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Control the drainage: the gospel accorded to sinkholes

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Abstract: Karst is a terrain distinguished by its underground drainage, natural cavities and sinkholes. New subsidence sinkholes (both dropout and suffosion) formed within the soil cover constitute the main karst geohazard. Nearly all are induced by increased drainage inputs or by water table decline, and control of the drainage is the primary means of reducing their hazard. Cave collapse and the development of collapse sinkholes in bedrock are less common, and the stability of a cave roof that is thicker than its width means that only those caves at shallow depth create any hazard. Predictions of the locations of caves or potential sinkhole sites are next to impossible, geophysical searches have severe limitations and borehole searches can incur significant costs. Consequently, controlling the drainage on construction projects is usually the most cost-effective means of minimizing the karst geohazard.

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With about 20% of our planet's land surface having limestones (and other soluble rocks) at outcrop, it is perhaps surprising how little their ground conditions are fully appreciated by civil engineers and engineering geologists. Their distinguishing feature is the natural development of ground cavities, with all their implications for ground subsidence, failure and collapse. The cavities are the result of dissolution by groundwater, the same process as that which defines karst by its suite of landforms related to the presence of underground drainage (Fig. 1). Karst can develop on any soluble rock, including limestone, marble, chalk, dolomite (dolostone or magnesian limestone), travertine (tufa) gypsum and salt (halite). Though rarely at outcrop, anhydrite and salt underlie huge areas of land in sedimentary basins. Pseudokarst terrains on loess and lava have cavities, but these are not formed by dissolution. Periglacial thermokarst involves neither cavities nor dissolution but merely mimics some karst landforms, and glacier karst is an extreme but ephemeral morphology entirely within glacier ice.

Most karst is developed on limestone, with about half the world's on-land limestone having some scale of karst landforms. Sinkholes are almost ubiquitous in karst, so about 10% of the land on our planet is prone to the sinkhole geohazard. There is no shortage of material for this year's Glossop Lecture.

Karst terrains

The landscapes of karst take on many guises. The fenglin towers of southern China, the conical hills of Jamaica's Cockpit Country, the Sinkhole Plain of Kentucky (Fig. 2), the bare limestone pavements of England's Yorkshire Dales, the rolling downlands of France's champagne region and the Nullarbor Plain in Australia are all variants of karst. There is an extensive literature on karst geomorphology; the standard reference is the book by Ford & Williams (2007), though the best introductory read is still that by Jennings (1985).

Types, scales and details of morphological features in karst vary enormously. Limestone dissolution increases with higher contents of carbon dioxide within the groundwater. That carbon dioxide is largely biogenic and dependent on bacterial and plant respiration within the soil cover. Wet tropical regions, with their high levels of plant activity, therefore contain the most mature karst. This means that they have larger caves, more sinkholes and higher local relief (both subaerial and sub-soil) compared with those in cooler, temperate or mountain terrains. Extremely mature karst in the limestone lowlands of southern China can provide nightmares for civil engineers; in contrast, many of the Himalayan summits are also limestone but are lacking in both karst development and engineering works.

The climatic influence on karst ground conditions is among the factors incorporated in an engineering classification of karst (Waltham & Fookes 2003) that recognizes the progressively older, more mature and more complex karst terrains occurring in warm and wet climates. Its defining parameters include the density and size of sinkholes and the frequency of new sinkhole events. It has proved useful in providing broad comparative descriptions of karst, but can only be a generalization (Fig. 3); quantified estimates of cave size, sinkhole density and rockhead relief are required to fully assess any local situation. The classification of karst and the descriptions of sinkholes in this paper are primarily concerned with limestone karst. Concepts and implications are also broadly applicable to gypsum karst (Gutiérrez *et al.* 2008), although the greater solubility and lower strength of gypsum do create some significant differences, some of which are referred to below.

Within the geomorphological literature, a sinkhole is known as a doline. The two terms are synonymous, but sinkhole, which originated in the USA, is now dominant in the engineering literature worldwide (though sinker is another US term, and this should never be used). All the main texts on karst include sinkholes in their descriptions of the relevant processes and landforms, and Ford & Williams (2007) even provided a short chapter on karst geohazards. The only book that is devoted to sinkholes and their engineering significance is largely the work of your Glossop lecturer (Waltham *et al*. 2005) and contains further details on much of what is presented in these pages. Perhaps the main aim of this Glossop Lecture and its paper is to raise awareness of sinkholes and potential sinkhole collapses among ground engineers and engineering geologists who may not be familiar with the processes and features of cavernous karst.

The karst geohazard

Though karst and sinkholes can be found in nearly every country in the world, experience and documentation of the karst geohazard is dominated by three regions that have the largest populations and infrastructure in limestone terrains. The eastern USA has numerous and extensive areas of karst with a well-known history of

Fig. 1. Sawn faces in a small old quarry in Turkey expose dissolutional fissures that are typical of those in limestone karst, transmitting and enlarged by groundwater. Although most voids are aligned on fractures there is no pattern in how far each extends; they are all interconnected in the third dimension.

(a)

(b)

Fig. 2. Variation in karst terrain. (**a**) Mountain karst in Sichuan, China, with bare rock on the hillsides and soil floors within isolated depressions. (**b**) A lowland plain in Kentucky, USA, with numerous sinkholes in a soil cover that overlies cavernous limestone.

destructive sinkhole collapses. Ground disturbance by civil engineering works was recognized long ago as a significant cause of new sinkhole failures (Newton 1987), and a wealth of experience went into the standard work on construction on karst terrain (Sowers 1996). Numerous sinkhole collapses in Florida led to establishment in 1984 of the biennial Sinkhole Conferences, and the proceedings of these provide a wealth of case studies from all over the USA and elsewhere in the world. In contrast, the western USA has more problems with sinkholes in its large areas of gypsum karst (Johnson & Neal 2003).

Southern China has the largest population living on the most extensive and most mature karst in the world. The Karst Institute in Guilin is accumulating a wealth of experience of sinkhole failures and construction on karst. Most is documented only in Mandarin, but many case studies do appear in the US Sinkhole Conference publications (e.g. Lei & Liang 2005; Lei *et al*. 2013).

The countries that once constituted Yugoslavia straddle the extensive Dinaric karst, and their engineers have had to learn to build infrastructure on cavernous limestone where sinkholes are commonplace (Milanović 2003). Expertise on caves and sinkholes is now concentrated in the long-established Karst Institute at Postojna, which publishes reports on numerous case histories in their own *Acta Carsologica* and elsewhere (e.g. Šebela & Mihevc 1995; Knez & Slabe 2005). Vast experience has also been gained, and documented, in construction of numerous reservoirs on the limestone karst of Croatia and Bosnia (Milanović 2004, 2011).

Britain experiences the karst geohazard on only a modest scale (Cooper *et al*. 2011). Though the book on sinkholes (Waltham *et al*. 2005) was produced in Britain, more than 90% of its case histories are from elsewhere in the world. Within Britain, the main cavernous limestones form upland areas, such as the high ground around the Yorkshire Dales, where sinkholes have minimal conflict with engineering works (Waltham & Lowe 2013). There is more infrastructure development on England's lowland outcrops of gypsum and chalk. Sinkholes over solution cavities in gypsum are a significant hazard in the Yorkshire town of Ripon (Cooper 1998), but the spate of new sinkholes in the chalk, induced by rainfall during the wet winter of 2013–2014, were failures over old mine workings. Karst and sinkholes are only a minor feature within the challenges of engineering works on chalk, as detailed in a previous Glossop Lecture (Mortimore 2012).

An extensive review of recent literature on karst geohazards has been presented by Gutiérrez *et al*. (2014). Combining that paper with the more recent publications by the writer (Waltham & Fookes 2003; Waltham *et al*. 2005; Waltham 2012) and the review that follows in these pages should provide the practising engineer with a reasonable understanding of the difficult ground conditions that may be encountered in karst. For a deeper study, and beyond what would be required on most engineering projects, the book by Ford & Williams (2007) provides and leads further into the science of rock dissolution. Current concepts and practicalities involved in engineering in the huge variety of karst terrains are accessible in the proceedings of the more recent sinkhole conferences (Land *et al*. 2013).

