Engineering classification of karst ground conditions

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Abstract

On a world scale, the dissolution of limestone and gypsum by natural waters creates extensive karst landforms that can be very difficult ground for civil engineers. Caves threaten foundation integrity, notably where their width is greater than their roof thickness. Sinkholes pose many problems, and are classified into six types, including subsidence sinkholes formed in soil cover within karst terrains. Rockhead morphology varies from uniform to pinnacled, also creating difficult ground to excavate or found upon. A proposed engineering classification of karst defines various complexities of ground conditions by the geohazards that they provide, mainly the caves, sinkholes and rockhead relief. Ground investigation techniques and foundation design philosophies are considered so that they are appropriate to the ground conditions provided by the different classes of karst.

Keywords: karst, classification, geohazards, limestone, gypsum

Introduction

Karst problems worldwide create huge annual costs that are increased due to insufficient understanding of karst by engineers. Karst is a distinctive terrain developed on soluble rock with landforms related to efficient underground drainage. Disrupted surface drainage, sinkholes and caves are diagnostic. Three-dimensionally complex natural cave passages create uniquely difficult ground conditions for civil engineering (Sowers 1975; Waltham 1989). Solid limestone of high bearing capacity is interspersed with open and sediment-filled voids at shallow depth that threaten foundation integrity and excavatability. The unpredictability of these features increases the problem for the ground engineer.

An engineering classification of karstic ground conditions provides guidelines to the potential variation in landforms and ground cavities that may be encountered in civil engineering works on karst. The different karst landforms relate to each other, but the local geological, hydrological and climatic conditions create suites of karstic features with almost infinite variety (Ford & Williams 1989). In our experience, there is no substitute for a proper understanding of local karst processes – and accepting that ground cavities may be encountered almost anywhere.

Karst processes

Karst occurs primarily on limestones (and dolomites), and ground cavities and dissolutional landforms develop best on competent, fractured rocks whose intact unconfined compressive strength is generally 30–100 MPa. Weaker limestones, chalk and unlithified carbonate sediments lack the strength to span large cavities, and develop limited suites of karst features that are generally smaller than those on stronger limestones (Higginbottom 1966; Jennings 1968; White 2000). Offshore carbonate sediments normally have no karst features, as most seawater is saturated with calcium carbonate. Dissolution and redeposition typify the coastal sabkha environment, but are components of diagenesis, and karstic features are modest. Subsea karst may develop in limestones carrying drainage from adjacent land and may also include features inherited from erosion during past times of lower sea levels. Gypsum karst has many features comparable with those on limestone, but is distinguished by wider development of interstratal karst and greater numbers of breccia pipes (Klimchouk *et al.* 1996), and it does not mature through to cone karst or tower karst; the following notes are generally applicable to gypsum karst except where identified separately. Rock salt is so rapidly dissolved that it has its own suite of landforms and ground conditions (Waltham 1989); this classification is not applicable to salt karst.

Dissolution of calcium carbonate in water is primarily dependant on the availability of biogenic carbon dioxide, which occurs at the highest concentrations in deep soils and in tropical areas where decomposition of organic matter is rapid. Regional climate has a strong influence on karstic landforms by its control of recharge to water flow regimes. Thus the most mature karst occurs in wet tropical environments. Limestone dissolution is reduced in temperate regions, and is minimal in arid, periglacial and glacial regimes (Smith & Atkinson 1976). However, while an expectation of ground conditions in civil engineering sites on karst is broadly related to climate, past climates are also significant. Features may survive from previous environments that were wetter and/or warmer, and many of these may be buried as palaeokarst.

Limestone dissolution is slow. Surface lowering and wall retreat within fissures and caves are no more than a few millimetres per 100 years, though may be faster in fissures under very high flow conditions created by dam leakage (Dreybrodt *et al.* 2002). The major engineering hazard is the downward washing of soil into old and

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Fig. 1. Dissolution features in the Yorkshire Dales karst of England. The Buttertubs are vertical-sided sinkholes that have been cut into the limestone, leaving between them undercut and unstable rock pillars about 10 m tall. These features are largely subaerial, but comparable sinkholes lie hidden beneath the soil cover in the same karst region.

stable rock voids to create failures. A lesser hazard is failure of limestone over voids that are marginally unstable after dissolution lasting a million years. Gypsum dissolution is much faster, and creation of a cavity potentially 1 metre across within 100 years is an extra geohazard in gypsum karst.

