed by special circumstances (Hills *et al.*, 1966). However, the lack of vegetation and the aridity of the ground conditions makes aeolian erosion more prominent in arid regions than in other regions: aeolian deposits can be prone to collapse (as described in detail in Section 3 *Problematic soils and their issues* of this manual), affecting the design of structures built in such conditions. Stabilisation may be necessary before constructing on these deposits. Aeolian deposits can also be extremely mobile, potentially swamping a site and making it unfit for purpose. Arid conditions can also experience extreme changes in diurnal temperature, resulting in both increased rates of mechanical and chemical weathering of soils and man-made structures, such as concrete, and can significantly reduce the engineering life of a structure. Certain geomorphic processes will only occur infrequently, such as fluvial erosion, yet can have a pronounced effect upon conditions on site.

29.3.1 Landforms within arid environments

There are two distinct types of arid region: shields and basins (or plains) (Lee and Fookes, 2005b), with four distinct zones (from a geomorphologic viewpoint) that control the topography within an arid region: uplands, foot-slopes, plains and base level plains (Lee and Fookes 2005b). Each of these zones exhibits different geotechnical problems as a direct result of their geomorphologic environments. Shields are defined as a 'major structural unit of the Earth's crust, consisting of large mass of Precambrian rocks, both metamorphic and igneous, which have remained unaffected by later mountain building' (Whitten and Brooks, 1973, p. 411). Such features are remarkably stable geological formations having survived intact since the Precambrian eon (Precambrian rocks were formed at least 570 million years ago and can be billions of years old). Therefore, many shield deserts do not contain active volcanoes (although there are examples of recently active volcanoes in arid regions of America; Hills *et al*., 1966) and many of the topographic features within a shield that were created by tectonic actions in a previous age have been affected by hundreds of millions of years of geomorphic processes (i.e. mountain ranges become reduced to hills by weathering and erosion). A shield may be overlain by younger rock formations, or soil, that will erode preferentially to the shield. Conversely a basin (defined as a 'depression of large size, may be of structural or erosional origin'; Whitten and Brooks, 1973, p. 49) will act as a sink for debris eroded from higher ground via fluvial and aeolian actions and will contain soils with a considerable range of particle sizes. A basin may have dunes.

29.3.1.1 Uplands and foot-slopes

Uplands are regions of hills, plateaus and canyons, characterised as having flat tops with scarps and ramparts (**Figure 29.5**). The topography of upland regions (with the exception of the ramparts) tends to be denuded of soil deposits by fluvial and aeolian processes leaving barren rock or boulder fields (Lee and Fookes, 2005b). The topography of upland regions is shaped by mechanical, chemical and thermal weathering and eroded by fluvial and aeolian action (and is also weathered by these processes), with weaker rock formations eroding preferentially to harder ones. This creates the prominent flat-topped, steeply sided features synonymous with arid environments (Monument Valley in the USA being a prime example).

Foot-slopes (**Figure 29.6**) are transitional regions between uplands and a basin. Gently dipping plateaus that form between two regions are known as piedmonts. Eroded materials from uplands are deposited, by fluvial and aeolian actions, within a piedmont to form transitionary topographic structures such as alluvial fans and pediment slopes, which can exhibit a significant potential for collapse.

The same geomorphic processes that created deposits on foot-slopes will also erode them, transporting the eroded material into a basin. Whilst chemical, mechanical and thermal weathering occurs in these regions, aeolian and fluvial processes dominate the shaping of the topography in foot-slope environments. The actual geomorphologic processes involved are not universally agreed. However, from a geotechnical engineering viewpoint, piedmonts can be valuable sources of readily available aggregates and other resources for construction projects (Lee and Fookes, 2005b), as illustrated in section 29.3.7.5.

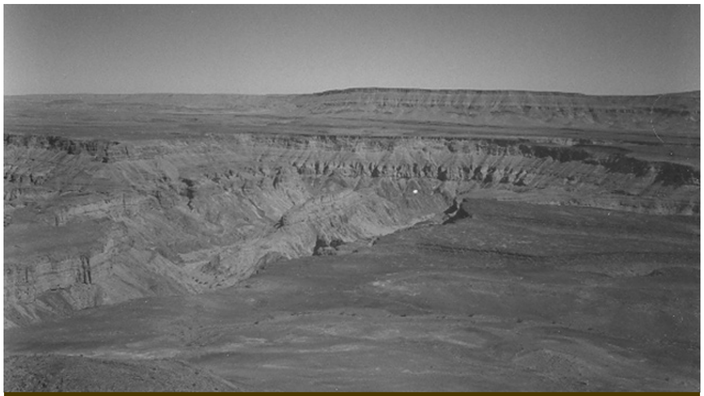

Figure 29.5 Fish River Canyon, Namibia; note the flat and barren tops, steep scarps, establishment of ramparts at the base of the scarps and the development of a mesa and a butte (centre) within the canyon
Image courtesy of Mrs Jackson-Royal

29.3.1.2 Plains and base level plains

The topography of plains tends to be dominated by the deposition and continued transport of previously weathered and eroded materials from uplands and foot-slopes. Aeolian and fluvial transport mechanisms dominate the changing topography of these regions, creating dunes and wadis, for example, and segregating the transported particles with respect to size and density depending on the location of the source material and the orientation of weathering process. Base level plains are naturally occurring depressions within a basin and they are also affected by aeolian and fluvial actions (akin to plains), although the groundwater level can be relatively near the surface. The proximity of groundwater, the moisture deficit experienced by the soils in the vadose zone and the chemistry of the pore water can result in an accumulation of salts within the vadose zone. These highly salty conditions can accelerate the weathering of soil and rock deposits within base level plains and can cause damage to man-made structures.

Whilst upland features such as scarps and inselbergs (Ayers Rock being a prime example, Hills *et al*., 1966) can be ancient, features such as pediment slopes, fans and dunes (**Figure 29.6**) are thought to be products of the Quaternary and are likely to be reshaped by future geomorphic processes (Lee and Fookes, 2005b). The lack of vegetation and predominantly dry surface soil result in coarse-grained soils being readily eroded by

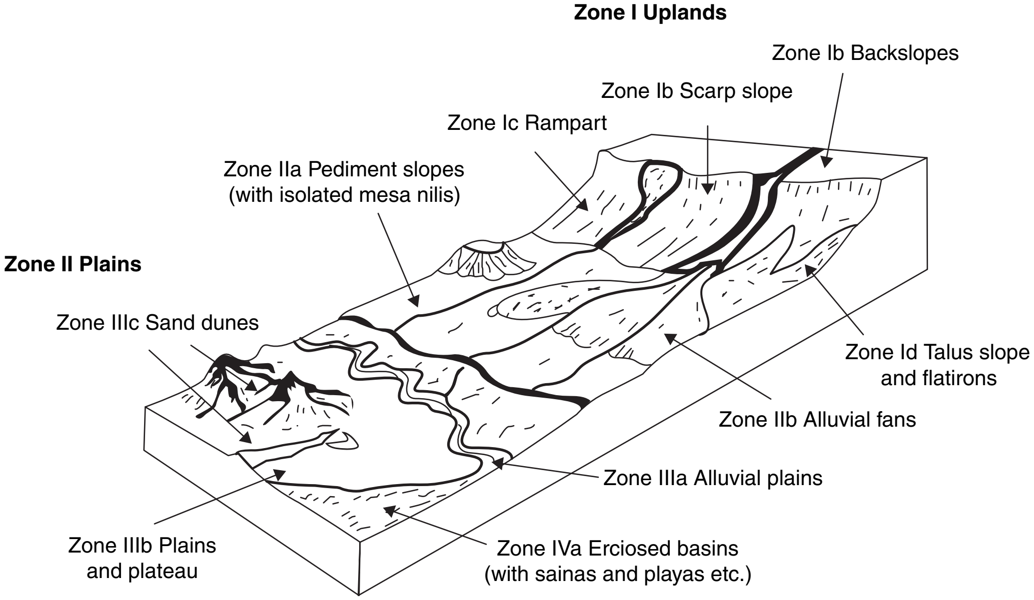

Figure 29.6 Illustration of hot desert topography
Reproduced from Lee and Fookes (2005b) Whittles Publishing

geomorphic processes; phreatic surfaces can be found in arid environments although the depth of the water table can vary considerably and can be very deep; Lee and Fookes (2005b) cite an example of a phreatic surface being 50 m below the ground surface in the Sahara, and this is echoed by Blight (1994) who cites similar groundwater levels in semi-arid conditions in southern Africa. The geomorphic processes that dominate arid environments include aeolian and fluvial erosion as well as chemical, mechanical and thermal weathering.

The transitional, and desiccated, nature of superficial deposits within arid landscapes, along with the bedrock being very close to the surface in upland areas, can prove to be a significant resource of aggregates for construction purposes, as illustrated in section 29.3.7.5.

29.3.2 Development of arid soils through weathering

Weathering by aeolian, chemical, fluvial, mechanical and thermal processes occurs in arid environments. These processes produce a complex array of landforms and associated ground conditions, many of which present a number of significant challenges to geotechnical engineers. An understanding of this behaviour is essential. Further details and other useful references can be found in Fookes *et al*. (2005b).

29.3.2.1 Mechanical weathering processes in arid environments

The process of eroding an upland is relatively slow; Lee and Fookes (2005b) cite rates for a scarp to recede as being of the order of millimetres per year. The resilience of upland formations is related to the nature of the upper layers of the topography, with rocks such as sandstone, or cemented soils (known as a duricrust), forming barriers that resist the erosive processes. These layers are called capping layers and they can slowly be eroded at the scarp by mechanical weathering. If the formations of uplands are jointed then a capping layer may be undermined by block-by-block failure (Lee and Fookes, 2005b; Howard and Selby, 2009); if the formations below the capping layer are susceptible to erosion by water (if they contain smectites, gypsum, etc.) then these formations can soften when inundated by water, resulting in the collapse of the capping layer blocks above (Howard and Selby, 2009). The capping layer may also be weathered if the rock underlying the capping layer is permeable. Water seeping through this rock may weaken it; eventually voids will form within the underlying rock and ultimately lead to collapse of the weakened capping layer above (Lee and Fookes, 2005b).

Mechanically weathered material will fall from the scarp and accumulate on the ramparts where it continues to weather, forming a debris slope (known as a talus slope). Talus (commonly known as scree) will form at or near the angle of repose; it can form metastable collapsible materials, and in response to changes in environmental conditions can collapse down the slope. Thus, talus slopes are dangerous places for construction and may require treatment to prevent slips causing disruption. Degradation of a scarp can result in a gradual reduction in the scarp angle (and height), producing smoother slopes, with the upland eventually being reduced to piedmont slopes (see Lee and Fookes, 2005b, for details).

Cyclic changes in climate experienced by the uplands, alternating from wet to dry, can result in the development of flatirons (wedge-shaped features, which can be of considerable size, that have detached from the rampart and slipped down the talus slope; for more information see Howard and Selby, 2009) within a talus slope. Repeated wedge failure, instigated by weakening of internal boundaries (joints, slip surfaces, dipping rock boundaries, etc.), with a change in climate (from dry to wet), may result in rapid degradation of a scarp and result in a number of flatirons being created on the ramparts.

29.3.2.2 Acceleration of mechanical weathering processes with changes in temperature

The mechanical weathering of arid landscapes, and man-made structures within these arid environments, can be accelerated by changes in temperature. Arid environments experience considerable changes in temperature throughout the year and more importantly diurnally, for example when working on a site in a hot arid region during the summer, the daily temperature would change from low twenties (°C), or less, in the early morning to the high forties (°C), or greater, in a matter of hours; therefore, the acceleration in weathering can be considerable. Rapid changes in temperature can result in the degradation of man-made structures; this is particularly true for composite structures containing materials with different thermal expansion coefficients (such as reinforced concrete), as differential expansion and contraction induce stresses within the material. The material need not be composite to experience such weathering, differential heating and cooling rates (i.e. the outer face compared to the core) can equally result in increased rates of weathering; the outer layers of the material can spall via a process known as exfoliation. Hills *et al*. (1966) suggest that this method of weathering can be very slow and that unconfined rocks, free to expand and contract, do not readily fail via exfoliation. However, rocks, or structures, that are partially buried in a different medium will experience differential rates of change in temperature (the surface exposed to the ambient temperature will expand or contract at a greater rate than the buried surface), the differential movements within the rock will result in additional stresses developing and lead to accelerated rates of weathering.