Sinkholes are the obvious karst geohazard, but are not the only type of 'difficult ground conditions' confronting engineers in karst environments (Waltham 2012). Table 1 summarizes the main factors that constitute the family of karst geohazards in limestone terrains, and Table 2 identifies the main contrasts in karst formed on rocks other than limestone. A troublesome aspect of karst ground conditions is provided by its rockhead relief. Convoluted buried morphologies are the product of extensive limestone dissolution at rockhead by aggressive waters from overlying organic soils (Zseni 2009). Unlike nearly all insoluble rocks, limestone does not weather by degrading to progressively weaker soils, but instead is totally removed in solution. Consequently, its rockhead is normally marked by a sharp contrast between the mechanically strong rock and the much weaker soil cover. Furthermore, the rockhead may be highly irregular owing to dissolutional widening of fissures between remnant pillars of intact rock (Waltham *et al*. 2005). In the extreme form known as pinnacled rockhead, which is common within tropical karst terrains, the potential instability of single, buried, rock pinnacles constitutes another type of karst

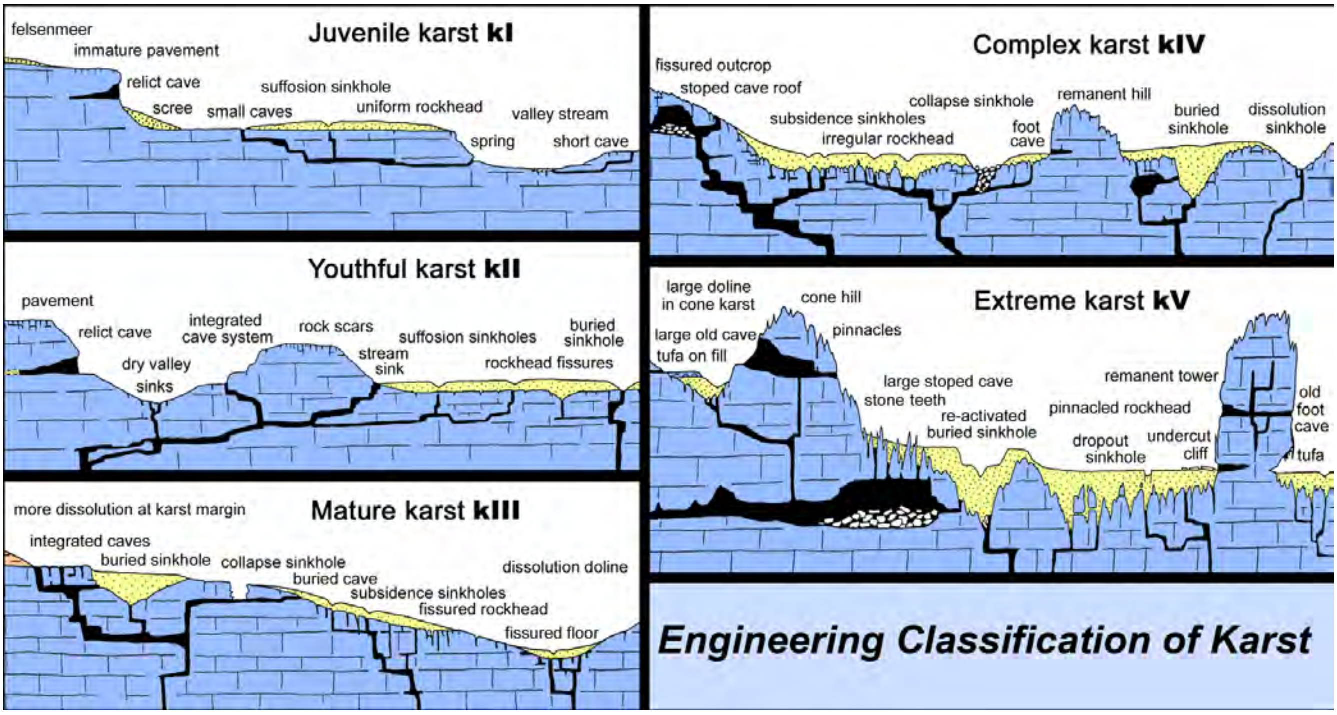


Fig. 3. Variation in karst morphology broadly described in an engineering classification that recognizes increasing sizes and numbers of caves, sizes and numbers of sinkholes, frequency of new sinkhole events, topographic relief and rockhead relief in the increasingly more mature karst terrains (from Waltham & Fookes 2003).

Table 1. *Features and processes that are widespread and significant to civil engineering in terrains of limestone karst, listed in a very rough order of significance in overall civil engineering practice*

Karst feature or process	Implications for civil engineering	Engineering response	Example	Figure
New dropout sinkholes in the soil cover	Rapid ground failure, mostly induced by drainage change	Compaction grouting within soil; minimize by control of drainage	Florida: Beck (1986)	7
Ground subsidence by soil loss into fissures	Slow settlement, commonly induced by drainage change, may precede dropout failure	Compaction grouting within soil; minimize by control of drainage	Winter Park, FL: Jammal (1984)	1
Reservoir leakage	Major potential losses must be expected	Best avoided on karst; extensive grouting frequently required	Lar and Keban dams: Milanović (2011)	5
Pinnacled rockhead	Huge variations in depth to rock, and in the stability and shape of pinnacles, for solid founding of structures	Anticipate large variations; clear soil and fill with crushed rock, or prove every footing	Ipoh and Kuala Lumpur: Tan (1990)	22
Buried sinkhole filled with soil	Large rockhead depression filled with weak and/or soft soil, which may compact under load and/or be lost by suffosion in drainage	Budget for deeper foundations; control the drainage	Transvaal Rand: Jennings (1966)	22
Unexpected cavity in bedrock	Size, shape and depth of a cave are almost totally unpredictable in strong limestone	May need to relocate structure, or fill cave with lean concrete, or pile through to solid floor	Remouchamps Viaduct: Waltham *et al.* (1986)	21
Bedrock collapse under structural load	Potential roof collapse over large or small cavities with totally random distribution	Prove sound rock beneath every pile tip and structural element; see Table 4	Tampa freeway: Waltham (2008)	19
Subsidence over a breccia pipe	Effectively a deep buried sinkhole, with fill that may be dense or weak	May need to relocate to avoid	Chiltern Hills: Edmonds (2005)	13
Solution depression	Large surface basin with soil floor and internal drainage	Best avoided, as soil floor is prone to subsidence sinkholes	Gunung Sewu, Java: Waltham *et al.* (2005)	10
Groundwater pollution	Rapid transmission of pollutants; no filtration through karst conduits	Define the sources and manage the drainage	Sinkhole Plain, KY: Quinlan & Ewers (1989)	–
Sinkhole flooding	Large depressions containing infrastructure can flood when outlet sinkhole becomes choked	Clear and maintain a drainage outlet to bedrock	Springfield, MO: Barner (1999)	–
Rock collapse by roof stoping over cavity that migrates to surface	Extremely rare; possible in thin-bedded caprock overlying cavernous limestone; similar to crown hole over old mine	There is no practicable response prior to an event; risk is usually acceptable	Obruk Plateau: Doğan & Yilmaz (2011)	16
Rock surface lowered by dissolution	Negligible in engineering timescales	None needed (in limestone)	–	–
New cavity in bedrock formed by dissolution	Negligibly slow (in limestone), but may increase reservoir leakage	Risk is acceptably small (except to reservoir leakage)	–	–

The last column indicates figures that are illustrative or relevant within this paper. Further details on types of sinkholes are given in Table 3, and details on all significant karst landforms have been given by Waltham *et al.* (2005).