Karst morphology

Karst has an infinitely variable and complex three-dimensional suite of fissures and voids cut into the surface and rock mass of the limestone (Fig. 1). Dissolution of rock occurs on exposed outcrops, at the rockhead beneath soil, and along underground fractures. Surface, rockhead and underground landforms are integrated within karst systems, but fall into five broad groups of features (Lowe & Waltham 2002):

Surface micro-features – karren runnels, mostly <1 m deep, produced by dissolutional fretting of bare rock (Bögli 1960), including grykes, cutters and inherited subsoil rundkarren, and ranging in size up to pinnacles 2–30 m high in pinnacle karst (Waltham 1995);
Surface macro-features – dry valleys, dolines, poljes, cones and towers, all landforms on the kilometre scale that are elements within different types of karst (Ford & Williams 1989);
Subsoil features – complex morphologies of rockhead with local relief that may exceed tens of metres, created by dissolution in soilwater (Klimchouk 2000);
Sinkholes – various surface depressions, 1–1000 m across, that are related to underlying rock cavities (Bell *et al.* 2004);
Caves – cavities typically metres or tens of metres across formed within the rock by its dissolution, and left empty or filled with sediment (Ford & Williams, 1989).

Karst types

Surface macro-features combine to make the distinctive landscapes of karst. Assemblages of karst landforms create the main types of limestone karst, each of which has its own characteristics, and is developed largely in a specific climatic regime (Ford & Williams 1989; Waltham 2003).

Glaciokarst has extensive bare rock surfaces with limestone pavements, rock scars and deeply entrenched gorges; it occurs at higher altitudes and latitudes, where it was scoured by the ice and meltwater of Pleistocene glaciers and has minimal development of postglacial soils; e.g. the Yorkshire Dales region of England.

Fluviokarst has extensive dendritic systems of dry valleys, cut by rivers before they were captured by underground drainage into caves; most occurs in regions that were periglacial during the cold stages of the Pleistocene; e.g. the Derbyshire Peak District of England.

Doline karst has a polygonal network of interfluves separating closed depressions (dolines), each 100–1000 m across, that have replaced valleys as the dominant landform because all drainage is underground; it is a mature landscape, developed in temperate regions with Mediterranean climates; e.g. the classical karst of Slovenia and the low-lying karst of Florida.

Cone karst (fengcong karst) is dominated by repetitive conical or hemispherical limestone hills, 30–100 m high,

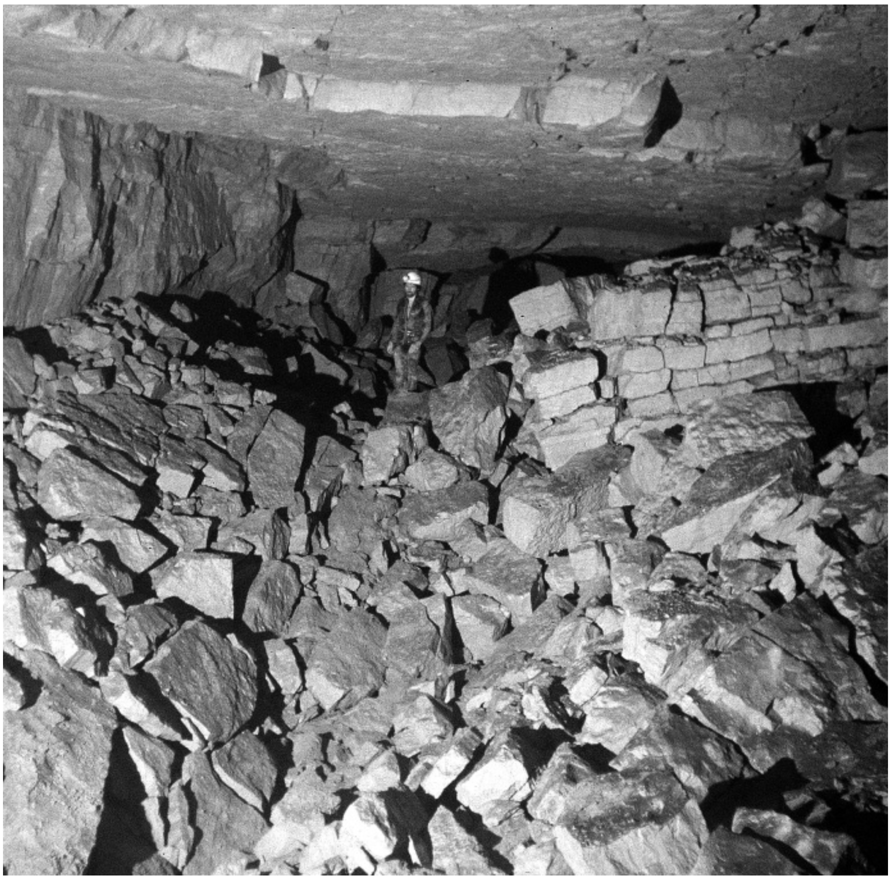

Fig. 2. Progressive bed failure of a passage roof in the Agen Allwedd Cave in South Wales. The breakdown process causes upward migration of the void over an increasing pile of rock debris; in this case, the original dissolution cave was 12 m below the present roof, but this migration has probably taken over 100 000 years.

between which the smaller closed depressions are stellate dolines and the larger are alluviated poljes; it is a very mature landscape, largely restricted to inter-tropical regions; e.g. the Cockpit Country of Jamaica, and the fengcong areas of Guizhou (China).

