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Chapter 38

Soluble ground

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CONTENTS

Limestones, gypsum, salt and varieties of these are the rock materials soluble in natural water, which can, therefore, be eroded to create ground cavities, which in turn can be the cause of ground failure and surface subsidence. These are features of karst terrains. The dominant karst geohazard is the development of new sinkholes within soil profiles overlying cavernous rock, where the rock remains stable but the soil is washed downwards into the open fissures. Most of these are induced by engineering activity, therefore they are preventable. Engineering problems are also caused by highly irregular rockhead profiles, and by cavities that may underlie foundations. Assessment of karst ground is very difficult, but the broad characteristics of karst are now well known and should be appreciated in practice. Less well known is the karst hazard in sabkhas, with increasing instances of ground failure encountered, but poorly documented, in the construction boom in the Middle East.

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38.1 Introduction

Naturally occurring soluble ground materials are limestones (including dolomite and chalk), gypsum (and also anhydrite) and salt (halite), in order of decreasing abundance and increasing solubility. Exposure of all of these to rainwater, stream water and groundwater commonly leads to the development of subsurface cavities, with all the attendant consequences of collapse and ground subsidence. Long-term underground erosion creates cave networks, which can take all of the surface drainage. The essentially streamless landscapes, with their distinctive suites of landforms, are known as karst. Any karst terrain, on any of these rocks, presents some degree of geohazard, which may include slow ground subsidence, catastrophic collapses and destructive sinkhole development.

38.2 Soluble ground and karst

Soluble rocks present a variety of geohazards where they lie within a few tens of metres of the ground surface (and sometimes also at greater depths). Direct dissolution of the rock is only rapid enough to undermine a built structure within its lifetime in the case of salt, and to a lesser extent gypsum; in both cases any significant loss of ground would take place only where it is exposed to a significant flow of aggressive water. Limestone dissolution is so slow that it would take thousands of years to impact on a structure founded upon it. The hazards for limestone, and gypsum, are created by open fissures and cavities that are dissolved out of the bedrock over geological time scales. Soil-filled fissures within a buried rockhead commonly form very difficult ground for founding structures, but collapses of rock over open caves are rare. The major hazard is presented by bedrock voids, which are capable of swallowing large volumes of unconsolidated soil cover possibly within 12 hours or days; the consequence is the formation of the most common type of sinkhole.

38.2.1 Sinkholes

Sinkholes are closed depressions, 1–100 m in diameter and depth, that are the diagnostic landforms of karst terrains (Waltham *et al.*, 2005); they are correctly known as dolines by geologists, but the sinkhole term dominates in the American and the engineering literature. The term implies that the ground has sunk; water does normally sink into them too, but few have visible streams sinking into them. It is important to recognise the contrasting types of sinkhole (see **Figure 38.1**). Small numbers of collapse sinkholes, formed where the rock collapses into a cave below, are found in most karst terrains, but the chances of a new failure are so low at any site that they present a negligible risk to engineering. Nearly all large collapse sinkholes have expanded in sequences of failure events, further minimising the risk of massively destructive ground collapse.

The main karst geohazard is the formation of subsidence sinkholes in the soil cover over a fissured and cavernous limestone (**Figure 38.2**). Not only are these the most abundant, but new subsidence sinkholes can form by rapid movement of the soil cover and, therefore, have the greatest impact on engineered structures. The suffosion and dropout types differ due to the properties of their soil cover and, therefore, in their mode of failure – either the slow ravelling in a sandy soil or an arch failure into an undermined void in a more fine-grained soil. A soil-filled buried sinkhole constitutes an extreme form of rockhead relief, perhaps described as a soft spot, and sometimes developing a shallow compaction sinkhole in the surface above. Sinkholes may also develop purely by rock dissolution, but these are long-term erosional features comparable to valleys in non-karst

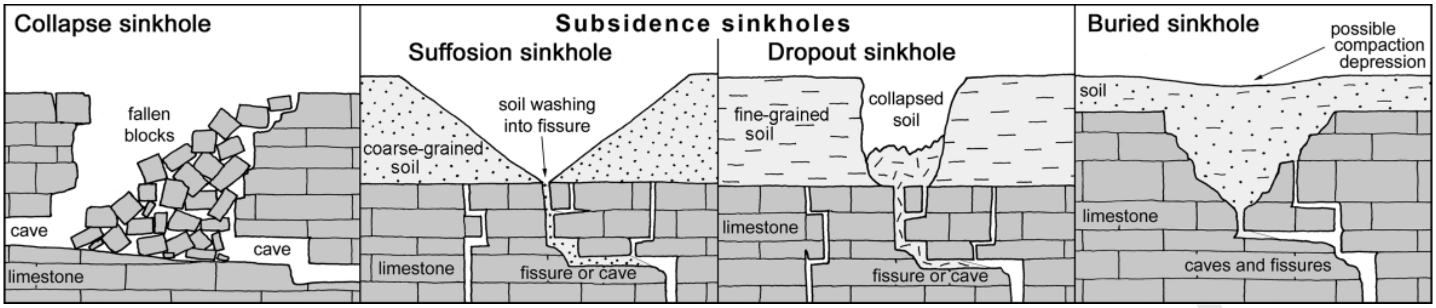

Figure 38.1 The main types of sinkhole developed in or above soluble rocks in karst terrains
Modified from Waltham and Fookes (2003)

Figure 38.2 A recently developed subsidence sinkhole in clay-rich alluvial soils in Turkey; this formed by a rapid collapse in the style of a dropout, but its slopes are already degrading to a wider profile; the bedrock is gypsum, which is visible at the outcrop in the background

terrains, and have little engineering significance except that the ground beneath is more likely to be more cavernous than adjacent ground. A shallow bowl, rather like a compaction sinkhole, can also be formed by localised rockhead dissolution, especially of salt. The engineering significance of both subsidence sinkholes and rock collapse are described in sections 38.3 and 38.4 below.

38.2.2 Distribution

Soluble rocks are widely distributed in all sedimentary sequences. Britain offers an assemblage of ground conditions that reasonably represents the proportions of the land area with soluble ground geohazards that can be found across the world (**Figure 38.3**). Limestones and varieties of carbonate rocks are the most widespread, with outcrops in almost every country in the world, but these do present considerable variation in the scale of their karst geohazards. It is notable in the British example that only some of the limestones are old, strong and cavernous, and, thereby, have widespread karst geohazards, while the weaker limestones rarely provide major difficulties for construction. Also, chalk is a special case, where rock strength and weathering are generally more significant than karstic conditions (Lord *et al.*, 2002). Worldwide, limestone karst causes the most extensive engineering difficulties in huge swathes of southern China, in large parts of the eastern USA and in the Dinaric karst that extends across the nations of the former Yugoslavia.

Gypsum is far less widespread than limestone. The small outcrops in the Midlands and northern England mean that Britain is perhaps under-represented when comparisons are made worldwide; the American mid-West and the Ukraine are the two large regions most impacted by their gypsum karst. Salt is of even more restricted extent, both in Britain and worldwide; its geohazards are well known in the developed lands of Britain and America, but it is the Middle East of south-western Asia that has the greatest areas directly underlain by salt.

