Soil failure in subsidence sinkholes
Sinkholes induced by engineering works

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Soil failure in subsidence sinkholes

The vast majority of ground failures within karst terrains are due to the erosion, transport and failure of the soils that overlie cavernous bedrock. Dissolution and removal of enough limestone to form a cave of significant size requires geological timescales that cover tens of thousands of years. In contrast, a comparable volume of soil can be removed during a single rainstorm, where there is a stable, old karstic cave somewhere beneath that can accept the displaced material. The rock left over a limestone cave is generally strong enough to stand for very long periods of time. In contrast, a soil arch over any void is inherently unstable, and may fail immediately or during a subsequent rainstorm. For these two reasons, soil failures are much more common than rock failures in karst. The chances of an engineered structure being damaged or destroyed by sinkhole development due to soil failure, during its design lifetime, are orders of magnitude greater that the chances of rock collapse.

These karstic subsidences and collapses caused by soil failure are collectively known as subsidence sinkholes. They can form in any unconsolidated soil that overlies a karstic limestone – the only requirements are caves or networks of fissures that can accept the inwashed soil, a fissure to rockhead as a corridor for the soil transport and percolation water (naturally from rainfall) that becomes the transporting agent. In soil-mantled karst terrains, they occur in their thousands, most of them just a few metres across, but some reaching 100 m in diameter. Most subsidence sinkholes are permanent or maturing features of the landscape, but new sinkhole events are a significant geohazard in many karst regions.

4.1 SUBSIDENCE SINKHOLE MORPHOLOGY

The classic profile of a subsidence sinkhole is an inverted cone, but this may vary to a rounded bowl or to a vertical cylinder. The slope angle is a function of the soil cohesion and the sinkhole's maturity. Those in sandy soils tend to have slopes

Figure 4.1. A typical small, fresh subsidence sinkhole formed in till overlying cavernous limestone in the Yorkshire Dales, U.K.; the new sinkhole is only about 3 m wide and 1 m deep, and it does not expose the limestone as rockhead is at a depth of about 3 m.
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close to their angles of rest around 35°. A fresh subsidence sinkhole in a clay soil can have vertical or even overhanging sides, but degrades over time into an ever-wider bowl. In 1994 a tropical storm over Georgia, U.S.A., triggered a population of new subsidence sinkholes in alluvium and residuum overlying the karstic Ocala limestone. Morphometric analysis of more than 300 new sinkholes and also over 300 old features (Hyatt *et al.*, 1999) showed that depths of both groups were comparable, but the older sinkholes were much wider due to slow degradation of their side slopes.

The depth of subsidence sinkholes is limited to that of the soil thickness. In a soil 2 m thick, a sinkhole cannot be more than about 8 m in diameter over a single input point to the bedrock, and many will be less in both depth and diameter. In the Yorkshire Dales, U.K., and in many other karst regions, depths of 1–5 m and diameters of 3–15 m are typical for the many hundreds of small subsidence sinkholes (Figure 4.1), commonly known as shakeholes, that pockmark benches of glaciokarst where the limestone lies beneath a veneer of till. In contrast, the Winter Park sinkhole in Orlando, Florida, was 30 m deep and just over 100 m across, because it developed in soils that are 45 m thick (Jammal, 1984). The Winter Park sinkhole is a fine example of a large single-event subsidence sinkhole (Figure 4.2), though its failure was induced by water table decline (Chapter 8). Most sinkholes

Figure 4.2. The large subsidence sinkhole in Winter Park, Florida, just after its initial dropout in May 1981; water is ponded within the steep-sided throat down through the clay soils, while the upper slopes were at the time still actively slumping back to form the wide bowl in the sand cover.
Photo: Orlando Sentinel.

that are much larger than these dimensions are either solution features eroded into bedrock or collapse features also into bedrock, though a soil mantle within the former or a soil cover slumped into the latter may create the false impression of a subsidence sinkhole.

Clearly, the volume of a subsidence sinkhole must be matched by the volume of pre-existing solutional voids within the bedrock, into which the soil can be washed, but there is no implication that bedrock caves should match the sinkholes in size. Most soil washed from sinkholes is lost into fissure networks. Even when a cave is associated with a subsidence sinkhole, its passages are normally much smaller than the surface feature (Box 4.1). Collapse of the Winter Park sinkhole in Florida involved nearly 150,000 m^3 of cover sediment disappearing into the bedrock voids, with a large proportion of this going in the few days of the main collapse event. No caves associated with this sinkhole are known, but passage sizes in the Floridan karst are commonly 5–10 m in diameter. The giant sinkhole that formed in the tailings

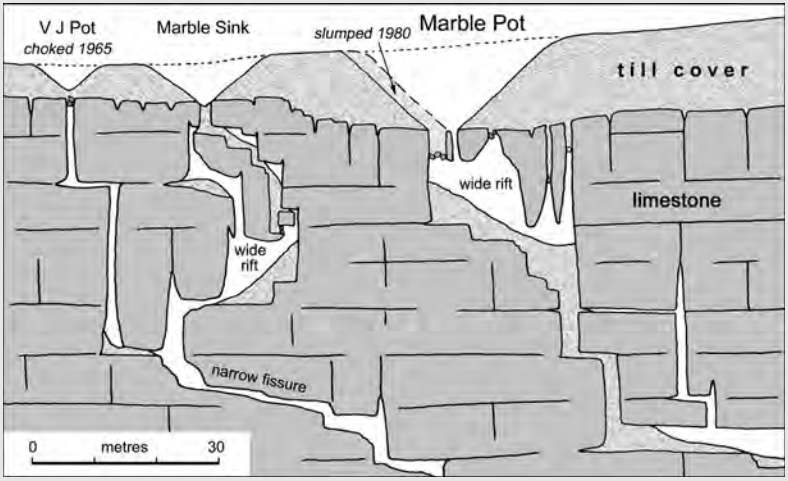

Figure 4.1.1. Profile through the three subsidence sinkholes at Marble Pot (simplified, with some passages omitted for clarity). Details of the rockhead and some of the totally choked cave passages are conjectured, but the sinkholes and main caves have been mapped by direct exploration.
After surveys by Dave Brook *et al.*

Figure 4.1.2. The subsidence sinkhole of Marble Pot, soon after its far side slumped into a newly open fissure in 1980.
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BOX 4.1. SUBSIDENCE SINKHOLE

An example – Marble Pot, Yorkshire Dales, U.K.

Within the Yorkshire Dales glaciokarst, many of the broad limestone benches are mantled by till sediments that are pocked by thousands of subsidence sinkholes. Marble Pot is one of the larger sinkholes in the area, 40 m across and 15 m deep, and circular except for a stream trench entering on one side. A small stream drains into it, so that the underlying fissure system has evolved to be large enough to be accessible, at least in parts. This has allowed the underground features of Marble Pot and two more adjacent sinkholes to be mapped by cavers (Figure 4.1.1). If this profile had its scale adjusted so that most of the fissures were only 100–200 mm wide, it would suffice as a model for the karst morphology beneath subsidence sinkholes worldwide, where significant surface depressions appear unrelated to any visible or accessible voids in the bedrock.

Marble Pot has been developing ever since the mantle of till was left over the limestone outcrop on the retreat of the late Pleistocene glaciers about 12,000 years ago. The fissures and cave passages that constitute the constricted cave system beneath it have some earlier origins, as some of the lower passages contain stalagmite deposits that appear to be interglacial. Once the till had been deposited, seepage water (derived both from direct rainfall and small flows of allogenic surface drainage off the adjacent shale slopes) fed through to the rockhead fissures, and suffosion by this water carried sediment down into the limestone voids. The cohesive nature of the Yorkshire Dales till meant that the sinkhole then developed in a series of dropout events, each one followed by slumping of the sinkhole sides so that they flared out into the characteristic, steep, inverted cone. The most recent event was in 1980, when the whole of one side of the sinkhole failed (Figure 4.1.2). The soil all slumped into a newly opened fissure, which had been previously seen from below when cavers had looked up at a hanging choke of boulders with water dripping from between them. This temporary plug had failed during a winter storm event, and many tonnes of debris had fallen into the underlying rift. This totally choked the route down, except for the stream that could filter through the rubble and sediment.

Two other adjacent sinkholes lie over the same set of roughly parallel fissures that follow joints in the limestone (Figure 4.1.1). Marble Sink has its main route choked by suffosed sediment, but an open loop passage (not shown on the profile) provides access to the passages below. V J Pot is a smaller sinkhole that has had its outlet blocked since its sides degraded in 1965. All three sinkhole drains consist of systems of fissure passages mostly less than 1 m wide, linked by vertical shafts 1–3 m wide, and including some rift chambers up to 5 m wide. Their volumes are smaller than those of their respective sinkholes, but large amounts of sediment have been washed through them and into deeper caves during their long periods of evolution.

lagoon over Zambia's Mufulira mine in 1970 had a volume of 700,000 m^3 (Spooner, 1971). The failure was partly induced by the mining, and 300,000 m^3 of sediment filled the mine below the inrush point 530 m below the surface. But 400,000 m^3 of sediment were lost into the unseen network of fissures and caves between there and the surface. The sinkhole that formed in this event was less than 20 m deep, but it grew to 300 m across in the saturated and very unstable mine tailings.

Subsidence sinkholes are typically almost perfectly circular in plan outline. This is because each one is formed by slumping of the soil cover into a single opening in the bedrock. This opening may be a local widening of a single fissure at rockhead, but is more commonly a solutional enlargement at the intersection of two joints (or faults or dipping bedding planes); larger openings may be discrete but totally choked cave passages or shafts. It is very unusual for soil to be washed down any length of a fissure long enough to impose an elongate shape to the surface depression. Ashtree Hole, in the English Pennines, is 25 m across and 10 m deep, and is almost perfectly round, with a rounded soil floor, even though it loses its sediment into a major fault fissure that can be seen in a cave passage 40 m below (see Section 4.4). Those sinkholes that do have more complex or elongate shapes are almost invariably formed by the coalescence of two or more circular features, each over their own bedrock entry point. Alternatively, a subsidence sinkhole may become elongated by surface erosion where a stream happens to drain over one margin into it.

Though subsidence sinkholes are formed by loss of the soil cover into bedrock, it is unusual to have the bedrock exposed in their floor. Slumping of the sides, after the initial more localised collapse, normally leaves a sediment floor in the sinkhole. This commonly blocks the bedrock conduit, to the extent that ponds are common in sinkholes, even where they are perched far above the regional water table (Figure 4.3). Where subsidence sinkholes capture surface streams, they develop active stream sinks or swallow holes in their floor, but these may be either open or choked where the stream drains through boulders. Only a few subsidence sinkholes have open caves at their throats. A cave of accessible size may be in proportion to a very large sinkhole (Box 4.1), but may also lie at the apex of a sinkhole only a few metres across where a thin soil has slumped through an opening in the roof of a cave passage that drains from elsewhere.

Subsidence sinkholes can form in any type of soil. They are perhaps most abundant in till, notably where Pleistocene glaciers left a veneer of sediment over a limestone surface with fissures already enlarged by pre-glacial or sub-glacial dissolution. Impermeable till with a clay matrix can prevent water reaching the underlying rock, but most till has enough permeability to allow some infiltration and consequent initiation of subsidence sinkholes. The disorganised topography of a sheet moraine tends to inhibit efficient rainfall run-off, so that areas of till on almost level ground, on either valley floors or plateau benches, are commonly pocked by hundreds of usually small subsidence sinkholes, forming one of the distinctive aspects of glaciokarst terrains (Figure 4.4). In these cases, all the sinkholes have formed in post-glacial time, about 12,000 years in the case of Devensian till.

Comparable sinkholes also form in alluvium, in colluvium and in the red soils

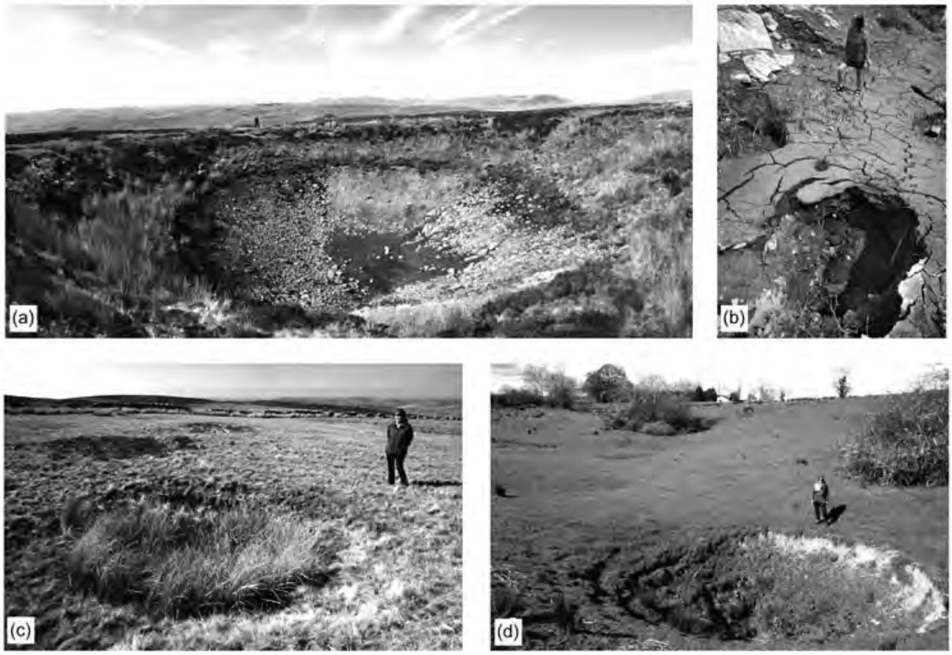

Figure 4.3. Variations in morphology of subsidence sinkholes; (a) – a large and old sinkhole in till, that holds a lake in wet weather but drains out in dry conditions, in the Yorkshire Dales karst, U.K.; (b) – a small new sinkhole in clays that floor a valley in Pennsylvania that loses all its water underground; (c) – an old, degraded sinkhole with its fissure drain sealed by inwashed clay so that it has reed grass growing in a small pond, in the Yorkshire Dales, U.K.; (d) – a newly reactivated sinkhole with fresh scars in its soil slopes, on the limestone of County Cavan, Eire.
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Figure 4.4. A cluster of subsidence sinkholes, locally known as shakeholes, in a patch of moraine till in the English Pennines.
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that are common in karst as a combination of insoluble residues and loessic silts blown in on the wind from beyond the limestone outcrops. Total numbers of sinkholes are often smaller than those on till, but can be large where rejuvenation has followed tectonic uplift. Beside the west coast of Florida, Citrus County has new sinkholes forming in thin cover sands at a rate approaching one per week (Beck, 1986); each sinkhole is typically less than 3 m wide and deep, and their frequency represents a new sinkhole rate (NSH) of 0.05 per km^2 per year, typical of a mature covered karst of class kIII.

4.2 TYPES OF SUBSIDENCE SINKHOLES

Ranges of morphologies and of processes are encompassed by the concept of the subsidence sinkhole. The key process that defines all subsidence sinkholes is suffosion – the transport of disaggregated soil or sediment into fissures in the underlying bedrock. In a karst, these fissures have been enlarged by dissolution at some time in their history. The transport is almost invariably by water, though it can theoretically be solely by gravity in some sandy desert soils. The resultant sinkhole is therefore matched by sediment that is displaced underground. This may appear as a debris cone within an open cave (Figure 4.5), it may be dispersed through an inaccessible network of narrow fissures or it may ultimately be transported out of the aquifer by a resurging cave stream.

Time determines the subdivision of subsidence sinkholes into the dropout sinkholes where the ground failures are rapid collapses, or the suffosion sinkholes where the ground subsides slowly (Figure 4.6). The overall process may be described as suffosion in both cases, though the dropout term is introduced as a graphic description of the surface impact where a large soil cavity fails in the one type. The contrasting types relate largely to soil lithology. Only a cohesive soil, that is clay-bearing or indurated, can bridge over a void for long enough for the cavity to grow to a size (by wall ravelling and then debris removal from its floor) large enough for its subsequent and inevitable roof failure to have significant impact as a surface collapse. In contrast, the theoretically perfect suffosion sinkhole develops by particulate tapping of a non-cohesive, purely sand soil into a narrow underlying fissure, matched by slumping and subsidence of the soil profile (Figure 4.7). Though these can develop to very large conical profiles, most of this type that occur in the non-cohesive soils of Florida are only a few metres deep and wide even in soils that are 15–30 m thick (Sinclair and Stewart, 1985).

Nearly all soils have enough cohesion provided by clay within their matrix (or by clay-rich horizons within a predominantly sandy profile) to make dropout sinkhole events far more common than the slow subsidences. Instantaneous or rapid surface failure of the dropout sinkhole is the main geohazard in terrains of soil-covered karst. The slow subsidence of suffosion sinkholes is sometimes recognised, but these sites commonly develop into dropout sinkholes by intermittent stages of rapid soil collapse. More confusion between the two types is created by the fact that steep-sided dropout sinkholes generally degrade by wall failure until they

Figure 4.5. A small subsidence sinkhole in the karst of Indiana, and the cone of debris emerging from a fissure directly beneath it in Blue Spring Cave.
Photos: Art Palmer.

develop the larger diameters and the shallow conical profiles of suffosion sinkholes. This would appear to account for the questionable deduction that a part of Georgia, U.S.A., is dominated by new dropout sinkholes while the same area has older sinkholes of both suffosion and dropout types (Hyatt *et al.*, 1999).

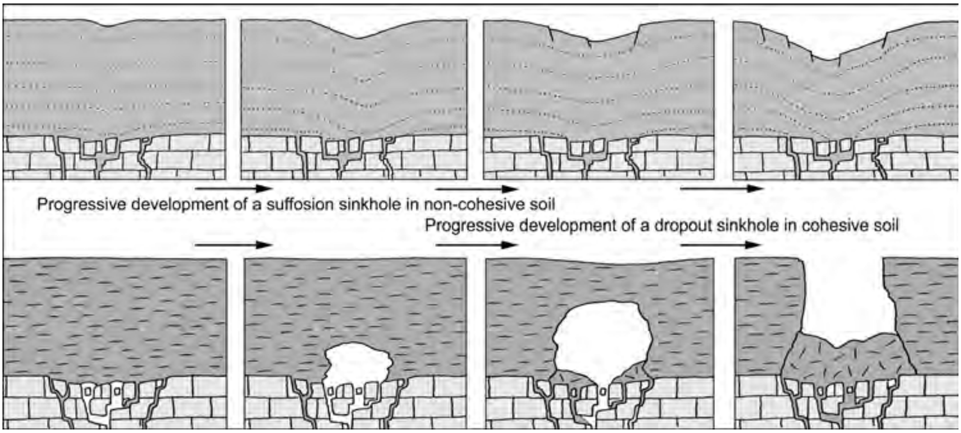

Figure 4.6. Sequences of progressive development of subsidence sinkholes, represented by stages in the two end members of morphologies, forming by perfect particulate suffosion in a non-cohesive sandy soil (above) and by dropout over an expanding soil cavity in a cohesive clay (below).

Figure 4.7. A small suffosion sinkhole newly developed in sandy soils near Kerman, Iran.
Photo: Habibeh Atapour.

The morphological variety and wide distribution of subsidence sinkholes have led to an extensive and sometimes conflicting collection of terms for them (Table 2.2). Subsidence sinkholes (Jennings, 1985) usefully describe all those formed within the soil profile. Suffosion sinkholes (Ford and Williams, 1989) accurately describes those formed by the slow downward removal of the soil. Dropout sinkholes grew in common parlance from the visual impact of the rapid surface failure. These three terms are now widely accepted (Williams, 2004). Cover collapse and cover subsidence sinkholes (Beck and Sinclair, 1986) are also useful and descriptive terms (popular in the U.S.A.), but are less favoured because they each require three words. Also the word collapse is undesirable in this context, as its use in karst is normally retained to describe rock collapse, which significantly is not involved in subsidence sinkholes. Ravelling sinkholes, soil piping sinkholes and shakeholes are all less satisfactory terms for subsidence sinkholes. Description as alluvial sinkholes is unacceptable, as large numbers of them occur in till soils that are not alluvial.

Poorly consolidated clays of Tertiary age (old enough to be called rocks by geologists, but treated as soils by engineers) can develop ground collapses that are described as either subsidence or caprock sinkholes. The distinction should be that subsidence sinkholes form by particulate suffosion of the soil down narrow fissures in the bedrock, while caprock sinkholes involve intact plugs of the clay dropping into voids created by rock collapse of a cave roof. Surface morphologies may be indistinguishable. Sinkholes in the clay-mantled gypsum karst of the Ukraine (Klimchouk and Andrejchuk, 2003) are clearly of both types, but are only distinguished where the nature of the failure can be seen in the caves beneath. Transitional morphologies are also displayed by some of the larger sinkholes in the chalk karst of southern England. Culpepper's Dish and others have long been known (Sperling *et al.*, 1977) but more have been recognised by subsequent geological mapping. Many of these are formed in Paleogene sediments, but are almost certainly subsidence sinkholes, because large dissolutional voids that could collapse to create caprock sinkholes generally do not exist within the chalk. However, others are known to have formed by settlement into sediment pipes and filled pre-Paleogene sinkholes (Chapter 5).

4.3 DROPOUT SINKHOLES

Unheralded ground collapses, seemingly random in time and space, form one of the most widespread geohazards in karst, and dropout sinkholes are distinguished by their rapid development. A sinkhole just a few metres across can form in a virtually instantaneous event. In Pennsylvania, a young dogwood tree, growing about 5 m tall in a house front lawn, dropped almost out of sight as a man walked past (Figure 4.8). The hole was only 3 m across, and was soon filled with soil to prevent its sides flaring out, but the residents of the house promptly decided to move out. Rarely can a dropout sinkhole much wider than this be described as instantaneous. Though the hazard to property is very real, the threat to life is greatly reduced where the timescale is more than a few minutes. The most dramatic failure occurs where a thin, cohesive surface layer fails over a relatively large soil cavity that has taken many months or years to enlarge by slow ravelling and suffosion. An asphalt road surface provides the worst case, and many roads in China and the eastern U.S.A. have developed dropout sinkholes without any warning. At least one in China has

Figure 4.8. A dropout sinkhole in the front lawn of a house in Pennsylvania; the hole was originally 5 m deep but was filled with soil to prevent the sides flaring out, and the soil fill had compacted and settled by 0.7 m by the time this photo was taken.
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opened rapidly enough to swallow and kill a person, and at least one in America has caused the death of a car driver who could not avoid the new hole.

A small dropout sinkhole developed in a highway across gypsum karst in eastern Michigan (Benson and Kaufmann, 2001). Though the hole in the road surface was only 1 m across, it opened below to about 1.5 m across, and appeared to be floored by a plug of soil that had dropped its full depth of about 1.5 m. Though the sinkhole was in sand, the dropout style was due to a clay soil at a depth of 1.2–4.8 m. Beneath the clay, sand extended to rockhead at about 12 m deep, and no large voids were known in the bedrock gypsum. The lower sand appeared to have been suffosed into fissures in the gypsum over an unknown period of time; this created a cavity bridged by an arch in the clay, which flaked away to the point of failure, when the remaining clay and upper sand collapsed into the lower void, leaving the road asphalt unsupported over the upper void until it broke through.