Tower karst (fenglin karst) forms the most dramatic karst landscapes with isolated, steep-sided towers rising 50–100 m above alluviated karst plains; it is the extreme karst type, restricted to wet tropical regions with critical tectonic uplift histories that have allowed long, uninterrupted development (Zhang 1980); e.g. the Guilin and Yangshuo region of Guangxi (China).

There are recognizable subdivisions of these main karst types, and there are also additional landscape styles, e.g. formed in arid regions where karst development is minimal. Construction practice is inevitably related to these geomorphological types, but an engineering classification of karst is more usefully based on the specific features that have the major influence on ground conditions, namely the caves, the sinkholes and the rockhead morphology.

Caves in karst

Caves form in any soluble rock where there is an adequate through flow of water. Flow rates and the water's aggressiveness (degree of chemical undersaturation) mainly determine rates of cave enlargement, which originates on bedding planes and tectonic fractures (Lowe 2000). These enlarge to networks of open fissures, and favourable flowpaths are enlarged selectively into caves (Palmer 1991; Klimchouk *et al.* 2000). Caves may be abandoned when their water is captured by preferred routes, they may be wholly or partially filled with clastic sediment or calcite stalagmite, or they may degrade and collapse when their dimensions create unstable roof spans (Fig. 2). Filled caves may appear as sand or clay pipes within the solid rock. Progressive roof collapse, and cavity stoping that propagates upwards may create a pile of fallen rock in a breccia pipe within the solid limestone.

Cave dimensions vary greatly. In temperate regions cave passages are generally less than 10 m in diameter; caves 30 m in diameter are common in the wet tropics. The largest single cave chamber is over 300 m wide and 700 m long, in a cave in the Mulu karst of Sarawak, Malaysia. All voids in a block of karstic limestone are interconnected because they were formed by through drainage; narrow fissures, wide river passages and large chambers are merely elements of a cave system. Though cave morphology may be understood in terms

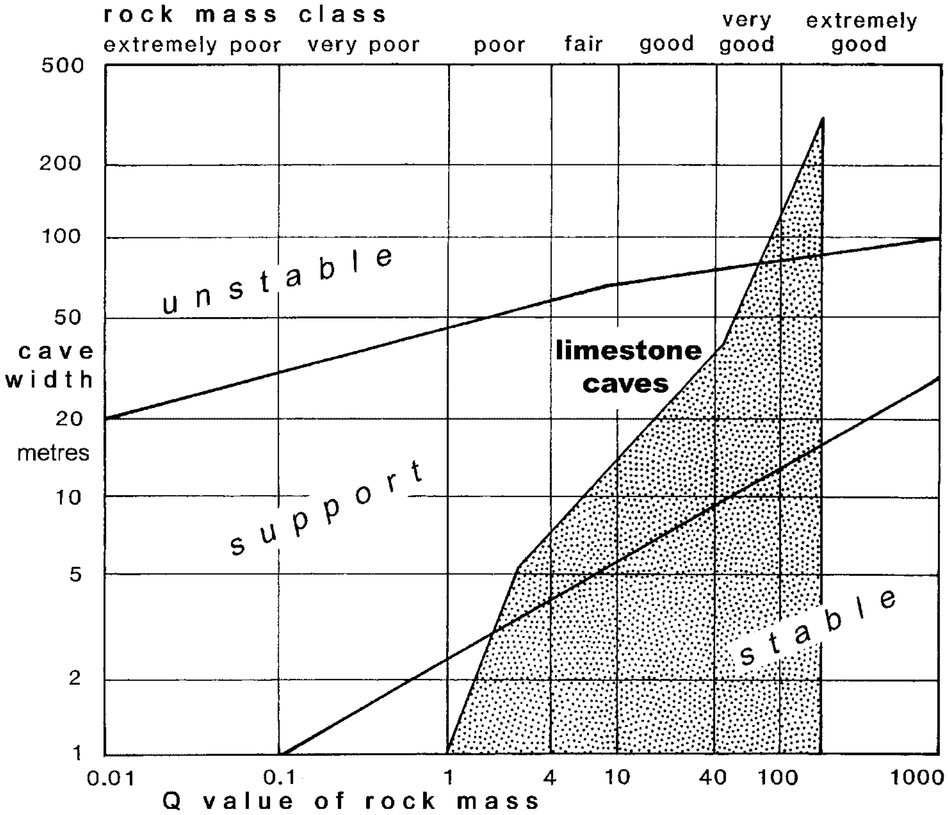

Fig. 3. Cave stability related to cave width and rock mass quality (Q value after Barton *et al.* 1974). The envelope of the limestone caves field is derived from observations of caves around the world. The labelled fields of *stable*, *support* and *unstable* are those applied in guidelines for the Norwegian Tunnelling Method; they refer to engineered structures with public access, and are therefore conservative when related to natural caves. The top apex of the envelope is defined by the parameters for Sarawak Chamber; the roof span of this chamber is stable on engineering timescales, but isolated blockfall from the ceiling would render it unsatisfactory were it to be used as a public space.

of limestone geology and geomorphic history, the distribution of cave openings in an unexplored limestone mass cannot be predicted (Culshaw & Waltham 1987). Unknown cave locations remain a major problem in civil engineering.