29.3.3 Degradation of arid environments and man-made structures through chemical weathering

Diurnal changes in temperature can cause chemical weathering of rocks, and man-made structures, via the precipitation of salts within the joints or pores of the rock or soil, or by chemical attack, as illustrated in **Figure 29.7**.

Miscible salts are often found naturally occurring in soils and sedimentary rocks, either as crystals or dissolved salts within the pore water. Vertical seepage of groundwater, induced by

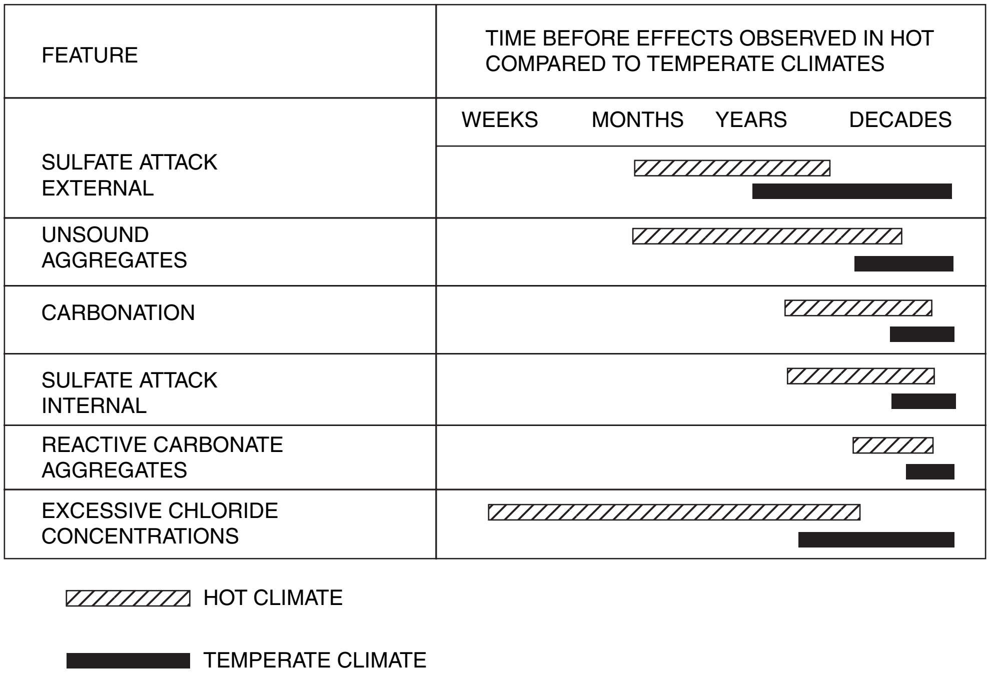

Figure 29.7 Deterioration of concrete due to environmental factors over time
Reproduced from Khan (1982), with permission from Elsevier

suction within the vadose zone, will transport dissolved compounds upwards. If the groundwater table is sufficiently close to the ground level, and suction due to capillarity acts on the groundwater, then the transport of water vertically upwards (see section 29.4.6 for more information) will increase the concentration of soluble compounds within the pores of the near-surface layers of soil.

The concentration at which water can no longer support additional quantities of miscible compounds is known as the saturation concentration. The solubility of a compound is related to a number of parameters including temperature (for more information please refer to Fetter, 1999) (**Figure 29.8**); thus, diurnal changes in temperature can be sufficient to result in a reduction in the saturation concentration and the precipitation of compounds above this threshold, resulting in crystal growth and pressures being exerted on the soil/rock fabric. If the ambient temperature is sufficiently high, evapotranspiration can dry out the pores causing the precipitation of all salts previously dissolved in the pore water. However, Goudie (1994) states that it is not necessary for pores to dry out before the precipitation of miscible compounds is an issue for naturally occurring rock, soil and man-made structures alike. Diurnal changes in temperature will result in cycles of precipitation and dissolution, and this is sufficient to weather the host material. Man-made structures can be particularly at risk with concretes spalling and steel reinforcing experiencing accelerated rates of corrosion. Al-Amoudi *et al*. (1995) suggest there is also the potential for solutes to enter placed fills, such as the layers of a highway, via capillarity and this can result in damage occurring to these structures with time.

Changes in environmental conditions, including a change in temperature, a change in the concentration of dissolved salts, a change in the volume of pore water, can result in the precipitation of compounds out of solution. The volume of a solid form of a salt is likely to be greater than that for the compound when dissolved in water, particularly if the compound hydrates on precipitation, applying a pressure in the pore or fissure and causing degradation of the soil or rock structure.

Bell (1998) gives crystallisation pressures for various salts: gypsum ($CaSO_4.2H_2O$) at 100 MPa, kieserite ($MgSO_4.H_2O$) at 100 MPa and halite (NaCl) at 200 MPa, and cites a study illustrating that the salts Na_2SO_4 and $MgSO_4$ caused a far more pronounced degradation of sandstone cubes that were exposed to solutions containing them, and that a mixture of salts within a solution can be far more destructive than when present individually. The pressures exerted by precipitation of miscible compounds can be considerable and man-made structures are equally at risk of degradation via this process (Goudie, 1994). Thus, detailed investigation is necessary before undertaking construction in highly salty ground conditions to ascertain the likely effect the salts will have on the engineering life of the structure. Ground conditions with high concentrations of salts can cause physical weathering of man-made structures (due to the expansion of precipitated crystals within pore spaces, cracks, etc.) and chemical weathering (such as the accelerated corrosion of steel reinforcing) (Goudie, 1994).

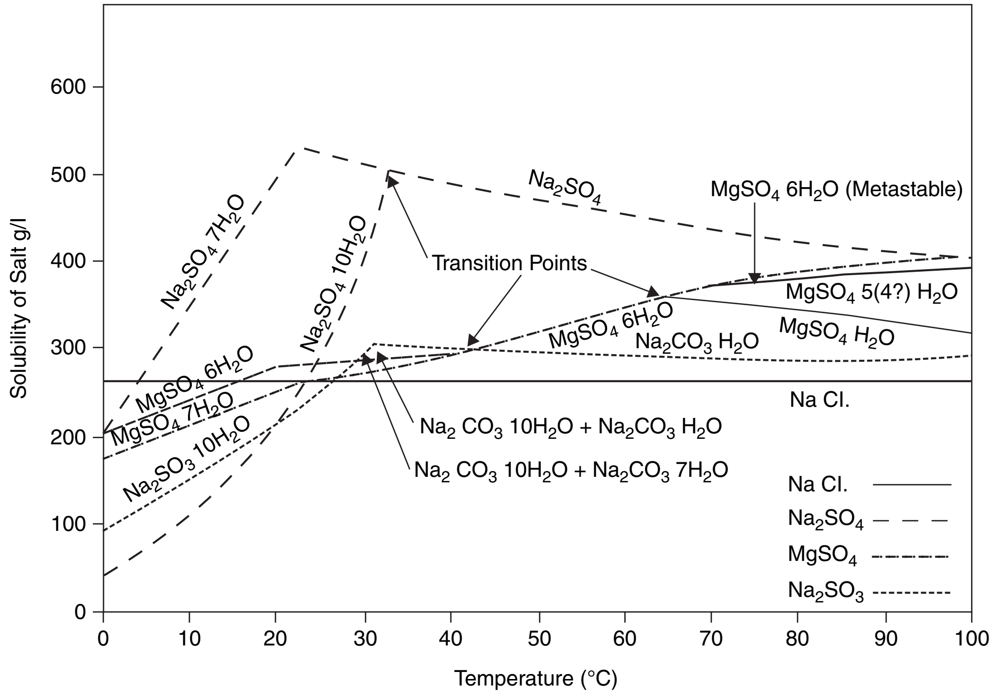

Figure 29.8 **Temperature/solubility relationship for some common salts**
Reproduced from Obika *et al*. (1989) © The Geological Society

The saturation concentration for a compound is also related to the presence of other compounds dissolved within the pore water. Pore water can only undergo a finite degree of restructuring to accommodate miscible compounds; thus, if more than one compound is present the saturation concentration for each will be reduced and the concentrations of salts precipitated out of solution will be greater than predicted by summing the saturation concentrations for each compound present. This situation is colloquially known as 'salt-out'. Understanding how dissolved compounds will behave within a pore is vital if the design of a proposed foundation is to include protection against this type of weathering. Numerical or analytical modelling, based on the Gibbs free energy, can be used to predict solubility, which can also be modelled within a laboratory using batch tests (Fetter, 1999).

29.3.4 Chemical bonding of soil creating duricrusts and cemented soils

Duricrusts (defined as 'a layer of strongly cemented material occurring in unconsolidated sediments, often found a short distance below the surface; usually formed as a result of water action; the cementing material may be calcareous, siliceous or ferruginous', Whitten and Brooks, 1973, p. 222) are cemented soils, and often form below ground and are exposed by erosion. Duricrusts are commonly a few hundred millimetres thick (300–500 mm), although the development of multiple crusts can result in significant duricrust thicknesses (3–5 m) (Lee and Fookes, 2005b), and are common in arid conditions (and other environments); for example calcrete duricrusts are estimated to cover 13% of the Earth's land mass (Dixon and McLaren, 2009).

The cementation process stabilises the soil and makes duricrusts resilient to weathering and provides strengths greater than those associated with unaffected soils. The types of duricrust commonly encountered in arid conditions include: aluminous, calcareous, gypseous and siliceous duricrusts; siliceous and aluminous duricrusts are considered to be stronger than calcareous duricrusts (Hills *et al*., 1966; Dixon and McLaren, 2009) although any of the duricrust formations found in arid conditions can prove to be very difficult to excavate. Excavation of a duricrust may necessitate drill and blast techniques or powerful plant (Lee and Fookes, 2005b). Once through the duricrust, the subsequent strata may require less effort to excavate. Therefore, not only do duricrusts create rock structures resilient to erosion, they can also create problematic conditions for construction and must not be underestimated when planning.

The formation of lightly cemented soil also occurs in arid environments, whilst not producing materials as resilient to erosion as the heavily cemented duricrusts, there may be an increase in stiffness and they may be self-supporting when excavated (the sides of an excavation in cemented, desiccated sands may not collapse with time if the degree of cementation is sufficient to resist movement). The soils may be cemented by precipitation of salts via the same mechanisms creating duricrusts (Dixon and McLaren, 2009) or they may be cemented via clay bridging, although soils cemented by clay structures are considered weaker than those chemically stabilised.

29.3.5 Fluvial erosion, the effect of flooding and the creation of challenging engineering environments including salinas, playas and sabkhas

The majority of watercourses found in arid regions are ephemeral: they only contain water directly after a storm, and the water rapidly evaporates or permeates the soil leaving the watercourse dry once more. The drainage path of the water from a storm will dictate how it interacts with the surrounding environment (**Figure 29.9**); flood water will readily migrate across rocky piedmont slopes to wadi drainage channels, forming ephemeral streams; conversely flood water entering tracts of loose sandy soil will rapidly diminish due to infiltration of the water into the soil and ephemeral streams are unlikely to form.

Lee and Fookes (2005b) cite a study indicating that 90% of the erosion on a site over a ten-year period occurred over five days involving seven storms. This is because the intensity of convective cell storms, which take place over a relatively short time frame, results in large volumes of water migrating through previously established drainage networks (or creates new networks when draining). The velocity of this water is sufficient to transport significant quantities of sediment as it migrates through the drainage pathways, creating new topographic features as the sediment is deposited (for more information, refer to Parsons and Abrahams, 2009). The infrequent storms encountered in arid conditions can also damage earthworks (particularly during construction when the earthworks and their drainage provision are incomplete); discharging water can erode the surface of an earthwork; and water permeating into an earthwork can reduce suction within the soil, thus, reducing the stiffness of the soil and inducing ground movement. The former can result in damage to the earthwork, necessitating remedial measures to reinstate the earthwork, and any ground movement can cause serviceability issues or the failure of structures on the earthwork, again necessitating remedial action. Puttock *et al.* (2011) describe a construction project in Morocco that experienced storms during the construction of an earthwork. **Figure 29.10** illustrates a drainage channel neighbouring the construction site in flood, this occurred after a storm, and jeopardised a section of the newly compacted earthwork.

There is often a lack of flood risk assessment for sites within arid environments and such an assessment should have been included during the planning stages for this project, as a matter of course, if potential flood risks were to be properly managed.