In contrast to the narrow fissures at the Michigan site, the Boxhead sinkhole in the Yorkshire Dales karst, U.K., was unusual in that its opening into the bedrock limestone was a metre wide, and over twice as long. This was revealed, overnight, when the floor of an older, shallow sinkhole dropped out (Figure 4.9), at the top of a vertical shaft 95 m deep, that flared out to a diameter of 8 m at its base. This open hole had been a significant pre-glacial stream sink taking drainage off the adjacent shale outcrop. Pleistocene glaciers then overrode the shaft, retreating to leave

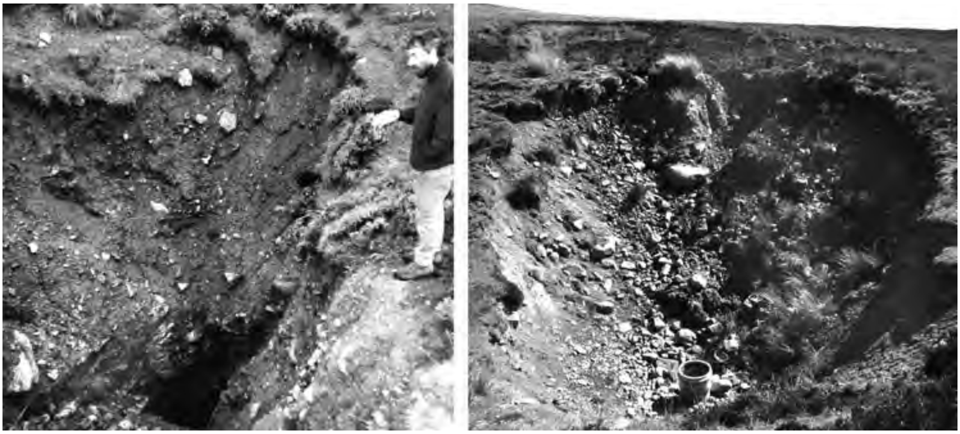

Figure 4.9. The Boxhead sinkhole in the Yorkshire Dales karst, U.K. On the left, very soon after the first dropout revealed the deep open shaft in the bedrock limestone, rockhead is visible beneath the till on the left of the shaft. On the right, after more till had slumped into the shaft, the metre-diameter pipe was installed to retain access, and the sides had flared to a stable profile.
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boulders jammed across the top and supporting a cover of till over 5 m thick. Subsequently, postglacial percolation drainage washed the fines out of the bridge of soil and boulders until it became unstable.

Truly instantaneous failures of large dropout sinkholes are rare. The most infamous example is the 1962 sinkhole in South Africa that swallowed a mine building, killing the 29 people inside it (Box 8.1). The Golly Hole developed on a forested hillside in Alabama in 1972. A local resident was disturbed by a house-shaking rumble and the sound of breaking trees, so it appears that there was a major instantaneous collapse. Two days later, a search of the forest found a subsidence sinkhole 35 m deep and 100 m in diameter, with steep soil slopes that must have degraded and widened to some extent in the two days since the main event.

Development of the Winter Park sinkhole in Florida was observed and documented (Jammal, 1984), because it was in a suburban district of Orlando. The ground was first broken when a large tree disappeared with a swishing noise into a new hole, and soil was then lost into it progressively over the next two days, when the sinkhole grew to a depth of 30 m and then had its sides flare out to a diameter of 106 m (Figure 4.10). Subsequently it achieved some sort of stability, before partially filling with water, and was later artificially modified to remain as a permanent lake. It appears that a large cavity had migrated up through the cohesive sandy clays of the Hawthorn Formation over an unknown length of time; its clay roof finally failed to breach the overlying loose sands, which slumped into the underlying pipe within the two days of observed sinkhole enlargement. Initially, the sinkhole was almost dry, but it soon filled to the piezometric level of the Ocala Limestone aquifer, indicating a restricted water flow through the debris-filled pipe beneath the sinkhole. The

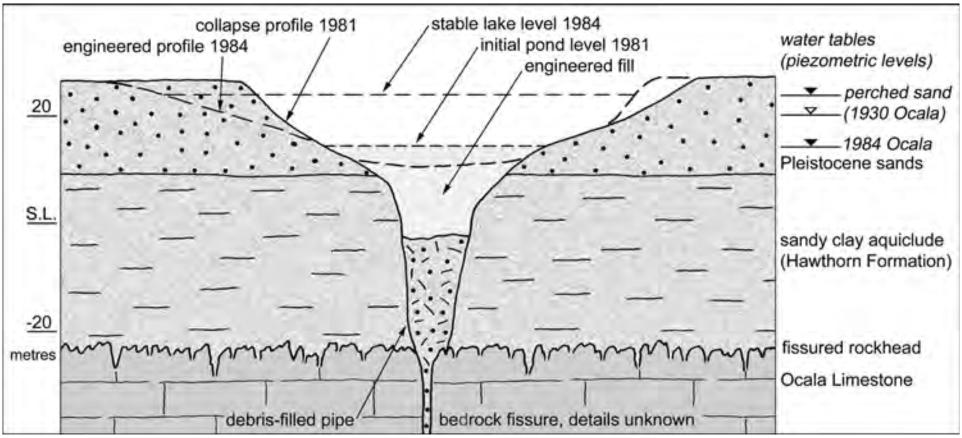

Figure 4.10. Profile through the large subsidence sinkhole that developed in Winter Park, Florida, showing the initial dropout through the lower clay soils, the flared bowl in the upper sands and the subsequently engineered lake.
After Jammal (1984).

remedial works on the slopes included pushing soil down into the sinkhole's throat, thereby choking it to prevent further drainage down to the limestone. Seepage from the sand then fed a lake that almost filled the sinkhole, with its surface at the level of the water table in the perched sand aquifer (Figure 4.10). Some years later the lake level fell close to that of the limestone water table, and this may indicate renewed drainage down the debris pipe, with implications for possible reactivation of the sinkhole. This non-instantaneous event is probably representative of most very large dropout sinkholes, and though infrastructure damage ran to millions of dollars, no lives were lost.

4.3.1 Growth and failure of soil cavities

The critical process in the formation of dropout sinkholes is the growth, migration and failure of ephemeral soil cavities; these are widely known as regolith arches in North America. They are generally initiated at the rockhead, as soil is carried down into bedrock fissures (Figure 4.11). As more soil is lost, the cavity grows beneath an arched roof, until this becomes unstable, causing roof stoping and upward cavity migration until surface failure is induced. Sediment transport is critical to continued cavity growth, and is normally dependant on water flow rates.

Soil cavities are relatively stable when they are small and at depth, so that compression arches may develop within the soil above them. As the cavities increase in size, either by concentric sloughing and ravelling failure of their roof material or by coalescence of adjacent voids, their growth and upward migration accelerate (Drumm *et al.*, 1990). Ultimately the soil arch is likely to fail in shear, but the progressive sloughing is related to variations of pore water pressure within the soil. Critical are situations where the pore water pressure is greater within the mass of the soil than it is immediately adjacent to the cavity wall (Tharp, 1999, 2001, 2003). This situation is created when water table decline creates a falling pore water pressure that lags behind drainage of the cavity, when a new wetting front of rain-fed percolation water advances through a dry soil after a drought, or by exsolution of groundwater air creating bubbles close to the cavity wall. The dominant soil failure process is that activated by pore pressure decrease due to water table decline. When this occurs, the rate of sloughing failure from the void roof is a function of the soil's compressibility, permeability and tensile strength (Tharp, 2001), and where these are known it could be possible to predict cavity migration rates for any planned drawdown.

The processes related to water table decline in open voids are described as vacuum effects in China, whereby the soil cavity fails by suction forces (Xu and Zhao, 1988). The role of suction is demonstrated by Chinese success with inserting open pipes into the ground to allow air recharge and thereby prevent further sinkhole failures in soils impacted by mine drainage. A quantification of soil-arch stability in incipient sinkholes largely relates the cover thickness and arch radius to the soil's angle of friction, but also relies on estimations of groundwater flow velocity, pore water pressure and cave atmosphere pressure (He *et al.*, 2003). Some field evaluations have been successful, but data on the variable parameters may not be available until collapses have occurred and can be observed.

Failure of a soil arch was monitored in South Africa's Pulik Cave, which has an arched soil roof spanning 3 m between walls of dolomite in a passage developed along the rockhead (Jennings, 1966). Processes were accelerated by experimental injection of water through boreholes into the soil profile over the cave. The roof arch was seen to fail progressively as concentric slices of soil about 700 mm thick fell into the cave, while surface subsidence at the same time was very small and considered to be due to elastic deformation.

A soil arch may also lose its integrity by classic piping failure that works headward along flow paths into the cavity, probably defined by soil microfractures. This is not activated by pore water pressures but by seepage flows that are capable of washing the fines out of a heterogeneous soil. Their significance may be observed where soil cavities are made accessible by partial failure of the roof. Most cavities do propagate vertically upwards, ultimately to form dropout sinkholes, but piping may open obliquely to the surface where it is directed by water inflow (Figure 4.12). Piping failures respond directly to flow increases, notably those induced by rainfall events. These are widely recorded as triggering multiple sinkhole events, including the Florida sinkhole maximum during summer thunderstorms (Currin and Barfus, 1989) and the large number triggered by a single storm in Georgia, U.S.A. (Hyatt *et al.*, 1999). In Florida, it appears that sinkhole events do not correlate with long-term rainfall data (Beggs and Ruth, 1984), but do correlate with localised rainfall events (Benson and La Fountain, 1984). Similarly, sinkhole development may be induced by artificially re-directed drainage input (see Chapter 8).

Other factors have been interpreted as contributing to soil cavity failure. Loss of buoyant support during water table decline may be significant (Newton, 1987), but its effects may be confused with those of increased seepage. Soil cavity failure may be

Figure 4.11. A soil arch beneath about 150 mm of cover over a cavity developed over a fissure in limestone rockhead, exposed in the side of a small collapse in Kentucky. Photo: Art Palmer.

Figure 4.12. A thick soil arched over a piping cavity in the edge of a fresh dropout sinkhole in the Xingwen karst in Sichuan, China; rockhead is deeply pinnacled in this mature karst, and the edge of a limestone pinnacle is exposed just to the right of the boy's feet. TW.

due to vibration from artificial sources (see Chapter 8), from earthquakes and from water hammer in collapsing ground (Chen, 1988). Soil weakening by growth of desiccation fractures appears to account for a number of sinkhole failures in drought conditions, and may be more important in sandy soils that gain much of their cohesion from surface tension (Tharp, 1999). Laboratory modelling of sinkholes demonstrates the main failure processes, and also shows that increased stress from slab loading (as opposed to point loading under small foundations) is irrelevant (Chen and Beck, 1989).

Timescales for void migration through soils are rarely recorded, because the sites are usually only known after failure reaches the surface. Rapid development is indicated by the records of new sinkholes developing within the first few hours or days after pumped water table decline in Florida (Bengtsson, 1987), in Alabama (Newton and Hyde, 1971), in China (Waltham, 1989) and elsewhere. These apparently rapid failures could be the final collapses of soil cavities that had developed previously over longer periods of time, and sites in Pennsylvania (Foose, 1968), Alabama, China and elsewhere do record new sinkholes appearing over months and years after the initial drawdown. Numerical modelling of a clay soil 2 m thick, with an unconfirmed compressive strength (UCS) of 0.15 MPa, water on its surface and a drained cave below, indicates that a void 20 mm across on the rockhead will grow to 1 m across in 12.9 years, but will break through to the surface within only another 0.7 years (Tharp, 1999). Combining this evidence with the many records of sinkholes very rapidly induced by drainage modification (Chapter 8), it is clear that dropout sinkholes can form within days or weeks wherever water has access to a soil overlying a fissured limestone, and they will always be a major geohazard in karst.

4.3.2 Evolution of subsidence sinkholes

Perfectly formed suffosion sinkholes are as rare as completely non-cohesive soil profiles. The Ebro basin, in north-east Spain, has hundreds of subsidence sinkholes in its alluvial terraces of gravel, sand and silt that overlie gypsum karst (Soriano and Simon, 2001). Active sites include both suffosion and dropout sinkholes. Four years of monitoring of one suffosion sinkhole, 60 m across, revealed steady subsidence of its bowl at a mean rate of 64.5 mm/y, and two other sinkholes were subsiding at rates of 39 and 21 mm/y. But the same area also recorded a number of dropout events and repeating soil collapses. The great majority of sinkholes in soil-covered karst occupy a spectrum of morphologies and development processes that lie between end-members that are the rare suffosion sinkholes and the usually small dropout events; they are nearly all best described just as subsidence sinkholes. Perhaps the most common type starts with some slow surface settlement, followed by an intermittent sequence of short but rapid soil failures and collapses. Some subsidence sinkholes mature and grow over hundreds or thousands of years, but only one of a series of collapses may impact a construction project within its lifetime. Patterns of repeat activity do demonstrate the folly of simply filling old sinkholes prior to land redevelopment.

Slow surface subsidence may be a precursor to imminent failure on a larger scale, either where this is due to particulate erosion in a suffosion sinkhole, or where a soil arch is settling prior to failure over a soil cavity as it develops into a dropout sinkhole. These movements can provide valuable warning signals, and are especially noticeable as hairline cracks in buildings and bridges prior to more extensive damage. In Kentucky, small ground movements have been ascribed to settlement of shear-bounded soil wedges over a growing soil void (Figure 4.13) and are interpreted as precursors of more serious ground failure as a dropout event (Crawford, 2001). This pattern of ground movements could also be explained by the growth of numerous small soil voids over a network of rockhead fissures (Cooley, 2001), creating a wide zone of soil deformation and settlement before the cavities start to coalesce and fail in larger dropout events.

Many large subsidence sinkholes expand by repeated failures of parts of their soil cover. Marble Pot in the English Pennines (Box 4.1) was reactivated when the boulders, jammed across the top of the rockhead fissure in a previous dropout, were washed out to initiate a second phase of rapid soil loss. The sinkhole profile was then maintained as a new slice of soil slumped into the open fissure. Fresh clearance of the bedrock outlet rejuvenates the sinkhole and helps to maintain its steep profile. In

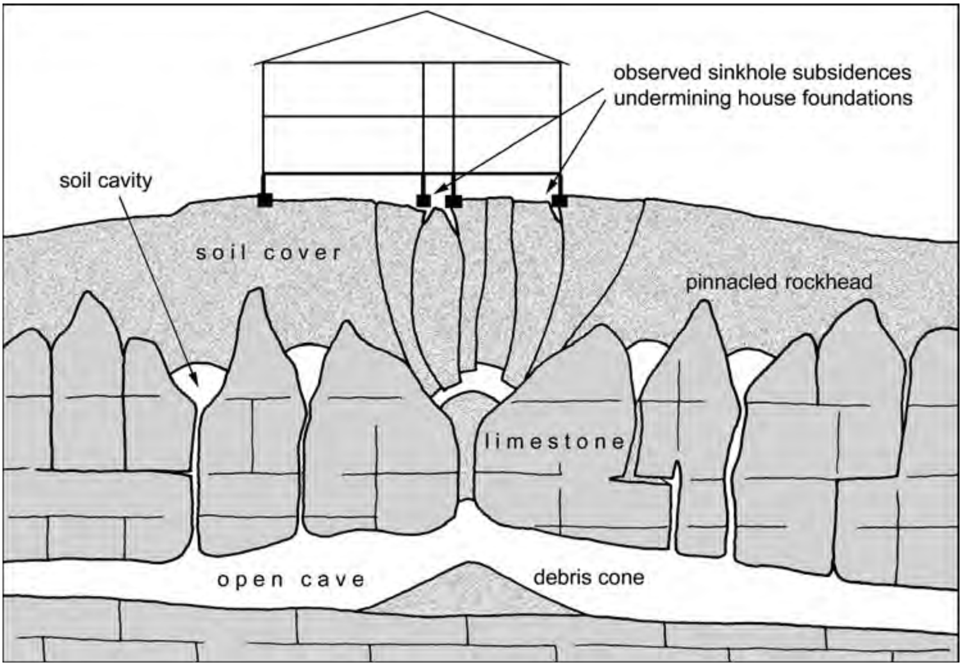

Figure 4.13. The concept of sinkhole growth by shear surfaces that allow soil wedges to fail into a cavity opened by ravelling of the soil into a bedrock fissure; based on a site in Kentucky that was investigated by soil borings and geophysical profiling.
After Crawford (2001).

contrast, a sinkhole with its outlet permanently choked by large boulders matures into old age as its sides degrade, even though water continues to drain through the coarse choke so that a lake does not form within it. The sinkhole's conical profile becomes wider and flatter, and ultimately evolves into a wide bowl where there is little or no scope for sediment transport towards the central outlet into bedrock. This sequence is well observed in Florida (Beck and Sinclair, 1986) where the thick cover of unconsolidated sediment allows the subsidence sinkholes to widen to diameters of hundreds of metres and reach levels below the regional water table, so that they hold many of the circular lakes that are common on parts of the Florida karst (Figure 4.14). Others among Florida's sinkhole lakes are perched in the soil aquifer, and suffer occasional rapid drainage events when small new subsidence sinkholes develop through their floors.

An alternative mechanism for sediment transport is indicated by striated columns of very viscous mud that have been extruded into some caves in Georgia, U.S.A., in limestone beneath a cap of Paleogene clay sediments (Jancin and Clark, 1993). These suggest a creeping plastic flow of the clay mass, in place of granular suffosion. Though sinkholes do not overlie most of these structures, land above their positions within the caves must be regarded as sites of potential subsidence.

Figure 4.14. Lakes stand in many of the very old subsidence sinkholes that have degraded to wide bowls in the thick sediment cover over the limestone in the Florida lowland karst. TW.

Though some of the very large and old subsidence sinkholes become almost permanent features of the karst landscape, they always have the potential for renewed activity, especially when disturbed by construction works (see Chapter 8). It is a sad fact that a new subsidence sinkhole can develop almost anywhere, and without any warning, in a soil-covered karst, but it is still advisable that even the degraded and apparently stable sinkholes should be avoided if possible when planning new development. The case from Pennsylvania of a site with a large dry subsidence sinkhole in the middle of it being offered for sale with the suggestion that "the hole would save on excavation costs for the house basement" showed either a frightening lack of knowledge or an indefensible excess of salesmanship by the vendor.

4.4 SPATIAL DISTRIBUTION OF SUBSIDENCE SINKHOLES

Any recognition of patterns in sinkhole distribution has to be welcomed as a possible tool for predictions of future events (Chapter 10), but sadly the concept is fraught with complexity and difficulty. While it is frequently possible to identify zones or areas that are more susceptible to subsidence sinkhole events, it is unreal to hope to predict where individual sinkholes will next occur. The few available data sets on old and new sinkhole distributions tend to confirm the very limited prospects for predicting the locations of future sinkhole events.

A karst terrain of 71 km^2 in Georgia, U.S.A., with a soil cover averaging 15 m thick, had 329 recorded sinkholes of various types; rainfall from a tropical storm then triggered 311 new subsidence sinkholes in 1994. The new sinkholes were not clustered near the old sinkholes, with the implication that locations of old sinkholes "have limited predictive utility to identifying sites for new sinkholes" (Hyatt *et al.*, 1999). It is possible that the old data was distorted by both the unrecorded filling of small features and also the inclusion of some large solution sinkholes, while the storm-induced events were all subsidence sinkholes; some new sinkholes were clustered within the larger older features. Locations of 2,303 old sinkholes were compared with those of 179 new sites in a karst in eastern Florida (Upchurch and Littlefield, 1987). In areas of bare karst with very thin soils and few sinkholes, there was a spatial correlation between old and new events, but there was no correlation in areas with more than 5 m of soil cover. A second area of Florida karst had 385 sinkholes within about 40 km^2, where 30 new sinkholes were distributed almost everywhere except in the areas of high density of old sinkholes (Bahtijarevic, 1989), and this is a karst with more than 30 m of soil cover. Predictions may be possible in almost bare karst where subsidence sinkholes are a minimal threat, but karst with thicker cover provides the main geohazard and also offers little hope for useful predictions.

Networks of fractures that include open fissures only a few metres apart in each direction are typical in a karst limestone. Beneath a soil cover, these provide an infinite number of locations for soil suffosion and collapse that could create new subsidence sinkholes. The difficulty for the engineer lies in the near-impossible task of recognising where the open fissures lie when they are obscured beneath the blanket of soil. Many attempts at recognising fracture traces, in order to predict new subsidence sinkhole events, notably at their intersections, have been based on analyses of topographic maps or air photographs (LaValle, 1967; Kemmerly, 1976; Littlefield *et al.*, 1984; Brook and Allison, 1986; Ogden *et al.*, 1989). Many of the results are less than convincing where "fracture traces" are interpreted from scattered sinkholes within the soil cover, and such studies have declined in numbers in the more recent literature. A comparable analysis in Minnesota found that sinkhole locations were not controlled by rock structure (Magdalene and Alexander, 1995).

Where the major joints and faults can be mapped in underlying cave systems, it may become clear that there is very little correlation with the distribution of subsidence sinkholes. This can be seen in parts of the Yorkshire Dales karst in northern England (Waltham and Hatherley, 1983). Within the area mapped in Figure 4.15, there is a clear line of large sinkholes along the Death's Head fault zone, but the fracture traces are not recognisable elsewhere from the sinkhole distribution. Fracture recognition by sinkhole elongation may also be unreliable. Along the Death's Head faults, only one sinkhole is elongated within the till, and this lies over an almost cylindrical shaft in the limestone, while the Ashtree sinkhole (Figure 4.16) is conspicuously circular and lies over a major joint. Even where fracture locations are known, sinkhole development is still highly variable. As a means of predicting future subsidence sinkhole events, the value of fracture trace interpretations must be seriously questioned, except where individual and very conspicuous linear features can be seen.

Certain other geological factors may influence the distribution of subsidence sinkholes. They tend to be concentrated close to boundaries where allogenic drainage is supplied from impermeable rock outcrops, and in areas of banded and

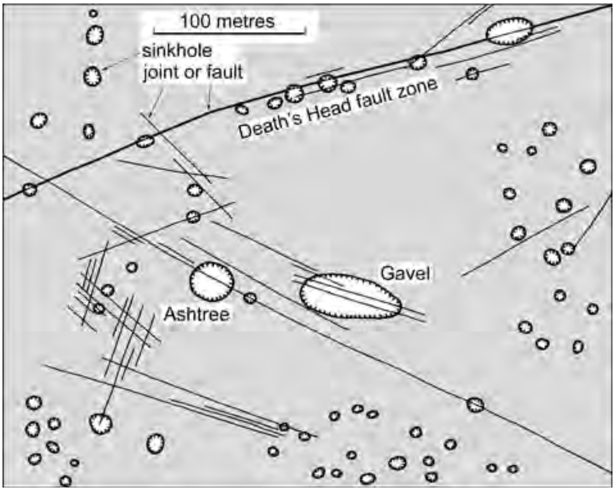

Figure 4.15. Sinkholes within a till cover correlated to fractures in the underlying limestone bedrock on Leck Fell in the English Pennines. The sinkholes were mapped on the ground and from aerial photographs, and the fractures are all recorded in underlying cave systems. Gavel Pot is a large collapse sinkhole, but all the other features are subsidence sinkholes within the till.