Table 2. *The rock types in which karst features may be developed, listed in order of frequency or extent*

Lithology of karst rock	Implications for civil engineering
Limestone	All features as in Table 1
Marble	Effectively the same as strong limestone with respect to its karst
Dolomite, dolostone, magnesian limestone	Similar to those of limestone, but in most cases all features are smaller and processes are slower owing to lower solubility of dolomite
Gypsum	Similar to those of limestone, except that cavities are smaller in the weaker rock, but new features can develop within engineering timescales because solubility is greater
Anhydrite	Normally converted to gypsum at and close beneath outcrop. May be disturbed by large expansion or shrinkage when converting to or from gypsum (by addition or loss of water)
Chalk	Similar to those of limestone, except that cavities are smaller in the weaker rock, buried sinkholes are particularly common, and groundwater pollution can be significant
Salt, halite, rock salt	Very rare at outcrop, where it forms extremely unstable terrain with rapid dissolution, active collapse of bedrock, and frequent new sinkholes in residual soil cover. Buried salt is prone to dissolution in groundwater wherever it is in contact with permeable soil or adjacent rock unit, causing widespread ground subsidence (which is exacerbated by brine pumping)
Sabkha	Widespread ground subsidence and development of new small sinkholes in unconsolidated sediments, mainly driven by dissolution of gypsum within the mixed sabkha sequences. Groundwaters are commonly very aggressive to concrete
Tufa, travertine	Numerous small cavities and weak rock can make for difficult ground conditions, and ground failure may occur where tufa overlies unconsolidated sediments
Basalt (pseudokarst)	Potential failure and collapse of thin rock roof over lava tubes that are typically at shallow depth
Loess (pseudokarst)	Piping failures in loess and in some pyroclastic sequences

Further details on all types of rock and karst have been given by Waltham *et al*. (2005) and Waltham (2012).

Fig. 4. Karst benefit. The cave of Mas d'Azil in the French Pyrenees, with a main road built beside the cave river to gain an easy route through a limestone ridge.

Fig. 5. Karst hazard. The Cong Canal in western Ireland that does not hold water because it was built on karst limestone.

geohazard. A construction project can incur greatly increased costs where stable foundations on bedrock can only be placed at hugely variable depths across a small site.

Occasionally, engineers can reap benefits from karst where large open caves can eliminate the need for tunnels. The roads through the Grotte de Mas d'Azil (in the French Pyrenees; Fig. 4) and the Grotta di San Giovanni (in Sardinia), and the railway through Natural Tunnel in Virginia (Waltham 1988), could all be described as geo-benefits in karst. They contrast the massive leakages from reservoirs, either through open caves or through networks of smaller fissures, that lie in the realm of geohazards. The Les Cheurfas Dam in Algeria failed because it was built partly on calcrete, the Cong Canal in Ireland could not hold water (Fig. 5), and the Xiaoheli Dam in China was bypassed by an unseen cave previously full of sediment (Smart & Waltham 1987). These failures were all due to groundwater losses in karst. Along with the rapid transfer of pollutants through the cavernous conduits of karst, all of these are outside the scope of this Glossop Lecture.

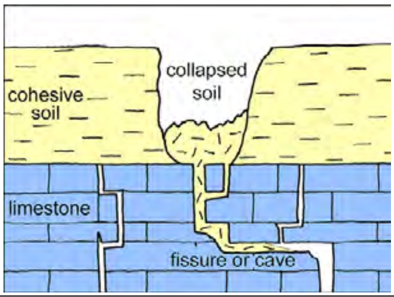
The sinkholes geohazard

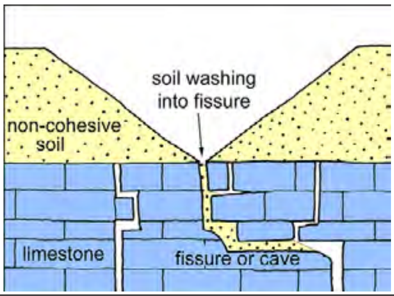
Most sinkholes can be sensibly described as one of six types (Table 3), each of which has its own implications for engineering works (Waltham *et al*. 2005). The suffosion and dropout variants of the subsidence sinkhole are by far the most numerous, and new ones are frequently formed wherever the hydrology of the soil cover is disturbed. New failures of bedrock, to form the two types of collapse sinkhole, with or without failure of a caprock, are rare, but can have significant impact. Solution sinkholes are formed by long-term erosion of the bedrock, many as large, shallow depressions hundreds of metres across, where the term doline is often more appropriate; they have minimal impact on engineering works except that their bedrock floors are likely to be more fissured so that subsidence sinkholes can develop within any sediment fill. Buried sinkholes can be regarded most simply as larger variations in the local rockhead profile.

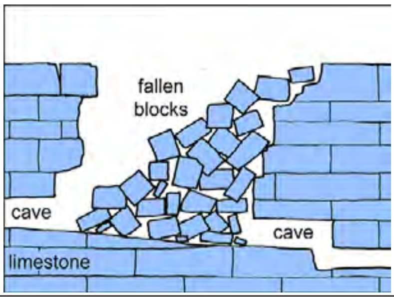
New subsidence sinkholes, and settlements within old sinkholes, are almost entirely driven by water movement and changes thereof. That is why 'control the drainage' really should be the gospel that is applied by engineers and geologists working on any project in karst terrain. Though inappropriate structural loading over unseen caves can cause spectacular ground collapses, nearly all ground failures in karst are due to disturbance of water flows

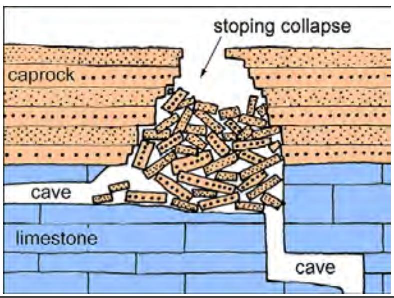
Table 3. *Generalized features of the six main types of sinkhole, with their contrasting modes of formation and various implications for engineering works*

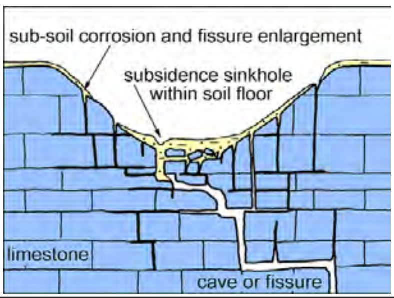
<table>
<tr><th>Type</th><th>Morphology</th><th>Profile</th><th>Engineering implications</th></tr>
<tr><td>1a

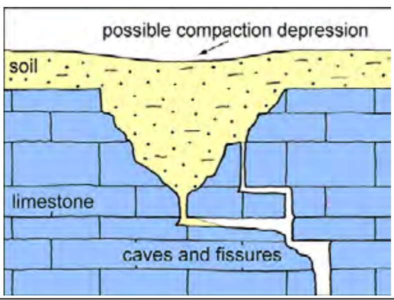
Dropout sinkhole</td><td>In the soil profile.
Collapse of soil arch in cohesive soil over void.
Instant failure, then widens as sides degrade.
Typically less than 40m wide and 20m deep, and limited by soil depth.</td><td>
</td><td rowspan="2">Subsidence sinkholes that are formed by removal of soil cover, without any rock failure, account for almost all new sinkhole events. Locations are virtually unpredictable, except that nearly all are induced by changes in drainage patterns. Caused by water washing soil down into the bedrock cavities, so engineering response is to control the drainage.</td></tr>
<tr><td>1b

Suffosion sinkhole</td><td>In the soil profile.
Progressive slumping of soil with little or no cohesion, as it is washed away into underlying fissures.
Generally less than 50m wide and 20m deep, and limited by soil depth.</td><td>
</td></tr>
<tr><td>2a

Collapse sinkhole</td><td>Failure of bedrock over a cave passage or chamber.
Multiple, progressive rockfall and widening on geological timescales.
Individual failures unlikely to exceed 20m wide and 20m deep.</td><td>
</td><td rowspan="2">Collapse sinkholes that are formed by natural rock failure of the limestone, or a caprock, are extremely rare. Ground failures that may be induced by imposed loading, can be avoided by appropriate ground investigation. Collapses are into caves, whose locations are totally unpredictable unless they can be reached from another entrance.</td></tr>
<tr><td>2b

Caprock sinkhole</td><td>Void forms in underlying soluble rock, and then migrates upwards by stoping of caprock.
Individual failures are unlikely to exceed 20m wide and 20m deep.</td><td>
</td></tr>
<tr><td>3

Solution sinkhole</td><td>Rock dissolution mostly at rockhead beneath soil, on geological timescales.
Can exceed 500m wide and 30m deep.</td><td>
</td><td>Rock dissolution is too slow to be relevant to engineering projects. Subsidence sinkholes are common in the soil floors of depressions where natural drainage is into underlying fissures.</td></tr>
<tr><td>4

Buried sinkhole</td><td>Surface feature from a past environment, which is now filled with weak soils or loose debris.
Typically less than 100m wide and 20m deep.</td><td>
</td><td>Compaction of sediment fill, where surrounded by stable rock, can cause differential subsidence at the ground surface. Avoidable by founding structures on bedrock.</td></tr>
</table>

The given sizes are only to indicate orders of magnitude of typical maximum dimensions; many sinkholes are much smaller, particularly when they first develop. Ultimate sizes are hugely variable, especially when sinkholes have evolved through multiple stages over days, weeks or millennia.