38.3 Influences on the geohazard of limestone karst

Dissolution causes the most conspicuous karst features in pure, strong limestones (unconfined compressive strength, UCS > 70 MPa) where extensive fractures can be enlarged to create fissures and caves between blocks of intact strong rock. Weaker and softer limestones, such as England's Cotswold oolites, are more porous, so have more diffuse groundwater flows through micro-fissures; chalk also has diffuse flows, but much of its groundwater is transmitted through open fissures, and caves can occur (Lord *et al.*, 2002). On a broad scale, the age of the limestone is irrelevant; Carboniferous limestones in England, Jurassic limestones in France and Tertiary limestones in South East Asia have identical engineering properties. Dolomites and dolomitic limestones are rather less prone to dissolution, so generally have a reduced scale of karst features. Larger cavities develop where streams of aggressive water enter the limestone from adjacent impermeable rock outcrops, so there is a tendency for increased karst development adjacent to geological boundaries. Beyond that, rock structure and lithology influence cavity development, which is mainly at large fractures and chemically favourable inception horizons, and the guiding features can be recognised in most mapped cavities. But the distribution, pattern and positions of caves cannot be predicted within the hugely variable structure of natural ground conditions.

The scale of karst development may vary considerably, as recognised by a broad classification of karst ground conditions (see **Figure 38.4**). Any description and assessment of karst for engineering purposes should not only define the limestone

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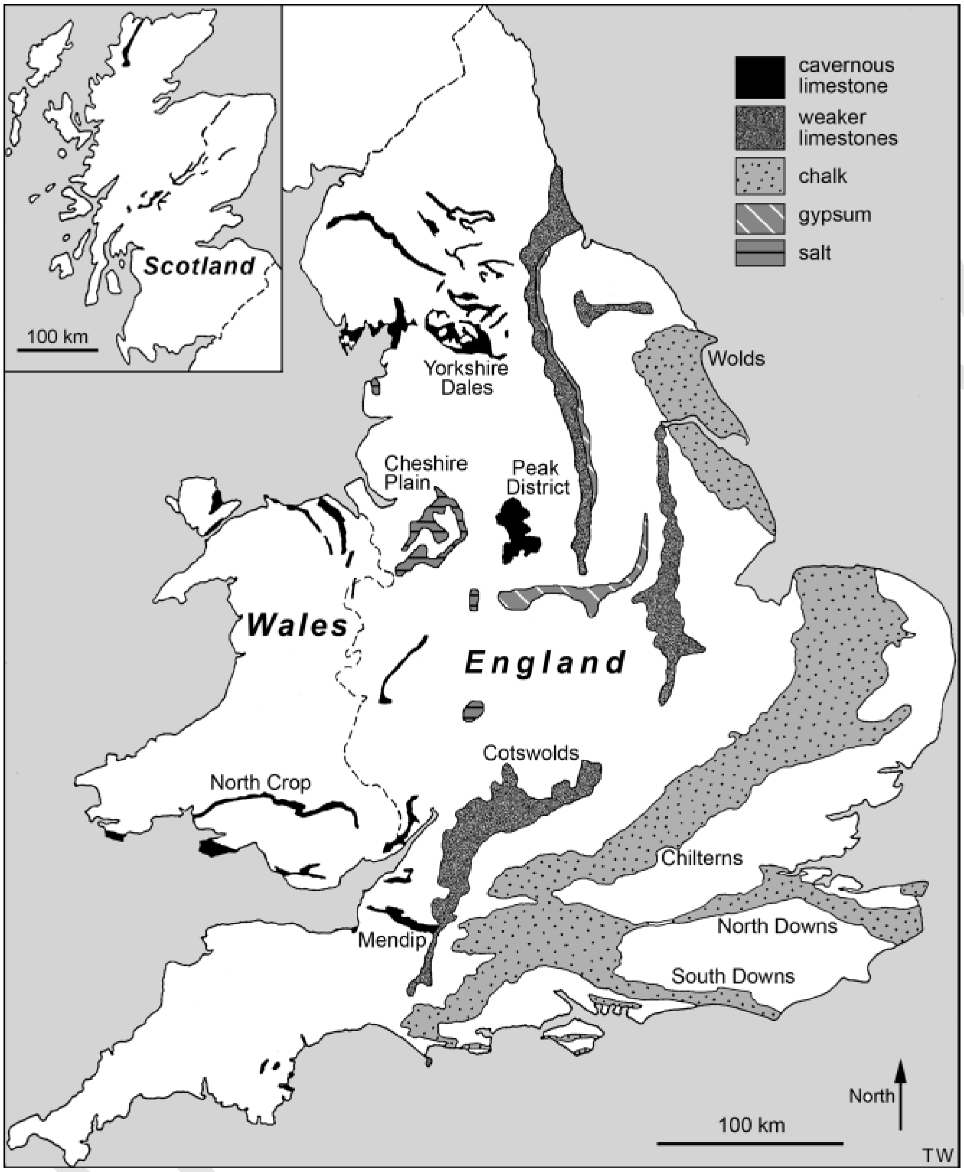

Figure 38.3 The distribution of soluble ground in Britain; all these areas are prone to karst geohazards, but recognisable karst landscapes are only widely developed on the cavernous limestones and on some of the chalk outcrops

lithology and the karst class, but should also determine or estimate approximate values for the three key parameters: typical cave size, frequency of new sinkholes and rockhead relief (Waltham and Fookes, 2003). Limestone dissolution in water is dependent on carbon dioxide to create soluble bicarbonate ions, and most dissolved carbon dioxide is derived from biogenic sources within soil profiles. Consequently, the scale of karst features, and, therefore, the karst class, is closely related to plant cover and, therefore, to the climate, and also to past climates. Karst in the colder climates of high latitudes and altitudes, such as in Britain and Canada, typically shows restricted development, to classes kII or kIII, with cave passages, rockhead fissures and rare new sinkholes all typically measuring less than 10 m. This contrasts with the humid tropics, such as in South East Asia or the Caribbean, where very well-developed karst terrains of classes kIV and kV have giant caves, pinnacled rockheads and numerous sinkholes, all with dimensions that approach or exceed 100 m. Limestones in hot and dry environments, such as in Australia and the Middle East, have modern karst development restricted by low rainfall, but commonly have isolated large caves and other karst landforms relict from wetter climates during the Pleistocene.