Most natural caves in strong limestone are stable in comparison to artificially excavated ground caverns (Fig. 3). Most caves lie at depths within the limestone where stable compression arches can develop within the roof rock so that they constitute no hazard to normal surface civil engineering works. The potential hazard lies in the large cave at shallow depth, where it may threaten foundation integrity. An informal guideline to the stability of the natural rock roof over a cave is that the ground is stable if the thickness of rock is equal to or greater than its span; this excludes any thickness of soil cover or heavily fissured limestone at rockhead. This guideline is conservative. In typical limestone karst the rock mass is of fair quality (Class III), with Q = 4–10 on the classification scheme of Barton *et al.* (1974), and RMR = 40–60 on the rock mass rating of Bieniawski (1973). In such material, a cover thickness of intact rock that is 70% of the cave width ensures integrity (Fig. 4) under foundation loads that do not exceed 2 MPa – which is half the Safe Bearing Pressure (SBP in Fig. 4) appropriate for sound limestone.

Simple beam failures provide a 'worst-case' scenario, as caves naturally evolve towards arched roof profiles with partial support from cantilevered rock at the margins. This concept of required roof thickness is therefore conservative. It covers limestone with a normal density of fractures and bedding planes; local zones of heavy fissuring may reduce cave roof integrity. Gypsum is weaker. A greater cover thickness is therefore required over a gypsum cave, even for low foundation loads, and this must also account for further enlargement of the cave within the lifetime of an engineered structure.

Sinkholes in karst

The diagnostic landform of karst is the closed depression formed where the ground surface has been eroded around an internal drainage point into the underlying limestone. These depressions are labelled dolines by geomorphologists, but are generally known as sinkholes by engineers (regardless of whether streams sink within

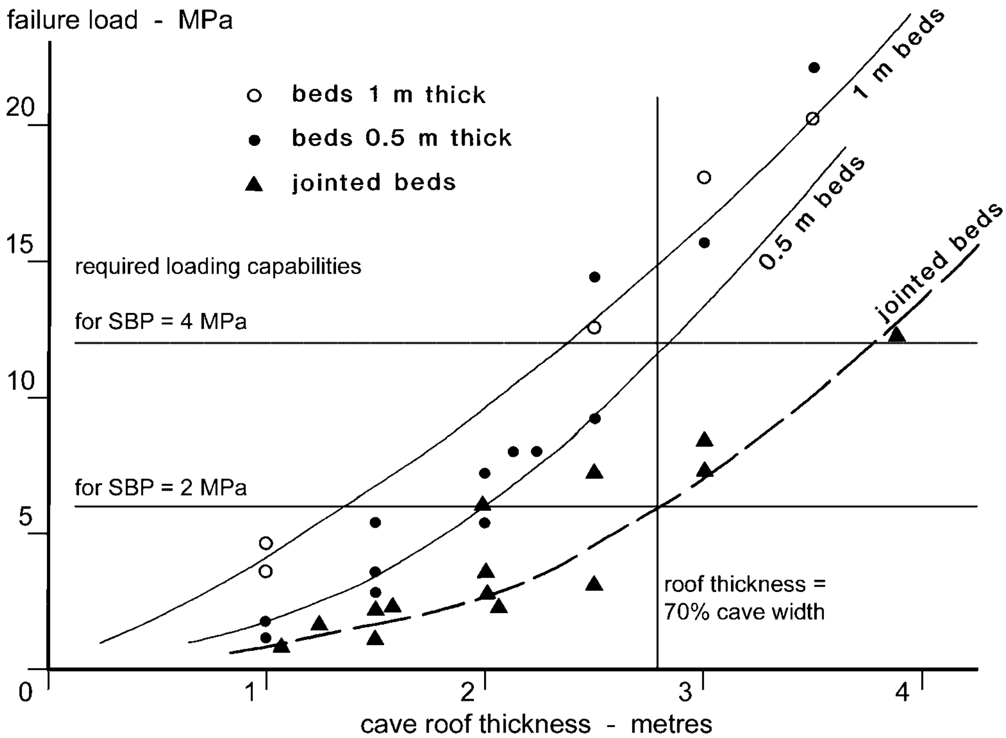

Fig. 4. The stability of cave roofs in limestone under engineering imposed load, related to the thickness and structural morphology of the roof rock. Data points are derived from destructive tests of laboratory scale models of caves all 4 m wide in limestone with unconfined compressive strengths (UCS) of about 80 MPa, centrally loaded by foundation pads of 1 m^2. Scale factors were calibrated by numerical modelling to a full-scale test, and the required loading capabilities are for Safe Bearing Pressures of 2 MPa and 4 MPa multiplied by a Factor of Safety of 3.