Figure 29.10 Ephemeral drainage channel in flood after a storm; note the proximity of the drainage channel to the newly placed earthwork places the earthwork at risk

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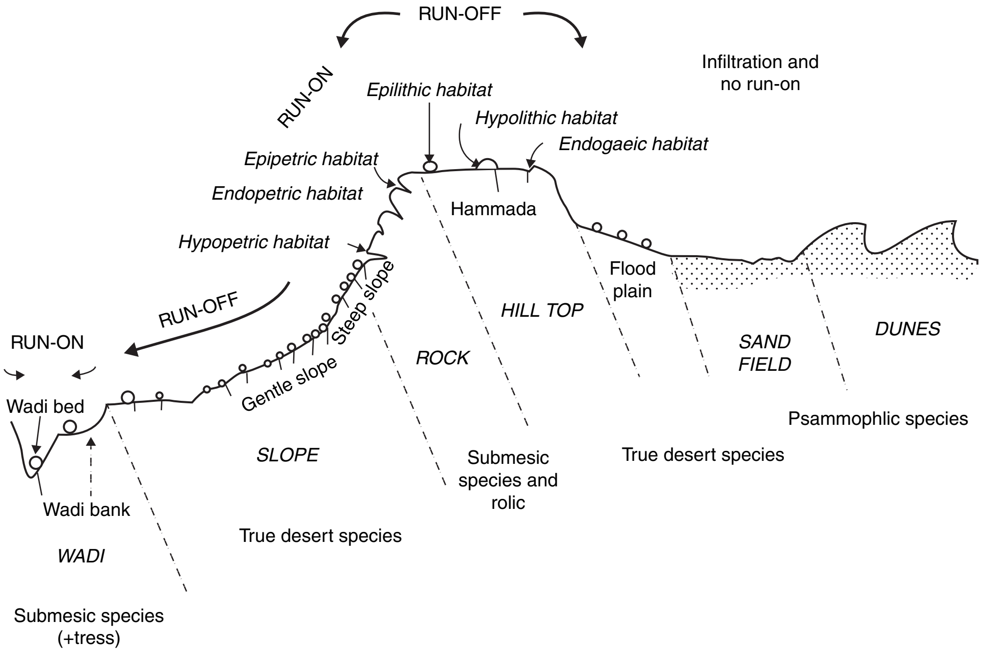

Figure 29.9 Elements of the hydrological cycle in arid lands

Thornes (2009), reproduced from Shmida *et al.* (1986)

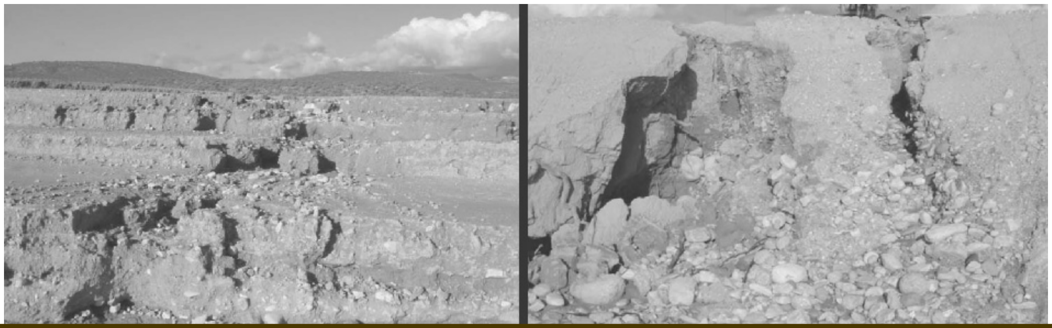

Figure 29.11 Damage to compacted earthwork
(left) Reproduced from Truslove (2010); (right) reproduced from Puttock *et al*. (2011). All rights reserved

Whilst the occurrence of a flood might be significantly lower in arid environments, the potential damage arising from such an event could still be significant. This requires suitable drainage provision for the placed earthwork. If storm water collects on the surface of an earthwork until it reaches a drainage pathway and then dissipates, damage to the earthwork will occur (**Figure 29.11**), requiring remedial measures to reinstate it to a functional condition.

29.3.5.1 Sediment transport and deposition

When precipitation falls on uplands, where the upper surfaces are commonly barren or comprise boulder fields, the water will rapidly drain through a discrete network of drainage pathways, via gullies, into the plains below. The limited nature of the drainage channels and gullies eroded into uplands creates locations for the repeated deposition of eroded materials around the base of the uplands. The materials deposited within these regions can vary greatly but can prove an excellent source of aggregates for the construction industry (Lee and Fookes, 2005b).

29.3.5.2 Alluvial fans

Sediment load is a function of velocity and as this decreases the water will start to deposit sediment, resulting in poorly graded fan-shaped deposits. These fan deposits (alluvial fans) are prominent features on piedmont slopes. Repeated storms will create newly deposited alluvial fans, with the flood water flowing through preferential pathways within previously established fans; the flood water will erode sections of a previously created fan, depositing it further away from the uplands and creating distinctive ‘lobe’ shapes within the fan. Alluvial fans can cover significant tracts of land; Hill *et al*. (1966) reported the extent of an alluvial fan in the Atacama Desert as stretching 60 km from the upland source. Further details can be found in Blair and McPherson (2009).

29.3.5.3 Wadis

Wadis (valleys with intermittent streams) are ephemeral in nature and form braided streams. Whitten and Brooks (1973, p. 62) define these as ‘a stream consisting of interwoven channels, constantly shifting through islands of alluvium and sandbanks; the banks are comprised of soft sediments (often self-deposited), which are easily eroded; the stream beds are wider and shallower than where meander occurs, and are more liable to flood, which in itself helps the constant shifting, widening process’. This creates new alluvium deposits along the river valley in what can seem like haphazard locations (when compared to deposition sites of meandering watercourses). Thus, subsequent patchy lavers of poorly graded, loose alluvium deposits (overlying previously deposited alluvium) can be encountered when working in these conditions. Loose deposits can be eroded and redeposited in subsequent storms; thus, the topography of wadis are transitory. These conditions can also be dangerous places to work during the ‘rainy’ season when flash floods can occur very quickly and with little warning (Waltham, 2009).

29.3.5.4 Sabkhas, salinas and playas

Fine-grained particles are the sediment likely to settle out of suspension last, and so they can be transported considerable distances by flood water. In base level plains the flood water will pond to form ephemeral lakes. As the lakes recede, silts and clays settle out and form a crust (an example of a crust formed as lake water evaporated can be seen in **Figure 29.12**, although this was not formed by receding flood water but due to changes in river pathways that previously fed the lake). These clay or silt crusts will accumulate with subsequent floods, forming additional layers and will thicken the crust (Lee and Fookes, 2005b). These layers may be interspersed (or overlain) by layers of sand, deposited by aeolian action between periods of flooding, or contain evaporites (in the case of sabkhas and salinas). The surfaces of these crusts can be resilient to settlement induced by light loading or inundation of water during flooding, and Al-Amoudi and Abduljawad (1995) suggest that (in the case of sabkha deposits) this is due to the desiccated and cemented nature of the crusts.

If the crusts form on plains adjacent to the sea then sabkhas or salt playa can form (see **Figure 29.13**). Sabkhas experience

Figure 29.12 Nxai Pan in Botswana, one of a series of salt pans created with the drying of a major lake (Makgadikgadi) due to regional changes in river pathways in southern Africa (caused by tectonic uplift)
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coastal flooding and are likely to have a water table close to the surface. The salt concentrations accumulated within these crusts can be extremely high (**Table 29.2**).

Salt playas can also have high salt concentrations (although not the same magnitude as sabkha) due to the precipitation of salt with the silts and clays as the flood water recedes (Lee and Fookes, 2005b). Sabkhas and salt playas may experience a degree of cementation with the precipitation of solutes from the pore water. Such precipitation can also lead to the creation of gypsum, and other evaporite lenses, developing within these landforms (Al-Amoudi and Abduljawad, 1995) – see also Chapters 37 *Sulfate acid soils* and 38 *Soluble ground* of this manual.

However, the soil below the crust can be metastable, it might contain minerals susceptible to dissolution (e.g. gypsum and halite), and it might be very soft, and, hence, potentially susceptible to ground movement once the upper surface of the crust is compromised (Al-Amoudi and Abduljawad, 1995).

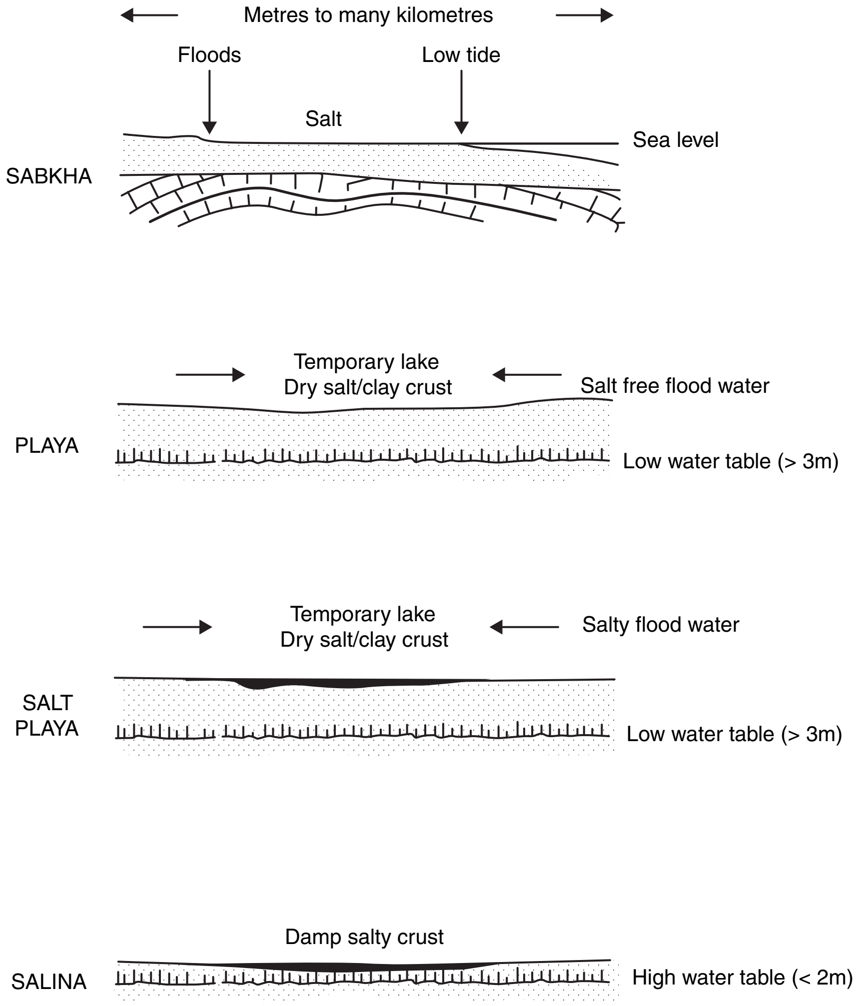

Figure 29.13 Idealised cross-sections through a sabkha, playa, salt playa and salina
Lee and Fookes (2005b), reproduced from Fookes (1976)

Ion (mg/l)	Open sea	Coastal seawater, Arabian Gulf	Sabkha water
Ca	420	420	1 250
Mg	1 320	1 550	4 000
Na	10 700	20 650	30 000
K	380	650	1 300
SO_4	2 700	3 300	9 950
Cl	19 300	35 000	56 600
HCO_3	75	170	150

Table 29.2 Typical compositions of seawater and sabkha water (in mg/l)
Data taken from Fookes *et al.* (1985)

The properties of sabkha soil can also change with the season; with once trafficable surfaces becoming impassable during the wet season as the cementing salts dissolve (Shehata and Amin, 1997). Sabkhas also formed during the Quaternary (Al-Amoudi and Abduljawad, 1995), leaving deposits along what formally was the coastline. However, the sea level has fluctuated since the Quaternary and many of the sabkhas created via this mechanism have been reworked, by action of the sea, to form carbonate sands and silts as well as bioclastic sands (Al-Amoudi and Abduljawad, 1995).

Care must be taken when constructing on these topographic features; the high concentration of salts within these crusts makes them problematic when coupled with the potential for flooding (Millington, 1994). Construction in such environments requires consideration of the stiffness of the underlying soil (particularly for salinas), as the density of these soils can be low (Al-Amoundi, 1994). Other issues include the collapse potential and the highly salty nature of the upper layers of the soil. Buried man-made structures within these landforms, e.g. concrete foundations or steel pipes, can experience accelerated weathering due to the high salt content within the soil (Shehata and Amin, 1997). Using materials from these areas for construction processes is not recommended (see section 29.3.7.5 for further details).