Though the natural environments dictate the overall scale of karst development, it is important to recognise that individual events of ground subsidence or collapse are commonly generated by man's activities that bring a sudden change to equilibrium situations. Engineering works that either remove or introduce water, or add an imposed load, all happen at far greater rates

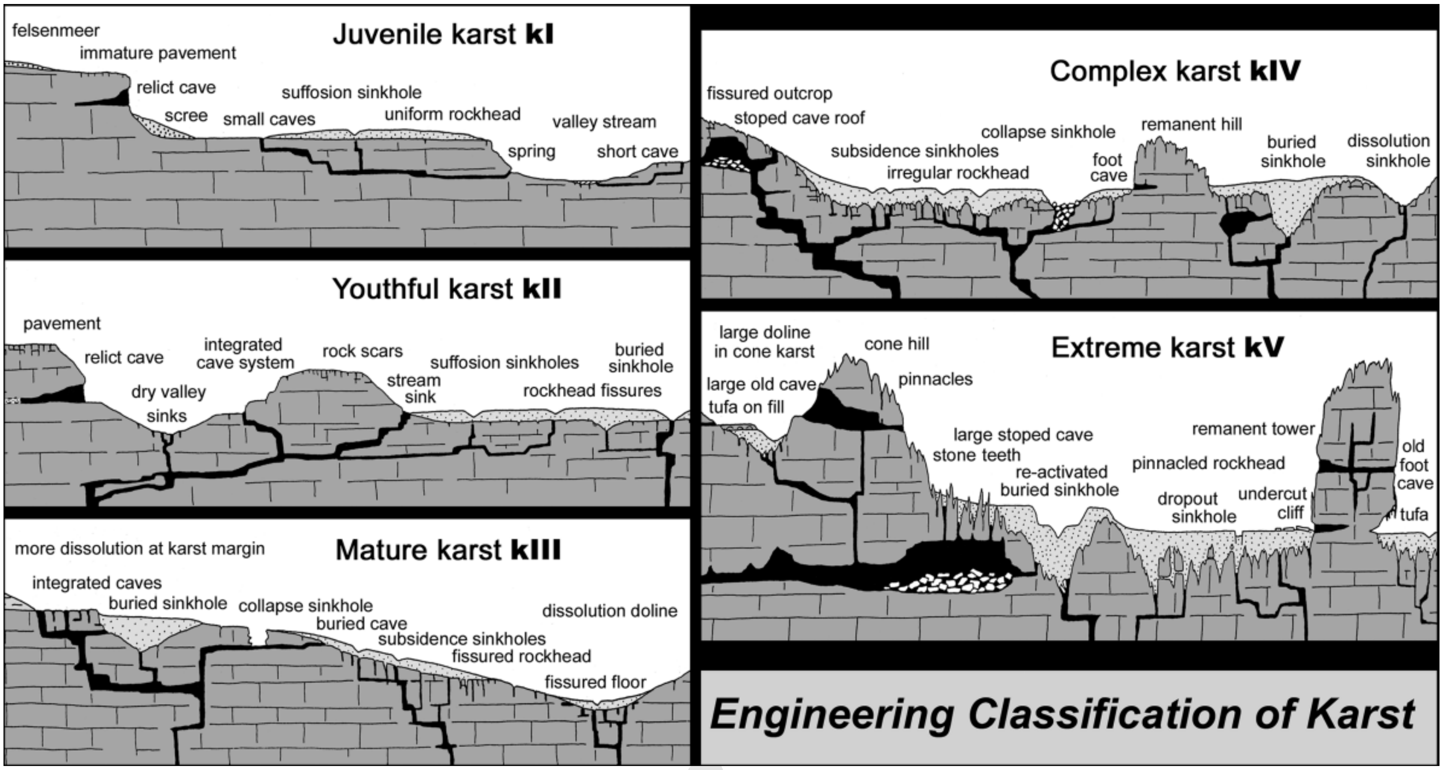

Figure 38.4 The five classes of karst that broadly demonstrate the variety and scale of landforms and ground conditions relevant to engineering
Modified from Waltham and Fookes (2003)

than normal geological evolution. In a natural and undisturbed karst, ground movements and collapses do occur, but typically as isolated events separated by hundreds or thousands of years. But any such event may be triggered prematurely by inappropriate engineering activity. A karst geohazard may be regarded as an event waiting to happen, unless appropriate precautions are exercised to avoid undue disturbance of the existing environment; these include thorough control of the drainage to avoid accelerated soil loss (see section 38.4.1), and the avoidance of excessive loads imposed on unstable rock (see section 38.5.1).

38.4 Engineering works on soil-covered limestones

The major geohazard of karst is the development of new subsidence sinkholes within the soil cover over fissured bedrock, because the process can develop very rapidly, well within structure lifetimes and even within construction periods (**Figure 38.5**), and without any imposed loading. Any unconsolidated soil lying over karst bedrock is prone to loss by downward migration, known as suffosion or ravelling, into the bedrock voids. Clean sand flows with ease and can, therefore, cause a slow lowering of the surface until the stable profile of a suffosion sinkhole is reached, with a throat at a bedrock opening (**Figure 38.1**). A soil with almost any clay content loses ground first from immediately above the rockhead, and it has the capability of developing a large soil void beneath an unstable soil arch. There is, therefore, no surface indication of the impending failure, until the thinned soil arch fails, instantly producing a dropout sinkhole (**Figure 38.1**). In reality, most soils have some degree of apparent cohesion, created in part by the negative pore water pressures, so they can develop soil voids and produce surface failures that vary between instantaneous and progressive; the profiles of most dropout sinkholes degrade into those of suffosion sinkholes either within a few days of the wall slumping or over longer periods. A thick soil mantle tends to reduce infiltration, such that the number of new sinkholes is greatly reduced in soils much more than about 10 m thick, but this is not an absolute limit, and ground failures have been recorded where the cavernous rock lies more than 100 m below the surface level.

38.4.1 Drainage and induced sinkholes

The suffosional removal of soil takes place almost entirely as downwashing by percolating water. It is, therefore, crudely predictable that many new sinkholes will develop during or soon after major rainstorms. However, the locations of new sinkholes are not predictable, as they will be located above open fissures that are unseen in the soil-mantled rockhead until the sinkhole develops (**Figure 38.6**). It is, however, significant that subsidence sinkholes are most likely to develop where and when there is a change to an existing equilibrium in rainfall infiltration and groundwater flow. Such a change

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Figure 38.5 Collapse of a road on a bridge approach undermined by a new subsidence sinkhole in alluvial soils in Pennsylvania; this was one of many ground failures that developed within the zone of the decline of the water table around a deep quarry that was kept dry by continuous pumping

Figure 38.6 Numerous small subsidence sinkholes in a thin soil of glacial till over limestone in the Yorkshire Dales; there is no pattern to the sinkholes, as each has developed over an open fissure in the buried limestone, comparable to the exposed fissures in the bare patches of the limestone pavement

may be increased input at any point, either by concentrated run-off from a built structure, by inappropriate use of a soak-away or infiltration pond, or from a fractured pipeline. Equally, the change may be the increased drawdown of surface water due to a water table that has declined within an aquifer that is over-pumped. More than 90% of new sinkhole appearances are related to the disturbance of the drainage equilibrium by civil engineering activities (Newton, 1987; Waltham *et al.*, 2005).