them). Sinkhole diameters vary from 1 m to 1 km and depths may be up to 500 m. They are classified into six types (Fig. 5), each with its own discrete mechanism of formation (Lowe & Waltham 2002); examples of all types are described by Bell *et al.* (2004). Dissolution, collapse and caprock sinkholes occur in rock, and are essentially stable features of a karst terrain except that open fissures or caves must exist beneath them. Natural events of rock collapse are rare, so constitute a minimal engineering hazard. The greater hazard in karst terrains is created by sinkholes formed in soil covers.

Dissolution sinkholes are formed by slow dissolutional lowering of the limestone outcrop or rockhead, aided by undermining and small scale collapse. They are normal features of a karst terrain that have evolved over geological timescales, and the larger features are major landforms. An old feature, maybe 1000 m across and 10 m deep, must still have fissured and potentially unstable rock mass somewhere beneath its lowest point. Comparable dissolution features are potholes and shafts, but these are formed at discrete stream sinks and swallow holes, whereas the conical sinkholes are formed largely by disseminated percolation water.

Collapse sinkholes are formed by instant or progressive failure and collapse of the limestone roof over a large cavern or over a group of smaller caves. Intact limestone is strong, and large-scale cavern collapse is rare (most limestone gorges are not collapsed caves). Though large collapse sinkholes are not common, small-scale collapse does contribute to both surface and rockhead degradation in karst, and there is a continuum of morphologies between the collapse and dissolution sinkhole types.

Caprock sinkholes are comparable to collapse sinkholes, except that there is undermining and collapse of an insoluble caprock over a karstic cavity in underlying limestone. They occur only in terrains of palaeokarst or interstratal karst with major caves in a buried limestone, and may therefore be features of an insoluble rock outcrop (Thomas 1974).

Dropout sinkholes are formed in cohesive soil cover, where percolating rainwater has washed the soil into stable fissures and caves in the underlying limestone (Fig. 6). Rapid failure of the ground surface occurs when the soil collapses into a void that has been slowly enlarging and stoping upwards while soil was washed into the limestone fissures beneath (Drumm *et al.* 1990; Tharp 1999). They are also known as cover collapse sinkholes.

Suffosion sinkholes are formed in non-cohesive soil cover, where percolating rainwater has washed the soil into stable fissures and caves in the underlying limestone. Slow subsidence of the ground surface occurs as the soil slumps and settles in its upper layers while it is removed from below by washing into the underlying limestone - the process of suffosion; a sinkhole may take