Figure 4.16. The deep and almost circular subsidence sinkhole known as Ashtree Hole that lies over a major joint in the Leck Fell limestone (see Figure 4.15).

steeply dipping bedrock they are more numerous over the outcrops of purer and more cavernous limestone. In one part of Georgia, U.S.A., new sinkholes occur more frequently in more permeable sandy soil cover (Hyatt *et al.*, 1999), while in another part of the same state, sinkhole sizes are related less to the permeability of the cover than to its type and age (Hyatt *et al.*, 2001); this may be influenced by more

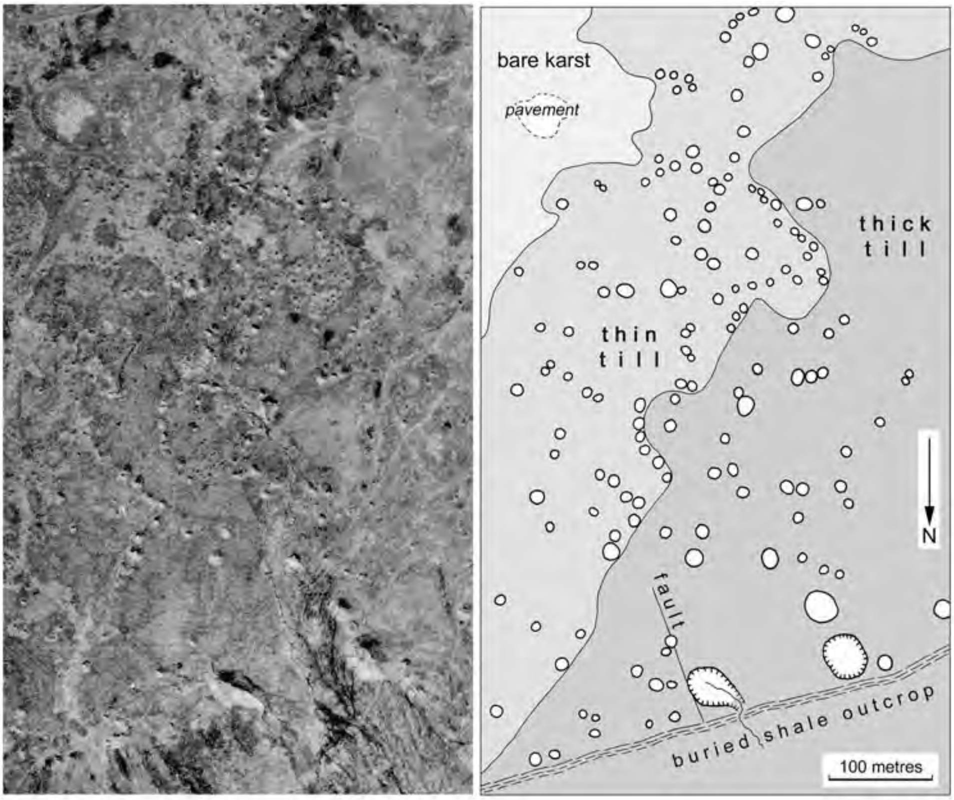

Figure 4.17. The distribution of subsidence sinkholes on part of the till-covered limestone benches that surround Ingleborough in the Yorkshire Dales karst, U.K., with the aerial photograph and the annotated map covering exactly the same area. Bare karst has a thin and incomplete cover of organic and loessic soil. The till is very variable and patchy in thickness, and the drawn boundary between thin and thick till is at an approximated thickness of 3–4 m. The marked fault is mapped inside a cave but has no surface expression. Many smaller sinkhole features are masked by a cover of sphagnum bog that is still expanding.
Aerial photo: Meridian.

of the older sinkholes that have degraded to larger diameters. Sinkhole development can also be inhibited by impermeable clays (Soriano and Simon, 2001). Contrasting lithologies within till soils appear to influence sinkhole distribution in the Pennine karst of England, but patternless variations within these soils generally produce chaotic distributions of the subsidence sinkholes. There is little or no recognisable pattern of the sinkholes on the Hurnel Moss slopes of Ingleborough in the Yorkshire Dales, U.K. (Figure 4.17); within this area, thicker areas of till restrict sinkhole development, mask effects from the one fault that can be mapped underground and almost obscure the buried shale margin. Though valley floors and dry

Figure 4.18. A new dropout sinkhole in the middle of a field on Kentucky's Sinkhole Plain; the top of a limestone pinnacle is just visible about 1 m down, but the open hole is 12 m deep within a fissure between the rockhead pinnacles.
TW.

thalwegs are significant sites for solution sinkholes, they have less influence on the distribution of subsidence sinkholes.

4.4.1 Subsidence sinkholes related to cover thickness

Maximum depths, and therefore maximum diameters, of subsidence sinkholes are broadly limited by the thickness of soil cover in which they form. While larger sinkholes can develop in them, thicker soils still have a preponderance of smaller sinkholes, with floors or apices that do not reach down to rockhead. Also, narrow and deep dropouts can form down previously soil-choked shafts, where the lower part descends between pinnacles of bedrock capped by only a thin soil cover (Figure 4.18). Overall, cover thickness is not a good predictor of sinkhole size

(Hyatt *et al.*, 2001), and models studies suggest that development of subsidence sinkholes is related more to soil type and structure than to soil thickness (Lei *et al.*, 2001). Cover thickness related to the depth to water table is not significant, as subsidence sinkholes can form where rockhead is either above or below the local water table. However, a declining water table, and particularly one that declines past rockhead, is one of the major causes of sinkhole development (Chapter 8).

In general, thicker soil covers develop fewer subsidence sinkholes. China has many thousands of recorded subsidence sinkholes, and data from different areas within the karst indicate that over 60% of sinkholes occur in cover soils less than 5 m thick and over 85% in cover less than 10 m thick (Yuan, 1987; Chen, 1988); a similar picture appears in karsts of many other countries. It is much more difficult to recognise any maximum soil thickness for sinkhole development. For the well-documented karst of Florida, it has been stated that most sinkholes occur in cover less than 20 m thick (Beggs and Ruth, 1984), less than 25 m thick (Upchurch and Littlefield, 1987) and less than 30 m thick (Currin and Barfus, 1989). This trend may reflect improvements in the database, but is probably due to more conservative interpretation. Only where soil cover is more than 60 m thick are sinkholes described as very rare (Sinclair and Stewart, 1985).

Very thick soil covers tend to preclude sinkhole development by preventing seepage drainage through to the underlying limestone, but it is very difficult to recognise any upper limit to cover thickness. Soil cover was 45 m thick where the 1981 dropout sinkhole developed in Florida's Winter Park, and is up to 50 m deep where some of the sinkholes have formed in the Rand area of South Africa, though the latter were in areas of exceptional water table drawdown (Box 8.1). Piping processes operating through cover up to 150 m thick have been indicated in Florida (Arrington and Lindquist, 1987), but no details are available. Tuscany, Italy, has two exceptional dropout sinkholes formed in Pliocene and Quaternary clastic sediments. A dropout 30 m across and 13 m deep destroyed two houses in Camaiore, when it formed where rockhead was at a depth of 100 m. The other was 100 m across, but only shallow, and formed in farmland over a period of two days where the limestone rockhead is 200 m deep. However, these sinkholes over such great cover thicknesses appear to be atypical as they are associated with rising water from geothermal sources (Beck, 2000). Sinkholes are reported as extremely rare in cover > 60 m thick in Florida (Wilson, 1995) and > 70 m thick in China (Xiang *et al.*, 1988), and these figures appear to represent a guideline limit applicable across many karst areas.

4.5 THE SUBSIDENCE SINKHOLE GEOHAZARD

In lowland karst where bedrock of limestone or gypsum is mantled by an unconsolidated soil cover, and therefore accounts for the majority of construction sites on karst, the major geohazard is presented by the occurrence of new subsidence sinkholes. Any small structures that are founded on the soil cover run the risk of losing integrity when the soil is washed down into underlying karstic voids. On complex or extreme karst (of classes kIV or kV), rates of new sinkhole development (NSH) may exceed 1 per km^2 per year – which implies the probability that a new sinkhole will develop inside a one-hectare site within a 100-year lifetime of its structure. Most new sinkholes are small, but can damage or destroy parts of structural foundations. On thick soils, larger sinkholes are less common, but can swallow entire houses. Risks are also lower on less mature karst and on some less permeable soils, but widely scattered individual sinkhole events present an intractable geohazard in any soil-mantled karst.

It is virtually impossible to predict new sinkhole locations in previously undisturbed soil, and there are serious difficulties in economically identifying soil voids that could propagate to create new surface dropouts (Chapter 9). Consequently the engineering response to the subsidence sinkhole hazard is to reduce the risk. The sinkholes are caused by water washing down through the soil, and the vast majority of new sinkholes on construction sites are induced by engineering works that are either unfortunate in their impact or are simply inappropriate to the karstic ground conditions (Chapter 8). Control of drainage is therefore fundamental to good practice in engineering on soil-mantled karst (Chapter 10). This concept does provide special difficulties in the retention of either reservoir water or landfill contaminants in areas of sinkhole karst (Chapter 12). Unfortunately individual subsidence sinkholes present superficially attractive sites for waste disposal to create level ground, but attempts at retaining either landfill or water within subsidence sinkholes usually end in failure. Even where drainage is well managed within new construction projects, natural water flows from rainfall onto any exposed soil still create some potential for the development or reactivation of subsidence sinkholes. It is therefore commonly appropriate either to found structures on stable underlying bedrock, or to create structures on soil that can survive a new sinkhole event under a part of their foundations (Chapter 12).

8

Sinkholes induced by engineering works

Subsidence sinkholes that develop within a soil cover are the major geohazard in karst. They are created rapidly by water transport of the soil, and any disturbance of the water regime that increases through-flow is more than likely to promote new sinkhole development. Such disturbance, either designed or unintended, is all too commonly due to engineering works, and in the developed modern world the great majority of subsidence sinkholes are induced by man's activities.

The proportion of new sinkholes that are induced in populated areas is generally accepted as being around 90%. Records in Alabama from 1900 to 1980 mark over 4,000 new sinkholes, mostly occurring since 1950, while there were less than 50 reported new sinkholes that were natural events (Newton, 1981). The sinkhole database from China (Table 8.1) is so large that its proportion of sinkholes that are induced (between 87% and 93%) should be representative of the overall picture in karst. Clustering of multiple sinkholes around single causes does have an impact on the statistics, and natural causes are assigned to 23% of the Chinese sinkhole sites (as opposed to numbers of individual sinkholes). Artificial water table decline and increase in imposed drainage are the two main factors that induce subsidence sinkholes, and which one is dominant depends on the local situation. The urbanised karst areas of Pennsylvania are characterised by deep water tables, where induced decline has little impact on sinkholes in the soil profile; its effects are therefore not recorded in Table 8.1, which partly accounts for the state's atypically low proportion of sinkholes that are induced as opposed to natural.

Sinkholes may be induced by engineering disturbance that comes in a variety of forms (Table 8.2). The major critical factor is any increase in water flow down through the soil and into cavernous rock beneath. This is most commonly due to drawdown in response to water table decline; whether this is due to abstraction or by de-watering, it may have to be regarded as an environmental factor for any particular site. Alternatively, water may be added at the surface to achieve the same effect.

Table 8.1. Proportions of new sinkholes that are either natural or induced by various means in China and parts of the eastern U.S.A.
After Gao *et al.* (2001) and Myers and Perlow (1984).

Location	China	Alabama	Missouri	Pennsylvania
Water table decline (including mine drainage)	80.0%	87%	8%	n.a.
Water impoundment	3.4%	12%	21%	
Construction works and drainage modifications	3.6%	1%	71%	58%
Total induced	87.0%			58%
Natural	6.2%	n.a.	n.a.	42%
Unknown	6.8%			
Total number of sinkholes	44,904	1,324	87	1,574

n.a. refers to statistics that are not available.

Table 8.2. Listing of the main processes by which sinkholes are induced through engineering activity.
Partly after Newton (1987), Waltham (1989) and Cai (1991).

Increased water input to soil cover
Uncontrolled run-off drainage from a site or structure
Installed drainage ditches that are unlined
Broken pipelines
Soakaway drains (dry wells) within the soil profile
Unsealed boreholes
Irrigation for agriculture
Impoundment of reservoirs and floodwater retention basins
Increased through drainage due to water table decline
Over-pumping for groundwater abstraction
Well pump-testing
De-watering to maintain dry quarry operations
De-watering to maintain dry mine workings
Physical disturbance to the ground
Partial removal and consequent thinning of the soil profile
Partial or total removal of vegetation on the soil cover
Vibrations from blasting or plant movements
Structural loads on foundations within the soil profile
Water table fluctuations.

In the short term this is commonly related to rain-storm events, but in the long term is a common result of drainage diversion within construction or built works, and these should be avoidable by best-practice engineering. The third group of inducement processes covers any physical disturbance of the soil conditions. This may include the effects of foundation loading on the soil profile, but excludes the rare collapses of rock due to imposed load over caves (see Chapter 7).

8.1 SINKHOLES INDUCED BY INCREASED WATER INPUT

Any disturbance of the natural patterns of run-off and infiltration of rainwater can lead to localised increases of drainage down through the soil, which can lead to renewed or accelerated soil suffosion at those points, and the ultimate development of new subsidence sinkholes. About 70% of new sinkholes in the Bowling Green area of Kentucky are induced by drainage disturbance either by farming practices or by urban development (Crawford, 1999). The disturbances may be unintentional diversions of drainage, either during construction works or where housing development places a quarter of the land under concrete and diverts its rainwater run-off elsewhere. Industrial or commercial development, that can totally seal large areas of land, demands installation of extensive drainage structures. At Bowling Green's airport in Kentucky, 25 sinkhole collapses have been recorded in the soil cover, but all are where run-off from the runways has been directed into channels, ditches and sinkhole basins, while none has occurred under the paved areas (Crawford, 2003). A large proportion of new sinkhole events are triggered by new drainage works that are inappropriate or inadequate for installation in or on soils that cover cavernous karst.

Unlined drainage ditches are a major source of problems in karst regions, and many develop sinkholes soon after their construction. By their very existence, they concentrate water flow at sites that previously took only direct rainfall infiltration. Run-off from an airport runway in Pennsylvania was fed into an unlined gully that is now broken into a series of large sinkholes (White *et al.*, 1986). Ditches on low gradients are traditionally left unlined along transport corridors. Seepage losses from unlined ditches accounted for 14 out of 54 severe sinkhole collapses along China's railways (many of the others were induced by water table decline; Guo, 1991), and also for 49 out of 72 sinkhole events along Tennessee's highways, where only 4 sinkholes developed along the lined ditches (Moore, 1988). Seepage into any unseen rockhead fissure can carry soil from beneath a ditch floor; by the time surface subsidence is apparent (Figure 8.1) it will require remediation to prevent potentially destructive expansion, when it may then be turned into a stable outlet to bedrock (Chapter 11). Though many unlined ditches do keep sinkhole initiation away from the actual road or railway, concrete-paved ditches can prove cost-effective in sinkhole-prone karst (Moore, 1988).

A leaking water main is a very effective means of supplying water to a soil and thereby initiating a subsidence sinkhole as both water and soil are lost into bedrock fissures. A mains failure under a rural road on the South Downs, in England, created about 80 dropout sinkholes in adjacent fields within a few hours (McDowell and Poulsom, 1996). There was no surface flow, as the water spread through the cover of loose sands and gravels until it found outlets in pipes and fissures within the underlying chalk. Some of the dropout failures occurred within minutes, suggesting that

Figure 8.1. Early stages of a sinkhole developing in the untreated soil floor of a ditch beside a Pennsylvanian highway; it is temporarily choked with clay, while the riprap in the foreground was placed to prevent erosion at a culvert outlet.
TW.

these may have formed as caps of more cohesive topsoil collapsed into soil voids already formed by suffosion of the sand and gravel into chalk fissures (Figure 8.2).

Pipeline fractures in cover soils are more destructive in urban areas, especially where large buildings are not founded on bedrock. Minor soil settlements induced by a building's loading can fracture utility lines, whose leaking water then accelerates the soil loss in a feedback loop that is both dramatic and inevitable. In the urban karst of Pennsylvania, utility failures account for nearly 30% of sinkhole events (Myers and Perlow, 1984), including some major structural failures (Case study #7). A single break in a 360 mm water main in Phillipsburg, New Jersey, created a cluster of sinkholes under a suburban street, the first of which completely destroyed a house within 4 hours of ground movement first being noted, even though the water was shut off within 3 hours (Figure 8.3). The houses, street and pipeline all stood on sandy soils that lay 3–15 m thick over a pinnacled rockhead of Cambrian dolomite. Subsequent drilling found a dozen cavities within the soil profile beneath the street, with the largest all around the water main break; these were grouted to prevent future failure (Canace and Dalton, 1984).

Early response to a water main leak can minimise expanding damage. However, a loss of pressure in a Pennsylvanian water main prompted a water company engineer to go out looking for the site of the escaping water, which he found when his van fell into a sinkhole that opened in the street in front of him (White *et al.*, 1986). At other locations, sinkholes are generated beneath towns due to widespread small-scale leakages from utility lines that are either poorly built or poorly maintained (Case study #12). The desert city-state of Kuwait has neither significant

Figure 8.2. One of the cluster of subsidence sinkholes induced by a broken water main on the English chalk downs; there was no surface flow, but the dropouts developed above suffosion points in the soil over bedrock fissures.
TW.

karst nor significant rainfall, yet four large sinkholes opened in the Al-Dhahar suburb in 1988/9. These all formed in sandy soils 40–60 m thick over the cavernous Dammam Limestone, and appear to have been triggered by water from leaking pipelines and also from garden irrigation within the zone of new housing (Abdullah and Mollah, 1999).

While sinkholes caused by pipeline fractures and ditch leakages may be counted as unintentional, those caused by dry wells (or soakaway drains as they may be known) can only be ascribed to engineering practice that is unacceptable on karst. Rainwater drainage from a new factory and its car park in Pennsylvania was directed entirely into dry wells sunk into the soil cover over a pinnacled limestone rockhead across the floor of a large and shallow closed depression. Within a few months, over twenty sinkholes had developed, mostly adjacent to the dry wells (Knight, 1971). Prior to development, rainwater had sunk into the soil with minimal temporary ponding in small hollows, but the new plant had placed half the site under concrete and had concentrated all its run-off at the dry wells dug entirely in the soil profile; sinkholes failures were inevitable. Soakaway drains are commonly installed in England's chalk, which is appropriate for their use because of its very high diffuse permeability. However, it is well established that they are not placed where there is any possibility of ground cavities (either natural or mined) that could permit suffosional loss of the soil cover. Such a ruling could well be applied more widely, to exclude their use in any soil-covered karst – except where appropriate measures were utilised.

It is possible to use dry wells to dispose of storm-water in soil-mantled karst as long as they drain directly into bedrock fissures so that there are no pathways for suffosion of the soil (Figure 8.4). The critical factor is to ensure that the well casing is sealed through to bedrock, with no routes for water to escape into the soil and through to other fissures, or for influent flow to wash soil into the dry well.

Figure 8.3. Terminal damage to a timber-frame house in Phillipsburg, New Jersey, caused when sinkholes developed underneath it and under the sidewalk after a water main burst beneath the street.
Photo: Rick Rader.

Hundreds of dry wells operate successfully in and around Bowling Green, which stands entirely on Kentucky's Sinkhole Plain. Many were drilled directly into open caves that had been previously located at minimal depths, and they have various grilles and traps that ensure they are not choked by sediment (Crawford and Groves, 1995). However, among 80 recent sinkhole collapses in the town, 24 were on poorly constructed drainage wells, while another 28 were beneath ponded storm-water in broad sinkhole depressions that lacked engineered conduits into the limestone below (Crawford, 2001). Such retention basins within sinkholes can be acceptable, but only with appropriate design and management (Chapter 12). The effect of diverting water into an existing sinkhole depression with no engineered outlet was demonstrated by the overnight collapse of the Boxhead sinkhole in England (Figure 4.9). A shallow subsidence sinkhole had developed by years of percolation suffosion, but its floor dropped out immediately after a small moorland stream was diverted into it.

There are many recorded cases of well drill rigs collapsing into sinkholes triggered by their own disturbance to the groundwater patterns. In 1959, a driller lost his life in Florida when he was buried 10 m deep in a dropout collapse. His well boring was approaching rockhead at a depth of 24 m where it breached a clay aquiclude and allowed rapid drainage and suffosion from the perched aquifer (in

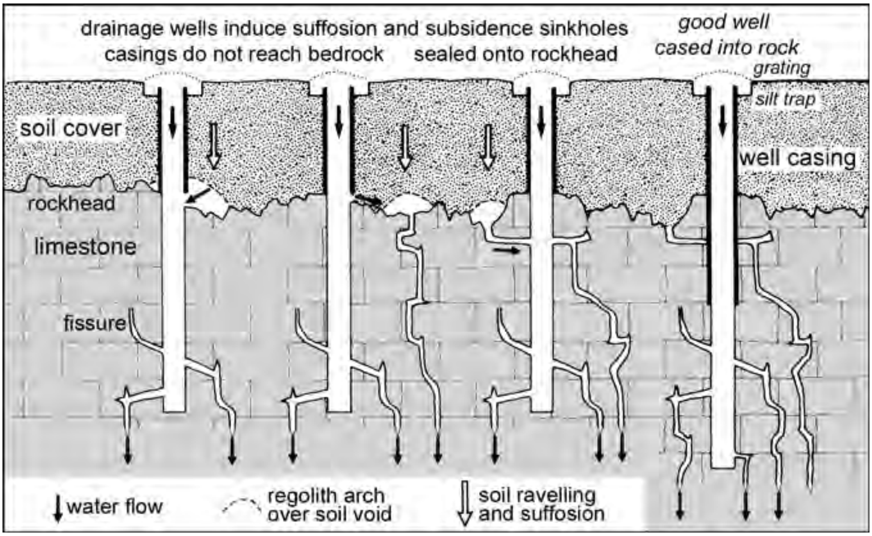

Figure 8.4. Dry wells in soil-covered karst. The three wells on the left provide pathways for suffosion of the soil and are likely to promote future sinkhole development, while the well on the right is sealed deep into bedrock fissures and should provide a stable drainage outlet. After Crawford and Groves (1995).

the upper sandy soil) down into the fissured limestone (Newton, 1987). Sudden downward drainage of a soil aquifer is the most common sinkhole trigger induced by drilling. The reverse was the trigger at a drilling site in South Dakota, where an artesian aquifer in cavernous gypsum was breached and the upward flow of water collapsed the well and created a large sinkhole, from which water continues to be discharged (Rahn and Davis, 1996). Investigative drilling at sites of ground subsidence always run some risk of triggering more catastrophic collapses, and water-flush drilling is certainly inappropriate for investigating potential sinkhole collapses. There have been cases where exploratory drilling of a site with modest prior subsidence provided the input of water, that drove the suffosion, that induced a sinkhole, that destroyed the structure under investigation.

Land irrigation may be a necessary and planned recharge of water to the soil, but it can have disastrous side-effects where the soil overlies cavernous rockhead. Small subsidence sinkholes are common in ploughed and irrigated farmland in karst regions all round the world, but their economic impacts are generally small, and could not justify stopping the irrigation except in the smallest of sinkhole-prone areas. An unusually large sinkhole opened in a pistachio field that was kept well irrigated in the desert lands just west of Kerman in Iran (Figure 8.5). It formed in alluvial soils more than 40 m thick, and though the groundwater pumping was causing steady water table decline, the irrigation recharge onto the surface appears to have been the critical factor in the sinkhole's very rapid collapse (Atapour and Aftabi, 2002). Dissolution of gypsum horizons within the alluvium sequence may have aided growth of large soil cavities, whose dramatic collapse was then marked by

Figure 8.5. The very large subsidence sinkhole that developed in 1998 in irrigated farmland near Ekhtiyarabad, southern Iran.
Photo: Habibeh Atapour.

"horrible noises" from the ground. Massive recharge of soil water is created during rare overnight freezing conditions in Florida, when farmers douse their strawberry crops with relatively warm groundwater to keep the frost off them, and rashes of sinkholes follow these events (Bengtsson, 1987). Though water tables decline due to the pumping, the speed of events suggests that the sinkholes are at least in part triggered by the surface recharge (Section 8.2.1).