Because most new sinkholes and karstic ground failures are induced by man's activities, the key feature to good engineering practice is to minimise or eliminate the hazard by control of the drainage. This includes the total collection of run-off from all built structures and areas of sealed ground, the proper disposal of that run-off directly into the bedrock or away from the site, the sound maintenance of all pipelines and stream channels, and the avoidance of increased infiltration when ground is exposed or replaced with granular fill during construction works. Failure or inadequate actions for any of these will almost inevitably lead to soil loss and sinkhole development, which will require far more costly remediation at some future date. Where sinkholes are induced by a decline of the water table, there may be no simple remedy that can be applied within the confines of a site or construction project. If that decline is due to groundwater pumping for municipal or private supply, to dewater ground to keep a quarry or mine dry, or temporary dewatering for a construction project, the costs of subsidence damage may simply have to be factored into that operation's budget, unless the economics determine a replacement water supply, a quarry closure or an alternative method of constructing deep foundations.

The placing of structural foundations within the soil profile over karst limestone is inevitable in the case of most roads, and also for many small, built structures over thick soil profiles. They can be perfectly appropriate where the proper drainage measures ensure that the ground is not unduly disturbed. Each project should be treated individually; foundations should be provided appropriate to that particular site (Sowers, 1996; Waltham *et al.*, 2005). A host of alternatives may involve engineered soils, geogrids, rafts and mattresses, partial excavations, replacement soils, load transfer to bedrock pinnacles, and reinforced foundations; all of these measures should be designed to minimise soil ravelling and to bridge any small voids that may develop subsequently (useful examples are provided by Vandevelde and Schmitt, 1988; Lei and Liang, 2005).

Grouting can be appropriate, but the sealing of all fissures within a karst limestone is likely to prove very expensive because huge quantities of fluid grout can be lost into large but unseen open voids. Compaction grouting, within the soil just above the rockhead, can effectively prevent the downward loss of soil, which is densified in the same process, and this commonly yields better results (Henry, 1987; Stapleton *et al.*, 1995).

Where an existing structure exhibits settlement damage following a history of stability, the key to remediation is to determine and rectify the feature that caused the new movement. In many cases this will be a drain or pipeline failure, and repairs may be all that is required to recover the integrity of the structure. Pressure grouting within the soil may be appropriate if action is not been taken before settlement damage becomes too severe. New open sinkholes commonly require repair, and this should entail backfilling with selected sizes of materials so that the sinkhole is choked to prevent further soil loss but it may be required to still drain surface water safely into bedrock fissures (Waltham *et al.*, 2005).

38.5 Engineering works on limestone bedrock

Foundations carried through to the bedrock eliminate the major dangers of soil movement and sinkhole development within the overburden, but karst ground buried beneath soil cover is very variable and not easily assessed. It offers two major difficulties: an uneven, fissured or pinnacled rockhead, and the threat of open caves lying just beneath any footings.

Dissolution down limestone joints, which may occur before soil cover is emplaced but also matures beneath the soil cover, creates open or soil-filled fissures within the buried karstic surface that is the rockhead. These fissures may be widely spaced, irregular or closely spaced, leaving blocks or pinnacles of bedrock between them; a pinnacled rockhead has a forest of narrow rock pinnacles between networks of wide fissures (**Figure 38.7**). Individual blocks or pinnacles may be loose, due to dissolutional undermining along sub-horizontal fractures or beddings, and are only held in place by the surrounding soil; completely loose blocks within the soil are known as floaters. The depths of fissures, and the heights of pinnacles, are commonly some metres in any karst, and may be many tens of metres in tropical karsts of classes kIV and kV. It is, therefore, not abnormal to find depths to the rockhead varying by tens of metres at adjacent investigation boreholes or structural piles that are only a few metres apart. On a larger scale, rockhead profiles may include buried sinkholes where bedrock depressions up to 100 m or more across are completely filled with breakdown, sediment and soil. These may cause small surface settlements in the form of compaction sinkholes over the soft soil fills, and may have floors of highly fissured bedrock that offer no easily definable sound footing for deep foundations.

Figure 38.7 Pinnacled rockhead in mature limestone karst (of class kIV), exposed on a construction site in southern China; some pinnacles have already been broken down (with sledge hammers) to create a solid and almost level footing for a new hotel; the grey top of the pinnacle on the right originally projected above the soil level, as do some undisturbed pinnacles in the background

Most deeply fissured and cavernous karst limestones are strong materials, so structural loads may be carried safely on pinnacles that have been proven to be of adequate width and are not disconnected from the underlying bedrock. In such cases reinforced foundations can bear on the pinnacles and span the intervening soil-filled fissures and buried sinkholes. Driven piles with any significant end-bearing on rockheads of strong limestone (UCS > 70 MPa) present their own difficulties (see **Figure 38.8**); it can be very difficult to gain a safe seating on steeply sloping bedrock surfaces, so it is normally necessary to drill sockets into the rock, and this can also be difficult through a steeply inclined interface. In chalk terrains, the ground profile generally lacks any sharp contrast between soft soil and