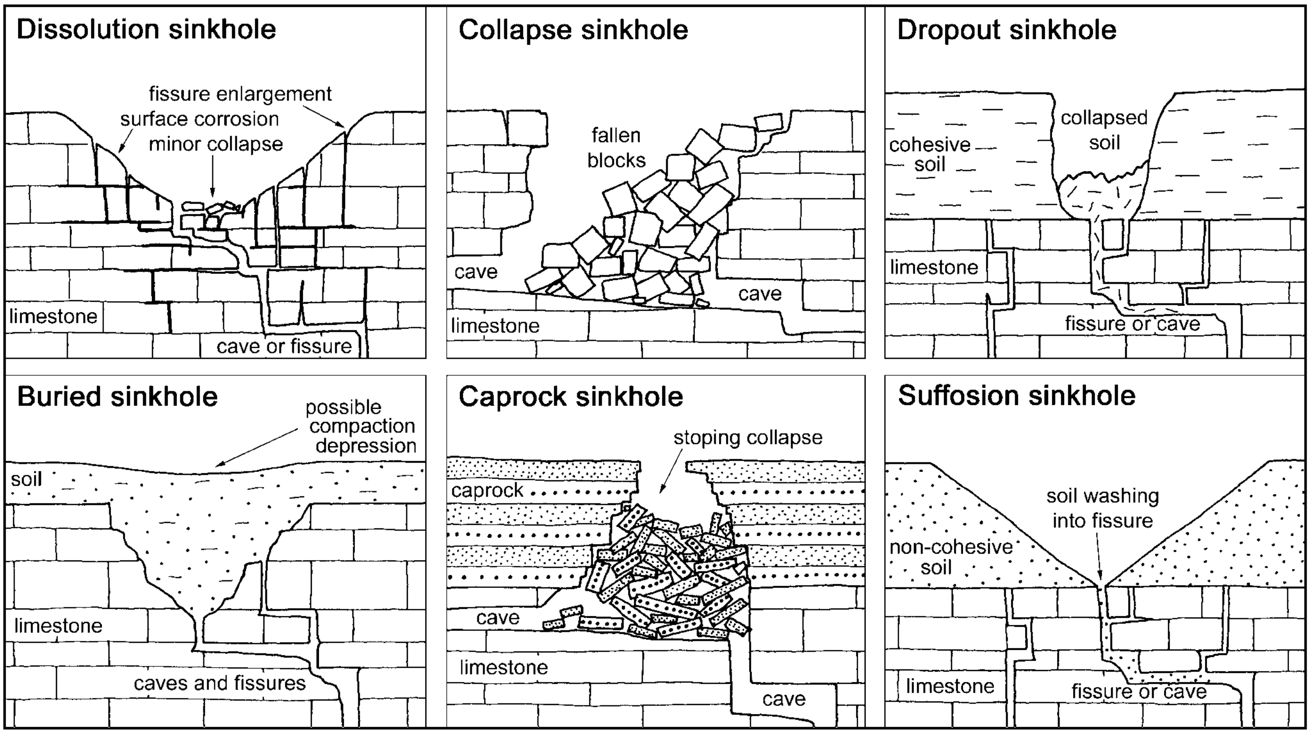

Fig. 5. A classification of sinkholes, with respect to the mechanisms of the ground failure and the nature of the material which fails and subsides; these features are also known as dolines (in the same six classes). The two types on the right may be known collectively as subsidence sinkholes. The structures, cave patterns and sinkhole profiles tend to be more complex in dipping limestone, but the concepts remain the same as those shown by these examples in horizontal limestone; except that the caprock sinkhole cannot exist in conformable vertical beds.

Fig. 6. A deep dropout sinkhole in glacial till, over a fissure 20 m deep in the underlying limestone. This is the new entrance to Marble Pot, in the Yorkshire Dales karst (class kIII) in England; the passages below are now choked with the collapsed till, though sinking water still drains through the debris.

years to evolve in granular sand. They are also known as cover subsidence sinkholes. A continuum of processes and morphologies exists between the dropout and suffosion sinkholes, which form at varying rates in soils ranging from cohesive clays to non-cohesive sands. Both processes may occur sequentially at the same site in changing rainfall and flow conditions, and the drop-out process may be regarded as very rapid suffosion. Dropout and suffosion sinkholes are commonly and sensibly described collectively as subsidence sinkholes and form the main sinkhole hazard in civil engineering (Waltham 1989; Beck & Sinclair 1986; Newton 1987). Subsidence sinkholes are also known as cover sinkholes, alluvial sinkholes, ravelling sinkholes or shakeholes.

Buried sinkholes occur where ancient dissolution or collapse sinkholes are filled with soil, debris or sediment due to a change of environment. Surface subsidence may then occur due to compaction of the soil fill, and may be aggravated where some of the soil is washed out at depth (Bezuidenhout & Enslin 1970; Brink 1984). Buried sinkholes constitute an extreme form of rockhead relief, and may deprive foundations of stable footings; they may be isolated features or components of a pinnacled rockhead. They include filled sinkholes, soil-filled pipes and small breccia pipes that have no surface expression. Large breccia pipes formed over deeply buried evaporites (Ford & Williams 1989; Lu & Cooper 1997) are beyond the scope of this paper. Slow settlement of the fill within buried sinkholes, perhaps induced by water table decline, creates shallow surface depressions known in South Africa as compaction sinkholes (Jennings 1966).

The sinkhole hazard in engineering

The major sinkhole hazards to civil engineering works are created by the rapid failures of soil to form dropout or suffosion sinkholes. Instantaneous dropouts are the only karst hazard that regularly causes loss of life, and most soils have enough cohesion that arches may develop over growing voids until they collapse catastrophically. Sinkhole failures are smaller and more numerous in thinner soil profiles, and most foundation problems occur where soils 2-10 m thick overlie a fissured rockhead. There is no recognizable upper bound of soil thickness beyond which sinkholes cannot occur; occasional large failures are known in soils 30–50 m thick (Jammal 1986; Abdullah & Mollah 1999).

Subsidence sinkholes (both dropout and suffosion) are created by downward percolation of water, therefore many occur during heavy rainfall events (Hyatt & Jacobs 1996). Many other failures occur when the natural drainage is disturbed by civil engineering activity (Waltham 1989; Newton 1987). Sinkholes are induced by civil engineering works that create local increases of water input to the soil (Knight 1971; Williams & Vineyard 1976), and failures are commonly triggered by inadequate drainage lines along highways (Moore 1988; Hubbard 1999). Numerous sinkholes develop where karstic limestone is dewatered beneath a soil cover, by either groundwater abstraction (Jammal 1986; Sinclair 1982; Waltham & Smart 1988) or mine and quarry dewatering (Foose 1969; LaMoreaux & Newton 1986; Li & Zhou 1999). New subsidence sinkholes are most likely to develop when the water table declines past the rockhead, thereby inducing downward vadose drainage and sediment transport into the limestone voids. Of sinkhole failures that impact upon civil engineering sites, those induced by human activities far outnumber those created by totally natural processes. Drainage control is essential in areas of soil cover on karstic limestones; by appropriate reaction to proper investigation, the hazard of collapsing sinkholes is largely avoidable.