8.1.1 Sinkholes caused by reservoir impoundment

The most massive recharge of water to any soil cover on karst is created by the impoundment of a reservoir. New sinkholes commonly develop in the floor of any reservoir on karst directly after it is first filled, causing rapid drainage of the impounded water, though the impact of the sinkholes themselves is usually minor in comparison to the loss of the reservoir's integrity (Chapter 12). Seven complete failures of reservoirs or sewage lagoons were recorded as due to sinkhole development and rapid drainage into the limestones of Missouri's Ozarks karst (Aley *et al.*, 1972), and six more are recorded in the eastern U.S.A. (Newton, 1987).

Nearly all these reservoir losses on karst create subsidence sinkholes entirely within the soil profile, but the massive through-flows of escaping water can scour out buried features and expose open solutional voids that reach deep within the bedrock. Shortly after the Al Marj dam was built on karst in the Jabal Akhdar (Green Mountains) of northeastern Libya, its reservoir was filled during a major rain storm. Local people gathered in celebration, only to see a huge whirlpool develop in the middle of their new lake, which was soon completely empty. Sinkholes left on the ex-reservoir floor included a vertical open shaft, down through 1 m of soil and 26 m of limestone to a rubble choke (Figure 8.6). This sinkhole appears to have developed when a previously filled shaft within the bedrock was washed out from below, where the main water flow (from the whirlpool) had entered through a side fissure 20 m down. Collapse of limestone bedrock is rare beneath a reservoir, but some measure of dissolution and subsequent rock collapse must occur during a catastrophic reservoir drainage event that occurs on gypsum.

Figure 8.6. The Karrubah sinkhole, in Libya, that formed beneath the waters of the short-lived reservoir impounded by the Marj dam, visible in the distance.
Photo: Attila Kosa.

Repeated sinkhole activity may be induced where reservoir levels fluctuate. In western Turkey, the May reservoir lost most of its water through 33 new sinkholes when it was first filled in 1960. These were all subsidence sinkholes that developed in the alluvial sediments forming an unstable reservoir floor over cavernous limestone (Dogan and Cicek, 2002). The sinkholes were repaired and sealed with clay, but the reservoir continued to suffer from massive leakage. When the reservoir again reached its maximum level, in 2002, three new large sinkholes developed under water, and drained most of the reservoir. These formed in valley-floor alluvium that is 20–50 m thick, when suffosional soil removal down into the limestone was driven by the increased head difference across the soil that was self-imposed by the reservoir. It appears that these sinkholes did not have time to develop in the few months of 1960 before the reservoir was drained through a sinkhole elsewhere, indicating a minimum timescale for suffosional piping through the thick soil.

8.2 SINKHOLES INDUCED BY WATER TABLE DECLINE

The most widespread cause of induced sinkholes is any form of water table decline, where the vertical drainage is quite literally drawn down to greater depths, in many cases carrying more soil with it. The effect is most powerful where the water table declines past the rockhead. In these cases, a regime of slow, multi-directional, phreatic flow beneath the water table is replaced by rapid, downward, vadose drainage above the water table within the critical zone where soil arches over rockhead fissures are ready to fail. Lesser impacts are felt through other regimes of water table decline, but may still be enough to induce sinkhole failures.

Natural water table decline is normally very slow, and its impact on sinkhole occurrences is lost within the slow evolution of landforms during ongoing rejuvenation. Hundreds of sinkholes, each up to 20 m wide and deep, have developed around the shores of the declining Dead Sea, in Jordan and Israel (Yechieli *et al.*, 2003). Sinkhole events started in the 1980s, and noticeably accelerated about 10 years later, after the Dead Sea had fallen by another 8 m. They have been caused by sediment collapse over cavities in salt beds at shallow depth, where the accelerated dissolution of the salt was due to an invasion of freshwater drawn in from the mountains in response to the falling level of the Dead Sea. Among induced sinkholes, this process of rock dissolution is unusual, but its relationship to water table decline compares to that of accelerated soil suffosion forming subsidence sinkholes.

Shrinkage of the Dead Sea is at least in part due to the over-use of the limited water resources in its basin, so those sinkholes may also be viewed as induced by man's activities. Similarly, sinkholes may be described as natural when induced by water table decline during a prolonged drought, but in any populated area that decline is likely to be increased by extra groundwater pumping (Newton, 1987). Most induced sinkholes are related to artificial water table decline that is either an accidental consequence of groundwater abstraction or the intentioned result of dewatering mines or quarries.

8.2.1 Sinkholes induced by groundwater abstraction

Though karstic limestones can be very productive aquifers, their water tables can decline in the face of intensive or long-term abstraction. Sinkholes are therefore an almost inevitable consequence of urbanisation, industrial expansion or over-thirsty agricultural development on many areas of soil-mantled karst. Water table decline may be limited to the cone of depression of a single well that is over-pumped for an industrial plant. In Brazil, a sinkhole collapsed in a karst that was not previously recognised as such because the cavernous rock was hidden beneath a deep soil cover (Figure 8.7); the new sinkhole was induced by water table decline around an over-abstracted well on an industrial site near Sao Paulo (Prandini *et al.*, 1990). On a regional scale, the water table decline is commonly due to abstraction for municipal supplies, as is all too common in the densely populated lowland karst regions of China and eastern U.S.A.

Sinkhole collapses have occurred in all China's many cities built on karst, and groundwater pumping is the main cause (Chen, 1988; Guo, 1991). More than 1,450 subsidence sinkholes have developed in the alluviated and soil-covered plains around Guilin, that lie between the limestone towers in Guangxi's famous fenglin karst. They have caused extensive damage, mainly in farmland but also destroying roads and buildings, and 90% of the new sinkholes were induced by water table decline due to groundwater abstraction. The alluviated Shuicheng basin is similarly underlain by

Figure 8.7. Collapse of a house in Cajamar, Brazil, in 1986 over a sinkhole induced in a thick soil cover by excessive groundwater abstraction at a nearby industrial site.
Photo: Jose Labegalini.

limestone within Guizhou's fengcong karst, but was the most convenient site for abstraction wells to supply the expanding new town of Liupanshui (Waltham and Smart, 1988). Wells were placed out in the rice fields, where clay soils are 3–10 m thick over a pinnacled rockhead, and the original water table was only 1–2 m below ground. Within about 8 years, 1,023 new subsidence sinkholes were formed over cones of depression 8–15 m deep and reaching up to 400 m from 14 of the 17 wells (Figure 8.8). Sinkholes were mainly in the open fields, but 89 buildings were damaged, roads were broken, sewers were reversed, and at least two of the pump houses were damaged in classic cases of self-induced destruction (Figure 8.9). The broad conclusions from experience in China's karst suggests that sinkholes are induced mostly where the water table declines past the rockhead and/or where it declines more than 3 m, while surface leakages are more important than water table decline where its original level is below rockhead (Lei *et al.*, 2001).

Decline of a water table that lies deep below rockhead is observed to have minimal influence on subsidence sinkholes in the dissected and deeply drained karst of Pennsylvania (White *et al.*, 1986), matching the data from China. The major sinkhole problems due to water table decline in America are in the lowland karst of Florida. Across most of the state, the Floridan aquifer is formed by the Ocala Limestone with its rockhead 30–50 m below ground level. The soil profile has a perched aquifer in sandy materials overlying an aquiclude formed by the clay-rich Hawthorn Formation that rests on rockhead. The piezometric surface of the

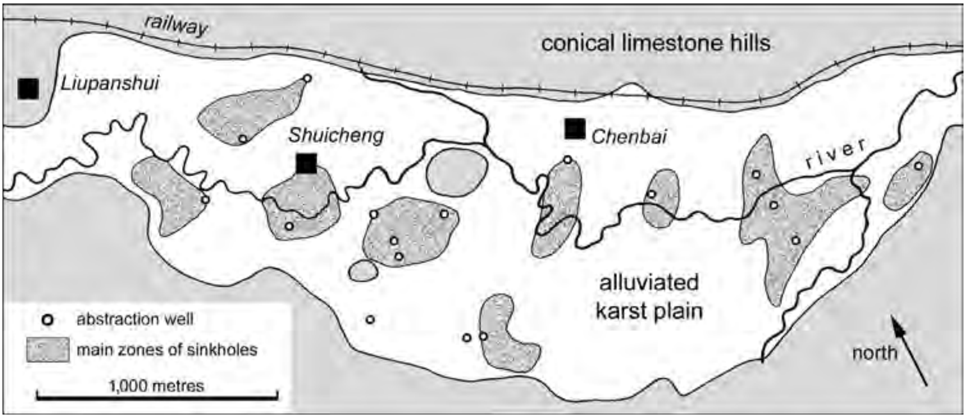

Figure 8.8. Distribution of abstraction wells and their induced sinkholes in the alluviated karst basin of Shuicheng, China.

Figure 8.9. A subsidence sinkhole induced by water table decline as groundwater was pumped through the well house visible beyond, in the Shuicheng karst basin, China. The crest of a limestone pinnacle is exposed in the sinkhole only a metre below the original ground level. TW.

Table 8.3. Sinkholes induced in three areas of western Florida.

Site	Date	Water table decline	Period of activity	Number of new sinkholes	Diameter of area of activity	Source of data, reference
North Tampa	1964	3.5 m	3 months	64	3 km	Sinclair (1982)
West Dover	1977	2.9 m	5 days	22	3 km	Metcalfe and Hall (1984)
East Dover	1985	5.2 m	3 days	27	6 km	Bengtsson (1987)

Floridan aquifer normally lies below the perched water table. The head difference drives seepage from the upper sands down through the lower clays, causing soil suffosion into open fissures in the limestone rockhead. Groundwater abstraction is nearly all from the Floridan aquifer, as the shallow aquifer is prone to pollution, and water table decline therefore increases the head difference across the Hawthorn, and increases sinkhole development. The Winter Park sinkhole in Orlando occurred when the water table in the Floridan aquifer had declined by 6 m, increasing the head difference from 4 m to 10 m (Figure 4.10).

Clusters of sinkholes have developed in the Tampa area of West Florida during at least three events of major water table decline due to pumping from the underlying Floridan aquifer (Table 8.3). These sinkholes are 1–23 m across and only 1–7 m deep, even though local depths to rockhead are 20–30 m. The two events in adjacent areas near Dover each occurred during short periods of sub-zero weather when massive quantities of warm groundwater were pumped from field wells and sprayed onto the strawberry crops to prevent them freezing. Both sites were marked by the very rapid development of sinkholes, on the third day of pumping in the 1985 event. The earlier event north of Tampa was induced by expansion of a new wellfield for municipal supplies, so no water was immediately recharged to the soil, and sinkholes developed over a period of about three months. Irrigation water added to the soil joins the perched aquifer above the Hawthorn Formation, while suffosion processes that form sinkholes are normally initiated at rockhead where soil cavities grow over bedrock fissures. However, it appears that the substantial water recharge to the soil directly over the pumped cones of depression at the two Dover sites had its own impact on sinkhole development in addition to that of the water table decline, and accounted for the new sinkholes appearing more rapidly than at the un-irrigated Tampa site.

Pump-testing and the development of new wells commonly induces massive water table decline, albeit under small areas, in terrains that have not previously been disturbed. They are therefore very effective at inducing new subsidence sinkholes in any available soil cover. Nine over-pumped wells in the eastern U.S.A. all developed sinkholes within their immediate vicinity and within a few days of the start of pumping (Newton, 1987). At five of these sites, the pumping was extended or intensified in attempts to clear muddy water, which was a sign of active suffosion and a warning sign of the sinkhole collapses that soon followed. A staged pumping test in the Guizhou karst, China, followed years of pumping from older wells that had induced over 70 subsidence sinkholes in cover soils 2–8 m thick (He *et al.*, 2003). In the first stage of pumping, drawdown was 6.8 m and no new sinkholes were formed, but subsequent stages that took drawdown eventually to 24 m induced 38 new sinkholes within two months. Sinkholes are most conspicuously induced when water tables first decline to levels not previously reached.

Well development by cyclic flushing is singularly effective at moving sediment through cavernous ground. In 1998, a well drilled 48 m into the Florida limestone aquifer triggered hundreds of sinkholes within just six hours of development flushing. These were all in a woodland area where 6 m of sand covered the limestone. Though most of the new sinkholes were only about a metre across, some expanded or coalesced into depressions nearly 50 m wide. The only more disastrous impact of well drilling is where a well is left uncased or unsealed through salt beds, so that it creates a new route for freshwater to reach the buried salt and there initiate large-scale dissolution. The end result can be large new sinkholes at the surface, as occurred at Wink, Texas (Case study #11).

8.2.2 Sinkholes induced by de-watering

Whether by surface quarries or underground mines, the extraction of limestone or any minerals within it invariably encounters serious water problems in karst terrains. Deep workings require massive pumping operations, and the effect of these is to create deep cones of depression. In any soil-covered karst, subsidence sinkholes are inevitably induced over the surrounding areas of water table decline, which extend well beyond the quarry or mine limits and continue to extend further as workings reach to greater depths while having to be kept dry. Numerous deep mines in limestone have encountered massive water problems underground, but internal drainage measures have minimal surface impact where the mines lie deep beneath mountainous karst terrains. Sinkholes are mostly induced in soil-mantled karst lowlands, and the major events have occurred in South Africa (Box 8.1), eastern U.S.A. and eastern China.

America's classic case of quarry de-watering involved the Pennsylvania factory that produces Hershey chocolate (Foose, 1953, 1968). The main quarry extracted limestone from a valley side 3 km upstream of the chocolate factory, which stands on valley alluvium over the same limestone. At the quarry, the water table was about 20 m down, and massive pumping was required as workings went deeper and then continued down as a mine following the steep dip of the good limestone. De-watering removed 0.45 m^3/s from the quarry and mine, dropping the water table by 75 m. The cone of depression extended across 30 km^2 (in which head decline was $>$3 m), and the valley floor springs ceased to flow. A pinnacled rockhead underlies valley soils that are about 20 m deep, and the original water table was about 8 m down. As the cone of depression grew, over 100 subsidence sinkholes developed within about 5 months. They were 2–7 m across and up to 8 m deep, and most were where water table decline exceeded 15 m – which is about where it declined past rockhead (Figure 8.10). The chocolate factory stood on the 15-m contour of head decline, with the area of sinkhole development expanding across the fields

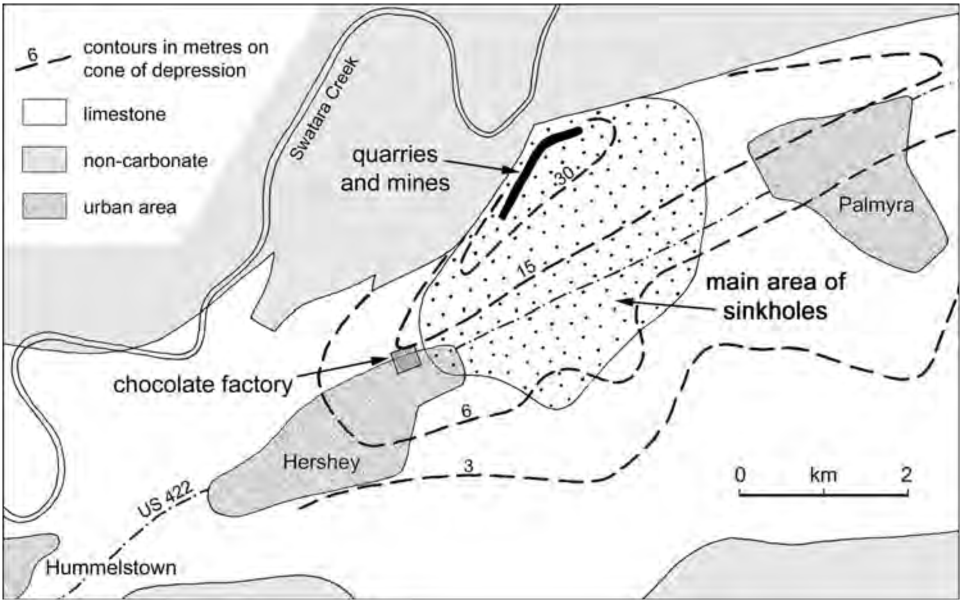

Figure 8.10. Map of the Hershey valley with the area of new sinkhole development related to the cone of depression around the de-watered quarry and mine.
After Foose (1968).

toward it, and the company resorted to groundwater recharge to inhibit the local water table decline. Legal actions ensued, and the mining company then sealed its workings behind a grout wall to isolate its zone of de-watering. This stopped sinkhole development. Mining and pumping have since ceased, so that the quarries are now flooded to the original water table, and chocolate production continues undisturbed.

The Hershey events were almost repeated 30 years later in the Dry Valley area of Shelby County, Alabama. Soils across the valley floor are only 1–6 m thick, and the original water table generally lay above the rockhead of heavily fissured limestone. Deep quarries and even deeper mining of the limestone have required de-watering at rates up to 0.9 m^3/s, which has dropped the water table by 120 m (LaMoreaux and Newton, 1986). Over 2,000 subsidence sinkholes, nearly all small, have formed in the valley soils within the induced cone of depression. Over 600 m from the mine, Highway 16 crosses the valley where water table decline has been 70 m, and sinkholes necessitated more than 30 repairs to the road within six years. The mine continued in use, and sinkholes continued to threaten the road, especially after periods of heavy rain. The advisory road signs (Figure 8.11) appear over-cautious in dry weather, but continue to offer pertinent advice during and soon after major rain events. Higher in the wooded hills of the same karst, a subsidence sinkhole collapsed and flared out to 90 m in diameter in 1972. The water table was 18 m

BOX 8.1. INDUCED SINKHOLES IN THE RAND MINING FIELD

The most catastrophic collapses of some of the world's largest sinkholes, and the greatest loss of life in any sinkhole disaster, occurred in one small area of dolomite karst in the Far West Rand district of Transvaal, South Africa, just south-west of Johannesburg. Events were due to an exceptional combination of a very mature karst, a thick soil cover and inducement by an unusually massive decline of the water table. Though the sinkholes have now been filled in (by vast quantities of readily available mine waste), the events of 30 years ago remain a classic within the field of engineering on karst (Brink, 1979; Swart *et al*., 2003).

The Rand karst is formed in over 1,000 m of gently dipping, Proterozoic, impure, chert-rich dolomites. These are capped to the south by Karoo sandstones, and underlain by a thick lava sequence below which lie the sedimentary Witwatersrand Group with their gold-bearing conglomerates. The dolomite outcrop is over 10 km wide along the Wonderfontein valley (Figure 8.1.1), where the karst rockhead is buried beneath soils generally 10–100 m thick. Vertical syenite dykes each about 50 m thick break the dolomite aquifer into hydrologically discrete compartments, each originally drained by a valley-floor spring against its downstream dyke (Figure 8.1.1). The very old karst has matured into a complex terrain with a pinnacled rockhead, large buried sinkholes and many shallow

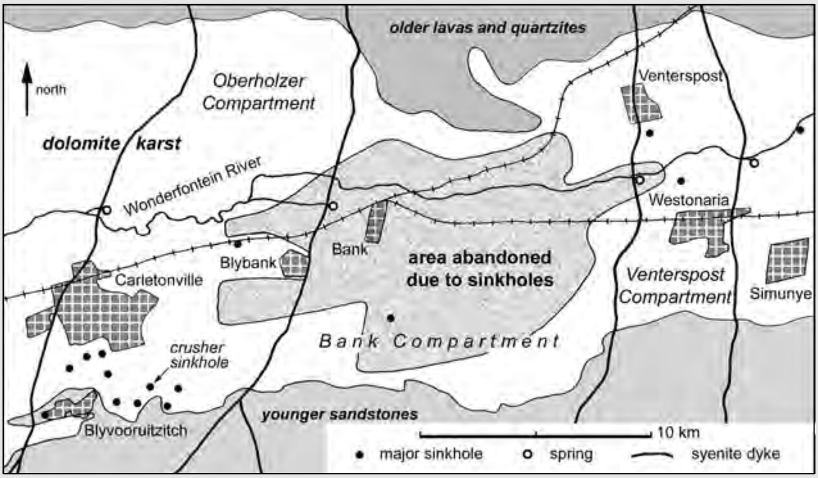

Figure 8.1.1. Map of the Rand sinkhole area.

Figure 8.1.2. The subsidence sinkhole that engulfed the mine crusher plant in 1962.
Photo: Consolidated Goldfields.

phreatic caves; the original water table lay 2–26 m above the average rockhead level. Pumping records indicate that porosity in the 30 m below the original water table is up to 10%, largely in sub-vertical fissure caves, but this declines rapidly with depth to values of about 0.1% more than a few hundred metres down.

In 1934 the first successful deep mine worked the valuable gold deposits in the Venterspost Compartment, but encountered water problems as the workings extended beneath increasing areas of the karst aquifer. Massive de-watering was therefore instigated, and the calendar of events (Table 8.1.1) recorded major sinkhole development following major water table decline in each compartment as the mines extended through the goldfield. The worst single event was the sudden collapse of the sinkhole that destroyed the mine's crusher plant at West Dreifontein and killed 29 people (Figure 8.1.2). The plant had been built on a grouted soil mat where rockhead was 117 m deep in a buried sinkhole elongated along a fault in the dolomite. Over a period of three years, minor precursor movements were on a scale regarded as normal over the buried karst (De Bruyn and Bell, 2001), but suffosion must have developed significant soil voids within the fill of the buried sinkhole to allow the instantaneous collapse large enough to swallow the entire crusher building.

Six years later, the same mine was flooded to a depth of 800 m before an inrush of nearly 5 m^3/sec could be controlled by splendid emergency operations (Cousens and Garrett, 1970). A heading had reached through the Bank dyke, where stopes were opened with just 30 m of quartzite separating them from the dolomite karst aquifer, then undrained within the Bank Compartment. Fractures opened up in the de-stressed hanging wall to let the water into the mine. Stemming the flood saved the higher workings in the Oberholzer Compartment, but left those in the Bank Compartment totally flooded, and the only way to resume mining was by total de-watering of the Bank Compartment. It was appreciated that this would induce sinkholes within the compartment, but the foreseeable costs of the damage were outweighed by the value of the mineable gold. In the event, new subsidence and compaction sinkholes were very effectively induced, and a threat of major dropout sinkholes was recognised after drilling revealed large soil voids. Consequently, the Bank township was completely evacuated (Figure 8.1.1). Abandoned houses in the closed area were slowly destroyed (Figure 5.12) by differential compaction over buried sinkholes up to 70 m deep. The greatest compaction subsidence was recorded where the original water table was less than 30 m deep within the soil profile, and the prime site for new dropout sinkholes was over the steepest margins of the large buried sinkholes. The land remains undeveloped today, as the dolomite is still de-watered.

In subsequent years, new sinkholes have continued to develop throughout the de-watered buried karst. Five more people have died in dropout sinkholes around Westonaria; after each event, nearby houses have been demolished and the sinkholes have been filled – and have remained stable. By 1987, a recorded 271 sinkholes had an average volume of 9,000 m^3 – a spectacular testimony to the effects of unusually massive de-watering of a soil-covered karst.

Table 8.1.1. Calendar of events in the Rand karst followed de-watering in the three mined compartments.