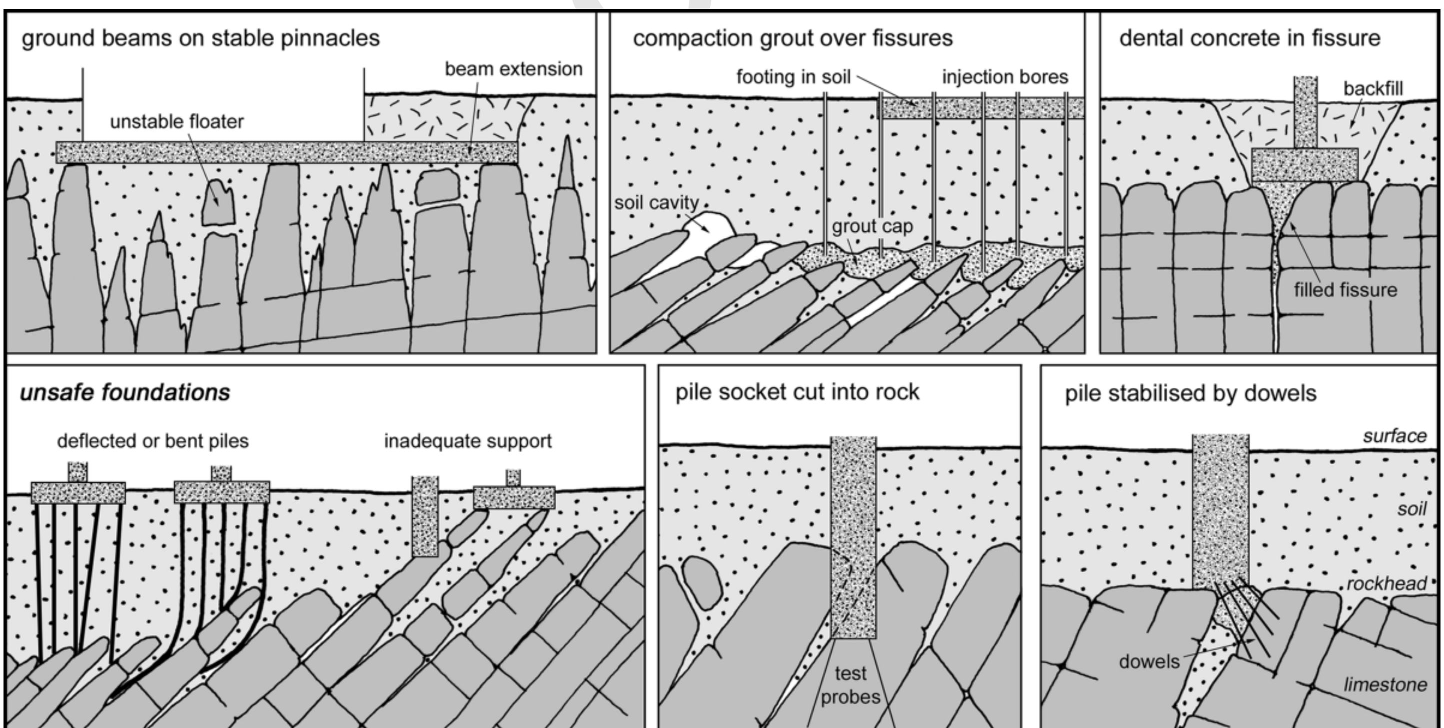

Figure 38.8 Various examples of good and bad foundations on soil-covered limestone karst (Waltham *et al.*, 2005), with due credit to the ideas and experience of the late George Sowers

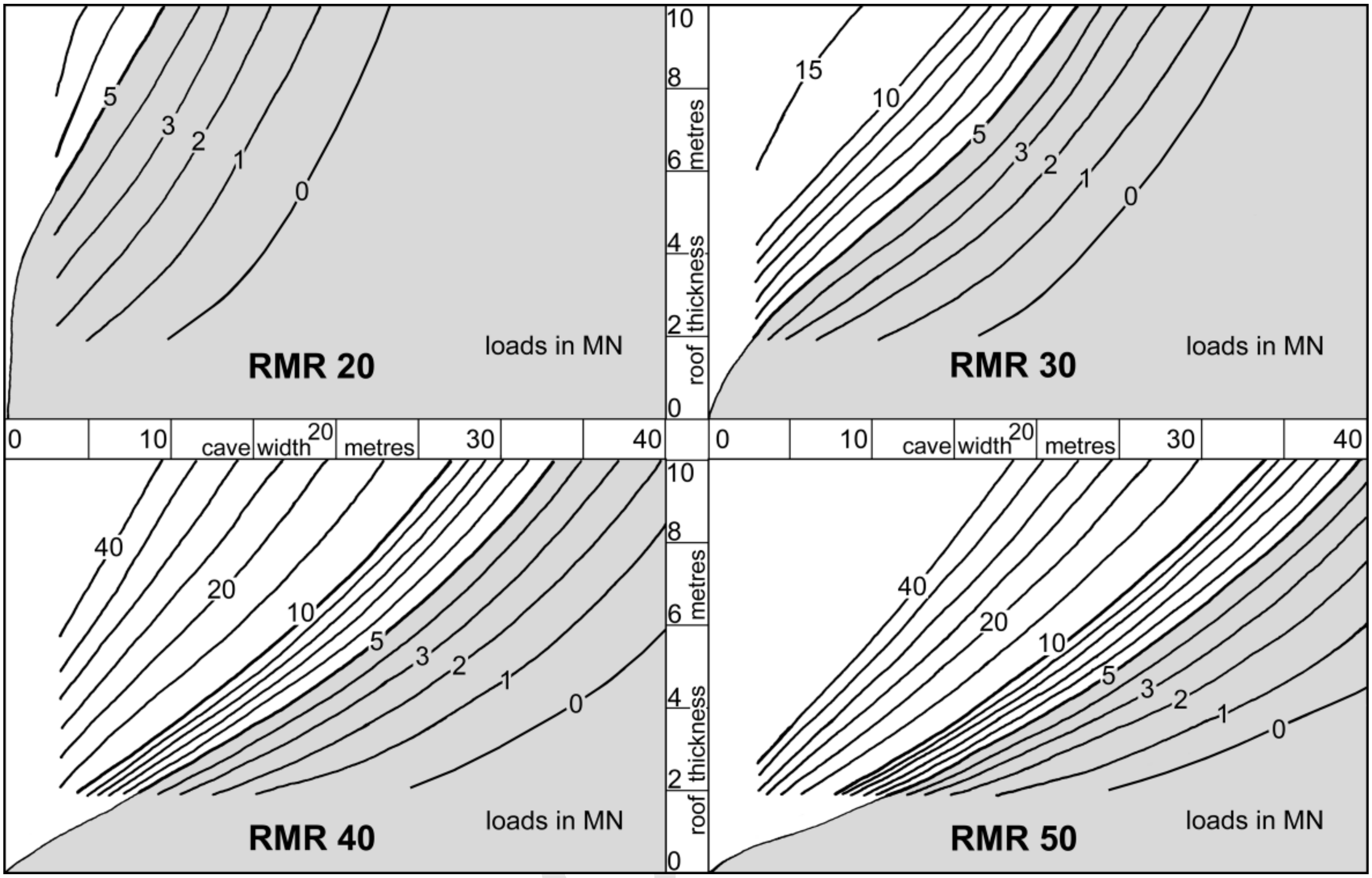

Figure 38.9 Nomograms that relate failure loads to cave width and roof thickness in ground of various rock mass ratings; the pink or grey shaded areas represent situations that should be regarded as unsafe for footings with imposed loads of 1 MN that lie directly over the caves
Modified from Waltham and Lu (2007)

strong rock, and a zone of weathered chalk further softens the rockhead, so foundations are simply taken to whatever depth is required to find adequate bearing capacity. Pinnacle loading on chalk is inappropriate, and details of the rockhead profile are less significant, except that buried sinkholes and filled solution pipes within chalk are frequently the sites of surface subsidence whenever soil movement is re-activated due to modified drainage or leaking pipelines (Edmonds, 2008).

38.5.1 The hazard of unseen caves

Where structural loads are carried down into bedrock limestone, the remaining concern is the presence of an unseen cave directly beneath. In nearly all karst terrains, there is only an extremely small statistical chance of a building being threatened by a cave that is directly beneath, that is large enough and that lies beneath a critically thin rock cover. Many structures have been inadvertently placed over large caves in tropical terrains, but collapse has not been instigated by the imposed loads, which are commonly very modest compared to the self-loads of the rock. The main geohazard from open caves in karst is to end-bearing piles with high point loads, and particularly to any heavily loaded bored piles or caissons. Guidelines exist for the thickness of roof required in limestones of various qualities in order to safely span caves of various sizes when loads are applied to them (Waltham and Lu, 2007); a cave generally has to be significantly wider than its cover thickness to create a threat (**Figure 38.9**). This means that, except in tropical karsts where large caves are typical, only a few metres of sound rock cover are generally required to provide integrity and render any deeper cave irrelevant to structural loading. Cases of rock failure in karst, as opposed to soil failure over karst, are extremely rare, and have only occurred where ground investigations have been grossly inadequate (Waltham, 2008).