Fig. 6. Suffosion, soil loss and collapse in action, exposed in the side of a large dropout sinkhole on an exposed salt dome on Qeshm Island, Iran. Because the bedrock, visible below the dark red soil, is salt (halite), dissolution is very rapid and the karst is developing far more rapidly than in limestone, although the processes are essentially the same in both.

Fig. 7. A new dropout sinkhole in cohesive silty soil in Turkey. It formed adjacent to recent construction works that had disturbed the local drainage patterns.

Fig. 8. A recent dropout sinkhole in clay-rich soil over limestone in Guizhou, China. It is still becoming larger: slices slump from its sides and the fallen debris is being washed away from beneath. The site is located downslope from a new highway, and the sinkhole was probably induced by a change in runoff pattern.

into and through the ground. Sinkhole failures caused by rainfall events can be regarded as natural and uncontrollable, but those caused by engineering activity are, or should be, avoidable.

Subsidence sinkholes

Distinct from all other karst landforms, subsidence sinkholes are formed entirely within the unconsolidated soil profile (i.e. regolith or overburden) overlying karst bedrock. They develop where soil is washed down into underlying cavities, a process known as suffosion or ravelling. Subsidence sinkholes are commonly 2–50 m across and 1–15 m deep, typically with a diameter that is less than three times the soil depth. Within the bedrock, the cavity that is the cause of the sinkhole, and is the outlet for the water and soil, might be a dissolutionally enlarged fissure as small as a centimetre wide at rockhead, or could be a shaft more than a metre across at a fissure intersection.

The two types of subsidence sinkhole (Table 3), dropout sinkhole and suffosion sinkhole (also known as cover collapse and cover subsidence sinkholes respectively), are opposite ends of a spectrum of morphologies, dictated largely by the soil's cohesion and its ability to bridge a void temporarily (Fig. 6). In reality, these extremes are rarely found, and nearly all subsidence sinkholes develop in a sequence of phases (over hours, weeks or decades) that increases depth and diameter. Their initiation may be a slow surface settlement, or a sudden appearance of a small open hole (the classic dropout). The initial event is typically no more than a few metres across (Fig. 7). A typical subsidence sinkhole then enlarges by its sides degrading to stable slopes and by its floor descending until stopped at bedrock (Fig. 8). This evolution may take place within just a few days, or the throat of the sinkhole may be temporarily choked, to be followed by multiple phases of reactivation over intervals of many years. People rarely die in sinkhole collapses, but the destruction of buildings and infrastructure can be extensive. A stronger cap material, notably concrete or asphalt road surfacing, may temporarily maintain the surface profile above an unseen soil cavity that might be many metres across, and the initial ground failures can then be both sudden and large in diameter.

Formation of these subsidence sinkholes is driven by water movement and the suffosional loss of soil. Consequently, it is to them that the mantra of 'control the drainage' is most applicable. It has long been recognized that the vast majority of new subsidence sinkholes are caused by man's activities (Newton 1987), and the message is still being repeated (Gutiérrez *et al*. 2014). New failures are caused either by increased inputs of water, normally by inadequate, changed or broken drainage systems, or by water table decline, which has a comparable drawdown effect or can induce failure by the loss of buoyancy support. A fissure large enough to swallow soil takes thousands of years to be formed by rock dissolution, but a new input of water, failure of a soil arch or washing out of a choke can cause a new sinkhole to develop in the soil profile within hours or days.

Many new sinkholes are triggered by major rainfall events. These can be described as natural features in the environment of an evolving landscape. It then has to be recognized that the rainstorms are very unlikely to be unprecedented, and their rainfall input is merely the 'final straw' following artificial changes in drainage patterns that have weakened the long-term equilibrium in the soil cover. The timing of a new sinkhole failure may well be determined by a rainfall event that is natural and unpredictable. However, it can still be considered to have been induced by prior changes to the drainage patterns, and that makes it predictable enough to be avoidable in most circumstances.

Sinkholes induced by drainage input

Almost any means by which a new or increased flow of water can pass through a soil cover into underlying fissured limestone, and thereby carry away soil, is likely to form a subsidence sinkhole. Because such drainage changes are commonly associated with engineering works, these induced sinkholes frequently cause

Fig. 9. An oil pipeline in Georgia is left with no support where it spans a sinkhole that developed beneath; this could have occurred soon after the inevitable drainage disturbance during construction, or subsequently owing to drainage water collecting in the trench-fill.

damage to built structures. In a typical cavernous limestone, fissures occur every few metres, and any could be large enough to allow removal of overlying soil, so new sinkhole locations are unpredictable in an area of total soil cover. However, an element of predictability is provided by the visibility, knowledge or interpretation of the sources of the water that are required to form each sinkhole. Any changes of surface drainage can disturb previously stable ground. Where not properly controlled, such changes thereby induce the majority of new sinkholes.

A stable situation of rainfall filtering through natural ground into myriad fissures in underlying limestone is easily disturbed by installation of a concrete or asphalt surface that concentrates runoff into a few perimeter points. Without built drains to carry the runoff away or directly to bedrock, any concentration of drainage input to the soil within a karst terrain becomes a potential site for a new sinkhole. Roads constitute effective rainfall catchments for runoff that requires careful control; unlined ditches are prime locations for new sinkholes (e.g. Moore 1988). Uncontrolled drainage along railways has also caused numerous sinkhole failures in China's karst (Guo 1991). Similarly, the granular seating within a pipeline trench can gather diffuse soil drainage that is then lost to a single fissure in underlying limestone, where a new sinkhole could rapidly undermine the site (Fig. 9); preventive measures include appropriate trench breakers and ditch linings. Changes to drainage are inevitable where soil cover is removed as part of almost any construction project, and account for the disproportionate number of new sinkholes during or soon after the period of site activity in a karst terrain. The hazard can be reduced only by *ad hoc* drainage control that is site-specific, and primarily avoids locally increased infiltration to the soil.

It is not always possible to engineer off-site drainage disposal away from roads, buildings, pipeline trenches, or any other built structure that gathers surface water. Retention ponds or soakaway drains (dry wells) that lose water into the soil cover are appropriate only where sited away from structures; an appropriate minimum distance is double that of the local soil thickness to allow for the flared sides of any new sinkhole and also some lateral flow along rockhead. It is better to direct flow into an open cave within bedrock, or construct wells that are cased into bedrock in order to avoid flow through the soil cover (Crawford & Groves 1995).

New sinkholes are all too common in the lowland karst that forms much of Florida, and structural damage is so extensive because many of the sinkholes occur beneath or adjacent to buildings. In part this is due to inadequate or poorly maintained storm-water drains around those building. Another major cause is leakage from fractured pipes (water supply lines, waste pipes or storm-water drains) beneath any building. A sinkhole in the Seffner suburb of Tampa received widespread publicity in early 2013 when it swallowed most of a house and one of its occupants. The unstable hole was quickly filled, so details went unseen, and the exact cause of the failure may remain unknown. It is likely that a leaking drain or water pipe was at least contributory to a failure that was entirely within the footprint of the building. However, a storm-water drainage pond adjacent to the back garden and less than 30 m from the house has to be considered as a possible source of water input and hence soil loss; the sinkhole was at least 10 m deep, and soil cover in the region is typically around 20 m thick. Subsequently, the remains of the house were demolished and the sinkhole was filled. Two years later, the sinkhole reopened when its debris fill subsided after a period of heavy rainfall. Such reactivation of a filled subsidence sinkhole is common; it is normally prevented only by clearing the site down to bedrock and then reinstating with a completely engineered fill (Vandervelde & Schmitt 1988; Waltham *et al*. 2005).