Silt or clay crusts formed by freshwater flooding are known as playas or salinas, with the difference in behaviour being dictated by the proximity of the water table to the ground surface. In base level plains the groundwater table can be relatively close to the surface, and suction within the vadose zone can result in a significant capillary rise, e.g. over 10 m in clays and between 1 to 10 m in silts (Bell 1998). If the playa is susceptible to the movement of water via capillarity then it is called a salina and salts are transported towards the surface (Lee and Fookes, 2005b). The increase in salt concentration within the salina, akin to sabkha and salt playa, can also make construction difficult. If the movement of groundwater intersects with the ground surface then the surface layers of the salina can be damp (**Figure 29.13**), with soft material directly below.

29.3.6 Aeolian erosion and the creation of challenging engineering environments including collapsible soils, hammadas and sand dunes

Arid soils are more susceptible to aeolian erosion than soils found in other regions due to climatic conditions and the resulting lack of vegetation. Aeolian erosion has two principal forms: firstly, the wind can transport soil particles from one location to another; the ability of the wind to transport soil particles is related to a number of factors including wind speed and particle type (e.g. size, shape, specific gravity), and secondly, soil transported by the wind can be used to scour existing topographic features (akin to the sea using transported sediment to erode the base of cliff faces). The scouring power of wind should not be underestimated and has negative connotations when working on site (for more information, see Parsons and Abrahams, 2009).

The mode of aeolian transport is dependent upon the size, shape and density of the soil particles (for given wind and topographic conditions). Very fine materials (less than 20 μm) will stay in suspension for a long time, their transport can last for several days and particles can be transported thousands of kilometres (Nickling and McKenna Neuman, 2009). Larger fine-grained materials (less than 70 μm but greater than 20 μm) are too heavy to stay in suspension for a long time, transport will last a few minutes to hours, and the particles can be transported tens of kilometres (Nickling and McKenna Neuman, 2009). Granular material is too heavy to transport via suspension and instead can be transported by saltation or rolling. Saltation describes the process where particles (up to 500 μm) move through the air in a cycle of collection, transportation and deposition via short elliptical paths. Larger particles will roll along the surface of the ground under the force of the wind; however, there is a point where the particles become too large to be transported by aeolian action.

The segregation of particles by size, shape and density, due to aeolian erosion, will result in a grading of particles within a basin relative to the dominant wind direction and source of material. The loss of transportable particles via aeolian action will result in a gradual lowering of the ground surface and at the same time an accumulation of particles too large to transport via aeolian action. Eventually the particles too large to be transported by the wind will cover the ground surface and prevent further erosion through aeolian action. The ground surface is then known as a hammada (see Stalker, 1999, for further details). These are resilient surfaces that can be beneficial to construction; the surface can be trafficable without the need for much preceding ground improvement, but once the surface is broken the affected area will once again be susceptible to aeolian erosion.

The movement of sand-sized particles – not necessarily quartz: the particles can be clay aggregations, salt crystals, non-quartz particles (Warren, 1994b) – via aeolian action can lead to the creation of dunes at the windward or leeward face of a topographic feature, whether naturally occurring or man-made, or where two or more winds converge (Lee and Fookes, 2005b). The type of dune formed (see Stalker, 1999, for details of common dune types) is dependent upon a number of factors including the volume of sand transported and the consistency of the direction of the wind, with wind consistency being considered of primary importance (Lancaster, 2009). The particle diameter size range commonly found in a dune is 0.1–0.7 mm, with median grain diameters between 0.2 mm and 0.4 mm. A dune is considered to be poorly graded (Lee and Fookes, 2005b).

The processes that create dunes can cause them to migrate across the surface of an arid region, and they are then known as active dunes. Sands accumulate on the slip face, which causes the crest of the dune to move with time and, hence, the location of the slip face. The migratory rates of dunes (see Warren, 1994b, for details of the rates of movement with height) are inversely related to the dune height, and are a function of the cross-section and bulk density of the dune as well as the aeolian transport rate of the sand (Lee and Fookes, 2005b). Dunes can form across vast areas (known as dune fields or sand seas; sand seas being far larger than dune fields). For example, it is considered that about four-fifths of arid lands are barren rock or boulder fields (Bell, 1998) and that less than 25% of arid and hyper-arid regions are covered in active dunes (Warren, 1994b), yet Hills *et al*. (1966) cite an uninterrupted sand sea in the Sahara covering a surface area greater than France. In such places the dunes can achieve considerable heights; Lee and Fookes (2005b) describe extreme transverse dunes in the Sahara reaching 240 m.

The transition from arid to semi-arid conditions can result in a stabilisation of the dunes as increased precipitation levels results in increased coverage of vegetation. Dunes can also be stabilised with the cementation of the sand particles, via the development of salt crystals, or the weathering of the non-quartz particles within the dune (Warren, 1994b). Lancaster (2009) gives the geographic locations of dune fields and sand seas across the world and the activity of their dunes.

The aeolian erosion of arid soils is likely to occur during and after construction and this must be taken into account during the planning stage of any construction project. Aeolian deposits can affect structures (blocking doorways and in extreme cases burying houses; see Shehata and Amin, 1997), can affect construction processes (e.g. engine filters readily become blocked with fine materials, prevent setting out using optical devices) and can create logistical problems (e.g. see **Figure 29.14**) where loose material can be problematic to negotiate, particularly large vehicles not equipped with caterpillar tracks, such as articulated lorries. Measures can be established to protect a site against the build-up of wind-transported soils, such as using porous fences as sand traps, illustrated in **Figure 29.15**, although the land required to protect a site can be considerable.

Aeolian erosion denudes landscapes of the finer-grained particles, and creates transitory features such as dunes. However,

Figure 29.14 Car stuck on loose, aeolian deposits covering a road. The road was perfectly trafficable two weeks before
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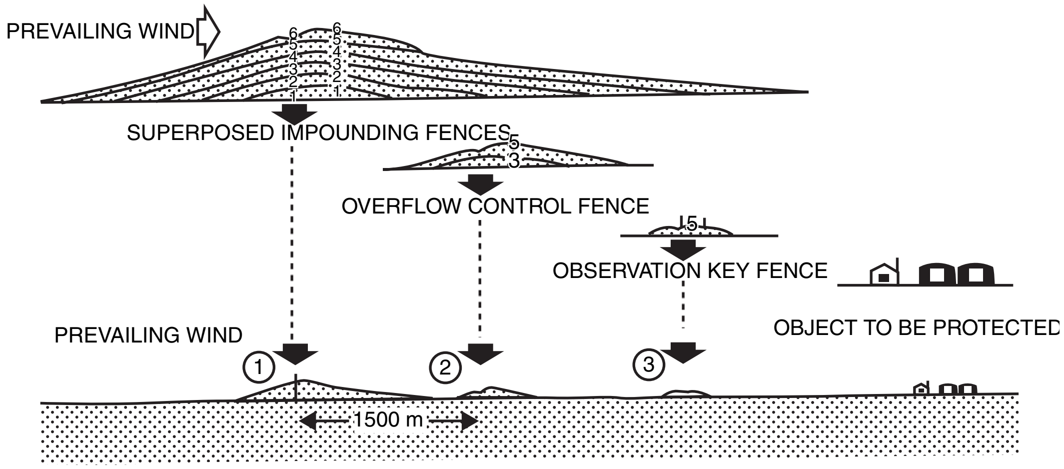

Figure 29.15 The use of porous fences as sand traps
Lee and Fookes (2005b), reproduced from Kerr and Nigra (1952); American Association of Petroleum Geologists

particle-laden winds (transporting particles with sizes in the range 60 μm to 2000 μm) also act as a geomorphologic process on rock formations, scouring them (akin to commercial sandblasting, if not as intensive) and further shaping the topography of the uplands and foot-slopes; this process is slow and continuous. Laity (2009) quotes abrasion rates of the order of magnitude of 0.01 mm/year to 1.63 mm/year (abrasion can be far greater in places like Antarctica, where wind speeds can be considerable, although this is not considered here). A variety of different rock formations (Bell, 1998) are created depending on the type of rock, rock strength and the alignment of the layers of rock.

29.3.7 Undertaking site investigations in arid areas and classifying arid soils

Soil classification for geotechnical engineering applications should provide sufficient information so that the design and construction phases of a project are cost effective whilst minimising the risks of failure. However, to ignore the very nature of arid soils courts failure of the project (during or after construction) via potentially unexpected means (Smalley *et al.*, 1994). Whilst construction projects often do not have sufficient resources to fully classify the properties of a soil found on site (in terms of mineralogy, formation, etc.), it is recommended that the classification process is extended beyond the scope of a laboratory study to determine the geotechnical parameters of the soil and to consider textural (e.g. fabric and soil structure) aspects of the soil (Rogers *et al*., 1994).

In arid conditions, soils are often unsaturated, can contain high salt concentrations and, due to the geomorphologic process that created them, can be loose, metastable and, therefore, collapsible, or expansive (see Chapters 32 *Collapsible soils* and 31 *Expansive soils* for further details). **Figure 29.16** can be used to help to identify soils that may experience changes in volume. Laboratory testing to identify physical parameters will not identify the risks posed to the foundation of a structure through chemical or physical weathering induced by high salt concentrations below the ground surface, or failure of the foundation via collapse (or expansion) of the soil skeleton upon wetting. Moreover, a perfectly serviceable structure could become expensive to maintain due to the continued accumulation of windblown deposits.

29.3.7.1 Guidance for site investigation in arid soils

The soil or rock formations encountered will depend on the location (as illustrated in section 29.3.1); soils found on uplands or foot-slopes will vary considerably from those in the plains and this must be considered when developing a site investigation strategy. Any deposits investigated are likely to be heterogeneous in nature due to the geomorphic processes that created them, so engineering parameters derived from a limited number of borehole samples or laboratory-derived data may be unreliable. Furthermore, any deposits encountered are likely to be unsaturated (unless within a base level plain, where the phreatic surface can be relatively close to the surface), could be dry, and are possibly metastable (e.g. talus slopes, aeolian deposits such as loess) making the collection of undisturbed samples effectively impossible. Therefore, any site investigation should be underpinned by a preliminary desk study to highlight the types of soil that may be encountered and identify the types of tests required to characterise the soils on site.

However, care is needed when using standards, e.g. British or European standards, as these may not be best suited to arid soil conditions (for tropical soil see Chapter 30 *Tropical*

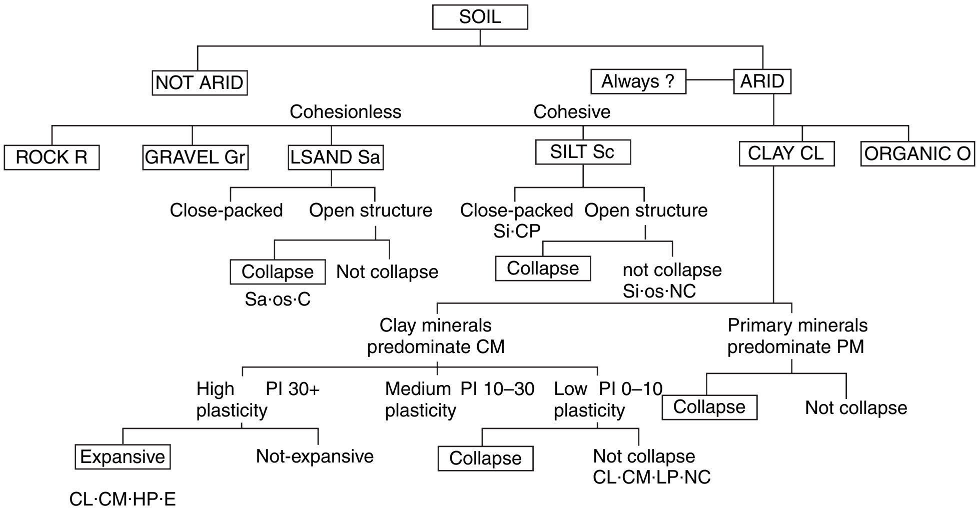

Figure 29.16 Proposed decision tree to indicate volume change problems . Si·CP, silt – close packed; Si·os·NC, silt – open structure – not collapse; Sa·os·C, sand – open structure – collapse; Sa·os·NC, sand – open structure – not collapse; Cl·CM·LP·NC, clay – clay minerals dominate – low plasticity – not collapse; Cl·CM·HP·E, clay – clay minerals dominate – high plasticity – expansive
Reproduced from Rogers *et al.* (1994)

soils). For example Puttock *et al*. (2011) constructed earthworks in an arid environment and found success when combining French standards (*Technical Guideline on Embankment and Capping Layer Construction*; LCPC and SETRA, 1992), which they suggest are more suited to arid conditions than British standards, with practices taken from British standards (end performance specifications and placed soil investigation techniques).