Dam foundation and reservoir impoundment attract a whole series of problems when carried out on, or partially on, karstic limestone. Most limestones are strong enough to bear the loads imposed, but the problems of leakage can be massive and very complex, and are beyond the scope of this account. Both foundation problems and hydrological situations are comprehensively reviewed by Milanovic (2004), based on extensive experience in the Dinaric karst. The Kalecik Dam in Turkey provides an accessible case history of karst leakage and its remediation (Turkmen, 2003).

38.6 Ground investigation and assessment of karst

Because karst is so extremely variable, each ground investigation is almost unique and has to be assessed in the light of local conditions and the available data. An overview of the local karst is essential for broadly evaluating the key parameters of sinkhole frequency, cave size and rockhead relief that may be anticipated; interpretation of these factors usually benefits from wider experience in karst terrains. Beyond that, the design of suitable structures and foundations can only be based on a sensible assessment of the immediate ground conditions in light of the recognised hazards and perceived risks. Numerical modelling of karst ground is likely to be unrealistic, because too many features and factors will always remain unseen or unknown. The morphological complexity of karst fissures and cavities means that any ground assessment based on borehole logs will inevitably be oversimplified; this applies to both unseen caves and rockhead profiles (**Figure 38.10**). Following even the most extensive borehole investigation, unforeseen cavities will almost certainly be revealed by any extensive ground excavation in karst; these will best be remediated on the spot by filling, sealing or spanning by means that can only be assessed after they are revealed. There is no simple answer to how many boreholes should be drilled to assess a karst terrain; the number required is as many as it takes to give the engineer confidence that the likely ground conditions are known or understood to a level that is adequate and appropriate for the risks involved in his particular project. Too few boreholes can create an unacceptable risk, while an excess of boreholes can be a frustrating necessity (Waltham *et al.*, 1986). Extra care may be needed where water flush can induce suffosional soil loss over limestone, or can cause rapid dissolution of gypsum and salt; drill rigs have been known to fall into self-induced sinkholes.

Though boreholes and probes do provide valuable insights into ground conditions, almost every investigative drilling into karst will intersect some extent of open voids or soil fills, most of which will have little or no influence on the overlying ground integrity. The length of a void, or the soil fill, down a single borehole is rarely critical; if it is down a narrow fissure, it is almost irrelevant. The critical factor is the void width in relation to the rock cover, and this can only be assessed from a number of closely spaced probes, or perhaps from a down-hole camera. The depths to which investigation boreholes should be taken into bedrock is indicated by the safe cover thickness that is required (**Table 38.1**). It is normally necessary to prove every pile site or loaded rockhead pinnacle with one or more probes, treating each one as an individual ground investigation.

The overall extent of bedrock voids encountered by boreholes may be used to indicate the scale of potential soil loss by suffosion from a soil cover, though such losses should be regarded as possible in almost any karst. The dominant factor in soil loss and sinkhole development is always the drainage, and this must be properly controlled on all construction

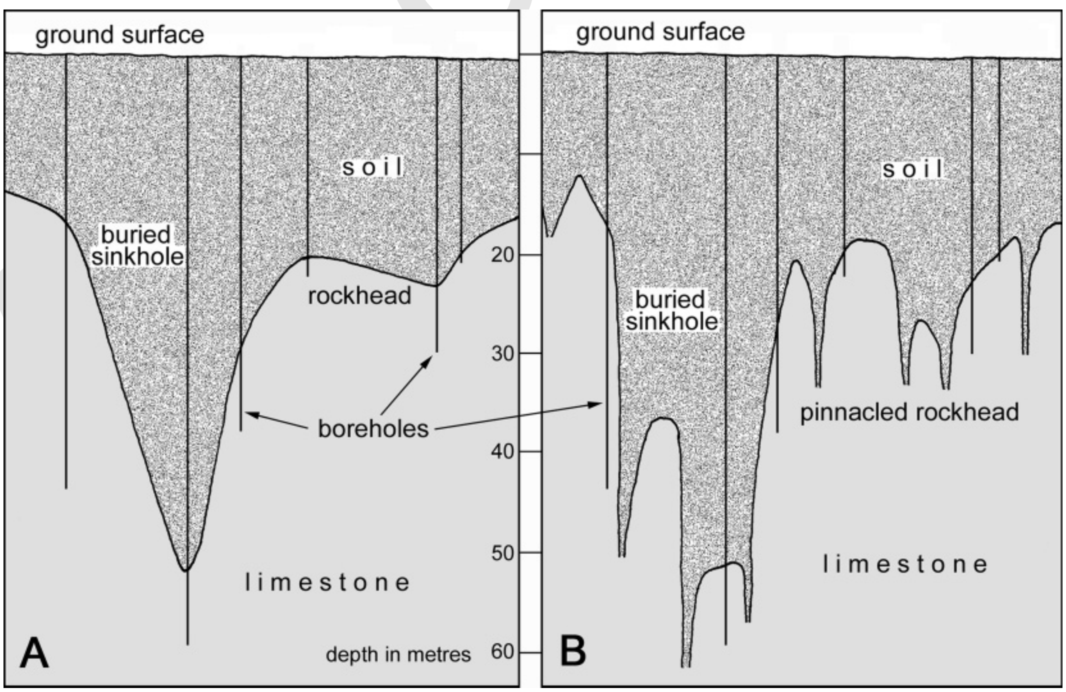

Figure 38.10 Two interpretations of the rockhead profile investigated beneath the site of a new tower block in Kuala Lumpur, Malaysia; (a) is the basic interpretation from the borehole data; (b) is a more likely interpretation based on an understanding of the pinnacled rockheads that are well known in the area

Rock	Imposed load (kPa)	Karst class	Cave width, likely maximum (m)	Safe roof thickness (m)
Strong karstic limestone	2000	kI – kIII	5	3
		kIV	5–10	5
		kV	> 10	7
Weak limestone and chalk	750		5	5
Gypsum	500		5	5

Table 38.1 Safe roof thicknesses for various cave situations, and, therefore, a guideline to the depths to be proven by probing prior to construction
Data taken from Waltham *et al.* (2005)

projects; the borehole data may only offer a broad indication of how much infiltration of rainfall directly into soil areas may be tolerated close to or within a developed site.

A construction project over a large area of karst ground may reap benefits from appropriate geophysical surveys that can focus attention on the areas of most fissured or cavernous ground. The various methods all require expert interpretation, and even then can only identify ground anomalies that must be validated individually by boreholes or excavation; the proving may be more difficult where the anomalies are offset from the causative features. Only microgravity surveys directly indicate ground voids as missing mass, but these may fail to distinguish between networks of narrow fissures and more hazardous large voids. Seismic or electrical tomography in 2D or 3D can provide more useful data where boreholes are available (Waltham *et al.*, 2005).

Karst ground conditions are probably the most variable that a civil engineer may encounter, and may, therefore, be the most difficult where responses to their extreme and unpredictable variability have to be within a reasonable budget. Major errors, unwarranted expenses and possible catastrophes occur where the rather special nature of karst ground conditions are not recognised at an early stage within a project. Those with no experience or understanding of karst can make the most elementary of errors. All too often, karst is only considered on a site after the first new sinkhole has appeared amid the construction works. Yet if karst is recognised early, if it is given due consideration, and if all site drainage is properly controlled, its geohazard may be marginalised to a point where risks are reduced to acceptable levels. Because most karst ground failures are induced by engineering activities, the geohazard should be largely eliminated by good practice.