Venterspost Compartment	
1957	*De-watering was largely completed*
1958	First sinkhole, 80 m across, collapsed in December
	Over the next 25 years, 165 more sinkholes occurred
Oberholzer Compartment	
1959	*De-watering was completed*
1962	29 people died when sinkhole 55 m across, 30 m deep, swallowed the crusher at West Dreifontein Mine
1963	Schutte's compaction sinkhole developed, reaching 180 m across after 3 years
1964	5 people died when a sinkhole 30 m deep collapsed beneath houses in Blyvooruitzicht
1966	*The water table had declined to 160 m below ground level*
	The largest of 8 sinkholes was 125 m across and 50 m deep in open countryside
	Over the past 4 years, 454 houses had been deomolished or evacuated
Bank Compartment	
1968	*The West Dreifontein mine was flooded where workings had breached the Bank dyke so that they were beneath the undrained karst aquifer in the Bank compartment*
1969	*De-watering was largely completed in the first 6 months*
1970	Bank township was evacuated in January, the road was closed and the railway made freight-only, after large compaction sinkholes developed and soil voids were found
1971	*The water table had declined to 300 m below ground level*
1975	The railway through Bank was reopened to passenger traffic; 8 days later a train was derailed into a sinkhole 20 m wide and 7 m deep

Figure 8.11. Road signs that warn of the ongoing hazard to a road across Alabama's Dry Valley, where sinkholes are induced in the soil by de-watering at a nearby limestone mine. TW.

down and still above rockhead, but the dropout occurred just a few months after a quarry 2 km away commenced working on a new lower level (Sowers, 1996).

Sinkholes may also be induced by de-watering on a very much smaller scale. In southern Ireland, a quarry worked limestone just 6 m deep beneath gravel soils 1–2.5 m thick (Beese and Creed, 1995). While pumping kept the excavation dry in a cone of depression, thirteen sinkholes, each up to 1.6 m across, developed along 200 m of nearby road where suffosion was induced as the water table declined below rockhead. Subsequently the quarry was flooded to form a landscaped lake, and no more sinkholes developed, even while heavy construction traffic was working on the covered karst. Dry working of the shallow quarries in the Ukranian gypsum has only lowered the water table by about 15 m, but the cavernous and nearly horizontal gypsum has been drained over distances of many kilometres (Klimchouk and Adrejchuk, 2003). A consequence has been the development of numerous new sinkholes, both subsidence sinkholes due to accelerated suffosion and also caprock sinkholes due to loss of hydrostatic support when the cave passages were drained. Sinkholes can also be induced by localised drainage into a

Figure 8.12. A dropout sinkhole 5 m deep between the railway tracks at Tai′an, eastern China, one of 24 sinkholes induced over a period of five years by water table decline in response in groundwater pumping.
Photo: Guo Xizhe.

tunnel under construction in karst; when the Nanting railway tunnel was being driven for 6 km in eastern China, 40 new sinkholes developed in the soil cover over the limestone that was draining into the tunnel (Guo, 1991).

China has an extraordinary record of inducing more than 30,000 sinkholes by mine de-watering, largely because its very productive coal seams are interbedded and capped by cavernous limestone and gypsum, notably in the provinces of Hunan and Guangdong (Yuan, 1987; Xu and Zhao, 1988). Numerous records prove beyond all doubt the correlation between de-watering the mines and development of the subsidence sinkholes that are now accepted as inevitable side-effects of safe mining beneath soil-covered karst (Figure 8.12). Induced sinkholes have damaged farmland, houses and infrastructure, and effects reach far beyond the mines. In Hunan, pumping at the Enkou mines induced 6,100 sinkholes across an area of 25 km^2, followed by another 5,800 sinkholes as increased de-watering widened the cone of depression beneath previously unaffected farmland (Li *et al.*, 1993). Also in Hunan, 7,290 new sinkholes were spread across 74 km^2 of farmland around the de-watered Liansao mines. Sinkholes that have captured surface river flows have directly caused disastrous inrushes of mud and water deep underground, so that some mines have had to be abandoned in Guangxi, in Guangdong and in Hubei (Chen, 1988). Remedial works have concentrated on minimising water flow into the mines, as it is recognised that predicting and pre-treating new sinkholes at the surface is next to impossible (Li and Zhou, 1999). Some sites have lent themselves to deep tunnels draining the mines at depth while the shallow karst is left relatively undrained, but others have required major grouting programmes, either sealing entry fissures within the mines or isolating the de-watered mines behind major grout curtains.

Though collapse of a cave's rock roof may be induced when buoyant support is lost due to drainage, there does not appear to be any recorded case where this is considered to have occurred due to artificial decline of the water table in limestone karst. The effects of water table decline have been limited to the movement of soils, and to the compaction of soft and weak limestones at some locations.

8.3 SINKHOLES INDUCED BY GROUND DISTURBANCE

Construction works inevitably involve ground disturbance, but the two principal activities by which sinkholes are induced are thinning of the soil cover – and removal of plant cover both of which increase potential rainwater infiltration and therefore increase potential suffosion. Mere access by construction traffic, which involves the stripping of topsoil and removal or destruction of the original vegetation, can be enough to initiate new sinkholes (Figure 5.15). These are most likely to be subsidence sinkholes, but may form over compacted or suffused fill in buried sinkholes. A large sinkhole developed in bare soil between the foundation trenches for a warehouse in Alabama (Newton and Hyde, 1971), while sinkholes clustered in a part of Shelby County, Alabama, were mostly in a zone where trees had been clear-felled or were close to infrastructure lines (Newton, 1987). Infiltration and suffosion increases in a soil cover that is reduced across karst, so that a road construction site in Ireland was broken by four small subsidence sinkholes after a shallow cut was excavated during a dry summer in soils 7 m thick over limestone (Beese and Creed, 1995).

Sinkhole dropouts can occur when soil arches fail due to vibration, and five new sinkholes added to the destruction wreaked by China's Tangshan earthquake in 1976. During explorations for water resources at Liangwu, in China's Guangxi karst, 157 sinkholes were triggered by blasting during engineering works, and the village had to be abandoned (Yuan, 1987). Vibrations from construction traffic could conceivably induce sinkholes in unstable soil cover, but their effects appear to be masked by the greater influence imposed by drainage modifications. At least three sinkhole collapses in Florida occurred when cars were driven over them (Metcalfe and Hall, 1984), but the events marked only the failures of the road surface under vehicle loading, after the sinkholes had been initiated previously with no influence of vehicle loading or vibration. Similarly, built structures are unlikely to induce subsidence sinkholes by their imposed loads on soil profiles. Instead, structures may cause loading compaction of the soils, so that associated ground deformation fractures buried pipelines, when escaping water may induce suffosional loss of the soil into underlying bedrock fissures. This secondary impact of broken drains under structural loading is the main cause of house damage on soft clay soils, and can be even more disastrous in soils that overlie karst.

Direct filling of an old sinkhole imposes a modest load, but creates a far more serious hazard by encouraging development across it. Within the karst lowlands of Pennsylvania, a sinkhole 60 m across was filled with rubbish and dead vegetation until the ground was level. This appears to have been a caprock sinkhole developed through a weak shale cover and already partially filled with natural soil (Figure 11.9). The site was then lost in the middle of a corn field. About 20 years later, the housing estates of Macungie extended across the farmland, and a road was built directly over the old and forgotten sinkhole. A few years after that, the sinkhole was reactivated, probably by leaking sewer and pipe lines, and the road was lost in a hole 26 m wide and 12 m deep (Dougherty and Perlow, 1988). Though the Macungie sinkhole was casually filled with rubbish, there is a direct need for planning legislation that bans the intentional but uncontrolled infilling of sinkholes by a developer who is long gone by the time that the almost inevitable subsequent collapse occurs. Some states and counties in eastern U.S.A. have such ordinances, but many have no protection.

8.4 THE AVOIDABLE GEOHAZARD OF INDUCED SINKHOLES

A college in Georgia, U.S.A., leased out part of its valley-floor land for a limestone quarry. The bedrock had 3–6 m of soil cover and the water table stood within the soil profile. Deepening and draining of the quarry depressed the water table, and subsidence sinkholes started to develop in an area expanding towards the college that was 750 m away (Sowers, 1996). However the college's royalties from the quarry were considered to outweigh the risk to their buildings. So quarrying continued with the proviso that de-watering was restricted to just the currently active part of the quarry (though this constraint would have minimal impact in a karstic limestone without installation of major grout curtains). At the same time, a small lake in the college grounds was enlarged. It almost immediately drained through new sinkholes, and the new section was subsequently filled in. By imposing both water table decline and also new surface water, this site was doomed to be peppered with sinkholes.

The Georgia site demonstrated everything that was inappropriate in a karst, and its subsequent problems were totally avoidable. However, the march of civilisation and its infrastructure expansion inevitably lead to disturbance of the natural environment, which is in so many ways all that is needed to induce new sinkholes in soil-mantled karst. In these cases, the potential costs of sinkhole damage must feature on the balance sheet for budgeting site development on karst.

Even though mine and quarry de-watering clearly has massive impacts on sinkhole development in soil-covered karst, the lateral extent of the zone of influence may be open to debate at any one site until the complexities of the local karst hydrology are proven by dye-tracing, and are mapped and fully understood (see Box 8.2). Debate may be significantly protracted where new sinkholes can have serious legal and economic implications. At many karst sites, sinkhole damage may

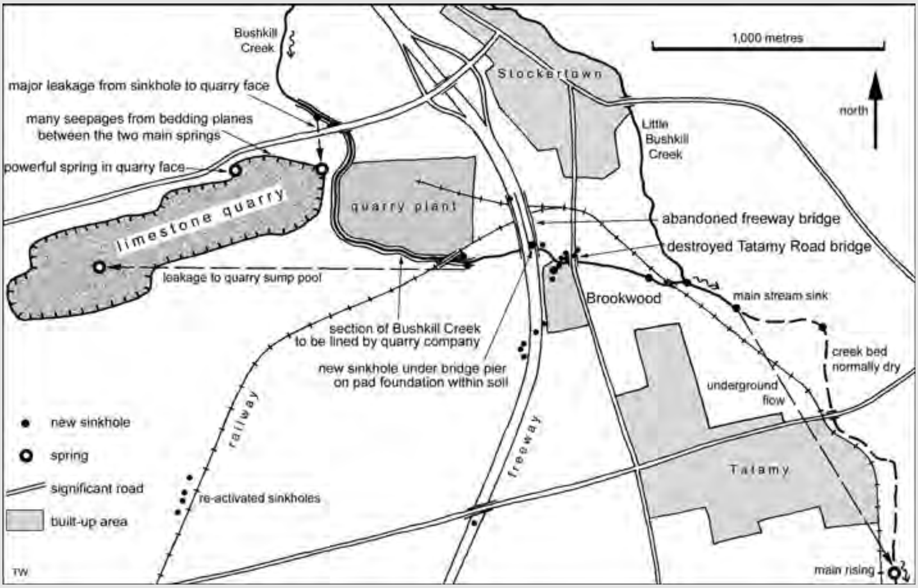

Figure 8.2.1. Outline map of the recent sinkholes and related subsidence features in the Bushkill Creek area, Pennsylvania; there are many other smaller and/or ephemeral sinkholes along the entire length of the creek covered by this map.

Figure 8.2.2. The bridge that carried Tatamy Road over Bushkill Creek, destroyed by an expanding and ever-changing cluster of sinkholes.
TW.

BOX 8.2. DISPUTED SINKHOLE ORIGINS IN PENNSYLVANIA

In the karst of eastern Pennsylvania, north-east of Allentown, a cluster of new sinkholes has destroyed road bridges and threatens a small rural community. Remedial action is delayed because the local karst hydrogeology is not fully understood and consequently the exact processes that induced the new crop of sinkholes are open to debate.

A nearby limestone quarry stays dry by pumping out water at a mean rate of $2\,m^3/s$. The quarry floor is about 50 m below the level of the adjacent small river, Bushkill Creek (Figure 8.2.1), which now loses all its water into its bed until it is replenished by the quarry pumping outfall. Water pours out of at least two open cave passages in the quarry wall, and also seeps out along certain bedding planes. A cone of depression (mapped at $5.6\,km^2$ but probably now larger) created by the pumping has caused a number of sinkholes to appear around the quarry. One sinkhole in the river bed downstream of the quarry diverted a major flow into the far end of the quarry, and was soon sealed, as the quarry pumping was merely re-circulating the same water. The quarry company plans to line about 1,200 m of the river bed to prevent new leakages, but 80 sinkholes have been recorded along 2.5 km of the Bushkill Creek.

Of greater concern are the more distant new sinkholes that started to develop in October 2000, in and around the Brookwood community beside the river a kilometre downstream of the quarry (Figure 8.2.1). Sinkholes opened in the river bed, damaging the Tatamy Road bridge and also removing much of the garden of one of the houses (Perlow, 2003). These initial sinkholes were filled with soil and rock but more have developed since. Three years later, the eastern abutment of the road bridge had been totally destroyed by an ever-changing cluster of four sinkholes adjacent to each other (Figure 8.2.2). The bridge originally stood on pads founded in the alluvial gravel that has since been washed into the limestone. An impermeable liner for more of the downstream river bed is being considered to provide long-term stability for a new bridge. No homes have yet been destroyed, but some residents have moved out because they have justifiably lost confidence as more sinkholes have developed around them.

In 2001, the abutment of the railway bridge over Bushkill Creek close to the quarry, was rebuilt after it was lost into a sinkhole. A freeway, that passes between Tatamy and the quarry, crosses the creek on two large bridges. Early in 2004, the east-side bridge (carrying the north-bound highway) sank 150 mm when a subsidence sinkhole developed under one of its southern piers. Nearly $100\,m^3$ of concrete was poured into the hole with no effect, except that the pier sank further and the bridge was abandoned; it had stood on pad foundations within the soil profile, and was therefore destroyed by a single subsidence sinkhole. At a cost of $6 million, a replacement bridge on deeper foundations was opened later in the year. Just 15 m to the west, the southbound bridge rested on piers that stood partly on bedrock limestone, but one of them was also damaged by subsidence later in 2004. Probing revealed depths to bedrock of 9–42 m, and this bridge was also closed for rebuilding on deeper footings.

It would seem reasonable to ascribe these new sinkholes to induced development within the quarry's cone of depression, but this is currently in dispute. Increased urbanisation since the 1970s, the realignment of stream channels, and even the construction of the freeway, have been proposed as causes of (or contributors to) the rash of new sinkholes. The river flow is lost into various sinkholes along, around and downstream of the road and freeway bridges, so that the channel becomes dry, and stays so as far as risings 2 km further downstream. The lower part of this underground stream channel may lie outside any area of water table decline around the quarry, but the destination of water sinking nearer to Brookwood is currently unknown. More data on levels of the water table are needed to determine the cause of the sinkholes. A dye trace showing that water from the Brookwood sinkholes flows back to the quarry would point a finger at the quarry pumping, though a negative result would still be inconclusive.

have to be budgeted as an essential cost of quarrying or mining. This could compare to the costs of obligatory repairs to subsidence damage that were accepted at 10–15% of the total production costs by longwall mining for coal in Britain. This could preclude quarry or mine development near to high-value sites, in the same way that Britain's deep coal mines could not afford to work beneath urban areas. It is notable that, since the case was taken through the courts, Hershey chocolate is still produced in Pennsylvania, while the local quarries and mines have closed. Widespread damage from induced sinkholes may have been tolerated by the remote officialdom that once made the decisions in China, but values have since changed, where fields once worked by peasant farmers have been replaced by new industrial plants within an expanding enterprise economy. This is reflected in the massive research effort by China's industry, academia and government, which has had considerable success in understanding and, more significantly, containing or reducing sinkhole damage (Li and Zhou, 1999; Lei *et al.*, 2001).

References

Abdullah, W.A. and Mollah, M.A. (1999) Detection and treatment of karst cavities in Kuwait. In: Beck, B.F., Pettit, A.J. and Herring, J.G. (eds), *Hydrogeology and Engineering Geology of Sinkholes and Karst*, pp. 123–127. Balkema: Rotterdam.

Abkemeier, T.J. and Stephenson, R.W. (2003) Remediation of a sinkhole induced by quarrying. *American Society Civil Engineers Geotechnical Special Publication* 122, 605–614.

Alexander, E.C. and Book, P.R. (1984) Altura Minnesota lagoon collapses. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 311–318. Balkema: Rotterdam.

Aley, T.J., Williams, J.H. and Massello, J.W. (1972) Groundwater contamination and sinkhole collapse induced by leaky impoundments in soluble rock terrain. *Missouri Geological Survey Engineering Geology Series* 5, 32pp.

Allred, K. and Allred, C. (1997) Development and morphology of Kazumura Cave, Hawaii. *Journal Cave Karst Studies*, **59**, 67–80.

Andrejchuk, V. (2002) Collapse above the world's largest potash mine, Ural, Russia. *International Journal Speleology*, **31**, 137–158.

Arrington, D.V. and Lindquist, R.C. (1987) Thickly mantled karst of the Interlachen, Florida, area. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 31–39. Balkema: Rotterdam.

Arthur, J.C.R., Haas, C., Shilston, D.T. and Waltham, A.C. (2004). The Sivas karst, from terrain evaluation to ground truth. *Proceedings International Conference on Terrain and Geohazard Challenges Facing Onshore Oil and Gas Pipelines*. Thomas Telford: London.

Asef, M.R., Reddish, D.J. and Lloyd, P.W. (2000) Rock-support interaction analysis based on numerical modelling. *Geotechnical Geological Engineering*, **18**, 23–37.

A.S.T.M. (1998) *Standard test method for mechanical cone penetration tests of soil*. Designation: D3441, Volume 04.08, Soil and Rock. American Society for Testing and Materials: Philadelphia, 5pp.

A.S.T.M. (1999a) *Standard guide for selecting surface geophysical methods*. Designation D6429. American Society for Testing and Materials: Philadelphia, 11pp.

A.S.T.M. (1999b) *Standard test method for penetration test and split-barrel sampling of soils*. Designation: D1586, Volume 04.08, Soil and Rock. American Society for Testing and Materials: Philadelphia, 5pp.

Atapour, H. and Aftabi, A. (2002) Geomorphological, geochemical and geo-environmental aspects of karstification in the urban areas of Kerman city, southeastern Iran. *Environmental Geology*, **42**, 783–792.

Atkinson, T.C. and Smith, D.I. (1974) Rapid groundwater flow in fissures in chalk. *Quarterly Journal Engineering Geology*, **7**, 197–205.

Bahtijarevic, A. (1989) Sinkhole density of the Forest City Quadrangle. In Beck, B.F. (ed.) *Engineering and Environmental Impacts of Sinkholes and Karst*, pp. 75–82. Balkema: Rotterdam.

Balázs, D. (1973) Comparative investigation of karst waters in the Pacific. *Proceedings 6th International Congress Speleology*, **3**, 23–32. Academia: Prague.

Barner, W.L. (1999) Comparison of stormwater management in a karst terrain in Springfield, Missouri – case histories. *Engineering Geology*, **52**, 105–112.

Barton, N., Lien, R. and Lunde, J. (1974) Engineering classification of rock masses for tunnel design. *Rock Mechanics*, **6**, 189–236.

Baumgardner, R.W. Jr., Hoadley, A.D. and Goldstein, A.G. (1982) Formation of the Wink Sink, a salt dissolution and collapse feature, Winkler County, Texas. *University of Texas at Austin, Bureau of Economic Geology, Report of Investigations* 114, 38pp.

Beck, B.F. (1986) A generalized genetic framework for the development of sinkholes and karst in Florida, USA. *Environmental Geology Water Science*, **8**, 5–18.

Beck, B.F. (1999) There is no such thing as karstish – an introduction. *Engineering Geology*, **52**, 1–2.

Beck, B.F. (2000) Report on Italian sinkhole conference. *KWI Conduit*, **8**(1): `www.karstwaters.org`

Beck, B.F. and Sinclair, W.C. (1986) *Sinkholes in Florida: An introduction*. Florida Sinkhole Research Institute Report 85-86-4, 16pp.

Beddows, P.A. (2004) Yucatan phreas, Mexico. In: Gunn. J. (ed.), *Encyclopedia of Caves and Karst Science*, pp. 786–788. Fitzroy Dearborn: New York.

Bednar, D. and Aley, T. (2001) Groundwater dye tracing: An effective tool to use during the highway development process to avoid or minimize impacts to karst groundwater resources. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 201–207. Balkema: Lisse.

Beese, A.P. and Creed, M.J. (1995) A database for subsidence sinkholes near Cork, Ireland. *Danish Geotechnical Society Bulletin*, **11**, 4.19–4.24.

Beggs, T.F. and Ruth, B.E. (1984) Factors affecting the collapse of cavities. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 183–188. Balkema: Rotterdam.

Bekey, T.J. and Rinne, R.W. (1975) One hundred foot wide lava tube complicates hospital foundation design. *Proceedings Annual Engineering Geology and Soils Engineering Symposium, Boise, Idaho*, **13**, 75–83.

Bell, F.G. (1975) Salt and subsidence in Cheshire, England. *Engineering Geology*, **9**, 237–247.

Bell, F.G. (1992) Salt mining and associated subsidence in mid-Cheshire, England, and its influence on planning. *Bulletin Association Engineering Geologists*, **29**, 371–386.

Bell, F.G. (1993) *Engineering Treatment of Soils*, 346pp. Spon: London.

Bell, F.G. and Coulthard, J.M. (1990) Stabilization of clay soils with lime. *Municipal Engineer*, **7**, 125–140.

Bell, F.G., Cripps, J.C., Culshaw, M.G. and O'Hara, M. (1987) Aspects of geology in planning. *Geological Society Engineering Geology Special Publication*, **4**, 1–38.

Bell, F.G., Culshaw, M.G., Moorlock, B.S.P. and Cripps, J.C. (1992) Subsidence and ground movements in chalk. *Bulletin International Association Engineering Geology*, **45**, 75–82.

Bell, F.G., Culshaw, M.G. and Cripps, J.C. (1999) A review of selected engineering geological characteristics of English chalk. *Engineering Geology*, **54**, 237–269.

Bengtsson, T.O. (1987) The hydrologic effects from intense ground-water pumpage in east-central Hillsborough County, Florida. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 109–114. Balkema: Rotterdam.

Bennett, D. (1997) Finding a foothold. *New Civil Engineer*, December 4, 24–25.

Benson, R.C. and Kaufmann, R.D. (2001) Characterization of a highway sinkhole within the gypsum karst of Michigan. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 103–112. Balkema: Lisse.

Benson R.C. and La Fountain, L.J. (1984) Evaluation of subsidence or collapse potential due to subsurface cavities. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 210–215. Balkema: Rotterdam.

Benson, R.C. and Yuhr, L.B. (1987) Assessment and long term monitoring of localized subsidence using ground penetrating radar. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 161–169. Balkema: Rotterdam.

Benson, R.C., Yuhr, L. and Kaufmann, R.D. (2003) Assessing the risk of karst subsidence and collapse. *American Society Civil Engineers Geotechnical Special Publication* 122, 31–39.

Bergado, D.T. and Selvanayagam, A.N. (1987) Pile foundation problems in Kuala Lumpur Limestone, Malaysia. *Quarterly Journal Engineering Geology*, **20**, 159–175.

Bieniawski, Z.T. (1973) Engineering classification of jointed rock masses. *Transactions South African Institute Civil Engineers*, **15**, 335–343.

Bing, Z. and Greenhalgh, S.A. (2000) Cross-hole resistivity tomography using different electrode configurations. *Geophysical Prospecting*, **48**, 887–912.

Bishop, I., Styles, P., Emsley, S.J. and Ferguson, N.S. (1997) The detection of cavities using the microgravity technique: Case histories from mining and karstic environments. *Geological Society Special Publication*, **12**, 155–168.

Bloomberg, D., Upchurch, S.B., Hayden, M.L. and Williams, R.C. (1988) Cone penetrometer exploration of sinkholes: stratigraphy and soil properties. *Environmental Geology Water Science*, **12**, 99–105.

Bögli, A. (1960) Kalkosung und Karrenbildung. *Zeitschrift Geomorphologie*, Supplement 2, 4–21.