Rockhead in karst

Subsoil dissolution at the soil/rock interface (and subaerial dissolution at the outcrop prior to burial) creates a clean rockhead without the gradual transition through a weathering sequence in insoluble rocks. However, rockhead profiles may be extremely irregular on karstic bedrock. Inclined or vertical joints and dipping bedding planes, that intersect the exposed or buried surfaces, provide pathways into the rock mass for rainwater and soil-water, so that they are preferentially enlarged into fissures. This is most rapid at and close to the rock surface, where corrosive soil-water first meets the limestone. With time, the upper part of the rock mass becomes more fissured, while intervening blocks of limestone are reduced in size and progressively isolated from their neighbours. The end product is a pinnacled rockhead that provides very difficult engineering ground conditions, notably where isolated and undercut pinnacles are supported only by the surrounding soil. Between the remnant pinnacles of limestone, fissures may enlarge downward into caves that are either soil-filled or open. Narrow, vertical, soil-filled pipes are particularly common in the more porous limestones, including both the younger reef limestones and the chalks (Rhodes & Marychurch 1998).

Karstic rockhead topography is notably unpredictable, with variations in the depth and frequency of fissuring, the height and stability of buried pinnacles, the extent of loose blocks of rock and the frequency of buried sinkholes. Figure 7 depicts ground profiles that vary from a modestly fissured rockhead to conditions of great complexity that provide major difficulties in excavation and establishment of structural foundations (Tan 1987; Bennett 1997).

Broadly, the degree of rockhead chaos is a function of climate and geological history. Large-scale pinnacled rockheads are almost limited to the wet tropics (Fig. 8), where they have had the time and environment to