38.7 Geohazards on gypsum terrains

Gypsum karsts are very similar to those on limestone, except that there are no climatic constraints on the extent and distribution of gypsum dissolution; they also lack the extreme landforms of vertical cliffs and tall towers, because the rock is mechanically weaker. The most widespread geohazard on gypsum is the development of new sinkholes within the soil cover, and in this respect the conditions, the processes, the extents and their assessment are very comparable to those in a limestone karst (Johnson and Neal, 2003).

Gypsum differs from limestone in that it is much more rapidly dissolved in natural water, so that rock removal by dissolution can become a factor within the lifetime of an engineered structure (though dissolutional loss is still hugely slower than soil movement with reference to the hazard of new sinkholes). As in the case of limestone, proper drainage control is the key to surface stability in gypsum karst. However, the simple disposal of large flows of water into clean bedrock fissures may not be appropriate in gypsum, where a raised level of dissolution activity may rapidly create new cavities and modify the existing drainage with negative side effects. Similarly, remedial sealing or blocking of any open voids or known sinkholes within gypsum may only deflect future processes, problems and subsidence to adjacent ground. The rapidity of gypsum dissolution makes it especially susceptible to environmental change due to engineering works, and this is a widespread hazard in the sabkha terrains of the Middle East (see section 38.8). Reservoirs impounded over gypsum have a significant failure rate because leakage is generated not only by the washing of sediment fills out of the bedrock fissures, as in any karst, but is then exacerbated due to dissolutional erosion by the large induced flows. Abstraction for water supply can also cause accelerated dissolution, and ground subsidence, by drawing in flows of unsaturated water, though on a much smaller scale than in salt terrains.

Caves and open bedrock voids are generally not as large in gypsum as they are in limestone, because gypsum is a weaker material within which caves collapse at an earlier stage. On the other hand, the weakness of bedded gypsum and its changes to and from anhydrite allow more rapid upward cavity migration by progressive roof failure (**Figure 38.11**), so small rock collapse features are more common. Collapse sinkholes more than 100 m across, known in some gypsum karsts, have developed by multiple failures that have extended the collapsed ground laterally, and not in single large collapse events. Ground failures can also be induced by engineering loads imposed on the gypsum bedrock. Buried cavities are generally small but they require a proportionately thicker cover to ensure the integrity of overlying structures, for even the most modest loadings, which is appropriate for a rock weaker than most limestones; this determines the depth of probes required to prove stable ground in gypsum karst (**Table 38.1**).

38.8 Geohazards in salt terrains

Salt (also known as rock salt or halite) is an evaporite material widespread in sedimentary sequences that have accumulated in arid environments. Because it is so rapidly soluble in rainwater, its occurrence and geohazard are restricted to three

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Figure 38.11 Cavity migration by progressive roof failure over a cave passage in massive gypsum at Pinega, Russia; flakes that are peeling away from the roof deform and sag before they break off

Figure 38.12 Collapsing ground on a salt dome in southern Iran; the person is standing at the edge of an active sinkhole in about 4 m of residual soil that is being undermined by rapid dissolution of the heavily eroded and cavernous salt beneath

environments: modern desert salars, salt domes in semi-arid terrains and buried rock sequences elsewhere.

Salars, salt pans, playas and continental sabkhas are areas of newly deposited evaporite salt, commonly with other minerals in thicker sequences. Groundwater is normally saturated, thereby restricting dissolution. Karstic cavities some metres across, which lie at shallow depths and may be revealed by smaller collapse openings at the surface, are generally restricted to marginal areas where the salt has been reached by aggressive surface run-off or groundwater input from adjacent hills. As active salt areas are largely prone to seasonal inundation, construction on them is very limited, but roads and driving routes that cross them can be threatened by the concealed cavities close to their margins.

Salt diapirs, or salt domes, rise from stratiform salt at depths of some kilometres. The salt is generally lost to rainfall at an outcrop, so that only caps of less soluble gypsum, anhydrite and clay survive at an outcrop. Actively rising salt diapirs form significant salt mountains, with or without salt glaciers flowing from them, but there are few beyond the many in the semi-arid Zagros Mountains of southern Iran (Talbot and Aftabi, 2004). These constitute mobile and cavernous terrains that are unsuitable for any development (Bosak *et al.*, 1999). Their thick mantles of residual soil are pitted by closely packed subsidence sinkholes that are actively collapsing and ravelling into dissolution cavities within the underlying salt (**Figure 38.12**). Cave chambers are up to 15 m across, with block failure and roof migration continuing at rates that are orders of magnitude faster than in limestone caves, so that bedrock collapses impact the ground surface as frequent events. Only when a diapir's rise virtually ceases, does surface lowering dominate, and then the residual mantle can become thick enough to prevent most rainfall reaching the salt, and its surface, therefore, will approach stability. By that stage, the salt sub-crop lies beneath a lowland terrain with chaotic sinkhole topography, but it is stable enough to be crossed by highways with minimal subsidence problems.

38.8.1 Subsidence over buried salt

Within environments of significant rainfall, salt does not appear at outcrops, but only survives beneath a cap of residual soil. In England's Cheshire Plain, a glacial drift 10–50 m thick overlies dissolution breccia that is around 50 m thick and consists of collapsed blocks of the mudstone that was originally interbedded with salt (Waltham, 1989). Underneath, the thick salt beds remain *in situ*, creating wide sub-crops due to their low angles of dip. Ground stability is ensured where any voids within the salt are filled with saturated brine, but subsidence takes place over any sites where the input of freshwater allows renewed dissolution of the salt. This is most extensive along linear subsidences (typically 1–10 m deep, 100–400 m wide and 1–5 km long) that develop over 'brine streams' of concentrated groundwater flow through the permeable dissolution breccia at the rockhead.

Subsidence is hugely accelerated when brine is pumped from these zones on an industrial scale, thereby drawing fresh water into the breccia. Even more destructive ground collapses and large sinkholes develop where brine is pumped from old flooded mine workings, so that support pillars are dissolved by the input of replacement water. These styles of brine-pumping have now been stopped in Cheshire, so the catastrophic collapses and rapid movements in the linear subsidences have virtually ceased, but comparable practices continue to cause surface damage in other parts of the world. Beds of salt with no outcrops can also create major surface subsidences where water and brine are able to flow through them. Some events are due to poorly managed brining operations, but the USA has many cases of large collapse sinkholes that developed after nearby wells, drilled for fresh water or petroleum through salt beds, were left uncased or poorly cased, thereby allowing brine outflow into aquifers that previously had no connection (Johnson and Neal, 2003).