Bögli, A. (1964) Mischungskorrosion: Ein Beitrag zum Verkarstungsproblem. *Erdkunde*, **18**(2), 83–92.

Bögli, A. (1980) *Karst Hydrology and Physical Speleology*, 284pp. Springer-Verlag: Berlin.

Bonaparte, R. and Berg, R.R. (1987) The use of geosynthetics to support roadways over sinkhole prone areas. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 437–445. Balkema: Rotterdam.

Bosak, P., Knez, M., Otrubova, D., Pruner, P., Slabe, T. and Vendohova, D. (2000). Paleomagnetic research of fossil cave in the highway construction at Kozina (Slovenia). *Acta Carsologica*, **29**(2), 15–33.

Božičević, A., Budanur, H, Nonveiller, E. and Pavlin, B. (1981) The Keban dam foundation on karstified limestone – a case history. *Bulletin International Association Engineering Geology* 24, 45–51.

Branston, M.W. and Styles, P. (2003) The application of time-lapse microgravity for the investigation and monitoring of mining subsidence. *Quarterly Journal Engineering Geology Hydrogeology*, **36**, 231–244.

Brink, A.B.A. (1979) *Engineering Geology of Southern Africa* (Vol. 1), 319pp. Building Publications: Pretoria.

British Standards (1986) *BS8004, British standard code of practice for foundations*, 160pp. British Standards Institution: London.

British Standards (1995) *BS8006, Code of practice for strengthened/reinforced soils and other fills*, 171pp. British Standards Institution: London.

British Standards (1999) *BS5930, British standard code of practice for site investigations*, 204pp. British Standards Institution, London.

Brook, G.A. and Allison, T.L. (1986) Fracture mapping and ground subsidence susceptibility modelling in covered karst terrain: The example of Dougherty County, Georgia. *International Association Hydrological Sciences*, **151**, 595–606.

Bruce, D.A. (1994) Trends and developments in American grouting practice. In: Bell, F.G. (ed.), *Grouting in the Ground*, pp. 573–589. Thomas Telford: London.

Bruce, D.A. (2003) Sealing of massive water inflows through karst by grouting: Principles and practice. *American Society Civil Engineers Geotechnical Special Publication* 122, 615–626.

Brune, G. (1965) Anhydrite and gypsum problems in engineering geology. *Bulletin Association Engineering Geologists*, **3**, 26–38.

Budetta, G. and Del Negro, C. (1995) Magnetic field changes on lava flow to detect lava tubes. *Journal Volcanology Geothermal Research*, **65**, 237–248.

Bull, P.A. (1980) The antiquity of caves and dolines in the British Isles. *Zeitschrift Geomorphologie*, Supplement 36, 217–232.

Burland, J.B., Hancock, R.J. and May, J. (1983) A case history of a foundation problem on soft chalk. *Géotechnique*, **33**, 385–395.

Burnett, A.D. and Epps, R.J. (1979) The engineering geological description of the carbonate suite rocks and soils. *Ground Engineering*, **12**(2), 41–48.

Buttrick, D.B. and van Schalkwyk, A. (1995) The method of scenario supposition for stability evaluation of sites of dolomitic land in South Africa. *Journal South African Institution Civil Engineers*, **37**, 9–14.

Buttrick, D.B., van Schalkwyk, A., Kleywegt, R.J. and Watermeyer, R.B. (2001) Proposed method for dolomite land hazard and risk assessment in South Africa. *Journal South African Institution Civil Engineering*, **43**(2), 27–36.

Calembert, L. (1975) Engineering geological problems in karstic regions. *Bulletin International Association Engineering Geology*, **12**, 39–82.

Canace, R. and Dalton, R. (1984) A geological survey's cooperative approach to analysing and remedying a sinkhole related disaster in an urban environment. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 343–348. Balkema: Rotterdam.

Cai, G. (1991) Karst environmental problems in China. In: Yuan, D. (ed.), *Karst of China*, pp. 136–157. Geological Publishing House: Beijing.

CH2MHill (2003) *Report to the Federal Energy Regulatory Commission on failure of the Swift No. 2 power canal embankment*, 520pp (on CD). Cowlitz County Public Utility District: Longview.

Chabert, C. (1981) *Les Grandes Cavités Françaises*, 154pp. Fédération Française de Spéléologie: Paris.

Chen G. (1994) Prediction of covered karst halls. *Proceedings 7th International Association Engineering Geology Congress*, pp. 1841–1845. Balkema: Rotterdam.

Chen J. (1988) Karst collapses in cities and mining areas, China. *Environmental Geology Water Science*, **12**, 29–35.

Chen J. and Beck, B.F. (1989) Qualitative modelling of the cover-collapse process. In: Beck, B.F. (ed.), *Engineering and Environmental Impacts of Sinkholes and Karst*, pp. 98–95. Balkema: Rotterdam.

Christiansen, E.A. (1971) Geology of the Crater Lake collapse structure in southeastern Saskatchewan. *Canadian Journal Earth Sciences*, **8**, 1505–1513.

Clark, R.G., Gutmanis, J.C., Furley, A.E. and Jordan, P.G. (1981) Engineering geology for a major industrial complex at Aughinish Island, Co. Limerick, Ireland. *Quarterly Journal Engineering Geology*, **14**, 231–239.

Clayton, C.R.I. (1983) The influence of diagenesis on some index properties of chalk in England. *Géotechnique*, **33**, 225–241.

Conrad, G., Geze, B. and Paloc, H. (1967) Observations sur des phenomenes karstique at pseudo-karstique du Sahara. *Revue Géographie Physique Géologie Dynamique* (Series 2), **9**(5), 357–370.

Cooley, T. (2001) Geological and geotechnical context of cover collapse and subsidence in mid-continent US clay-mantled karst. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 19–24. Balkema: Lisse.

Cooley, T. (2002) Engineering approaches to conditions created by a combination of karst and faulting at a hospital in Birmingham, Alabama. *Engineering Geology*, **65**, 197–204.

Cooper, A.H. (1986) Foundered strata and subsidence resulting from the dissolution of Permian gypsum in the Ripon and Bedale areas, North Yorkshire. *Geological Society Special Publication* 22, 127–139.

Cooper, A.H. (1995) Subsidence hazards due to the dissolution of Permian gypsum in England: investigation and remediation. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 23–29. Balkema: Rotterdam.

Cooper, A.H. (1998) Subsidence hazards caused by the dissolution of Permian gypsum in England: geology, investigation and remediation. *Geological Society Engineering Group Special Publication* 15, 265–275.

Cooper, A.H. (1999). Description, interpretation and assessment of subsidence features at Ure Bank Terrace, Ripon, N. Yorkshire. *British Geological Survey Technical Report WA/99/09R*.

Cooper, A.H. and Saunders, J.M. (2002) Road and bridge construction across gypsum karst in England. *Engineering Geology*, **65**, 217–223.

Cooper, A.H. and Waltham, A.C. (1999) Subsidence caused by gypsum dissolution at Ripon, North Yorkshire. *Quarterly Journal Engineering Geology*, **32**, 305–310.

Cooper, A.H., Farrant, A.R., Adlam, K.A.M. and Walsby, J.C. (2001) The development of a national Geographic Information System (GIS) for British karst geohazards and risk assessment. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 125–130. Balkema: Lisse.

Coussens, R.R.M. and Garrett, W.S. (1970) The flooding at West Dreifontein mine, South Africa. *Proceedings 9th Commonwealth Mining Metallurgical Congress*. Institution Mining Metallurgy: London, **1**, 931–972.

Crawford, N.C. (1984) Sinkhole flooding associated with urban development upon karst terrain, Bowling Green, Kentucky. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 283–292. Balkema: Rotterdam.

Crawford, N.C. (2001) Environmental problems associated with urban development upon karst, Bowling Green, Kentucky. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 397–424. Balkema: Lisse.

Crawford, N.C. (2003) Karst hydrogeological investigation for proposed Kentucky trimodal transpark. *American Society Civil Engineers Geotechnical Special Publication* 122, 385–403.

Crawford, N.C. and Groves, C.G. (1995) Sinkhole collapse and ground water contamination problems resulting from storm water drainage wells on karst terrain. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 257–264. Balkema: Rotterdam.

Crawford, N.C., and Ulmer, C.S. (1993) Groundwater investigations to determine contaminant movement in the karst aquifers of the Lewisburg, Tennessee area. In: Beck, B.F. (ed.), *Applied Karst Geology*, pp. 79–87. Balkema: Rotterdam.

Crawford, N.C., Lewis, M.A., Winter, S.A. and Webster, J.A. (1999) Microgravity techniques for subsurface investigations of sinkhole collapses and for detection of groundwater flow paths through karst aquifers. In: Beck, B.F., Pettit, A.J. and Herring, J.G. (eds), *Hydrogeology and Engineering Geology of Sinkholes and Karst*, pp. 203–218. Balkema: Rotterdam.

Culshaw, M. G. and Kelk, B. (1994) A national geo-hazard information system for the UK insurance industry – the development of a commercial product in a geological survey environment. In: *Proceedings 1st European Congress on Regional Geological Cartography and Information Systems, Bologna, Italy, 4, Paper 111, 3pp.*

Culshaw, M.G. and Waltham, A.C. (1987) Natural and artificial cavities as ground engineering hazards. *Quarterly Journal Engineering Geology*, **20**, 139–150.

Currin, W.E. and Barfus, B.L. (1989) Sinkhole distribution and characteristics in Pasco County, Florida. In: Beck, B.F. (ed.), *Engineering and Environmental Impacts of Sinkholes and Karst*, pp. 97–106. Balkema: Rotterdam.

Cuss, R.J. and Beamish, D. (2002) Ground penetrating radar and ground conductivity investigation of fissuring of the A690 road in Houghton-le-Spring. *British Geological Survey Report IR/02/142.*

Cvijic, J. (1893) Das Karstphaenomen. *Geographische Abhandlungen Wien*, **5**(3), 218–329.

Daily, W. and Ramirez, A.L. (1999) Electrical imaging of engineered hydraulic barriers. *Geophysics*, **65**, 83–94.

Daniel, A.J. and Styles, P. (1997) Topographic accessibility and the tectonic interpretation of gravity data. *Geophysical Prospecting*, **45**(6), 1013–1026.

Davies, W.E. (1951) Mechanics of cavern breakdown. *Bulletin National Speleological Society*, **13**, 36–43.

Davis, S.T. (1997) Interstate assessment of governmental regulations on landfills in karst areas. In: Beck, B.F. and Stephenson, J.B. (eds), *Engineering Geology and Hydrogeology of Karst Terrains*, pp. 433–438. Balkema: Rotterdam.

Day, M.J. (2003) An assessment of karstic collapse hazards at Mount Rooser, Ewarton, Jamaica. *American Society Civil Engineers Geotechnical Special Publication* 122, 40–49.

De Bruyn, I.A. and Bell, F.G. (2001) The occurrence of sinkholes and subsidence depressions in the Far West Rand and Gauteng Province, South Africa, and their engineering implications. *Environmental Engineering Geoscience*, **7**, 281–295.

Derbyshire, E., Meng X. and Dijkstra, T.A. (eds) (2000) *Landslides In The Thick Loess Terrain of North-west China*, 288pp. Wiley: New York.

Destephen, R.A. and Wargo, R.H. (1992) Foundation design in karst terrain. *Bulletin Association Engineering Geologists*, **29**, 165–175.

Devilbiss, T.S. (1995) A local government approach to mitigating impacts of karst. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 499–504. Balkema: Rotterdam.

Dogan, U. and Cicek, I. (2002) Occurrence of cover-collapse sinkholes in the May Dam reservoir area (Konya, Turkey). *Cave Karst Science*, **29**, 111–116.

Dotson, D.W. and Tarquinio, F.S. (2003) A creative solution to problems with foundation construction in karst. *American Society Civil Engineers Geotechnical Special Publication* 122, 627–634.

Dougherty, P.H. (1991). Spatial-temporal characteristics of karst subsidence in the Lehigh Valley of Pennsylvania. In Kastning, E.H. and Kastning, K.M. (eds), *Appalachian Karst*, pp. 138–145. National Speleological Society: Huntsville.

Dougherty, P.H. and Perlow, M. (1988) The Macungie sinkhole, Lehigh Valley, Pennsylvania: cause and repair. *Environmental Geology Water Science*, **12**, 89–98.

Dragoni, M., Piombo, A. and Tallarico, A. (1995) A model for the formation of lava tubes by roofing over a channel. *Journal Geophysical Research*, **100**, 8435–8447.

Drew, D.P. (1972) Geomorphology of the Big Muddy Valley area, southern Saskatchewan, with special reference to the occurrence of piping. *Proceedings Southern Prairies Symposium, International Geographical Union Conference, Montreal, 197–212*.

Drew, D. (1985) *Karst Processes and Landforms*, 240pp. Macmillan: London.

Dreybrodt, W. (2000) Equilibrium chemistry of karst water in limestone terranes. In: Klimchouk, A.B., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (eds), *Speleogenesis: Evolution of Karst Aquifers*, pp. 126–135. National Speleological Society: Huntsville.

Dreybrodt, W. and Eisenlohr, L. (2000) Limestone dissolution rates in karst environments. In: Klimchouk, A.B., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (eds), *Speleogenesis: Evolution of Karst Aquifers*, pp. 136–148. National Speleological Society: Huntsville.

Dreybrodt, W., Romanov, D. and Gabrovsek, F. (2002) Karstification below dam sites: A model of increasing leakage from reservoirs. *Environmental Geology*, **42**, 519–524.

Drumm, E.C., Kane, W.F. and Yoon, C.J. (1990) Application of limit plasticity to the stability of sinkholes. *Engineering Geology*, **29**, 213–225.

Dunham, R.J. (1962) Classification of carbonate rocks. *American Association Petroleum Geologists Memoir* 1, 108–121.

Eck, W. and Redfield, R.C. (1965) Engineering geology problems at Sanford Dam, Borger, Texas. *Bulletin Association Engineering Geologists*, **3**, 15–25.

Edmonds, C.N., Green, C.P. and Higginbottom, I.E. (1987) Subsidence hazard prediction for limestone terrains, as applied to the English Cretaceous chalk. *Geological Society Engineering Geology Special Publication* 4, 283–293.

Edmonds, C.N. (1988) Induced subsurface movements associated with the presence of natural and artificial underground openings in areas underlain by Cretaceous Chalk. *Geological Society Engineering Geology Special Publication* 5, 205–214.

Edmonds, C.N. (2001) Predicting natural cavities in chalk. *Geological Society Engineering Geology Special Publication* 18, 29–38.

Einstein, H.H. (1997) Landslide risk systematic approaches to assessment and management. In: Cruden, D. M. and Fell, R. (eds), *Proceedings International Workshop Landslide Risk Assessment, Honolulu*, pp. 25–50. Balkema: Rotterdam.

Erwin, J.W. and Brown, R.A. (1988) Karstic foundation problems Sunny Point Railroad. *American Society of Civil Engineers Geotechnical Special Publication* 14, 74–85.

Fell, R. and Hartford, D. (1997) Landslide risk management. In: Cruden, D. M. and Fell, R. (eds), *Proceedings International Workshop Landslide Risk Assessment, Honolulu*, pp. 51–109. Balkema: Rotterdam.

Field, M.S. (2002) A lexicon of cave and karst terminology with special reference to environmental karst hydrology. http://www.speleogenesis.info/glossary/

Fischer, J.A. (1999) Limestone ordinances of New Jersey and Pennsylvania: A practioner's experiences. *Engineering Geology*, **52**, 61–66.

Fischer, J.A. and Lechner, H. (1989) A karst ordinance – Clinton Township, New Jersey. In: Beck, B.F. (ed.), *Engineering and Environmental Impacts of Sinkholes and Karst*, pp. 357–361. Balkema: Rotterdam.

Fischer, J.A. and Fischer, J.J. (1995) Karst site remediation grouting. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 325–330. Balkema: Rotterdam.

Folk, R.L. (1962) Spectral subdivision of limestone types. *American Association Petroleum Geologists Memoir* 1, 62–84.

Folk, R.L. (1973) Carbonate petrology in the post-Sorbian age. In: Ginsburg, R.N. (ed.), *Evolving Concepts in Sedimentology*. Johns Hopkins University Press: Baltimore.

Fookes, P.G. (1997) Geology for engineers: The geological model, prediction and performance. *Quarterly Journal Engineering Geology*, **30**, 293–424.

Foose, R.M. (1953) Ground-water behaviour in the Hershey Valley, Pennsylvania. *Bulletin Geological Society America*, **64**, 623–645.

Foose, R.M. (1968) Surface subsidence and collapse caused by ground water withdrawal in carbonate rock areas. *Proceedings 23rd International Geological Congress*, **12**, 155–166.

Foose, R.M. and Humphreville, J.A. (1979) Engineering geological approaches to foundations in the karst terrain of the Hershey Valley. *Bulletin Association Engineering Geologists*, **16**, 355–381.

Ford, D.C. and Williams, P.F. (1989) *Karst Geomorphology and Hydrology*, 601pp. Unwin Hyman: London.

Ford, D.C. and Williams, P.F. (2005) *Karst Hydrogeology and Geomorphology*. Wiley: New York.

Ford, T.D. (1984). Paleokarsts in Britain. *Cave Science*, **11**, 246–264.

Franklin, J.A. (1989) Stability of shallow caverns. In: Malone, A.W. and Whiteside, P.G.D. (eds), *Rock Cavern – Hong Kong*, pp. 203–212. Institution Mining Metallurgy: London.

Frumkin, A. and Raz, E. (2001) Collapse and subsidence associated with salt karstification along the Dead Sea. *Carbonates and Evaporites*, **16**, 117–130.

Frye, J.C. and Schoff, S.L. (1942) Deep-seated solution in the Meade basin and vicinity, Kansas and Oklahoma. *American Geophysical Union Transactions*, **23**, 35–39.

Gao Y., Alexander, E.C. and Lei M. (2001) A comparison of human-induced sinkholes between China and the United States. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 25–30. Balkema: Lisse.

Garlanger, J.E. (1991) Foundation design in Florida karst. *Concrete International*, **13**(4), 56–62.

Gascoyne, M., Ford, D.C. and Schwartz, H.P. (1983) Rates of cave and landform development in the Yorkshire Dales from speleothem age data. *Earth Surface Processes Landforms*, **8**, 557–568.

Gilli, E. (1986) Les grandes cavités souterraines: Études et applications. *Karstologia*, **7**, 3–11.

Gilli, E. (1993) Les grands volumes souterrains du massif de Mulu. *Karstologia*, **22**, 1–13.

Grainger, P., McCann, D.M. and Gallois, R.W. (1973) The application of the seismic refraction technique to the study of fracturing of the Middle Chalk at Mundford, Norfolk. *Géotechnique*, **28**, 219–232.

Grosch, J.J., Touma, F.T. and Richards, D.P. (1987) Solution cavities in the limestone of eastern Saudi Arabia. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 73–78. Balkema: Rotterdam.

Grouting Committee of Geo-Institute (1998) Grouts and grouting. *American Society Civil Engineers Geotechnical Special Publication* 80, 195pp.

Guo X. (1991) *Geological Hazards of China and their Prevention and Control*, 260pp. Geological Publishing House: Beijing.

Guyot, C.A. (1984) Collapse and compaction of sinkholes by dynamic compaction. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 419–423. Balkema: Rotterdam.

Gutiérrez, F. and Cooper, A.H. (2002) Evaporite dissolution subsidence in the historical city of Calatayud, Spain: Damage appraisal and prevention. *Natural Hazards*, **25**, 259–288.

Gutiérrez, F., García-Hermoso, F. and Cooper, A.H. (2000) Spatial assessment, mitigation and prevention of evaporate dissolution subsidence damage in the historical city of Calatayud, Spain. In: Carbognin, L., Gambolati, G. and Johnson, A.I. (eds), *Proceedings Sixth International Symposium Land Subsidence, Ravenna, Italy*, **1**, 237–248.

Habič, P., Knez, M., Kogovšek, J., Kranjc, A., Mihevc, A., Slabe, T., Šebela, S. and Zupan, N. (1989) Škocjanske Jame speleological review. *International Journal Speleology*, **18**(1–2), 1–42.

Hagerty, D.J. and Pavoni, J.L. (1973) Geologic aspects of landfill refuse disposal. *Engineering Geology*, **7**, 219–230.

Hall, P.J., McCusker, A.J. and Bingham, C.T. (1995) Site investigation, monitoring and successful landfill closure within a karst terrain. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 189–194. Balkema: Rotterdam.

Halliday, W.R. (2004a). Piping caves and badlands pseudokarst. In: Gunn, J. (ed.), *Encyclopedia of Caves and Karst Science*, pp. 589–593. Fitzroy Dearborn: New York.

Halliday, W.R. (2004b). Pseudokarst. In: Gunn, J. (ed.), *Encyclopedia of Caves and Karst Science*, pp. 604–608. Fitzroy Dearborn: New York.

Handfelt, L.D. and Attwooll, W.J. (1988) Exploration of karst conditions in central Florida. *American Society Civil Engineers Geotechnical Special Publication* 14, 40–52.

Harrison, H.D. and Hiltunen, D.R. (2003) Characterization of karst terrane via SASW seismic wave method. *American Society Civil Engineers Geotechnical Special Publication* 122, 519–528.

He K., Liu C. and Wang S. (2003) Karst collapse related to over-pumping and a criterion for its stability. *Environmental Geology*, **43**, 720–724.

Heath, W.E. (1995) Drilled pile foundations in porous, pinnacled carbonate rock. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 371–374. Balkema: Rotterdam.

Henry, J.F. (1987) The application of compaction grouting to karstic limestone problems. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 447–450. Balkema: Rotterdam.

Herbert, S.M., Roche, D.P. and Card, G.B. (1987) The value of engineering geological desk study appraisals in scheme planning. *Geological Society Engineering Geology Special Publication* 4, 151–154.

Higginbottom, I.E. (1966) The engineering geology of chalk. *Proceedings Symposium on Chalk in Earthworks and Foundations*, pp. 1–13. Institute Civil Engineers: London.

Hill, C.A. (2000) Sulfuric acid, hypogene karst in the Guadalupe Mountains of New Mexico and West Texas, USA. In: Klimchouk, A.B., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (eds), *Speleogenesis: Evolution of Karst Aquifers*, pp. 309–316. National Speleological Society: Huntsville.

Hobson, D.M. (1992) Site investigation – making the most of your money. In: Forde, M.C. (ed.), *Proceedings 2nd International Conference on Construction on Polluted and Marginal Land*, pp. 151–158. Engineering Technics Press: Edinburgh.

Hoenstine, R.W., Lane, E., Spencer, S.M. and O'Carroll, T. (1987) A landfill site in a karst environment, Madison County, Florida – a case study. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 253–258. Balkema: Rotterdam.

Holliday, D.W. (1970) The petrology of secondary gypsum rocks: A review. *Journal Sedimentary Petrology*, **40**, 734–744.

Hon, K., Kauahikaua, J., Denlinger, R. and McKay, K. (1994). Emplacement and inflation of pahoehoe sheet flows – observations and measurements of active lava flows on Kilauea Volcano, Hawaii. *Bulletin Geological Society America*, **106**, 351–370.

Hoover, R.A. (2003) Geophysical choices for karst investigations. *American Society Civil Engineers Geotechnical Special Publication* 122, 529–538.

Horwitz, H.H. and Smith, T.J. (2003) Characteristics of stable and reactivated in-filled paleokarst features in west-central Florida. *American Society Civil Engineers Geotechnical Special Publication* 122, 50–60.