Southern China and the eastern USA have lost the greatest numbers of buildings to sinkhole collapses, the great majority of which have been induced by drainage failures. In a case of false economy, a multi-storey office building in Pennsylvania was founded on spread footings within a deep soil profile over limestone. It failed only 8 years after its construction during a wet winter when a sinkhole developed beneath some of the footings (Dougherty 2005). Expansion of the sinkhole was greatly accelerated when buried water pipelines were broken by the early stages of ground deformation, when the supporting soil was washed into underlying fissures in the limestone. The resultant subsidence caused terminal damage to the building. If the foundations had been extended to bear on bedrock, the sinkhole could have developed in the soil with little or no impact on the structure. It was inevitable that construction of the building had created some scale of change to the soil drainage. It was therefore wishful thinking that the soil could remain undisturbed during subsequent storm events that affected the modified urban environment.

Massive inputs of water can be generated by the filling of reservoirs impounded in karst terrains, so that sinkholes are induced within soil cover within or adjacent to the reservoir's footprint. In either situation, the sinkhole development is normally associated with major leakage from the impoundment, where massive grouting schemes then become necessary. Such was the situation at the Lar Dam, in the Elburz Mountains of Iran (Messerklinger 2014). Subsidence sinkholes are rare in soil cover that is more than about 50 m thick, but the scale of hydrological change imposed by impoundment of the Lar Reservoir was so great that a number of subsidence sinkholes developed in overburden that is several hundred metres thick. Though instigated by suffosional soil loss into fissured rockhead at depths of 200 m or more, the sinkholes' surface expressions were no more than about 25 m wide and deep after cavity migration from depth. A thick soil cover does not completely eliminate the sinkhole hazard in karst.

Water input also induces sinkholes in other situations. Compaction grouting is widely used in remediation of sinkholes in

Fig. 10. A large solution sinkhole in the gypsum karst of Sivas, Turkey (note person on left for scale). The floor of clastic soils is typical of these sinkholes and is of unknown thickness. Commonly there are small subsidence sinkholes developed within the soil cover; there are none at this site, but small-scale suffosion may be indicated by settlement of a pipeline buried in the soil.

Fig. 11. One of the pump-houses over wells into the limestone of the Shuicheng basin in China. The small new sinkhole just metres from it has been caused by water and soil descending into the cone of depression, aided by leakage from the broken pipe where it emerges from the building.

soil, but its injection can cause undesirable side effects (Zisman 2013). Boreholes using water flush have caused sinkhole collapses when investigating initial signs of ground movement. Emptying a swimming pool onto a garden lawn in the English chalk karst reactivated a buried sinkhole and undermined the house to the extent that it had to be demolished (Edmonds 2005). The dramatic effect of water input has been recognized by cavers in the Yorkshire Dales, who have opened up sinkhole entrances into caves by temporarily turning small streams to sites directly above known passages. Buried pipelines carrying Caspian oil through Turkey have to traverse a large area of gypsum karst near Sivas (Arthur *et al.* 2004), and inevitably cross numerous solution dolines that are typically around 100 m across with floor sediment 10 m or more thick (Fig. 10). These sinkhole floors have proved to be stable, except one where a pipeline settled very slightly after the local farmer had taken to ploughing his land on the sinkhole floor. This allowed increased rainwater infiltration to drive suffosional soil loss into fissures in the sinkhole's buried floor. The ground movement was slight, and the remedy was to compensate the farmer for not ploughing his field.

Sinkholes induced by water table decline

A lowered water table increases downward flow of water, with its accompanying soil suffosion, and can also remove or reduce buoyant support of soil and rock. It can induce clusters of new subsidence sinkholes across wide areas. These sinkholes are more numerous than those induced by drainage input, but many occur in farmland with less impact on structures. New ground failures are most common where the water table declines past the rockhead, so that minimal, lateral groundwater flow is replaced by focused, downward flow at the critical points of soil loss into bedrock fissures. The greatest clusters of new sinkholes develop during the first major rainstorm event after the water table decline, thereby confirming the role of increased downward flow. The two main reasons for water table decline are excessive abstraction for water supply and dewatering around mines and quarries. Both provide numerous examples of multiple sinkhole failures.

The early stages of China's grand expansion into the modern world saw many cases of over-exploitation of karst aquifers. Wells were sunk into the limestone floor of the Shuicheng basin in Guizhou to allow industrial development of the city of Liupanshui. The wellfield development was soon followed by formation of new subsidence sinkholes, totalling more than 1000 during the next decade. Nearly all were in the cones of depression around the abstraction wells (Waltham & Smart 1988). Many of these small sinkholes in the thin soil cover were in open farmland, but two of the 17 well housings were damaged beyond use by self-induced sinkholes (Fig. 11).

The Hamedan Plain of western Iran is formed on alluvial sediments 0–160 m deep in which the water table has declined by about 3 m per year through a combination of long droughts and increased abstraction of groundwater over a period of more than 20 years. This has induced both areal land subsidence by compaction of the alluvial clays and also a suite of sinkholes in areas where the alluvium overlies karstic limestone (Karimi & Taheri 2010; Khanlari *et al.* 2012). More than 30 new sinkholes include both dropout and suffosion types, reaching 100 m in diameter and 30 m depth. Most have formed close to deep abstraction wells. These new sinkholes are a greater geohazard than the areal subsidence, and a system of land zoning based on the extent of the buried limestone outcrop, the drawdown rate, and the relative levels of the water table and the rockhead is now in place.

It was recognized in the 1970s that over-abstraction of the western Florida aquifer in the Palaeogene Ocala Limestone was a major cause of sinkhole development (Metcalfe & Hall 1984). This was primarily due to the emergency pumping of warm groundwater to spray on fruit crops to protect them from frost damage during brief cold spells in winter. The resultant water table decline causes a significant peak in new sinkhole events in January, with another in May at the height of the dry season (Galloway *et al.* 1999). Sadly, there is no other way of protecting the valuable fruit crops, and another 60 new sinkholes were induced during a short cold spell in 2012.

The classic case of sinkholes induced by mine dewatering was that over the South African gold mines during the 1960s, when hundreds of houses were destroyed, more than 30 people died, and an entire town was evacuated (Swart *et al.* 2003; Waltham *et al.* 2005). Since then, the processes of mine-drainage-induced sinkholes have been repeated many times in China, creating a total of more than 30 000 new sinkholes across numerous sites. Remedial

Fig. 12. A chamber in the Koonalda Cave, Australia, with a roof that has evolved into a relatively stable roof in the horizontal, bedded limestone, above a floor of breakdown blocks and in-washed red sand.

action by the Chinese has largely been to control the drainage by selective abstraction, grouting at great expense and even air injection to reduce suction forces as water levels decline in closed conduits (Li & Zhou 1999).

Deep quarry drainage has induced numerous sinkholes in the USA, with some of the earliest recorded being those involving the Hershey chocolate factory in Pennsylvania (Foose 1968). Disputes between quarry companies and nearby home-owners who live over the cone of depression are frequently repeated. The case involving the Brookwood community, also in Pennsylvania, was typical in that no final resolution was attained; the quarry company has purchased and demolished a number of houses before and after they were undermined by new, induced sinkholes, but there are families still living with the threat of new sinkholes opening close to or beneath their homes (Waltham 2008). Short of closing the quarry and allowing it to flood, any remedial works can only be a short-term compromise.