Flows from brine springs, in Cheshire and elsewhere, indicate that dissolution of buried salt can continue in an undisturbed natural environment. The result is ground subsidence, albeit on a modest scale, that can only be described as natural and uncontrollable. An appropriate engineering response may be the construction of houses on rafts, which prevent structural damage and are prone only to tilting; these may then be jacked back to horizontal, in the manner that was common on a large scale in past times of active brining in Cheshire, though current movements are generally too small to warrant such an operation. Natural subsidence, generally on a small scale but locally with sinkhole development, is widespread over salt beds in the USA (Johnson, 2005), and can extend to the rare formation of large collapse sinkholes as at the McCauley Sinks in remote country in Arizona (Neal and Johnson, 2003).

38.9 Karst geohazards on sabkha

Geohazards within the sabkha environment of arid coastal plains have grown in importance with the huge increase of construction activity on the lands fringing the Arabian Gulf. Coastal sabkhas are supratidal flats up to about 10 km wide, formed of evaporites and carbonates typically with a thin cover of aeolian sand (Warren, 2006). Continental sabkhas in inland basins are dominated by halite, with the attendant hazards due to dissolution (see section 38.8). Coastal sabkha lithologies are normally only a few metres thick, but can accumulate to significant thicknesses along the margins of subsiding basins; when subsequently uplifted, the carbonate and sulphate materials are subject to erosion and the consequent development of the more conventional karst geohazards.

The special concern for sabkha relates to the modern sediments that immediately underlie the coastal plains. These include relict and buried sabkha horizons within sequences dominated by aeolian sands that extend some kilometres inland from the active sabkhas. Sediments include carbonate sands, algal mats and dolomitised facies, or are dominated by clastic quartz with variable amounts of carbonate. Typically these are poorly consolidated to depths of 5–10 m; sandy materials have weak cements of anhydrite, gypsum and calcite, which are prone to loss by dissolution when the groundwater regime is changed. Denser, more competent and more lithified sediments persist at greater depths, where any halite in the coastal sabkhas may have been lost by dissolution during diagenesis.

The primary source of a sabkha's karst geohazard is due to gypsum that occurs at shallow depths within the poorly lithified sequence. This is deposited both within the capillary zone and beneath the shallow water table. Beds of almost pure gypsum are generally no more than a metre thick; they contain nodules of anhydrite and have an open texture with small cavities (vugs) and high primary permeability. Halite is locally present, but is not in massive beds; carbonates are present, but only in some of the sand grains. Groundwater in a sabkha is dominated by brines leaking upward from buried aquifers, and these are normally saturated with respect to gypsum. Consequently, evaporation causes interstitial precipitation of gypsum, which converts easily to anhydrite with the characteristic chicken-wire texture, producing ground with locally reduced bearing capacity.

38.9.1 Sinkholes on sabkha

Natural ground subsidence on sabkha appears to be rare, as there are few known or documented examples, and natural ground cavities are almost unknown. This is because dissolution is almost impossible in the undisturbed environment of solute precipitation from saturated waters, and the minimal rainfall is too low to disturb this equilibrium. Karstic ground subsidence, including sinkhole development, is, however, widespread throughout the Gulf coastal regions, where there have been reports of multiple sinkholes developing on construction sites. Most new sinkholes are no more than 5 m across and 2 m deep, appearing in ground at the perimeter of a construction works but rarely impacting the built structures, so they have been rapidly filled and forgotten. Some much larger sinkholes have also occurred.

All recorded new sinkholes on sabkha appear to have developed as a consequence of engineering activities that include leaking pipelines, uncontrolled drainage disposal, site dewatering and drilling with water flush that is not sulphate saturated. Many of these appear to have developed from dissolutional cavities in the underlying, gypsum-rich, Neogene sequences and not in the thin sabkha cover itself. It remains uncertain as to how much cavitation is due to dissolution of sabkha gypsum horizons at multiple levels within the Quaternary sequences. But it does appear that all have been the consequences of rapid dissolution in gypsum horizons, mostly within a few metres of the surface, when stable groundwater was replaced by the input of unsaturated water subsequent on engineering works. Suffosion of the unconsolidated cover sands then produced the sinkholes (**Figure 38.13**).

38.9.2 Sabkha karst in the Gulf region

A second subsidence mechanism occurs where the new input of unsaturated water dissolves the sulphate or halite cement of the sabkha sands, allowing localised compaction and displacement of the loose material. Of the many undocumented 'collapse settlements' in Saudi Arabia, one event at a large, steel-framed desalination plant near Jubail involved a number of column bases, founded on pads 1 m below the surface level, each sinking by about 50 mm (Sabtan, 2005); this was the result of leakage from old, corroded and fractured pipelines, which had been observed for some time before the implications were appreciated. The structure was remediated with mini-piles, 15 m long, driven into stable ground. The collapse potential is high in some of these sabkha silts, but they do not show instantaneous compaction in the style of hydrocollapse, because time is required for the dissolution of the natural cement, so conventional oedometer testing interrupted by inundation is not indicative.

As the dissolution of sabkha soils and their subjacent gypsum sequences is largely or entirely at shallow depths,

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Figure 38.13 A small new sinkhole, already partly backfilled, which developed within a construction site on the coastal sabkha of the Arabian Gulf, after engineering works appeared to have induced dissolution of the gypsum that lies within either the bedrock sequence or the Quaternary cover
Photo courtesy of Laurance Donnelly, Halcrow

geohazards may be avoided by the use of deep pile foundations. This is normal practice for large built structures in the Gulf region, which have, therefore, not been affected by the sinkholes that their construction has undoubtedly triggered in adjacent ground. But the sinkhole hazard persists for roads and infrastructure that lack deep foundations, and where there is any failure to control all water movement. While it appears that direct rainfall can infiltrate the ground without disturbing the chemical equilibrium, any points of localised run-off from large built structures and areas of hard standing may displace saturated groundwater and permit new dissolutional activity after rare rainfall events. Soakaways and infiltration basins, which may be appropriate on some types of permeable ground, cannot be used for rainwater disposal on sabkha and the associated coastal plains. Where cavities are detected or become apparent, remedial action may include induced compaction, sinkhole sealing and spread footings.

It may be significant that sinkholes have developed, and ground cavities have then been revealed, on sites where prior investigation drilling had found no voids or karstic features. Small ground cavities, followed by larger surface sinkholes, may have developed only after disturbance and hydrological change were induced by the construction activity. Such a timescale is likely where halite is present, and it is possible in sulphate lithologies, though it is impossible in carbonate rocks. It is also possible that borehole disturbance exacerbated the geohazard, either with chemically aggressive water flush or by linking aquifers and changing the groundwater flow within the sabkha horizons. Sealing an area of ground with grout may merely deflect dissolutional activity into adjacent ground with soluble materials, unless the causative input of water is at the same time controlled and disposed of properly. Remediation of subsided ground by grout injection may also run certain risks when water-based grouts are used in such rapidly soluble ground.

Karst processes in sabkha soils are still not completely understood, and are subordinate to flooding, settlement and sulphate attack in terms of the geohazard. But it does appear possible that all sinkhole events on sabkha and its underlying gypsum are induced by engineering activity, so the established karst mantra of 'control the drainage' is even more critical than usual.

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38.11.1 Further reading

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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*

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.*

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