29.3.7.2 *In situ* testing

In situ testing can determine geotechnical data or classify soil properties and can complement data obtained from laboratory tests (such as characterising and index testing, physical testing: including swelling and the collapse potential of reformed samples). *In situ* testing may disturb the soil but in loose, unsaturated, granular deposits (or those with collapse potential) this is likely to be less than the disturbance from extracting samples for laboratory analysis; British and European standards provide guidance on the suitability of various drilling methods in given soil conditions and describe the quality of the samples likely to be obtained (see section 29.7.2 British Standards). Guidelines for the application of various *in situ* geotechnical tests can be found in for example BS2247 (parts 1 to 12) (British Standards Institution, 2009).

An illustration of potential issues can be found in Livneh *et al.* (1998), who undertook a site investigation for a proposed runway in arid ground conditions containing gypsum. The ground conditions included sandy soils containing clays and gravels with silt and clay lenses and gypsum-rich lenses interspersed between the sandy soils; the authors suggest that the site could be characterised as a sabkha. The gypsum formed through precipitation of soluble minerals with changes in groundwater conditions and concern was raised over the performance of the ground if the gypsum was wetted during loading. Various *in situ* tests were undertaken including dynamic cone penetrometer testing, density determination and loss of weight with wetting of the gypsum-bearing deposits. It was found that low *in situ* density values, coupled with the potential for dissolution of the gypsum, were the parameters that dictated the pavement design for the runway. Livneh *et al*. (1998) carried out the following laboratory tests on samples taken from the site: plasticity index testing, dry density, California bearing ratio (CBR), unconfined compressive strength (UCS) and analysis of pore water chemistry, to supplement the information gathered from *in situ* testing.

Various *in situ* tests to evaluate the collapse and swell potential are discussed in Chapters 32 *Collapsible soils* and 33 *Expansive soils*, respectively, and details of the various control, interpretation and assessment issues are given in these chapters.

29.3.7.3 Laboratory testing

Care must be taken when investigating some arid soils in the laboratory, notably those that are metastable or those that contain high solutes such as sabkhas. Laboratory tests for collapsible soils and expansive soils can be found in Chapters 32 *Collapsible soils* and 33 *Expansive soils*, respectively.

An example of an arid soil that requires careful handling in the laboratory is described in a study by Aiban *et al*. (2006). The sabkha soil investigated was found to exhibit different behaviour depending on the water used in the laboratory tests. For this soil, **Figure 29.17** shows the differences in the particle-size distribution and **Table 29.3** gives the plasticity index for this sabkha soil when prepared with distilled water or sabkha brine.

These differences are believed to be related to the difference in the salt concentration between the soil and the water used; distilled water only contains minute concentrations of the solutes in the soil so a proportion of the crystalline salts cementing the soil would precipitate into solution. This change in the salt concentration within the soil changed the physical properties of the soil. Thus, it is important that any liquid used in a soil investigation is similar to the liquid that will be used on site.

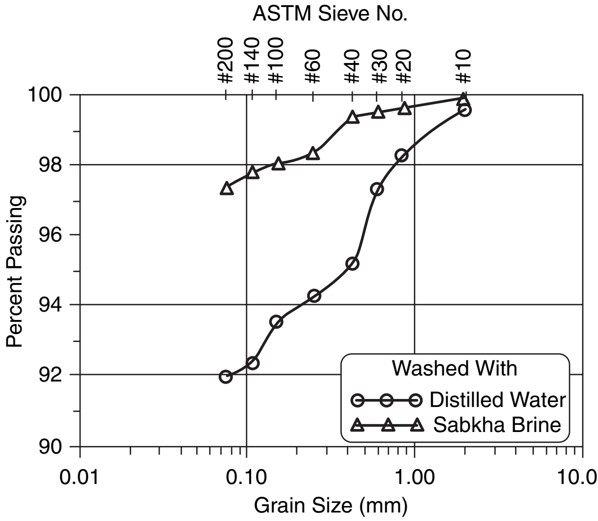

Figure 29.17 Grain-size distributions of a sabkha soil using either distilled water or sabkha brine to wash the soil
Reproduced from Aiban *et al*. (2006), with permission from Elsevier

Property particle-size range (passing ASTM sieve 200)		Value more than 50%
Liquid limit (LL)	Distilled water	42.5
	Sabkha brine	33.0
Plastic limit (PL)	Distilled water	26.3
	Sabkha brine	20.4
Plasticity index (PI)	Distilled water	16.2
	Sabkha brine	12.6

Table 29.3 Difference in plasticity index with the solution used to investigate a sabkha soil (Aiban *et al*., 2006)

29.3.7.4 Geophysical investigation of arid soils

Geophysical testing can be successfully used in arid ground conditions, it can be non-disruptive and it can cover significant tracts of land. Geophysical testing augments information derived from traditional borehole or trial-pit surveys. Guidance on the use of geophysical techniques in site investigations can be found in the *Geological Society's Engineering Geology Special Publication 19* (McDowell *et al*., 2002); although not written specifically for arid ground conditions this guide does introduce the geophysical techniques commonly associated with site investigations.

Shao *et al*. (2009) investigated the use of polarimetric synthetic aperture radar (SAR) to detect subsurface hyper-saline deposits in arid conditions and found promising results. Ray and Murray (1994) report on research into the use of airborne SAR, AVIRIS (Airborne Visible/infra-red Imaging Spectrometer) and thermal imaging to investigate the nature of surface sand deposits in an arid region within the USA and found that mobile sand deposits could be distinguished from fixed deposits using these techniques. The ability to detect mobile deposits stems from the difference in particle-size distribution (active soils tend to comprise a greater proportion of particles in the saltation range and also tend to be poorly graded) and the relative density of active and fixed sand deposits (Ray and Murray, 1994). The ability to detect certain problematic soil deposits geophysically provides an opportunity to optimise any additional investigation and provides the means of identifying geotechnical processes that will have to be undertaken before construction can continue.

29.3.7.5 Material resources for construction projects in arid environments

Various landforms within uplands, foot-slopes and plains (see section 29.3.1) are potentially sources of aggregates. **Table 29.4** indicates potential locations for sourcing aggregates and suggests potential applications within construction processes for these materials. Lee and Fookes (2005b) recommend alluvial deposits (fans and wadi channels) when sourcing aggregates; it is suggested that dune deposits can be used but with caution as the particle grading often encountered in dunes can be too fine to be readily applicable. It is recommended that deposits containing high concentrations of salts should be avoided (or treated to remove the salts). Lee and Fookes (2005b) also suggest that care should be taken when sourcing aggregates

Feature	Aggregate type	Nature of material	Engineering properties of fills	Potential volume
Bedrock mountains	Crushed rock suitable for all types of aggregate	Angular, clean and rough texture	Depends on rock type and processing. Good fills	Very extensive
Duricrust	Road base and sub-base	Often contains salts. Needs crushing and processing	May be self-cementing with time. Quite good rockfill	Often only small deposits of good quality
Upper alluvial fan deposits	Concrete and can be crushed for road base	When crushed and screened angular and clean. Otherwise sometimes dirty and often rounded	Good compaction as fill	Often very extensive but good quality material may be found only in small deposits
Middle alluvial fan deposits	May make road base	Often high fines content	Often good compaction as fill. Good bearing	Small to extensive
Lower alluvial fan deposits	Generally not useful	High fines content. Needs processing	Poor bearing and as fill	Small to extensive
Other piedmont plain alluvium	Variable, locally good concrete aggregate	Dirty, rounded and well graded. May contain salts	Good bearing capacity (dense sediments) and as fill. Locally poor due to clay and silt layers	Very extensive but good quality material in small deposits
Old river deposits	Concrete	Variable	Difficult to locate in field	Often deposits patchy and thin
Dunes	Generally not good	Usually too fine and rounded	Fills of poor compaction	Locally extensive
Interdunes	Fine aggregate	Coarse to fine, angular. Needs processing	Fills of poor compaction	Very localised
Salt playas and sabkhas	Not suitable	Very salty and aggressive	Poor. Special random fill.	Locally extensive
Coastal dunes	Generally not suitable	Generally too fine and rounded	Special fills often poor compaction	Sometimes extensive
Storm beach	Fine aggregate may be sharp or salty	Sufficiently coarse for concrete sand. Clean after processing	Random fill	Sometimes extensive
Foreshore	Generally not suitable	Fine, rounded sand	Salt contaminated, but might make random fill	Locally extensive

Table 29.4 Landforms and aggregate potential
Reproduced from Lee and Fookes (2005b); data taken from Fookes and Higginbottom (1980) and Cooke *et al*. (1982)

as cemented deposits are likely to require processing before being suitable.

The availability of water for construction projects in arid regions must be considered, as this can severely affect the processes being undertaken. Arid regions are often located in developing countries (Wallen and Stockholm, 1966), which have, potentially, limited infrastructure away from urban centres, and the climatic and geomorphologic processes affecting the site must be understood. Thus, water may have to be brought to a site, or groundwater must be extracted (if the phreatic surface is sufficiently close to the surface to make this option economically viable); groundwater can contain significant concentrations of dissolved minerals, which can have a detrimental effect on construction (casting of concrete, etc.) and these factors should be considered by a site investigation.

29.4 Aspects of the geotechnical behaviour of arid soils

When engineering a site in an arid environment it is vital to understand how the aridity will affect the work and what geomorphologic processes will (more than likely) continue to act on the site once construction is complete. This section contains a description of generalised aspects of the geotechnical behaviour of arid soils, and, therefore, considers:

- generalised aspects of the geotechnical behaviour of arid soils;
- various aspects that should be considered when dealing with arid soils including: the generalised behaviour of unsaturated soils; the development of suction within the soil; the relationship between total stress, effective stress, pore water pressure and pore air pressure; and how the shear and volume change behaviour can be evaluated;
- the behaviour of expansive and collapsible soils in arid regions and the effects of cemented soils, together with how such soils can be treated.

29.4.1 Generalised aspects of the geotechnical behaviour of arid soils

Arid soils, by definition, have a moisture deficit, which is likely to result in unsaturated conditions being prevalent (in the surface layers of the soil at least, as is the case in base level plains). This is not to suggest that groundwater cannot exist in arid locations, but it may be at a significant depth below the ground surface. The resulting suction may lead to an increase in effective stress of the unsaturated soil and can induce groundwater flow vertically upwards from the phreatic surface to the vadose zone. Both phenomena can have a marked impact on the behaviour of arid soils.

The suction in an arid soil is a function of the interaction between water and air within the pores. In simple terms, suction forms due to the creation of menisci within the pores because of surface tension between the pore water and pore air (Fleureau and Taibi, 1994) as the pore water preferentially lines the surfaces of particles before filling the pore space. However, in soils containing a distribution of pore sizes, some of the pores may fill completely with fluid (known as bulk water) whilst others remain unsaturated (containing meniscus water), resulting in a heterogeneous distribution of suction within the soil (Wheeler *et al*., 2003). Thus, the effective stress of the unsaturated soil is a function of the suction within the soil (see section 29.4.2), which in turn is a function of the fabric of the soil. Therefore, a change to the structure of the soil (such as could occur when obtaining samples for laboratory investigation), for a constant water content, will result in a different effective stress of the soil (Wheeler *et al*., 2003).

Suction within a soil may be described as matrix suction (a function of the relationship between pore water and pore air pressure) or total suction (which incorporates suction due to osmotic pressure within the soil in addition to matrix suction), although at high suction (1500 kPa and greater) total suction and matrix suction are considered to be the same (Fredlund and Xing, 1994). The relationship between the suction experienced within a soil and the water content is illustrated by a soil–water characterisation curve (Fredlund and Rahardjo, 1993a, 1993b); see **Figure 29.18**. The nature of these curves is determined by soil parameters such as the pore size distribution, the minimum radius of the pores as well as the stress history and the plasticity of the soil (Fredlund and Xing, 1994).