Cave chambers and potential collapse

Failures of strong limestone bedrock are rare and are unlikely to occur within engineering timescales, except where directly caused by excessive imposed loads. However, very large cave chambers do exist in limestone, and are continuing to evolve on geological timescales. Their evolution normally involves roof collapse by stoping, possibly accompanied by wall failure (Fig. 12). The effect is upward migration of the cavity, potentially as far as the surface where a collapse sinkhole may then be formed. The size, stability and migration rate are largely functions of the fracture density and mass strength of the limestone.

Fractures and fissures in many cavernous limestones render them of only moderate or fair rock mass strength (rock mass rating (RMR) = 30–50, rock mass quality (Q) = 2–7). It is massive and minimally fractured limestone with very high mass strength (RMR > 90, Q > 100) that contains the largest cave chambers (Waltham & Fookes 2003). Sarawak Chamber, on the island of Borneo, has a roof spanning some 300 m with a stable, low-profile arch that rises less than a third of its width in gently dipping limestone where bed thickness is many tens of metres. The cavern is more than 600 m long and floored with breakdown blocks, but calcite dripstone on these indicate that the site has been broadly stable for at least 30 000 years; the cave is probably more than a million years old (Smart 2015).

In contrast to Sarawak Chamber, a number of large cave chambers in China are narrower but reach heights around 300 m. Their roofs have migrated upwards by stoping of successive beds while their cave rivers have removed the fallen debris by dissolutional erosion. Ultimately these cave chambers may reach the surface, as others have already done, to create the giant collapse sinkholes known as tiankengs (Zhu & Waltham 2005). The largest of these, also in China, are many hundreds of metres across. It appears that many of these giant sinkholes have formed by the coalescing of multiple collapsing chambers over geological timescales (Waltham 2005). However, Cloud Ladder Hall, in a cave in China's Wulong karst, is about 100 m in diameter and is 340 m tall, with only about 50 m of rock between its domed roof and the hillside above; this has been described as a proto-tiankeng, and could well evolve by way of a massive ground failure. It is, however, a little different from most other tiankengs in that its more thinly bedded limestone has facilitated the roof stoping and cavity migration. In contrast, some other roof collapses that have migrated far have filled their underlying chamber with bulked rock debris when there is no cave stream to remove it from below. The resultant pile of debris, with or without a void over its top, can be described as a breccia pipe (Fig. 13).

Fig. 13. A natural cliff, about 40 m high, in thin-bedded limestone on one of the islands in Halong Bay, Vietnam. It has exposed a breccia pipe of fallen rock debris filling a void that was originally close to water level and has migrated upwards by roof stoping. The small cave on top of the debris column is now probably stable with its arched roof across a reduced span.

Smaller cave chambers are known in karst terrains around the world. The typical chamber has an arched roof over a pile of breakdown blocks, which obscures details of the original and present floor profile (Fig. 14). With roof profiles at or close to that of a voussoir compression arch, these chambers can generally be regarded as stable features within the ground. Exceptions are rare, where clear signs of active breakdown of the roof or walls indicate instability of a cavern. Stalagmites being formed on the breakdown confirm a lack of movement in most caverns. Numerical modelling has indicated that caves less than 18 m wide remain stable with a cover thickness that is only a third of the cave span, whereas much

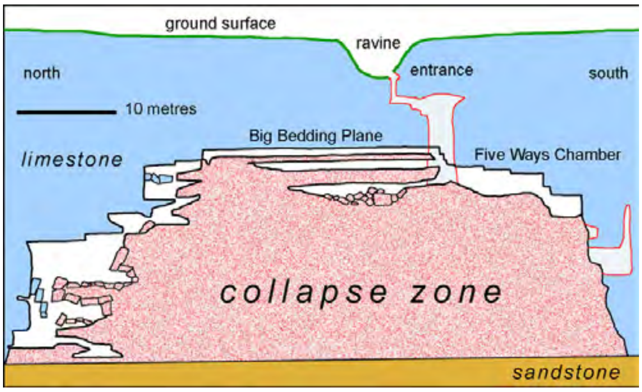


Fig. 14. Section through a cave chamber in the Yorkshire Dales, with a thick bed of almost horizontal limestone forming the crest of a stable arch over a pile of fallen rock (after Harrison & Ryder 2016). This is the long profile of a collapse zone that is largely constrained by parallel fractures only about 15 m apart. At the top of the collapse, Big Bedding Plane is the name given to the chamber that is 25 m long, 12 m wide and just 1 m high. The two very large slabs of limestone beneath it are not held in cantilever but are supported on fallen blocks in the third dimension outside this line of section. The floor of the debris pile is unseen, but the initial cave development was almost certainly on the base of the limestone (whose position is known from adjacent caves). Bulking of the collapse debris has been accommodated by dissolutional removal by streams draining through its base.

Fig. 15. A new caprock sinkhole in the Obruk Plateau of central Turkey. A circular zone nearly 50 m across has dropped by less than 2 m as it settled on the column of debris that lies beneath (compare with the breccia pipe in Fig. 13).

wider caves are stable only where cover and span are equal (Hatzor *et al.* 2010). This may reflect spanning of smaller caves by unbroken beds of limestone, whereas wider caves have to evolve towards an arched roof profile. Without the imposition of structural load, the statistical risk of a chamber in a limestone cave failing, and thereby creating a collapse sinkhole, are extremely small. Though collapse sinkholes are widespread features of karst landscapes, they have developed over long intervals of time.

Collapse sinkholes

New sinkholes formed by random rock collapse are not normally a significant geohazard in karst. This concept includes both collapse sinkholes entirely within a cavernous limestone, and also caprock sinkholes that incorporate collapse in beds above the limestone. Both types are common enough in some karst terrains, but have formed over geological timescales, and new collapses are rare. The southern part of the Konya basin, in central Turkey, provides unusual examples of new failures (Doğan & Yilmaz 2011; Waltham 2015). The Miocene limestone of the Obruk Plateau has numerous sinkholes, each hundreds of metres across and 50–100 m deep. These are old collapse features now partially degraded, though many still have limestone cliffs round their perimeters; some have lakes on their floors. The 20 sinkholes that have formed within the last 40 years are in the Quaternary sequence of mudstones and siltstones that reaches 100 m thickness on top of the limestone. These are therefore caprock sinkholes. The new features are 10–50 m across and 1–80 m deep, with vertical or overhanging sides.

All these new sinkholes have formed over caves that lie unseen beneath the water table and drain the plateau northwards. They developed by roof stoping. It is likely that the seven holes that opened to depths of more than 20 m previously had significantly large chambers or active stream caves. Some others opened to smaller depths where the surface block just dropped onto the top of a column of debris (Fig. 15). There were no visible signs on the surface prior to the sudden collapses. However, the villagers of Inoba heard the rumblings of the progressive underground collapses for a few days before the hole opened up overnight adjacent to their village and 35 m deep (Fig. 16).

The main trigger for the recent phase of accelerated sinkhole development has been a 24 m decline of the water table owing to large-scale abstraction for farmland irrigation. Roof collapse of deep cavities has been exacerbated by the loss of buoyant support with the decline of the water table. However, it is very likely that a contributory factor at some sites has been suffosional loss by the increased input of irrigation water. The large old sinkholes in the Obruk Plateau are unusual in that their origins trace back to dissolution by aggressive, rising volcanic water (Bayari *et al.* 2009). The new collapses probably relate to similar deep-seated processes, which makes their locations over an unknown pattern of basement fractures effectively unpredictable. This plateau is just one of many sites where hypogene dissolution is now recognized as having played an important role in cave development (Klimchouk 2007). Such caves may bear little or no relationship to the karst topography, making their locations even more difficult to determine from surface observations. Though the final ground failures in the Obruk Plateau appear to be induced by both drainage factors, namely losses from below and increased input on the surface, their deep-seated origins allow neither predictions of, nor precautions against, future events.

Collapse sinkholes can be more active and more common in gypsum karst, owing to the low strength of gypsum and its more rapid dissolution in water. The cluster of sinkhole events that continue to affect the Yorkshire town of Ripon are well documented (Cooper 1998, 2005). These originate by collapse into unseen, active, water-filled caves within the gypsum and about 50 m below ground level; lines of sinkholes may relate to major fractures or cave passages within the gypsum. Some failure events are due to settlement within the columns of debris and soils that form breccia pipes infilling old collapse features. These can be reactivated by incursions of surface water, so appropriate drainage control can reduce, but not eliminate, this geohazard (Fig. 17).