Hose, L.D. and Strong, T.R. (1981) The genetic relationship between breccia pipes and caves in non-karstic terranes in northern Arizona. *Proceedings 8th International Congress Speleology*, pp. 136–138. National Speleological Society: Huntsville.

Hyatt, J.A., Wilkes, H.P. and Jacobs, P.M. (1999) Spatial relationships between new and old sinkholes in covered karst, Albany, Georgia, USA. In: Beck, B.F., Pettit, A.J. and Herring, J.G. (eds), *Hydrogeology and Engineering Geology of Sinkholes and Karst*, pp. 37–44. Balkema: Rotterdam.

Hyatt, J.A., Wilson, R., Givens, J.S. and Jacobs, P.M. (2001) Topographic, geologic and hydrogeologic controls on dimensions and locations of sinkholes in thick covered karst, Lowndes County, Georgia. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 37–45. Balkema: Lisse.

I.C.E. (1977) *Ground Subsidence*, 99pp. Institution Civil Engineers: London.

Jackson, P.D. and McCann, D.M. (1997) Cross-hole seismic tomography for engineering site investigation. *Geological Society Engineering Geology Special Publication* 12, 247–264.

Jackson, P.D., Gunn, D.A., Flint, R.C., McCann, D.M., Bent, M. and Howes, D. (2001) Cross-hole seismic measurements for detection of disturbed ground beneath existing structures. *Non-Destructive Testing Exploration International*, **34**, 155–162.

Jammal, S.E. (1984) Maturation of the Winter Park sinkhole. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 363–369. Balkema: Rotterdam.

James, A.N. and Kirkpatrick, I.M. (1980) Design of foundations of dams containing soluble rocks and soils. *Quarterly Journal Engineering Geology*, **13**, 189–198.

James, A.N. and Lupton, A.R.R. (1978) Gypsum and anhydrite in foundations of hydraulic structures. *Géotechnique*, **28**, 249–272.

James, N.P. and Choquette, P.W. (1988) *Paleokarst*, 416pp. Springer: New York.

Jancin, M. and Clark, D.D. (1993) Subsidence sinkhole development in light of mud infiltrate structures within interstratal karst of the coastal plain, southeast United States. *Environmental Geology*, **22**, 330–336.

Jansen, J., Anklam, J., Goodwin, C. and Roof, A. (1993) Electromagnetic induction and seismic refraction surveys to detect bedrock pinnacles. In: Beck, B.F. (ed.), *Applied Karst Geology*, pp. 115–122. Balkema: Rotterdam.

Jappelli, R. and Liguori, V. (1979) An unusually complex underground cavity. *Proceedings International Symposium Geotechnics of Structurally Complex Formations, Associazione Geotecnica Italiana, Rome*, **2**, 79–90.

Jennings, J.E. (1966) Building on dolomites in the Transvaal. *The Civil Engineer in South Africa*, **8**, 41–62.

Jennings, J.N. (1975) Doline morphometry as a morphogenetic tool: New Zealand examples. *New Zealand Geographer*, **31**, 6–28.

Jennings, J.N. (1983) The disregarded karst of the arid and semiarid domain. *Karstologia*, **1**, 61–73.

Jennings, J.N. (1985) *Karst Geomorphology*, 293pp. Blackwell: Oxford.

Johnson, K.S. (1989a) Salt dissolution, interstratal karst and ground subsidence in the northern part of the Texas Panhandle. In: Beck, B.F. (ed.), *Engineering and Environmental Impacts of Sinkholes and Karst*, pp. 115–121. Balkema: Rotterdam.

Johnson, K.S. (1989b) Development of the Wink Sink in west Texas, USA, due to salt dissolution and collapse. *Environmental Geology Water Science*, **14**, 81–92.

Johnson, K.S. (1997) Evaporite karst in the United States. *Carbonates and Evaporites*, **12**, 2–14.

Johnson, K.S. (1998) Land subsidence above man-made salt-dissolution cavities. *Association Engineering Geologists Special Publication*, **8**, 385–392.

Johnson, K.S. and Neal, J.T. (2003) Evaporite karst and engineering/environmental problems in the United States. *Oklahoma Geological Survey Circular*, **109**, 353pp.

Johnson, K.S., Collins, E.W. and Seni, S.J. (2003) Sinkholes and land subsidence due to salt dissolution near Wink, West Texas, and other sites in western Texas and New Mexico. *Oklahoma Geological Survey Circular* 109, 183–195.

Kaderabek, T.J. and Reynolds, R.T. (1981) Miami Limestone foundation design and construction. *Proceedings American Society Civil Engineers*, **107**(GT7), 859–872.

Kambesis, P., Crawford, N., Croft, L.A., Moore, R. and Pfaff, R. (2003) Dishman Lane collapse, Bowling Green, Kentucky. *American Society Civil Engineers Geotechnical Special Publication* 122, 404–414.

Kannan, R.C. (1999) Designing foundations around sinkholes. *Engineering Geology*, **52**, 75–82.

Kauahikaua, J., Cashman, K.V., Mattox, T.N., Heliker, C.C., Hon, K.A., Mangan, M.T. and Thornber, C.R. (1998) Observations on basaltic lava streams in tubes from Kilauea volcano, island of Hawaii. *Journal Geophysical Research*, **103**, 27303–27323.

Kaufmann, O. and Quinif, Y. (2001) An application of cone penetration tests and combined array 2D electrical resistivity tomography to delineate cover-collapse sinkholes prone areas. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 359–364. Balkema: Lisse.

Kaufmann, O. and Quinif, Y. (2002) Geohazard map of cover-collapse sinkholes in the Tournaisis area, southern Belgium. *Engineering Geology*, **65**, 117–124.

Kemmerly, P.R. (1976) Definitive doline characteristics in the Clarkesville quadrangle, Tennessee. *Bulletin Geological Society America*, **87**, 42–46.

Kemmerly, P. (1981) The need for recognition and implementation of a sinkhole-floodplain hazard designation in urban karst terrains. *Environmental Geology*, **3**, 281–292.

Kesserü, Z. (1997) Assessing the risk of cave-collapse sinkholes using analogous information from mining. In: Beck, B.F. and Stephenson, J.B. (eds), *Engineering Geology and Hydrogeology of Karst Terrains*, pp. 55–60. Balkema: Rotterdam.

Kleywegt, R.J. and Enslin, J.F. (1973) The application of the gravity method to the problem of ground settlement and sinkhole formation in dolomite on the Far West Rand, South Africa. *Proceedings Hannover Symposium on Sinkholes and Subsidence*, T301–T315. International Association Engineering Geology.

Klimchouk, A.B. (2000) The formation of epikarst and its role in vadose speleogenesis. In: Klimchouk, A.B., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (eds), *Speleogenesis: Evolution of Karst Aquifers*, pp. 91–99. National Speleological Society: Huntsville.

Klimchouk, A. and Andrejchuk, V. (1996) Breakdown development in cover beds and landscape features induced by interstratal gypsum karst. *International Journal Speleology*, **24**(3–4), 127–144.

Klimchouk, A. and Andrejchuk, V. (2003) Karst breakdown mechanisms from observations in the gypsum caves of the western Ukraine: Implications for subsidence hazard assessment. *Speleogenesis and Evolution of Karst Aquifers* (www.speleogenesis.info), **1**(1), 1–20.

Klimchouk, A., Lowe, D., Cooper, A. and Sauro, U. (1996) Gypsum karst of the world. *International Journal Speleology*, **25**(3–4), 1–307.

Klimchouk, A., Cucchi, F., Calaforra, J.M., Aksem, S., Finocchiaro, F. and Forti, P. (1996) Dissolution of gypsum from field obsevations. *International Journal Speleology*, **25**, 37–48.

Knez, M. and Slabe, T. (1999) Unroofed caves and recognising them in karst relief (discovered during expressway construction at Kozina, South Slovenia). *Acta Carsologica*, **28**(2), 103–112.

Knez, M. and Slabe, T. (2001) Karstology and expressway construction. *Proceedings 14th IRF Road World Congress, Paris* (on CD-Rom). International Road Federation: Geneva.

Knez, M. and Slabe, T. (2002a) Unroofed caves are an important feature of karst surfaces: Examples from the classical karst. *Zeitschrift Geomorphologie*, **46**, 181–191.

Knez, M. and Slabe, T. (2002b) Karstology and the opening of caves during motorway construction in the karst region of Slovenia. *International Journal Speleology*, **31**, 159–168.

Kochanov, W.E. and Kochanov, J.S. (1997) The Pennsylvania sinkhole inventory: design and application in a relational database. In: Beck, B.F. and Stephenson, J.B. (eds), *Engineering Geology and Hydrogeology of Karst Terrains*, pp. 49–54. Balkema: Rotterdam.

Kortnik, J. (2002) Stability appraisal of the Medvedova Konta pothole. *International Journal Speleology*, **31**, 129–135.

Kozary, M.T., Dunlap, J.C. and Humphrey, W.E. (1968) Incidence of saline deposits in geologic time. *Geological Society America Special Paper* 88, 43–57.

Knight, F.J. (1971) Geologic problems of urban growth in limestone terrains in Pennsylvania. *Bulletin Association Engineering Geologists*, **8**, 91–101.

Knott, D.L., Newman, F.B., Rojas-Gonzalez, L.F. and Gray, R.E. (1993) Foundation engineering practice for bridges in karst areas in Pennsylvania. In: Beck, B.F. (ed.), *Applied Karst Geology*, pp. 225–230. Balkema: Rotterdam.

Kortnik, J. and Šušteršič, F. (2000) Modelling the stability of a very large cave room, case study, Brezno pri Medvedovi Konti. *Acta Carsologica*, **29**, 149–160.

LaMoreaux, P.E. and Newton, J.G. (1986) Catastrophic subsidence: an environmental hazard, Shelby County, Alabama. *Environmental Geology Water Science*, **8**, 25–40.

LaValle, P. (1967) Some aspects of linear karst depression development in south-central Kentucky. *Association American Geographics Annals*, **57**, 49–71.

Leddin, M.M. (1994). Sinkhole. *BOCA, Building Official and Code Administrator Magazine*, **28**(3), 28–34.

Lei M., Jiang X. and Yu L. (2001) New advances of karst collapse research in China. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 145–151. Balkema: Lisse.

Li G. and Zhou W. (1999) Sinkholes in karst mining areas of China and some methods of prevention. *Engineering Geology*, **52**, 45–50.

Li J., Niu J., Liu Q. and Li G. (1983) Subsidence and its treatment in karst coal mines in China. *Proceedings 11th International Congress Speleology, Beijing*, pp. 180–181.

Littlefield, J.R., Culbreth, M.A., Upchurch, S.B. and Stewart, M.T. (1984) Relationship of modern sinkhole development to large scale photolinear features. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 189–195. Balkema: Rotterdam.

Loke, M.H. and Barker, R.D. (1996) Rapid least-squares inversion of apparent resistivity pseudosections by quasi-Newton method. *Geophysical Prospecting*, **40**, 131–152.

Lord, J.A., Clayton, C.R.I. and Mortimore, R.N. (2002) *Engineering in Chalk*. Publication C574, CIRIA: London.

Lowe, D.J. (1992) Chalk caves revisited. *Cave Science*, **19**, 55–58.

Lowe, D. and Waltham, T. (2002) Dictionary of karst and caves. *British Cave Research Association Cave Studies*, **10**, 40pp.

Lowry, D.C. and Jennings, J.N. (1974) The Nullarbor karst, Australia. *Zeitschrift Geomorphologie*, **18**, 35–81.

Lu Y. (1986) *Karst in China*, 288pp. Geological Publishing House: Beijing.

Lu Y. and Cooper, A.H. (1997) Gypsum karst geohazards in China. In: Beck, B.F. and Stephenson, J.B. (eds), *Engineering Geology and Hydrogeology of Karst Terrains*, pp. 117–126. Balkema: Rotterdam.

Luke, B.A. and Chase, D.S. (1997) Detecting caves using seismic surface waves: a feasibility study. In: Beck, B.F. and Stephenson, J.B. (eds), *Engineering Geology and Hydrogeology of Karst Terrains*, pp. 419–424. Balkema: Rotterdam.

Magdalene, S. and Alexander, E.C. (1995) Sinkhole distribution in Winona County, Minnesota, revisited. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 43–51. Balkema: Rotterdam.

Maire, R. (1981) Giant shafts and underground rivers of the Nakanai Mountains, New Britain. *Spelunca*, Supplement 3, 8–30.

Marinos, P.G. (2001) Tunnelling and mining in karstic terrane: an engineering challenge. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 3–16. Balkema: Lisse.

Martinez, J.D., Johnson, K.S. and Neal, J.T. (1998) Sinkholes in evaporite rocks. *American Scientist*, **86**, 38–51.

Martini, J. (2004) Silicate karst. In: Gunn, J. (ed.), *Encyclopedia of Caves and Karst Science*, pp. 649–653. Fitzroy Dearborn: New York.

Matthews, M.C., Clayton, C.R.I. and Rigby-Jones, J. (2000) Locating dissolution features in the Chalk. *Quarterly Journal Engineering Geology Hydrogeology*, **33**, 125–140.

McCann, D.M., Jackson, P.D. and Culshaw, M.G. (1987) The use of geophysical surveying methods in the detection of natural cavities and mineshafts. *Quarterly Journal Engineering Geology*, **20**, 59–73.

McCann, D.M., Culshaw, M.G. and Fenning, P.J. (1997) Setting the standard for geophysical surveys in site investigation. *Geological Society Engineering Geology Special Publication* 12, 3–34.

McDowell, P.W. (1975) Detection of clay-filled sink-holes in the chalk by geophysical methods. *Quarterly Journal Engineering Geology*, **8**, 303–310.

McDowell, P.W. (1989) Ground subsidence associated with doline formation in chalk areas of southern England. In: Beck, B.F. (ed.), *Engineering and Environmental Impacts of Sinkholes and Karst*, pp. 129–134. Balkema: Rotterdam.

McDowell, P.W. and Hope, V. (1993) The location and delineation of karst and solution collapse features by acoustic tomography. In: Beck, B.F. (ed.), *Applied Karst Geology*, pp. 123–129. Balkema: Rotterdam.

McDowell, P.W. and Poulsom, A.J. (1996) Ground subsidence related to dissolution of chalk in southern England. *Ground Engineering*, **29**(2), 29–33.

McDowell, P.W., Barker, R.D., Butcher, A.P., Culshaw, M.G., Jackson, P.D., McCann, D.M., Skipp, B.O., Matthews, S.L. and Arthur, J.C.R. (2002) *Geophysics in Engineering Investigations*. Construction Industry Research and Information Association Report C592 (and Geological Society Engineering Geology Special Publication 19) CIRIA, London. 252pp.

Mendonca, A.F., Pires, A.C.B. and Barros, J.G.C. (1993) Pseudo-sinkholes in lateritic terrains, Brasilia, Brazil. In: Beck, B.F. (ed.), *Applied Karst Geology*, pp. 43–49. Balkema: Rotterdam.

Merrill, R.H. (1957) Roof-span studies in limestone. *US Bureau of Mines Report of Investigations* 5348, 38pp.

Metcalfe, S.J. and Hall, L.E. (1984) Sinkhole collapse induced by groundwater pupage for freeze protection irrigation near Dover, Florida, January 1977. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 29–33. Balkema: Rotterdam.

Mihevc, A. (1998) Dolines, their morphology and origin. Case study: dolines from the Kras, west Slovenia (the Skocjan karst). *Geografia Fisica Dinamica Quaternaria Supplement 3 (Proceedings Fourth International Conference Geomorphology)*, **4**, 69–74.

Milanovic, P.T. (2000) *Geological Engineering in Karst*, 347pp. Zebra: Belgrade.

Milanovic, P.T. (2003) Prevention and remediation in karst engineering. *American Society Civil Engineers Geotechnical Special Publication* 122, 3–28.

Miller, T. (1987) Fluvial and collapse influences on cockpit karst of Belize and eastern Guatemala. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 53–57. Balkema: Rotterdam.

Mirabito, M.R., Dermatas, D. and Jancin, M. (2001) Characterization and grouting beneath an impending landfill cap. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 297–305. Balkema: Lisse.

Mishu, L.P., Godfrey, J.D. and Mishu, J.R. (1997) Foundation remedies for residential construction over karst limestone in Nashville, Tennessee. In: Beck, B.F. and Stephenson, J.B. (eds), *Engineering Geology and Hydrogeology of Karst Terrains*, pp. 319–327. Balkema: Rotterdam.

Mitchell, J.K. (1986) Hazardous waste containment. *Geological Society Engineering Geology Special Publication* 3, 145–157.

Molecke, M.A. (ed.) (2000) Final status of the Strategic Petroleum Reserve (SPR) Weeks Island mine. *Sandia National Laboratories Report*, 56pp. SAND2000-0400: Albuquerque.

Moneymaker, B.C. (1968) Reservoir leakage in limestone terrains. *Bulletin Association Engineering Geologists* 6, 3–30.

Monroe, W.H. (1976) The karst landforms of Puerto Rico. *US Geological Survey Professional Paper* 899, 1–69.

Moore, H.L. (1984) Geotechnical considerations in the location, design and construction of highways in karst terrain – the Pellissippi Parkway extension, Knox-Blount counties, Tennessee. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 385–389. Balkema: Rotterdam.

Moore, H. (1988) Treatment of karst along Tennessee highways. *American Society Civil Engineers Geotechnical Special Publication* 14, 133–148.

Moore, H. and Amari, D. (1987) Sinkholes and gabions – a solution to the solution problem. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 305–310. Balkema: Rotterdam.

Mossop, G.D. and Shearman, D.J. (1973) The origin of secondary gypsum. *Transactions Institution Mining Metallurgy*, **82**, B147–B154.

Myers, P.B. and Perlow, M. (1984) Development, occurrence and triggering mechanisms of sinkholes in the carbonate rocks of the Lehigh Valley, eastern Pennsylvania. In: Beck, B.F. (ed.), *Sinkholes: Their Geology, Engineering and Environmental Impact*, pp. 111–115. Balkema: Rotterdam.

Mylroie, J.E. and Carew, J.L. (1987) Field evidence of the minimum time for speleogenesis. *Bulletin National Speleological Society*, **49**, 67–72.

N.C.B. (1975) *Subsidence Engineers' Handbook*, 111pp. National Coal Board: London.

Neal. J.T. (1995) Supai salt karst features: Holbrook basin, Arizona. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 53–59. Balkema: Rotterdam.

Neal, J.T., Bauer, S.J. and Ehgartner, B.L. (1998) Mine-induced sinkholes over the U.S. Strategic Petroleum Reserve (SPR) storage facility at Weeks Island, Louisiana; geologic causes and effects. *Association Engineering Geologists Special Publication* 8, 327–336.

Neal, J.T. and Myers, R.E. (1995) Origin, diagnostics, and mitigation of a salt dissolution sinkhole at the US Strategic Petroleum Reserve storage site, Weeks Island, Louisiana. *International Association Hydrological Sciences Publication* 234, 187–195.

Newton, J.G. (1981) Induced sinkholes: an engineering problem. *Journal Irrigation Drainage, American Society Civil Engineers*, **107**(IR2), 175–185.

Newton, J.G. (1987) Development of sinkholes resulting from man's activities in the eastern United States. *US Geological Survey Circular* 968, 54pp.

Newton, J.G. and Hyde, L.W. (1971) Sinkhole problem in and near Roberts industrial subdivision, Birmingham, Alabama. *Geological Survey Alabama Circular* 68, 42pp.

Nichol, D. (1998) Sinkholes at Glan Llyn on the A55 North Wales Coast Road, UK. *Engineering Geology*, **50**, 101–109.

Ogden, A.E., Curry, W.A. and Cummings, J.L. (1989) Morphometric analysis of sinkholes and caves in Tennessee comparing the Eastern Highland Rim and Valley and Ridge physiographic provinces. In: Beck, B.F. (ed.), *Engineering and Environmental Impacts of Sinkholes and Karst*, pp. 135–142. Balkema: Rotterdam.

Owen, T.E. (1983) Detection and mapping of tunnels and caves. *Developments in Geophysical Exploration Methods*, **5**, 161–258.

Padgett, D.A. (1993) Remote sensing application for identifying areas of vulnerable hydrogeology and potential sinkhole collapse within highway transportation corridors. In: Beck, B.F. (ed.), *Applied Karst Geology*, pp. 285–290. Balkema: Rotterdam.

Palmer, A.N. (1991) Origin and morphology of limestone caves. *Bulletin Geological Society America*, **103**, 1–21.

Panno, S.V., Weibel, C.P., Krapac, I.G. and Storment, E.C. (1997) Bacterial contamination of groundwater from private septic systems in Illinois' sinkhole plain: Regulatory considerations. In: Beck, B.F. and Stephenson, J.B. (eds), *Engineering Geology and Hydrogeology of Karst Terrains*, pp. 443–447. Balkema: Rotterdam.

Parry-Davies, R. (1992) Consolidation of old mine workings. *Proceedings Symposium on Construction over Mined Areas, Pretoria, South African Institution of Civil Engineers*, pp. 223–227.

Partridge, T.C., Harris, G.M. and Diesel, V.A. (1981) Construction upon dolomites of the south-western Transvaal. *Bulletin International Association Engineering Geology*, **24**, 125–135.

Patterson, D.A, Davey, J.C., Cooper, A.H. and Ferris, J.K. (1995) The investigation of dissolution subsidence incorporating microgravity geophysics at Ripon, Yorkshire. *Quarterly Journal Engineering Geology*, **28**, 83–94.

Paukštys, B. (1999). Is human activity accelerating karst evolution? In: Beck, B.F., Pettit, A.J. and Herring, J.G. (eds), *Hydrogeology and Engineering Geology of Sinkholes and Karst*, pp. 103–106. Balkema: Rotterdam.

Paukštys, B., Cooper, A.H. and Arustien, J. (1997) Planning for gypsum geohazards in Lithuania and England. In: Beck, B.F. and Stephenson, J.B. (eds), *Engineering Geology and Hydrogeology of Karst Terrains*, pp. 127–135. Balkema: Rotterdam.

Paukštys, B. and Karise, V. (1998) Karst in the Baltic Republics. In: Yuan D. and Liu Z. (eds), *Global Karst Correlation*, pp. 91–108. Science Press: New York.

Paukštys, B., Cooper, A.H. and Arustiene, J. (1999) Planning for gypsum geohazards in Lithuania and England. *Engineering Geology*, **52**, 93–103.

Pazuniak, B.L. (1989) Subsurface investigation response to sinkhole activity at an eastern Pennsylvania site. In: Beck, B.F. (ed.), *Engineering and Environmental Impacts of Sinkholes and Karst*, pp. 263–269. Balkema: Rotterdam.

Perlow, M. (2003) An overview of recent Lehigh Valley, Pennsylvania, sinkhole problems. *American Society Civil Engineers Geotechnical Special Publication* 122, 644–651.

Petersen, W.K., Meyers, J.R. and Mackey, R.R. (2003) Sinkhole remediation measures for a highway in King of Prussia, Pennsylvania. *American Society Civil Engineers Geotechnical Special Publication* 122, 569–579.

Peterson, D.W., Holcomb, R.T., Tilling, R.I. and Christiansen, R.L. (1994). Development of lava tubes in the light of observations at Mauna Ulu, Kilauea volcano, Hawaii. *Bulletin Volcanology*, **56**, 343–360.

Pitman, J.I. (1983) Chemical weathering of the East Yorkshire chalk. In: Paterson, K. and Sweeting, M.M. (eds), *New Directions in Karst*, pp. 77–113. Geo Books: Norwich.

Pope, S.R. (2001) Karst void mitigation for water quality and quantity protection in Austin, Texas. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 307–312. Balkema: Lisse.