In arid environments, soils can be uncemented (with particles free of any cementing bonding material) or cemented. Various aspects of their behaviour including suction must be considered. These will be considered in turn, highlighting key features pertinent to arid soils. However, only brief details

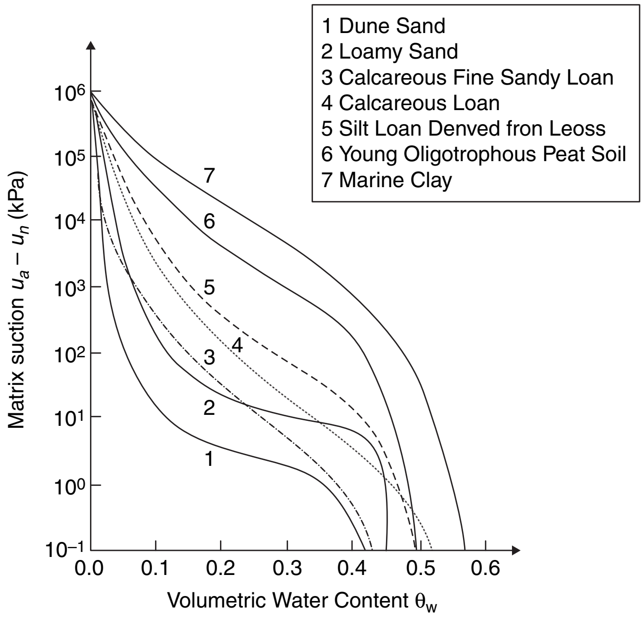

Figure 29.18 Typical soil–water characterisation curves for various soils Mitchell and Soga (2005)
Reproduced from Koorevaar *et al*. (1993), with permission from Elsevier

are provided and further details can be found in Fredlund and Rahardjo (1993a).

29.4.2 Engineering behaviour of unsaturated, uncemented arid soils

If a soil is uncemented and has reached the air entry point, the relationship between stress and pore water pressure must be modified to consider the effect of suction in the soil on the effective stress, and, hence, the shear strength, of the soil. At this point effective stress is a function of total stress, pore water pressure and pore air pressure (μ_a), which control the engineering response of an uncemented arid soil.

The shear strength of uncemented unsaturated arid soils may be determined using Equation (29.1) below (in which stress is σ, net stress is $\sigma - \mu_a$, effective stress is σ', shear strength is τ, angle of friction is φ', matrix suction is μ_a–μ_w and cohesion is c′), although this may overestimate the shear strength, particularly at low suction. Instead of combining the net stress and the matrix suction to form the shear strength, which is affected by the angle of shearing resistance, an alternative relationship can be derived if the shear strength is considered to be a function of both the net stress and the matrix suction. This relationship for shear strength is given in Equation (29.2), where *a* and *b* are parameters for net stress and matrix suction, respectively. Using two angles of shearing resistance allows for the reduction in the effect of suction on shear strength, given by Equation (29.3), where ϕ^b is the angle of shearing resistance with respect to matrix suction. The angle of shearing resistance with respect to matrix suction is equal to the angle at high suction but can be reduced by an increase in saturation (Rassam and Williams, 1999).

$$\tau = c' + \left(\left(\sigma - \mu_a\right) + \left(\mu_a - \mu_w\right)\right)\tan\phi' \tag{29.1}$$

$$\tau \propto a\left(\sigma - \mu_a\right) + b\left(\mu_a - \mu_w\right) \tag{29.2}$$

$$\tau = c' + \left(\sigma - \mu_a\right)\tan\phi' + \left(\mu_a - \mu_w\right)\tan\phi^b\,. \tag{29.3}$$

The compressibility and volume change behaviour for uncemented unsaturated soils have been studied using various models (e.g. the Barcelona model) developed by Alonso and Gens (1994). These allow net stress, deviatoric stress and volumetric strains to be assessed together for the soils. This suggests that matrix suction improves the ability of a soil to resist movement, even after the soil experiences plastic deformation. If suction within the soil dissipates then a new stress path will develop within the soil; this stress path results in the soils exceeding the pre-consolidation pressure and the soil will yield without an increase in external load (Alonso and Gens, 1994). The dissipation of suction results in a softening of the soil and an associated deformation.

Whilst an uncemented, unsaturated soil experiences elastic deformation with the dissipation of suction, i.e. the pre-consolidation pressure has not been reached, the soil will expand when water enters its pores (Alonso and Gens, 1994). Once the pre-consolidation pressure is reached the sample will yield and experience plastic (i.e. unrecoverable) deformation and the soil will compress. Even though suction continues to dissipate, the soil will not expand due to restructuring of the soil fabric on yielding (Alonso and Gens, 1994).

Restructuring of the soil fabric at the microscale in response to the dissipation of suction can result in disruption to the soil packing on the macroscale (Alonso and Gens, 1994). Thus, the overall effect may soften the soil and the actual pre-consolidation pressure may be less than predicted from the results of small-scale experiments. Softening may also occur if a soil experiences shearing. As the soil deforms under shear, the menisci within the pores may fail, and until the menisci reform the soil will experience a decrease in suction and as a result it will soften (Mitchell and Soga, 2005).

29.4.3 Relationship between net stress, volumetric strain and suction for collapsible and expansive arid soils

By studying the behaviour of soil samples taken from a site, Blight (1994) was able to describe the relationship between net stress, suction and volumetric strain for expansive and collapsing soils. In this section, drawing from the work of Blight (1994), a brief description of the relationship between net stress, volumetric strain and suction for collapsible and expansive soils is given. More details are given in Chapters 32 *Collapsible soils* and 31 *Expansive soils*, respectively.

An expansive soil with a low load will experience an increase in volumetric strain with the dissipation of suction and the associated increase in water content until the suction has fully dissipated and then the soil will experience additional swelling under saturated conditions (**Figure 29.19**). The dissipation of suction and the increase in volumetric strain may result in the expansive soil becoming unstable and at a critical level of suction the structure will become unable to support itself and will collapse. Once the soil structure has collapsed, additional expansion can occur with a continued reduction in suction. The load experienced by the soil will dictate the degree of volumetric strain experienced by the unsaturated expansive soil. Once suction has dissipated the soil may experience swelling or shrinking with a change in total stress.

Blight (1994) investigated the behaviour of a clayey silt sample using an oedometer at the natural water content of the soil and under saturated conditions. An oedometer was chosen because it allows a load to be applied to the soil sample, which was then inundated with water to simulate conditions likely to occur within the field, thus, allowing the degree of settlement for the soil to be predicted. The saturated soil sample in this investigation initially experienced heave under light consolidating pressure before yielding and suffering plastic deformation (see **Figure 29.20**). The unsaturated sample did not experience heave on loading and yielded at a greater pre-consolidation pressure

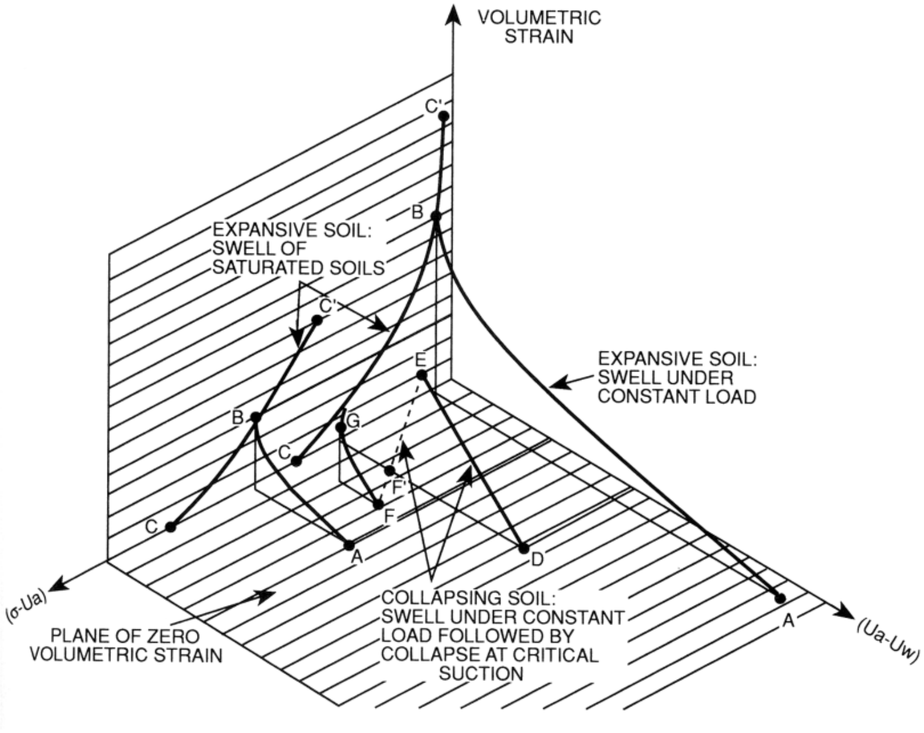

Figure 29.19 Figure 29.19 Three-dimensional stress--strain diagrams for partially saturated soil for the swell of a partially saturated soil under constant isotropic load
Reproduced from Blight (1994)

and, having yielded, was initially stiffer than the saturated sample (**Figure 29.20**). This is not a constant relationship, the soil particles within both the saturated and unsaturated samples will be forced together as the void ratio is reduced with increasing consolidating pressure, resulting in the samples becoming stiffer.

Thus, it is clear that actual deformations experienced by an unsaturated soil on site due to changes in loading can be very difficult to predict and it is recommended that laboratory or field trials are undertaken to determine the behaviour of the soil. Blight (1994) states that arid soils can be particularly problematic, due to the geomorphologic processes that formed them, as they can be prone to both expansion and collapse (echoed by Wheeler, 1994). Thus, some form of experimental investigation is considered fundamental if the behaviour of a soil is to be understood; oedometer testing is a popular laboratory method and plate loading has successfully been used in the field to describe the behaviour of arid soils (as illustrated in section 29.5).

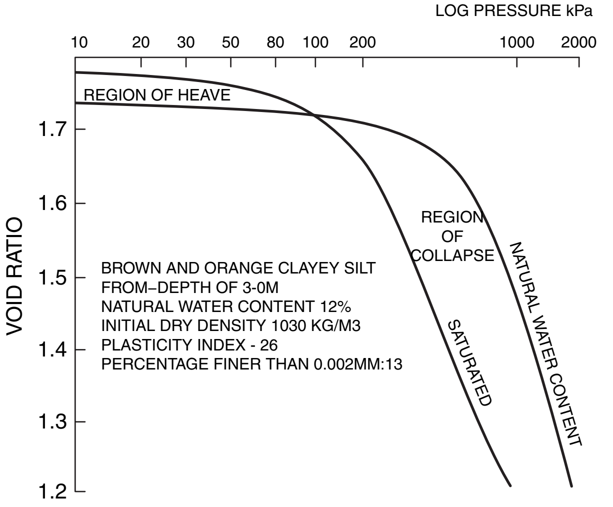

Figure 29.20 Behaviour of clayey silt at natural water content and after saturation
Reproduced from Blight (1994)

29.4.4 Cemented soils in arid conditions

Light cementation of soils (as opposed to the degree of cementation required to create a duricrust) is common in arid environments (see section 29.3.4 above) and will affect how a soil behaves on loading. Cemented soils may have increased tensile strength and may remain stable even after excavation; **Figure 29.21** shows aeolian sand deposits in a semi-arid environment during the wet season. The soil is stable after excavation due to cementation of the soil grains.

Care should be taken when assuming that the walls of an excavation will remain stable due to cementation; localised loading may still cause the sides of an excavation to deform and ultimately fail. Cementation of the particles will result in an increase in the shear strength, increased elastic deformation during loading (**Figure 29.22**) and an increased yield stress. However, once the cemented soil yields, the residual strength of the uncemented soil and lightly cemented soils (assuming all other parameters are the same) are similar. This is because the crystals bonding the particles within the cemented soil together are relatively brittle and will shear at low strains (Mitchell and Soga, 2005). Once the cementation is disrupted the shear strength reduces and becomes a function of the behaviour of the soil particles, following the behaviour of uncemented soils.

Figure 29.21 Excavation with sides of stable cemented sand (aeolian deposits) during the wet season in semi-arid conditions
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29.4.5 Sabkha soils

Sabkha soils are heterogeneous in nature, may be cemented, may be metastable and may contain high salt concentrations. Much like other metastable deposits, changes in water content can induce collapse in sabkha soils. The dramatic effect of water on sabkha soil was demonstrated by Aiban *et al.* (2006), who showed how the CBR for unsoaked specimens was around 50% at the maximum dry density, compared to around 5% when soaked at the same density. This difference in behaviour is due to dissolution of the cementing salts.