The gypsum karst near Sivas, Turkey, contains a scattering of large, old collapse sinkholes, and the possibility of new sinkhole events presented a small but significant geohazard to recent construction of pipelines across the karst (Waltham 2008). Any cave in gypsum is unlikely to reach more than about 30 m across, but the largest of the collapse sinkholes at Sivas is more than 300 m in diameter. A nearby sinkhole is filled by a lake to within less than 10 m of its rim mainly formed by large collapsed blocks; this site demonstrated the sinkholes' evolution by progressive collapse in staged increments, each of which is also no more than about 30 m across (Fig. 18). A pipeline that could span a void of 44 m was therefore deemed safe in this terrain. Drainage control measures

Fig. 16. The caprock sinkhole that appeared overnight near the village of Inoba, on the southern side of Turkey's Obruk Plateau. The hole has vertical sides to a depth of 35 m.

Fig. 17. One of the destructive caprock sinkholes formed by collapse over cavities in the gypsum that underlies the town of Ripon.

would have minimal influence on the collapse process; they were, however, warranted, and included in the design, where clastic sediments filled old sinkholes along the pipeline corridor (Fig. 10).

Rock collapse under imposed loads

Natural caves can be formed at any position, at any depth and to any size within karst terrains, but only the larger caves at smaller depths are relevant to engineering works on the ground surface. The load-bearing capacity of the rock roof over caves can vary enormously, depending on the shape of the cave and the fracture patterns and mass strength of the rock. Each situation requires separate assessment. Numerical modelling relates cave width, cover thickness and rock mass rating to safe loads (Waltham & Swift 2004; Waltham & Lu 2007), and a roof thickness that exceeds about half the cave width appears to be stable for most structural loading on typically strong cavernous limestone. This can be only a rough guideline, but is supported by observations in various caves that lie beneath built structures, and can provide some guidance for depths to be investigated during ground assessment (Table 4). In an ideal, but non-existent, world every cave would be assessed separately, but the numbers in this table can give an engineer some indication of the scale of the problems in karst terrain.

Table 4. *Stable roof thicknesses for caves in various rock types and karst environments*

Rock type (and karst class)	Imposed load (kPa)	Cave width (m)	Stable thickness of rock cover (m)
Strong limestone (kI–III)	2000	5	3
Strong limestone (kIV)	2000	5–10	5
Strong limestone (kV)	2000	>10	7
Weak limestone (and chalk)	750	5	5
Gypsum	500	5	5
Basalt lava	2000	5–10	3

These values can only be very rough guidelines, but are an indication of the depths at which caves become irrelevant to most surface engineering works. Values for cave widths are merely representative of the larger sizes that might be anticipated in each rock and karst class. Caves wider than about 10 m require separate assessment. Values for the imposed loads are broadly those of the safe bearing pressure on intact rock of the type. The derivation of these guidelines has been explained by Waltham & Lu (2007); the karst classes refer to the designations of Waltham & Fookes (2003).

Sadly, there are cases where structures have collapsed into caves. Failure of a pier of an elevated freeway under construction in Florida was a simple case of excessive loading on a thin rock roof over a small cave that had not been found by an insufficient

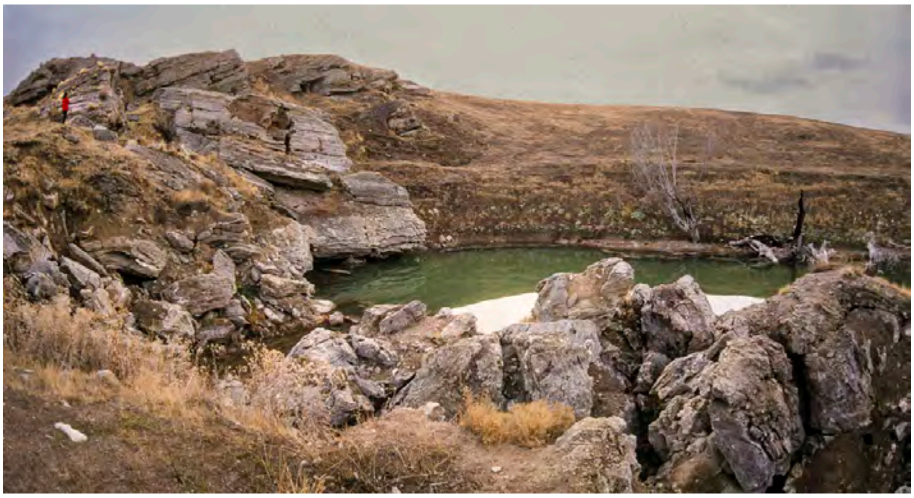


Fig. 18. A collapse sinkhole developing where the ground surface is locally only a few metres above the water table in the gypsum karst of Sivas, in Turkey (note person on the left for scale). Sizes of the displaced blocks suggest that the collapse develops by increments that are each only 10 or 20 m across.

Fig. 19. The collapse sinkhole that destroyed Dishman Lane in Kentucky, with an initial failure where ground collapsed into the wide cave less than 5 m below the surface. This image was taken when collapse debris had been removed prior to installing a stable fill. The thin cave roof is exposed in profile, with some of the deep soil-filled fissures and miniature buried sinkholes visible above the arm of the backhoe (photograph by courtesy of Hilary Lambert).

ground investigation. Probes to only 3 m below toe depth for heavily loaded piers in weak limestone, which is known to be cavernous, are not sufficient to eliminate undue risk (Waltham 2008). Failures in planning management led to a Kentucky highway being constructed over a large cave that was known but not fully appreciated. Soon after project completion the roof of the cave, just a few metres thick, completely collapsed (Kambesis & Brucker 2005). The modest load imposed by the highway was only partly to blame for the collapse. The roadbed was founded on soil overlying the limestone, and rainwater seepage created unstable soil cavities beneath the road by subsoil suffosion into bedrock fissures (Fig. 19). It is likely that the final trigger for the failure was collapse of a soil arch, which dropped an additional load onto a critical point in the thin and marginally stable limestone over the cave. It was a rare case of rock collapse induced by uncontrolled drainage, rare because water moves soil very easily but has little impact on rock that is either intact or in compression.

Where a cave is found to exist, and a structure cannot be relocated away from it, filling with mass concrete may be the easy option. However, this can encounter difficulties in restricting losses of fill into potentially extensive cave passages outside the area to be stabilized. An alternative can be the installation of metre-diameter bored piles that pass through the cave into stable rock beneath (Fig. 20), as was the case to support the courthouse in Huntsville, Alabama (Waltham *et al*. 2005). The Yucatan Peninsula, Mexico, is a limestone platform with extensive networks of caves at shallow depth; these were formed at past positions of the halocline (freshwater–saltwater interface) when sea levels were lower during the Pleistocene. The main coastal highway successfully crosses above a number of these caves, utilizing pile foundations that pass through them where high point loads and thin rock covers dictate.

Prediction of cave locations

It is an inconvenient truth that the only thing predictable about caves is that they are unpredictable. Caves and karstic fissures are developed by water flows, but the positions of a stream sink and of the resurgence to which it drains provide no indication of the path and position of the intervening caves (Fig. 21). It is usual that caves and fissures are developed along joints, faults and bedding planes within their host rock, but it is rarely possible to determine which particular fractures are followed. Once seen, a cave may be interpreted, but it cannot be predicted ahead of inspection.

The apparently random distribution of karstic cavities has implications in ground investigation. Almost any interpretation of ground conditions in karst will be a major simplification of the 3D complexities that really exist, or are revealed only after large-scale excavations commence (Fookes *et al*. 2015). Importantly, voids intersected by two adjacent boreholes cannot be simply interpreted as one cave extending between them in something close to a straight line. Multiple boreholes, or direct access, are required to delimit any cave topography and footprint. Beyond probing every column base, the spacing of boreholes for an extensive project has to be assessed with reference to both the intended structural loading and the best possible acquired data on the local extent and size of caves. A conservative approach would require each probe to confirm intact rock to a depth roughly equal to the width of caves likely to occur at the particular site (Waltham *et al*. 2005). The actual width of a cave remains unknown until it is found, so estimates of the likely width can be based only on any available local data, on inspection of nearby known caves, and on the scale of karst development or maturity that can be recognized in the surrounding terrain.