Prandini, F.L., Nakazawa, V.A., Dantas, A.M.A. and Holzer, T.L. (1990) Karst and urbanization: Investigation and monitoring in Cajamar, Sao Paulo State, Brazil. *International Association of Hydrogeologists, Selected Papers from 28th International Geological Congress*, **1**, 53–65.

Qubain, B.S., Seksinsky, E.J. and Aldin, E.G. (1995) Techniques to investigate and remedy sinkholes. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 341–347. Balkema: Rotterdam.

Quinlan, J.F. and Ewers, R.O. (1989) Subsurface drainage in the Mammoth Cave area. In: White W.B. and White, E.L. (eds), *Karst Hydrology, Concepts from the Mammoth Cave Area*, pp. 65–103. Van Norstrand Reinhold: New York.

Quinlan, J.F., Smith, A.R. and Johnson, K.S. (1986) Gypsum karst and salt karst of the United States of America. *Le Grotte d'Italia*, **4**(13), 73–92.

Raghu, D. (1987) Determination of pile lengths and proofing of the bearing stratum of piles in cavernous carbonate formations. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrology: Engineering and Environmental Applications*, pp. 307–402. Balkema: Rotterdam.

Rahn, P.H. and Davis, A.D. (1996) Gypsum foundation problems in the Black Hills area, South Dakota. *Environmental Engineering Geoscience*, **2**, 213–223.

Reynolds, J.M. (2005) *An Introduction to Applied and Environmental Geophysics*, 544pp. Wiley: Chichester.

Rhodes, S.J. and Marychurch, I.M. (1998) Chalk solution features at three sites in southeast England: their formation and treatment. *Geological Society Engineering Geology Special Publication* 15, 277–289.

Rigby-Jones, J., Clayton, C.R.I. and Matthews, M.C. (1993) Dissolution features in the chalk: From hazard to risk. In: Skipp, B.O. (ed.), *Risk and Reliability in Ground Engineering*, pp. 87–99. Thomas Telford: London.

Rigby-Jones, J., Clayton, C.R.I. and Matthews, M.C. (1994) Dissolution features in the chalk: From hazard to risk. *Geotechnical Engineering Bulletin*, **3**(3), 187–201.

Rigby-Jones, J., Matthews, M.C. and McDowell, P.W. (1997) Electrical resistivity imaging systems for ground investigations, with particular reference to dissolution features in chalk areas. *Geological Society Engineering Geology Special Publication* 12, 235–246.

Rogers, C.D.F., Glendinning, S. and Dixon, N. (1996) *Lime Stabilisation*, 182pp. Thomas Telford: London.

Roth, M.J.S., Mackey, J.R., Mackey, C. and Nyquist, J.E. (2002) A case study of the reliability of multi-electrode earth resistivity testing for geotechnical investigations in karst terrains. *Engineering Geology*, **65**, 225–232.

Ryan, M. and Meiman, J. (1996) An examination of short-term variation in water quality at a karst spring in Kentucky. *Ground Water*, **34**, 23–30.

Sauro, U. (1996) Geomorphological aspects of gypsum karst areas with special emphasis on exposed karst. *International Journal Speleology*, **25**(3–4), 105–114.

Schmidt, L.A. (1943) Flowing water in underground channels, Hales Bar dam, Tennessee. *Proceedings American Society Civil Engineers*, **69**, 1417–1446.

Šebela, S. (1996) The dolines above the collapse chambers of Postojna Jama. *Acta Carsologica*, **25**, 241–250.

Self, S., Thordarson, Th., Keszthelyi, L., Walker, G.P.L., Hon, K., Murphy, M.T., Long, P. and Finnemore, S. (1996) A new model for the emplacement of Columbia River basalts as large inflated pahoehoe lava flow fields. *Geophysical Research Letters*, **23**, 2689–2692.

Senior, K. (1995) The Yangtze Gorges expedition: China Caves Project 1994. *Cave Karst Science*, **22**, 53–89.

Shugg, A. (1998) Whey disposal, Allansford, western Victoria. *Proceedings Conference International Association Hydrogeologists, Melbourne*, 563–568.

Siegel, T.C., Cargill, P.E. and McCracken, D.W. (2001) Geosynthetic reinforcement above sinkholes to protect landfill liners. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 173–176. Balkema: Lisse.

Siegel, T.C. and McCracken, D.W. (2001) Geotechnical characterization and modelling of a shallow karst bedrock site. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 169–172. Balkema: Lisse.

Siegel, T.C., Belgeri, J.J., McCracklin, D.W. and Cargill, P.E. (2003) Seismic stability analysis of shallow caves. *American Society Civil Engineers Geotechnical Special Publication* 122, 457–465.

Simpson, D. (2001) It's a vision thing. *Ground Engineering*, **34**, 22–23.

Sinclair, W.C. (1982) Sinkhole development resulting from ground-water withdrawal in the Tampa area, Florida. *US Geological Survey Water Resources Investigation* 81-50, 19pp.

Sinclair, W.C. and Stewart, J.W. (1985) Sinkhole type, development and distribution in Florida. *US Geological Survey Map Series*, 110.

Slabe, T. (1997) Karst features discovered during motorway construction in Slovenia. *Environmental Geology*, **32**, 186–190.

Slifer, D.W. and Erchul, R.A. (1989) Sinkhole dumps and the risk to groundwater in Virginia's karst areas. In: Beck, B.F. (ed.), *Engineering and Environmental Impacts of Sinkholes and Karst*, pp. 207–212. Balkema: Rotterdam.

Smart, P.L. and Waltham, A.C. (1987) Cave dams of the Guanyan system, Guangxi, China. *Quarterly Journal Engineering Geology*, **20**, 239–243.

Smith, D.I. (1972) The solution of limestone in an Arctic environment. *Transactions Institute British Geographers Special Publication* 4, 187–200.

Smith, D.I. and Atkinson, T.C. (1976) Process, landform and climate in limestone regions. In: Derbyshire, E. (ed.), *Geomorphology and Climate*, pp. 367–409. Wiley: New York.

Sofianos, A.I. (1996) Analysis and design of an underground hard rock voussoir beam roof. *International Journal Rock Mechanics, Mining Science, Geomechanics Abstracts*, **33**, 153–166.

Soriano, M.A. and Simon, J.L. (2001) Subsidence rates of alluvial dolines in the central Ebro basin, Northeastern Spain. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 47–52. Balkema: Lisse.

Sotiropoulos, E. and Cavounidis, S. (1979) Cast in situ piles in karstic limestone. *Proceedings Conference on Recent Developments in the Design and Construction of Piles, Institution Civil Engineers, London*, pp. 59–66.

Sowers, G.F. (1975) Failures in limestones in humid subtropics. *Proceedings American Society Civil Engineers*, **101**(GT8), 771–787.

Sowers, G.F. (1986) Correction and protection in limestone terrane. *Environmental Geology Water Science*, **8**, 77–82.

Sowers, G.F. (1996) *Building on Sinkholes*, 202pp. ASCE Press: New York.

Sperling, C.H.B., Goudie, A.S., Stoddart, D.R. and Poole, G.G. (1977) Dolines of the Dorset chalklands and other areas in southern Britain. *Transactions Institute British Geographers*, **2**, 205–223.

Spooner, J. (1971) Mufulira interim report. *Mining Journal*, **276**, 122.

Stangland, H.G. and Kuo, S.S. (1987). Use of ground penetrating radar techniques to aid in site selection for land application sites. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 171–177. Balkema: Rotterdam.

Stapleton, D.C., Corso, D. and Blakita, P. (1995) A case history of compaction grouting to improve soft soils over karstic limestone. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 383–387. Balkema: Rotterdam.

Statham, I. and Baker, M. (1986) Foundation problems on limestone: A case history from the Carboniferous Limestone at Chepstow, Gwent. *Quarterly Journal Engineering Geology*, **19**, 191–201.

Stelmack, M.J., Sheridan, T. and Beck, B.F. (1995) Cap reinforcement over a sinkhole as part of a landfill closure. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 389–395. Balkema: Rotterdam.

Stephenson, J.B., Kaufmann, R.D., Archer, J.A., Bertz, C. and Bradley, P. (2003) Environmental investigation of a diesel spill in a karst area of Kentucky. *American Society Civil Engineers Geotechnical Special Publication* 122, 415–428.

Styles, P. and Thomas, E. (2001) The use of microgravity for the characterization of karstic cavities on Grand Bahama, Bahamas. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 389–394. Balkema: Lisse.

Šušteršič, F. (1998) Rakovska kukava – collapse or tumour doline. *Acta Carsologica*, **27**, 231–259.

Swart, C.J.U., Stoch, E.J., van Jaarsveld, C.F. and Brink, A.B.A. (2003) The Lower Wonderfontein Spruit: An exposé. *Environmental Geology*, **43**, 635–653.

Sweeting, M.M. (1972) *Karst Landforms*, 362pp. Macmillan: London.

Swiger, W.F. and Estes, H.M. (1959) Major power station foundation in broken limestone. *Proceedings American Society Civil Engineers*, **85**(SM5), 77–86.

Tan, B.K. (1987) Some geotechnical aspects of urban development over limestone terrain in Malaysia. *Bulletin International Association Engineering Geology*, **35**, 57–63.

Tan, B.K. and Batchelor, B. (1981) Foundation problems in limestone areas: A case study in Kuala Lumpur, Malaysia. *Proceedings International Conference on Weak Rock*, *Tokyo*, pp. 1461–1463. Balkema: Rotterdam.

Tan, B.K. and Komoo, I. (1990) Urban geology case study of Kuala Lumpur, Malaysia. *Engineering Geology*, **28**, 71–94.

Tarquinio, F.S. and Pearlman, S.L. (2001) Pin piles in karst topography. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 177–181. Balkema: Lisse.

Telford, W.M., Geldart, L.P., Sherriff, R.E. and Keys, D.A. (1990) *Applied Geophysics*, 769pp. Cambridge University Press: Cambridge.

Terashi, M. and Juran, I. (2000) Ground improvement – state of the art. *Proceedings GeoEng2000: Melbourne* (on CD-Rom).

Tharp, T.M. (1995) Design against collapse of karst caverns. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 397–406. Balkema: Rotterdam.

Tharp, T.M. (1999) Mechanics of upward propagation of cover-collapse sinkholes. *Engineering Geology*, **52**, 23–33.

Tharp, T.M. (2001) Cover-collapse sinkhole formation and piezometric surface drawdown. In: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, pp. 53–58. Balkema: Lisse.

Tharp, T.M. (2003) Cover-collapse sinkhole formation and soil plasticity. *American Society Civil Engineers Geotechnical Special Publication* 122, 110–123.

Thomas, T.M. (1963) Solution subsidence in southeast Carmarthenshire and southwest Breconshire. *Transactions Institute British Geographers* 33, 45–60.

Thomas, T.M. (1974) The South Wales interstratal karst. *Transactions British Cave Research Association*, **1**, 131–152.

Thompson, A., Hine, P.D., Greig, J.R. and Peach, D.W. (1996) *Assessemnt of subsidence arising from gypsum dissolution: Technical report for the Department of the Environment*, 288pp. Symonds Group: East Grinstead.

Tinjun, J.M., Krantz, B.J., Ditto, W.L. and Aldern, J.L. (2003) Investigation and remediation of karst features at foundry landfill site. *American Society Civil Engineers Geotechnical Special Publication* 122, 349–358.

Toulemont, M. (1987) Les risques d'instabilité liés au karst gypseux lutétien de la région parisienne. *Bulletin liaison Laboratoires Ponts et Chaussées* 150/151, 109–116.

Trudgill, S.T. (1976) The marine erosion of limestones on Aldabra Atoll, Indian Ocean. *Zeitschrift Geomorphologie*, Supplement 26, 164–200.

Upchurch, S.B. and Littlefield, J.R. (1987) Evaluation of data for sinkhole-development risk models. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 359–364. Balkema: Rotterdam.

Vandevelde, G.T. and Schmitt, N.G. (1988) Geotechnical exploration and site preparation techniques for a large mall in karst terrain. *American Society Civil Engineers Geotechnical Special Publication* 14, 86–96.

Van Rooy, J.L. (1989) A new proposed classification system for dolomitic areas south of Pretoria. *Contributions to Engineering Geology*, **1**, pp. 57–65 (Pretoria).

Van Schalkwyk, A. (1998) Legal aspects of development on dolomite land in South Africa. *Environmental Geology*, **36**, 167–169.

Varnes, D. J. (1984) Landslide hazard zonation: A review of principles and practice. *Natural Hazards 3*, 63pp. UNESCO: Paris.

Vasquez Castillo, L.V. and Rodriguez Molina, C.R. (1999) Geotechnical engineering and geology for a highway through cone karst in Puerto Rica. In: Beck, B.F., Pettit, A.J. and Herring, J.G. (eds), *Hydrogeology and Engineering Geology of Sinkholes and Karst*, pp. 431–445. Balkema: Rotterdam.

Venter, I.S. and Gregory, B.J. (1987) A risk assessment in dolomitic terrain – a case history. *Geological Society Engineering Geology Special Publication* 4, 329–334.

Villard, P., Gourc, J.P. and Giraud, H. (2000) A geosynthetic reinforcement solution to prevent the formation of localized sinkholes. *Canadian Geotechnical Journal*, **37**, 987–999.

Wagener, F.v.M. (1985) Dolomites; problems of soils in South Africa. *The Civil Engineer in South Africa*, **27**, 395–407.

Wagener, F.v.M. and Day, P.W. (1986) Construction on dolomite in South Africa. *Environmental Geology Water Science*, **8**, 83–89.

Walsh, P.T., Boulter, M.C., Itjaba, M. and Urbani, D.M. (1972) The preservation of the Neogene Brassington Formation of the southern Pennines and its bearing on the evolution of upland Britain. *Quarterly Journal Geological Society*, **128**, 519–559.

Walters, R.F. (1977) Land subsidence in central Kansas related to salt dissolution. *Bulletin Kansas Geological Survey* 214, 82pp.

Waltham, A.C. (1989) *Ground Subsidence*, 202pp. Blackie: Glasgow.

Waltham, A.C. (1996) Limestone karst morphology in the Himalayas of Nepal and Tibet. *Zeitschrift Geomorphologie*, **40**, 1–22.

Waltham, T. (1997) Mulu – the ultimate in cavernous karst. *Geology Today*, **13**, 216–222.

Waltham, T. (2002a) Gypsum karst near Sivas, Turkey. *Cave Karst Science*, **29**, 39–44.

Waltham, T. (2002b) The engineering classification of karst with respect to the role and influence of caves. *International Journal Speleology*, **31**, 19–35.

Waltham, T. and Cooper, A. (1998) Features of gypsum caves and karst at Pinega (Russia) and Ripon (England). *Cave Karst Science*, **25**, 131–140.

Waltham, A.C. and Fookes, P.G. (2003) Engineering classification of karst ground conditions. *Quarterly Journal Engineering Geology Hydrogeology*, **36**, 101–118.

Waltham, T. and Hatherley, P. (1983) The caves of Leck Fell. *Cave Science*, **10**, 245–251.

Waltham, T. and Middleton, J. (2000) The Khammouan karst of Laos. *Cave Karst Science*, **27**, 113–120.

Waltham, A.C. and Park, H.D. (2002) Roads over lava tubes in Cheju Island, South Korea. *Engineering Geology*, **66**, 53–64.

Waltham, A.C. and Smart, P.L. (1988) Civil engineering difficulties in the karst of China. *Quarterly Journal Engineering Geology*, **21**, 2–6.

Waltham, A.C. and Swift, G.M (2004) Bearing capacity of rock over mined cavities in Nottingham. *Engineering Geology*, **75**, 15–31.

Waltham, A.C., Smart, P.L., Friederich, H., Eavis, A.J. and Atkinson, T.C. (1983) The caves of Gunung Sewu, Java. *Cave Science*, **10**, 55–96.

Waltham, A.C., Vandenven, G. and Ek, C.M. (1986) Site investigations on cavernous limestone for the Remouchamps viaduct, Belgium. *Ground Engineering*, **19**(8), 16–18.

Waltham, T., Brook, D. and Bottrell, S. (1993) The caves and karst of Xingwen, China. *Cave Science*, **20**, 75–86.

Waltham, A.C., Simms, M.J., Farrant, A.S. and Goudie, H.S. (1997) *Karst and Caves of Great Britain* (Geology Conservation Review Series, 12), 358pp. Chapman and Hall: London.

Warren, C.D. and Mortimore, R.N. (2003) Chalk engineering geology – Channel Tunnel Rail Link and North Downs Tunnel. *Quarterly Journal Engineering Geology and Hydrogeology*, **36**, 17–34.

Wassmann, T.H. (1979) Mining subsidence in the east Netherlands. In: Saxena, S.K. (ed.), *Evaluation and Prediction of Subsidence*, pp. 283–302. American Society Civil Engineers: New York.

Welsh, J.P. (1988) Sinkhole rectification by compaction grouting. *American Society Civil Engineers Geotechnical Special Publication* 14, 115–132.

Wenrich, K.J. and Sutphin, H.B. (1994) Grand Canyon caves, breccia pipes and mineral deposits. *Geology Today*, **10**, 97–104.

West, G. and Dumbleton, A.J., (1972) Some observations on swallow holes and mines in the Chalk. *Quarterly Journal of Engineering Geology*, **5**, 171–177.

Weyl, P.K. (1959) The solution kinetics of calcite. *Journal Geology*, **66**, 163–176.

Whittaker, B.N. and Reddish, D.J. (1989) *Subsidence; Occurrence, Prediction and Control*, 528pp. Elsevier: Amsterdam.

White, E.L., Aron, G. and White, W.B. (1986) The influence of urbanization on sinkhole development in central Pennsylvania. *Environmental Geology Water Science*, **8**, 91–97.

White, E.L. and White, W.B. (1969) Processes of cave breakdown. *Bulletin National Speleological Society*, **31**, 83–96.

White, W.B. (1988) *Geomorphology and Hydrology of Karst Terrains*, 464pp. Oxford University Press: New York.

White, W.B. and White, E.L. (2003) Gypsum wedging and cavern breakdown: studies in the Mammoth Cave System, Kentucky. *Journal Cave Karst Studies*, **65**, 43–52.

Williams, D.M. and McNamara, K. (1992) Limestone to dolomite to dedolomite conversion and its effect on rock strength: a case study. *Quarterly Journal Engineering Geology*, **24**, 131–135.

Williams, P.W. (1983) The role of the subcutaneous zone in karst hydrology. *Journal Hydrology*, **61**, 45–67.

Williams, P.W. (1985) Subcutaneous hydrology and the development of doline and cockpit karst. *Zeitschrift Geomorphologie*, **29**, 463–482.

Williams, P.W. (2004) Dolines. In: Gunn, J. (ed.), *Encyclopedia of Caves and Karst Science*, pp. 304–310. Fitzroy Dearborn: New York.

Wilson. W.L. (1995) Sinkhole and buried sinkhole densities and new sinkhole frequencies in karsts of northwest peninsular Florida. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 79–91. Balkema: Rotterdam.

Wilson, W.L. (2000) *Reported sinkhole density map of Florida*. Subsurface Evaluations Inc.: Tampa, Florida.

Wilson, W.L. and Beck, B.F. (1988) Evaluating sinkhole hazards in mantled karst terrane. *American Society Civil Engineers Geotechnical Special Publication* 14, 1–24.

Wilson, W.L., Mylroie, J.E. and Carew, J.L. (1995) Caves as a geologic hazard: a quantitative analysis from San Salvador Island, Bahamas. In: Beck, B.F. (ed.), *Karst Geohazards*, pp. 487–495. Balkema: Rotterdam.

Wood, C. (1981) Exploration and geology of some lava tube caves on the Hawaiian volcanoes. *Transactions British Cave Research Association*, **8**, 111–129.

Wood, C., Watts, R., Waters, E. and Cheetham, P. (2002) *Laki Underground 2001*, 32pp. Bournemouth University: Bournemouth.

Wyllie, D.C. (1999) *Foundations on Rock*, 401pp. Spon: New York.

Xiang S., Chen J., Wilson, W.L. and Beck, B.F. (1988) Sinkholes as a consequence of groundwater development in karst regions. *American Institute of Hydrology Journal*, **4**, 160–173.

Xu W. and Zhao G. (1988) Mechanism and prevention of karst collapse near mine areas in China. *Environmental Geology Water Science*, **12**, 37–42.

Yechieli, Y., Abelson, M., Wachs, D., Shtivelman, V., Crouvi, O. and Baer, G. (2003) Formation of sinkholes along the shore of the Dead Sea – preliminary investigation. *American Society Civil Engineers Geotechnical Special Publication* 122, 184–192.

Yuan D. (1987) Environmental and engineering problems of karst geology in China. In: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, pp. 1–11. Balkema: Rotterdam.

Zenger, D.H., Dunham, J.B. and Etherington, R.L. (1980) Concepts and models of dolomitisation. *Society Economic Palaeontology Mineralogy Special Publication* 28, 320pp.

Zhou W., Beck, B.F. and Adams, A.L. (2003) Sinkhole risk assessment along highway 1-70 near Frederick, Maryland. *American Society Civil Engineers Geotechnical Special Publication* 122, 591–601.

Zhu X. (2001) China's karst tiankeng and its value for science. *Science and Technology Review Beijing*, **160**(10), 60–63.

Zhu X. and Zhang Y. (1995) The world's largest dolines and Great Crack Gorge in southern Sichuan. *Carsologica Sinica*, **14**, Supplement, 1–11.

Zhu X., Huang B., Zhu D. and Chen W. (2003) *Dashiwei Tiankeng Group, Leye, Guangxi*, 184pp. CIP: Beijing.

Zisman, E.D. (2001) A standard method for sinkhole detection in the Tampa, Florida, area. *Environmental and Engineering Geoscience*, **7**, 31–50.

Zisman, E.D. (2003) Guilty until proven innocent – sinkhole definition and identifying features. *American Society Civil Engineers Geotechnical Special Publication* 122, 124–130.

A major data resource is the series of volumes containing the papers from the multisdisciplinary conferences on sinkholes and their various aspects of geology, geotechnics, hydrogeology and engineering, that have been held in America since 1984. The volume references are as follows:

First, 1984: Beck, B.F. (ed.), *Sinkholes: their Geology, Engineering and Environmental Impact*, 429pp. Balkema: Rotterdam.

Second, 1987: Beck, B.F. and Wilson, W.L. (eds), *Karst Hydrogeology: Engineering and Environmental Applications*, 467pp. Balkema: Rotterdam.
Third, 1989: Beck, B.F. (ed.), *Engineering and Environmental Impacts of Sinkholes and Karst*, 384pp. Balkema: Rotterdam.
Fourth, 1993: Beck, B.F. (ed.), *Applied Karst Geology*, 295pp. Balkema: Rotterdam.
Fifth, 1995: Beck, B.F. (ed.), *Karst Geohazards*, 582pp. Balkema: Rotterdam.
Sixth, 1997: Beck, B.F. and Stephenson, J.B. (eds), *Engineering Geology and Hydrogeology of Karst Terrains*, 528pp. Balkema: Rotterdam.
Seventh, 1999: Beck, B.F., Pettit, A.J. and Herring, J.G. (eds), *Hydrogeology and Engineering Geology of Sinkholes and Karst*, 478pp. Balkema: Rotterdam.
Eighth, 2001: Beck, B.F. and Herring, J.G. (eds), *Geotechnical and Environmental Applications of Karst Geology and Hydrology*, 437pp. Balkema: Lisse.
Ninth, 2003: Beck, B.F. (ed.), Sinkholes and the engineering and environmental impacts of karst. *American Society of Civil Engineers Geotechnical Special Publication* 122, 737pp.