Sabkha soils are considered to be metastable; once the strength of the salts cementing the particles is exceeded (or the influence of the cementing salts is reduced as dissolution occurs with changes in the pore water) then there can be rapid rearrangements of the particles within the soil resulting in compression. This behaviour is not universally encountered in laboratory investigations of the collapse potential of metastable sabkha samples; soils loaded and inundated with water do not always collapse. Al-Amoudi and Abduljawad (1995) suggest that this is a function of the volume of water introduced into the sample, with an equilibrium forming between the concentration of salts in the water and the cemented soil. They used a modified oedometer that applied a constant head of water across the sample and allowed fluid to flow through the soil whilst it experienced loading. The modified oedometer test exhibited collapse compression and lower resulting void ratios under a load, whereas a sample in a traditional oedometer test did not collapse.

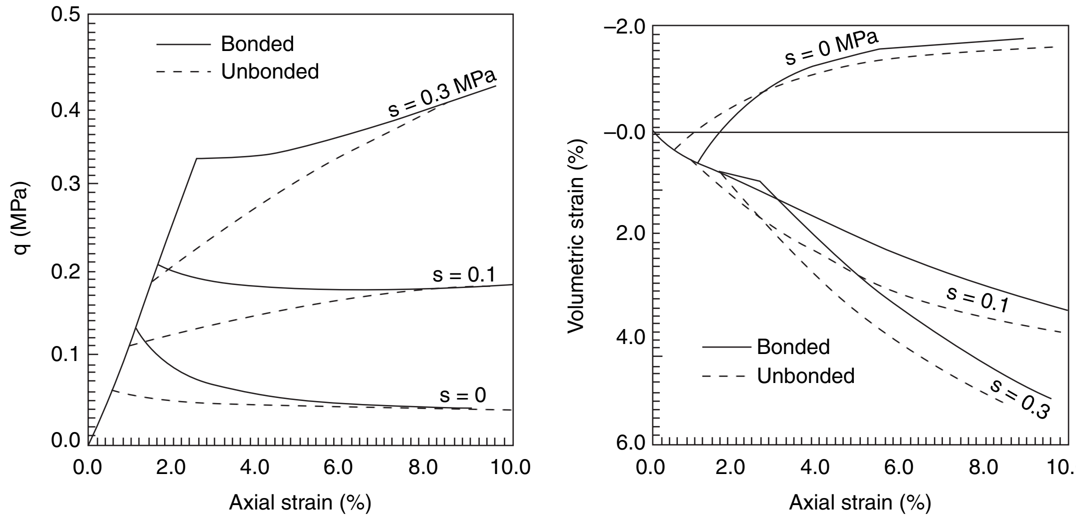

Figure 29.22 Simulated triaxial tests on unsaturated cemented and uncemented soils; (left) shear stress shear strain relationship and (right) volumetric response
Reproduced from Alonso and Gens (1994)

Al-Amoudi and Abduljawad (1995) suggested two simple equations that can be used to predict if the magnitude of the collapse in the oedometer signals problematic soil conditions on site. In Equations (29.4) and (29.5), i_{c1} and i_{c2} are the collapse potentials, Δe_c is the reduction in the void ratio on wetting, e_0 is the initial void ratio and e_1 is the void ratio at the beginning of saturation:

$$i_{c1} = \left(\frac{\Delta e_c}{1 + e_1} \right) \times 100 \tag{29.4}$$

$$i_{c2} = \left(\frac{\Delta e_c}{1 + e_0} \right) \times 100. \tag{29.5}$$

Equation (29.4) gives the change at the commencement of flooding and Equation (29.5) the collapse potential at the commencement of the consolidation test. Al-Amoudi and Abduljawad (1995) cite findings by Jennings and Knight (1975) that relates the collapse potential to the severity of the problem (see Chapter 32 *Collapsible soils* for further details).

29.4.6 Hydraulic conductivity and groundwater flow in unsaturated soils

Darcy's Law can be applied to unsaturated soils with modification. Mitchell and Soga (2005) give a relationship for the vertical seepage velocity in unsaturated soils, Equation (29.6), where $k(S)$ is the saturation-dependent hydraulic conductivity, ψ is the matrix suction and $\delta z/\delta x$ a gravitational vector measured upwards in the direction of z, for flow in direction i. This equation can be incorporated into a mass conservation equation to give Equation (29.7), which predicts changes in flow for changes in saturation and suction. Here, η is the porosity and $k(\psi)$ is the matrix suction-dependent hydraulic conductivity, derived from $k(S)$ using the soil–water characterisation curve.

$$v_i = -k(s) \left(\frac{\delta \psi}{\delta x_i} + \frac{\delta z}{\delta x_i} \right) \tag{29.6}$$

$$\eta = \left(\frac{\delta S}{\delta \psi} \frac{\delta \psi}{\delta t} \right) = \frac{\delta}{\delta x_i} \left[k(\psi) \left(\frac{\delta \psi}{\delta x_i} + \frac{\delta z}{\delta x_i} \right) \right], \tag{29.7}$$

in which vertical seepage velocity is v_i, matrix suction equivalent head is ψ, saturation is S, time is t, hydraulic conductivity is k, acceleration due to gravity is g.

This solution is valid provided that there are no changes in the soil structure or loss of water from the system (i.e. no loss of water due to biological activity, etc.). The transitional nature of the groundwater flow in unsaturated media, with changing permeability, degree of saturation and suction with flow and time, lends itself to numerical solutions (Mitchell and Soga, 2005).

Measurement of the hydraulic conductivity in unsaturated soils can be problematic due to the dependent relationship between the hydraulic conductivity, saturation and the matrix suction. The soil–water characterisation curve of a soil may be used to derive the hydraulic conductivity; an alternative approach is to use the apparent permeability (see Mitchell and Soga, 2005, for further details). The apparent permeability (k_r) and the saturated hydraulic conductivity (k_s), or the intrinsic permeability (K), may be used to estimate the hydraulic conductivity for an unsaturated soil, Equation (29.8), where ρ_{pf} and η_{pf} are the density and dynamic viscosity of the permeating fluid, respectively. The intrinsic permeability is defined by Equation (29.9), where e is the void ratio, k_0 is a pore shape factor, T is a tortuosity factor and S_0 is the wetted surface area per unit volume of particles.

$$k = k_r K \frac{\rho_{pf} g}{\eta_{pf}} = k_r k_s \tag{29.8}$$

$$K = \frac{1}{k_0 T^2 S_0^2} \left(\frac{e^3}{1 + e} \right). \tag{29.9}$$

Lee and Fookes (2005b) suggest that in arid conditions the fines content can reach 30% without having a significant effect on the ability of the soil to drain.

29.5 Engineering in problematic arid soil conditions

The creation of metastable, expansive and chemically aggressive (from the viewpoint of the durability of man-made structures) soil deposits within arid regions results in a number of geohazards, which must be addressed by the geotechnical engineer. Therefore, this section introduces case studies of various ground conditions encountered in arid regions, including:

- foundations in expansive, desiccated or collapsible soils;
- foundations in chemically stabilised soil or rock formations;
- compaction of placed fill;
- stabilisation of sabkha soils.

Chapters 32 *Collapsible soils* and 33 *Expansive soils* describe the behaviour of collapsible soils and expansive soils, with more detailed explanations of structure–ground interactions. This section provides an overview of problems encountered when dealing with soil deposits in arid environments with the aim of highlighting areas that may necessitate the attention of the geotechnical engineer during design and construction.

29.5.1 Geohazards encountered in desiccated, expansive and collapsible soils

29.5.1.1 Examples of foundation behaviour in expansive soils

A detailed review of foundations suitable for arid soils that exhibit expansive behaviour can be found in Chapter 33 *Expansive soils*. That chapter deals with assessment and the foundation or remediation options available to deal with such soils. The key aspect is the implication of the unsaturated state due to the arid environment, which dictates the nature of the problem and the responses needed.

For example, Kropp (2010) reviewed changes in the foundation design for domestic dwellings on expansive soils in the San Francisco Bay Area. Here, the preference in the local community is for grassed or planted gardens and watering is common. It was suggested that homeowners regularly overwatered the ground, to the point where the mass of water penetrating the ground exceeded that exiting the ground via evapotranspiration, and this change in localised groundwater conditions results in considerable, and potentially differential, ground movement; movement which strip footings were ill-suited to resist.

Nusier and Alawneh (2002) report on the distress caused to a single-storey concrete building with a mat foundation (a reinforced concrete slab) constructed on expansive clay in Jordan. The shallow foundation experienced differential ground movement as the ground under most of the house heaved, yet one corner of the building settled (due to the desiccating action of a tree); the mat was not sufficiently rigid to withstand these movements, the concrete foundation walls were not reinforced and the building suffered significant cracking. It was suggested that the soil under the building heaved due to a thermal gradient existing across the soil below the building and the soil surrounding the building directly exposed to sunlight, resulting in the migration of water from the surrounding area towards the ground below the house. Nusier and Alawneh (2002) concluded that had the foundation been deeper, to a depth where the pressure from the building acting on the soil equalled, or exceeded, that of the pressure from the expanding soil, then the situation could have been avoided. Instead, the building was repaired by installing a reinforced concrete skeleton to the outside of the building and a ring beam to the mat. This intervention cost approximately 25% of the original cost of constructing the building, highlighting the need to understand the probable behaviour of the ground before undertaking construction.

When a desiccated clayey soil experiences infiltration of water during, and directly after, a storm (or because of a leaking utility) the soil fabric will undergo restructuring as it swells. This phenomenon can be pronounced if the soil comprises a significant fraction of clays, or an active clay mineral such as smectite. The seasonal cycle of desiccation/wetting may also cause problems with deep foundations. Blight (1994) reports that pile tests in soil conditions in southern Africa indicate that soil shrinks away from the surface of a pile as it dries in the dry season; clearly this has significant implications when designing a deep foundation if there is a considerable reduction in the skin friction acting on a pile.

Various improvement approaches can be used to treat expansive arid soils (see Chapter 33 *Expansive soils*). For example Rao *et al*. (2001) investigated the performance of lime-stabilised expansive-clay compacted samples exposed to repeated cycles of wetting and drying. Samples were created with lesser and greater amounts of lime than the initial consumption of lime (ICL) value of the soil and were then exposed to several wetting and drying cycles. Both the wetting and drying phases each took 48 hours to complete. It was noted that repeated cycles of wetting and drying had a detrimental effect upon the lime-stabilised soil, in particular for samples with lime contents slightly above or below the ICL. Increasing the number of wetting and drying cycles resulted in:

- more clay detected in the stabilised samples, which Rao *et al*. (2001) suggest is illustrative of the decaying stabilisation of the clay soil;
- a higher liquid limit;
- a lower plastic limit;
- a lower shrinkage limit.

29.5.1.2 An example of foundation behaviour in a collapsible soil

A detailed review of how to deal with foundations in arid soils that exhibit collapsible behaviour can be found in Chapter 32 *Collapsible soils*. That chapter deals with assessment and the foundation or remediation options available to deal with such soils. The key aspect, as with expansive arid soils, is the implication of the unsaturated state due to the arid environment, which dictates the nature of the problem and the responses required.

Loess, a collapsible arid soil, is often considered to be a problematic soil readily collapsing after inundation by water or an increase in load. However, loess often initially experiences a small degree of settlement before experiencing heave, particular at low applied pressures (see section 29.4.3 and **Figure 29.20**). For example, during a plate-loading test, Komornik (1994) applied cycles of loading and unloading to a plate in a loess soil, at the natural water content and after wetting the soil. Wetting resulted in collapse, leading to large unrecoverable deformations. The difference between the behaviour of the soil at the natural water content and the soil after wetting illustrates the necessity of designing a foundation carefully if swelling or collapse potential is considered a possibility, and also the necessity of protecting the location from possible inundation during storms in order to prevent movement of the foundation after completion of construction.

A range of treatment and improvement approaches can be employed to mitigate the behaviour of collapsible arid soils (e.g. dynamic compaction, cement stabilisation) and further discussion can be found in Chapter 32 *Collapsible soils*.