Construction of the Remouchamps Viaduct in Belgium provided a classic case of the karst geohazard when a system of caves was just missed by the four boreholes at the one pier site (Waltham *et al*. 1986). By good fortune, one extremity of the caves was breached by subsequent excavation for the footing; the pier was then re-sited. Four boreholes were too few to ensure foundation stability for such a large structure on limestone that was known to be cavernous, and the potential cost of extra boreholes was far

Fig. 20. Big Spring Cave, beneath the courthouse in Huntsville, Alabama. (left) Part of the width of the main passage, where beds of the nearly horizontal limestone have fallen from the roof, so that the open space is now on top of slabs stacked 5 m deep. (right) A steel-cased, bored pile that extends through the cave and debris fill, and carries its load to stable rock beneath the cave floor.

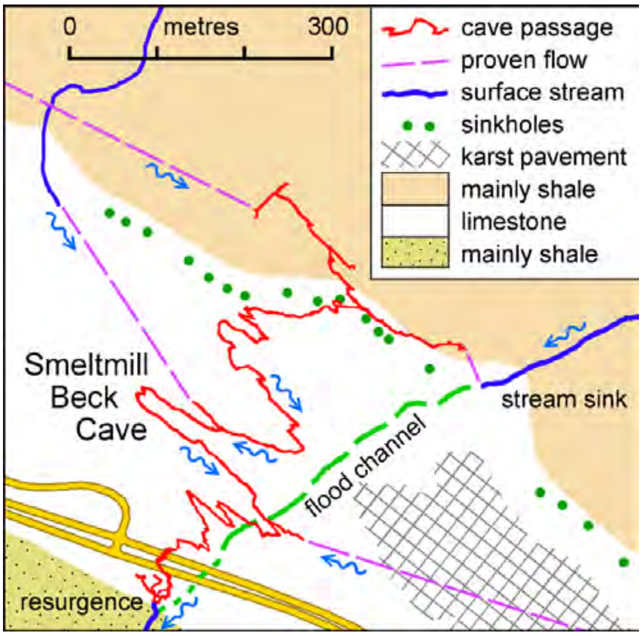


Fig. 21. A cave in northern England guided by joints to take a zig-zag course between sink and resurgence. This map shows only open cave passages and cannot include fissures too small to enter but very capable of transmitting water and swallowing soil. Most of the cave passage is less than 4 m high and 2 m wide, with 5–25 m of cover to the ground surface. Away from the limestone pavement, most of the outcrop is obscured by a thin cover of glacial till, and the marked line of sinkholes has been formed by runoff from the shales overlying the horizontal limestone.

exceeded by the costs incurred owing to the consequent project delay.

Geophysics offers some prospect in cavity searches, and numerous techniques have been attempted (Benson & Yuhr 2016). Microgravity surveys are probably the most useful because a cave creates a clear negative anomaly even if it is filled with water, breakdown or sediment (Styles *et al*. 2005). An extensive microgravity survey in the Bahamas revealed numerous water-filled caves at depths of around 10 m, some of which were subsequently ground-truthed by cave divers. Whatever its form, 'missing mass' revealed by a microgravity survey has to indicate ground of poorer quality with respect to planned engineering works. Cross-hole seismic tomography can be useful to define single features where the borehole network is available, but all other methods have debatable value and variable or low success rates in cavernous limestone (Waltham *et al*. 2005).

Anticipation of sinkhole events

New subsidence sinkholes have elements of predictability, in that they are likely to follow after major rainfall events and to be located where new drainage water (either seen or unseen) has been allowed to enter the ground. Beyond those indicators, the potential locations of new sinkholes are practically impossible to determine where a continuous soil cover overlies limestone. They could occur wherever there are dissolutionally enlarged fissure open at rockhead. Most fissures have some pattern in that they are nearly all aligned on joint systems, but which parts of which fissure have been widened follows no predictable pattern (Fig. 22).

Short of stripping away the soil cover, open fissures and potential sinkhole sites cannot be determined by any practicable level of ground investigation. Among geophysical techniques, only electrical resistivity surveys are economically viable over large sites or along transport corridors. However, such surveys suffer from the fact that a cavity filled with clay or water creates a negative anomaly whereas a dry, open cavity creates a positive anomaly. Consequently, ground with both open and filled fissures tends to cancel out its own anomalies. Of 21 electrical anomalies identified along a pipeline corridor across gypsum karst in Turkey, only one was proven by confirmation drilling to have a significant cavity beneath it (Arthur *et al*. 2004). It would appear that the complex of underground karst features did not provide interpretable resistivity signals. However, a resistivity survey in the Tournaisis karst in Belgium has proved useful in identifying buried fissure zones that are potential sinkhole sites, although 3D modelling was found to provide results that were more reliably interpreted than those from modelling in two dimensions (Kaufmann *et al*. 2012). Depth limitations on ground-penetrating radar restrict its use in karst, but the rockhead throats of potentially active sinkholes have been recognized at some sites (Tallini *et al*. 2006). Radar instruments towed behind vehicles can offer rapid surveys of newly disturbed ground beneath roads, which may indicate suffosion and imminent sinkhole failure. Radar surveys have also been used in soil-covered karst on chalk and limestone in France to identify similar, small, initial disturbances that can be critical to the integrity of high-speed railways. Evolution in technology continues to offer improvements in ground investigations and site characterizations; a useful suite of case histories, using various geophysical techniques and borehole investigations, has been presented by Benson & Yuhr (2016).

The drainage factor

It is inevitable that buildings and infrastructure have to be placed on the huge areas of soil-covered karst terrain that exist around the

Fig. 22. Limestone exposed in a pre-split face about 5 m high alongside a road in Alabama, USA. Every few metres along the face there is a clay-filled fissure, a zone of narrow fissures or a buried sinkhole. All of these would have been potential sites for new subsidence sinkholes within the few metres of soil cover that has been removed along the crest (and replaced by the bank of limestone boulders).

Fig. 23. A small, new subsidence sinkhole in soil-covered dolomite karst in South Africa, clearly induced by the leakage from the water pipeline that is now exposed (photograph by courtesy of the late Fred Bell).

world. It is equally inevitable that most of the buildings and nearly all the infrastructure are founded within the soil profile that overlies the cavernous limestone. All these soil-founded structures are then prone to undermining by suffosional soil losses and development of subsidence sinkholes. It then has to be accepted that the position and state of almost every rockhead fissure lies unassessed and unseen beneath the soil cover. Ground investigation to locate every fissure, and thereby every potential sinkhole site, is practically impossible within any reasonable budget.

Subsidence sinkholes within the soil profile are the predominant karst geohazard, and consequently the most cost-effective means of reducing the sinkhole risk is to control the drainage. Essentially this means preventing any new inputs of water to the soil profile. Water is insidious, with every new inflow finding its own outlet; the resultant flow creates the potential for suffosion and soil loss into the underlying limestone. New inputs are created by increased runoff from concrete or asphalt, or by poorly placed soakaways, or by broken drains and pipelines (Fig. 23), or by uncontrolled stormwater, or merely by stripping off topsoil. Preventing these changes is the best means of minimizing new sinkhole events, and is normally within the scope of appropriate site management. Water table decline also causes new sinkholes, but generally requires regional management and control. Storm events trigger new sinkholes, most of which occur where the drainage has been disturbed since the previous excessive rainfall event. Storms are little more than the trigger process for sinkhole development in natural ground that has evolved over geological timescales. The formation rate for purely natural new sinkholes is only a tiny fraction of the rate at which new sinkholes are induced by engineering activity.

'Control the drainage' should therefore be a mantra for engineers working in karst terrains. It is certainly the gospel that should be accorded to sinkholes, in order to minimize the potential for development of new and destructive ground failures.

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