29.5.2 Compaction of fill

In an arid environment, where water is not generally plentiful, applying too little water to the soil (or, in a hot arid environment, applying the desired amount and losing a proportion to evaporation) may result in the development of suction within the soil as it is compacted. The suction will resist the compactive effort and the net effect is a low-density fill, which may experience undesirable levels of settlement. It has been suggested that in such circumstances compacting the soil when it is dry might be more appropriate (Newill and O'Connell, 1994). Of course, dry compaction will produce fills with a high volume of air voids and measures must be taken to ensure that subsequent ingress of water is prevented or the fill may undergo restructuring of its fabric, causing the fill to deform or collapse.

In large construction projects, the volume of water required can be significant, which can create logistical problems when working in arid conditions. For example, Newill and O'Connell (1994) investigated the construction of a major road in an arid environment and estimated that the water required to create one kilometre of the road could be as much as 2800 m^3 and equated to approximately 20% of the total construction cost in sourcing and transporting the water to site. This value, by far, exceeds the cost of water for construction in tropical or temperate climates. It must also be considered that arid conditions are often located in developing countries (White, 1966), and the infrastructure can be, at best, extremely limited outside urban areas. Due to the potential lack of infrastructure in rural areas, the source of water may be from boreholes and it is unlikely that any treatment will be applied to the extracted water before it is used for construction. Therefore, the extracted water can potentially contain significant concentrations of salts, salts that will remain within the fill and can have a detrimental effect on the man-made structures placed upon it.

In addition, not all construction projects in developing countries boast the resources necessary to surmount the logistical problems of sourcing sufficient water for a project. For example, whilst working on a site in arid conditions a sister site (approximately 100 km away) faced significant problems when it was announced that the local village borehole was at risk of running dry and a moratorium was placed on the use of water for anything other than critical functions (which did not include construction). In order to continue construction, and ensure that the workforce had water for drinking and washing, 5 m^3 of water was transported by bowser daily. This placed a strain on the efficiencies of both sites and it was difficult to justify the use of water when compacting fills, when other more critical functions (drinking, washing, casting concrete, etc.) took precedence. Eventually it was decided that in order to meet the specifications (end-product specifications were being used) water would have to be used during compaction and the programmes for both sites overran.

When compacting soils in arid environments, particularly for significant geotechnical structures such as roads or embankments, the processes applied are likely to be governed by a framework or standard. Truslove (2010) and Puttock *et al.* (2011), by considering suitable earthwork specifications in arid environments, reviewed a number of standards used in various countries with arid lands. Truslove (2010) concluded that currently there are standards that permit the use of compaction of dry fill in rural areas (such as Kenya), whereas other standards refer to an end-product specification (minimum acceptable dry density, etc.) and do not necessarily comment on the amount of water used. Kropp *et al.* (1994) investigated a compacted fill that had suffered excessive deformation; the soil was a granular material that contained clay and had been compacted to a density greater than the minimum required in the end-product specification, although with a water content less than the optimum (up to 7% less). It was concluded that wetting had induced collapse and that, perhaps, the standard should also impose conditions on the water content of the compacted fill to try to avoid this scenario. Truslove (2010) cites studies that suggest that consideration must be given to the nature of the soil underlying the compacted fill and that care should be taken when selecting the water content of the fill as there is the potential for water to migrate from the fill into the underlying soil, which could induce structural changes within the underlying soil, jeopardising the performance of the fill above.

Sahu (2001) investigated the performance of six regionally sourced soils, from locations in Botswana, when mixed with fly ash with the aim of producing a range of materials that could be used as base courses in highway construction. The six soils ranged from Kalahari sand, calcrete, silts (of various plasticities) and silty sands as well as an expansive clay soil. Various proportions of fly ash were mixed with the soils, and the mixtures were hydrated and left to cure. With the exception of the expansive clay, the inclusion of fly ash lowered the maximum dry densities. However, the inclusion of the fly ash did increase the CBR for the soils containing silts and the calcite; therefore it was suggested that this made these soils suitable for use in highway construction. The inclusion of fly ash in the Kalahari sands and the expansive clays did not have a noticeable impact on the CBR and these were deemed unsuitable for highway construction.

29.5.3 Stabilisation of sabkha soils

Al-Amoudi *et al.* (1995) cites instances where geotechnical improvement techniques such as dynamic compaction, stone columns, densification piles and the creation of drainage have all successfully been used to improve the physical properties of these notoriously weak materials. Al-Amoudi *et al.* (1995) quotes unconfined strengths of around 20 kPa and SPT N ranges of 0 to 8 for these types of formations of sabkha soils, although a value of 30 kPa can be achieved at depth (Shehata and Amin, 1997).

Alternative ground-improvement materials, such as the use of filler particles (limestone dust or marl), to reduce the void ratio of the soil and potentially increase the UCS, have been trialled with sabkha soils (Al-Amoudi *et al.*, 1995). The limestone dust (a by-product of an industry local to the study) and marl increased the maximum dry density of the sabkha soil, with the limestone dust reducing the optimum water content and the marl increasing the optimum water content. However, varying the content of limestone dust or marl did not noticeably change the UCS of the sabkha soil, suggesting that the incorporation of these materials can reduce the volume of voids of the compacted sabkha soil but not have a noticeable increase on its strength.

Cement and lime have also been investigated and found to be beneficial as stabilising agents for sabkhas soils (**Figure 29.23**), although there are concerns with the long-term durability of the stabilised materials (Al-Amoudi *et al*., 1995).

Damage to the base and sub-base courses of highways due to movement in the underlying sabkha sub-grades has resulted in investigations into the use of geotextiles between the road foundation and the sub-grade (Abduljawad *et al*., 1994; Aiban *et al*., 2006). Static and dynamic testing of dry and wet sabkha soils, underlying various geotextiles and sub-base materials in a laboratory, illustrated that geotextiles could increase the load required to induce deformation within the soil. **Table 29.5** illustrates the force required to induce a 30 mm deformation at the load plate on the soil for soaked and 'as moulded' conditions with and without a geotextile.

29.6 Concluding comments

Arid soils form in environments where evapotranspiration rates exceed rainfall. Arid soils cover about a third of the Earth's land mass and occur in hot and cold arid regions. However,

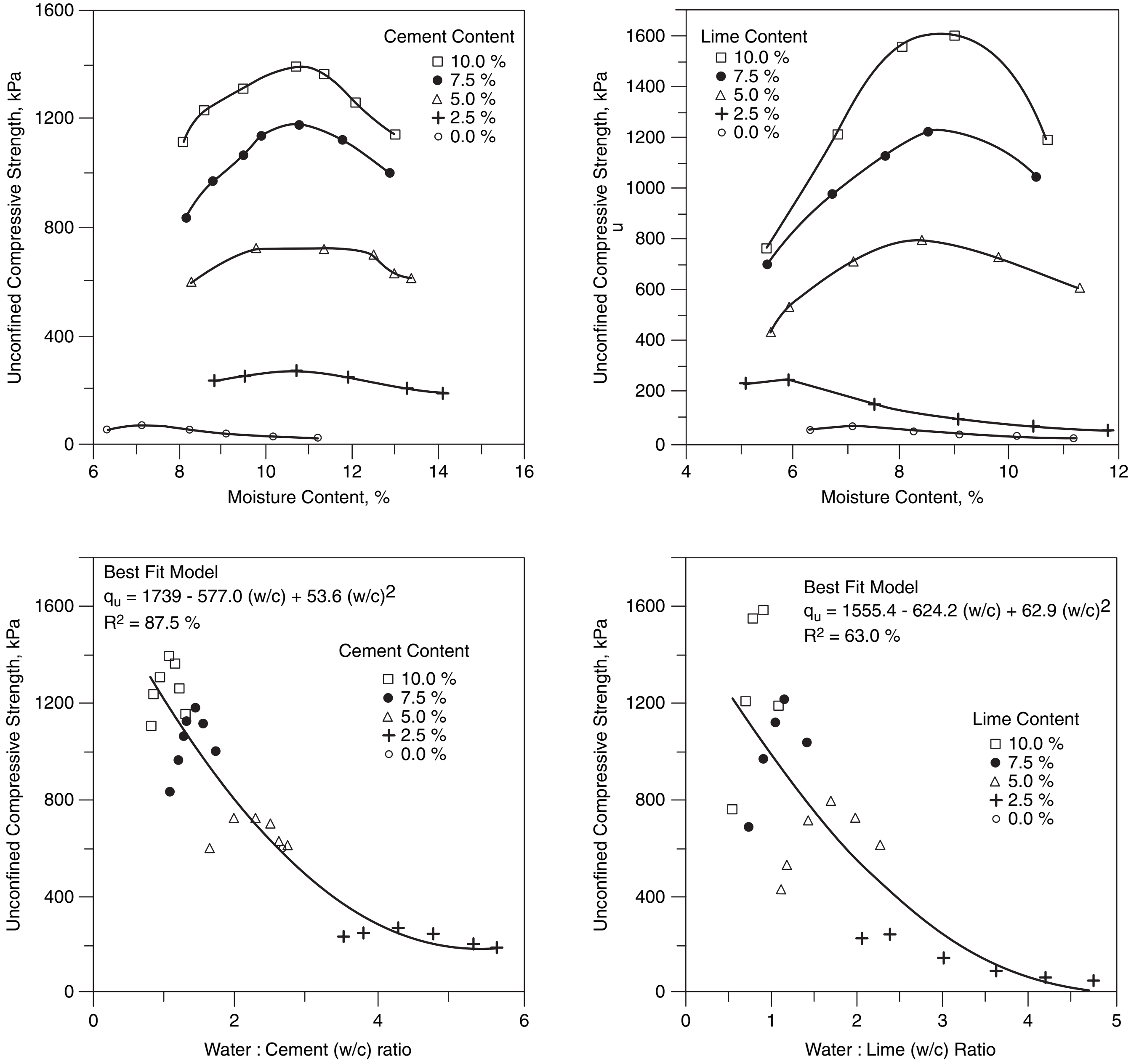

Figure 29.23 Stabilisation of a sabkha soil with cement (top left) and lime (top right). Illustration of the relationship between the UCS and the water/cement ratio (bottom left) or the water/lime ratio (bottom right)
Reproduced from Amoudi *et al*. (1995) © The Geological Society

Sample code	Load at 30 mm deformation (kN)	Test condition
Without geotextile		
SG0H65W	1.8	Soaked
SG0H65D	14.3	As moulded
With geotextile		
SG140H65W	2.8	Soaked
SG300H65W	6.1	Soaked
SG400H65W	6.7	Soaked
SG300H65D	23.5	As moulded

Table 29.5 Loads required to achieve a deformation of 30 mm at the load plate on a sub-base overlying a sabkha sub-grade, with or without a geotextile, in soaked and 'as moulded' conditions (Aiban *et al*., 2006)

soils formed under arid climates can also be found in temperate regions due to ancient geological processes.

Arid soils present a number of challenges to engineers owing to:

- the highly variable nature of their engineering properties associated with active and ancient geomorphic processes;
- the considerable diurnal temperature ranges experienced, potentially resulting in accelerated disintegration of soil and rock formations as well as man-made structures;
- lithification processes, which can result in cementation of the soil particles, making excavation problematic;
- various problematic soils, which occur in arid conditions, such as those with significant shrink–swell or collapsing potentials, or aggressive salt environments.

Key to understanding how arid soils behave and how these soils can be engineered is achieved through an appreciation of how geomorphology controls their formation. Associated with these processes are soils that can be cemented or uncemented, whilst being unsaturated. Once the geomorphologic effects are understood, the appropriate engineering assessments and mitigation can be applied. A number of logistical challenges associated with water also occur in arid environments: limited availability (resulting in the use of groundwater with high salt concentrations in construction processes, or having to bowse water from external locations to the site); or poor management (for example through lack of appreciation of the significant impact of flash flooding on the erosion of natural, or man-made, soil formations, or the impact of water containing high salt concentrations on construction processes such as the casting of concrete).

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29.7.1 Further reading

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29.7.3 Useful websites

British Geological Survey (BGS); www.bgs.ac.uk
British Standards Institution (BSI); http://shop.bsigroup.com/
US Geological Survey (USGS); www.usgs.gov

It is recommended this chapter is read in conjunction with

- Chapter 7 *Geotechnical risks and their context for the whole project*
- Chapter 40 *The ground as a hazard*
- Chapter 76 *Issues for pavement design*

All chapters in this book rely on the guidance in Sections 1 *Context* and 2 *Fundamental principles.* A sound knowledge of ground investigation is required for all geotechnical works, as set out in Section 4 *Site investigation.*