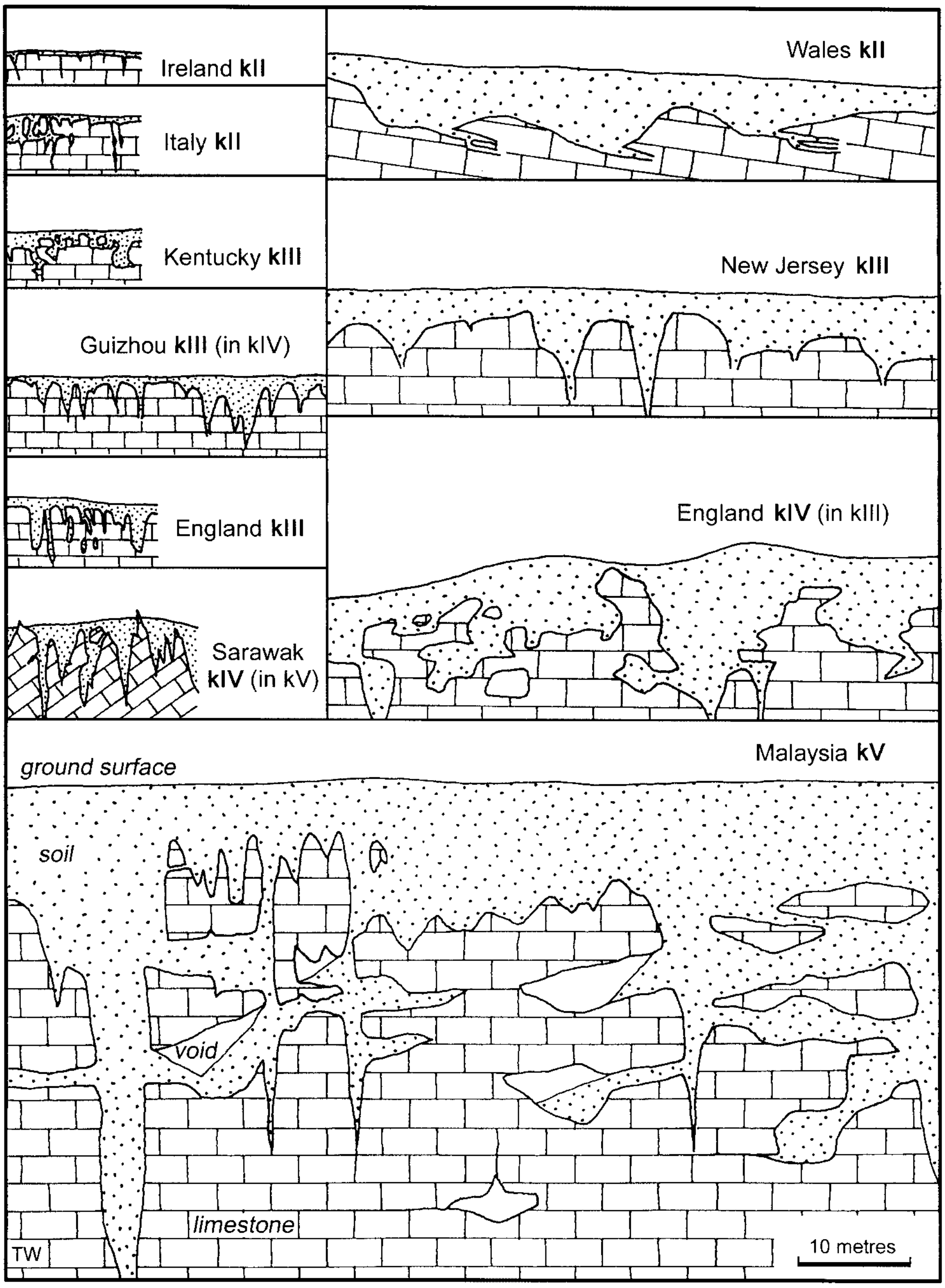

Fig. 7. Rockhead profiles at various karst sites, drawn from exposures and borehole profiles; scale and ornament are the same in each drawing. The notations kII etc refer to the karst classes to which their morphologies belong (see Fig. 9); some are atypical of their region in that the local rockhead profile represent a karst class that is different from the class of the regional landscape. Most of the isolated limestone blocks in the Malaysia profile are connected to bedrock in the third dimension, unseen in the drawing, though some may be 'floaters' left as dissolutional remnants within the soil.

mature fully. Most limestone that was covered by Pleistocene ice was at that time stripped down to a strong surface, and post-glacial dissolution has created only minimal fissuring up to the present time. Site conditions are also relevant, and a karst rockhead beneath a valley floor or adjacent to a shale outcrop is likely to be more complex where it has been corroded by acidic, shale-derived run-off or soil-water draining towards it. Rockhead relief may vary across an engineering site, but it generally lacks the extreme unpredictability of isolated caves or sinkholes that can threaten integrity of a single structure.

An engineering classification of karst

A classification of ground conditions that is usable and useful for the civil engineer identifies the degree to which any parameter or group of parameters is present. It

Fig. 8. Pinnacled rockhead partially exposed on a construction site in class kV ground at Lunan, in Yunnan, China. The original ground surface had only a few protruding pinnacle tips. Excavation to a lower level achieves a greater proportion of rock to soil for bearing purposes, but requires removal of the taller pinnacles.

should broadly quantify rockhead variability, the spatial frequency of sinkholes and the sizes of underground cavities. Other karst features are generally less significant. Intact rock strength is not a part of the classification, though the classes may relate back to broader definitions of rock mass strength. The following classification of karst ground conditions is based on features that occur in the stronger limestones; suites of features on gypsum and other carbonates, notably the weaker chalks, may be regarded as variants.

Karst ground conditions are divided into a progressive series of five classes, which are represented in Figure 9 by typical morphological assemblages, and are identified in Table 1 by available parameters. The five classes provide the basis of an engineering classification that characterizes karst in terms of the complexity and difficulty to be encountered by the foundation engineer. The concept diagrams in Figure 9 show horizontal limestone; folded limestones may have more complex dissolutional features, but this should affect the karst classification only marginally. Most features of the lower classes also appear within the more mature karsts. Parameters listed in Table 1 are not exclusive; a desert karst may have almost no current dissolutional development, and therefore appear to be of class kI, while it may contain large unseen caves remaining from phases with wetter palaeo-climates. In any karst, dissolutional activity is greatest near the surface where aggressive water is introduced to contact with the soluble rock. This creates a shallow zone of epikarst (Klimchouk 2000), and within any class of karst there is a vertical contrast between it and the less fissured rock at depth.

The extreme local variabilty of karst ground means that there are limits to how successfully karst can be classified. Whereas rockhead relief may be quantified, the distribution of sinkholes and caves is so diverse, chaotic and unpredictable that a classification provides only broad concepts of their likely abundances. The karst is generally more mature and cavernous along the outcrop boundaries with insoluble rocks that provide inputs of allogenic drainage. Karst beneath a soil cover inevitably provides greater geohazards than a bare karst because dissolutional features are obscured. Such a covered karst will have a greater frequency of new subsidence sinkhole events, which will indicate a higher karst class. New sinkholes in a soil cover are also related to short-term water movement at rockhead, and frequencies therefore vary across a site of uniform morphology (and karst class) in response to drainage patterns and/or abstraction.

The class parameters (Table 1) cannot be more than guidelines to the typical state. A further problem is caused by the lack of interdependence between the components of the karst. Within a region whose overall topography is best classified as a mature karst of class kIII, a single small construction site may reveal a minimally fissured rockhead that is best ascribed to class kII, and an isolated large cave chamber at shallow depth that is more typical of class kIV. The original classification of the karst region into class kIII remains valid, whereas the local variations that typify karst ground conditions mean that any small site sample may fall into a higher or lower class.

Previous classifications of karst

Geomorphological literature classifies karst features and types with reference to processes that are related largely

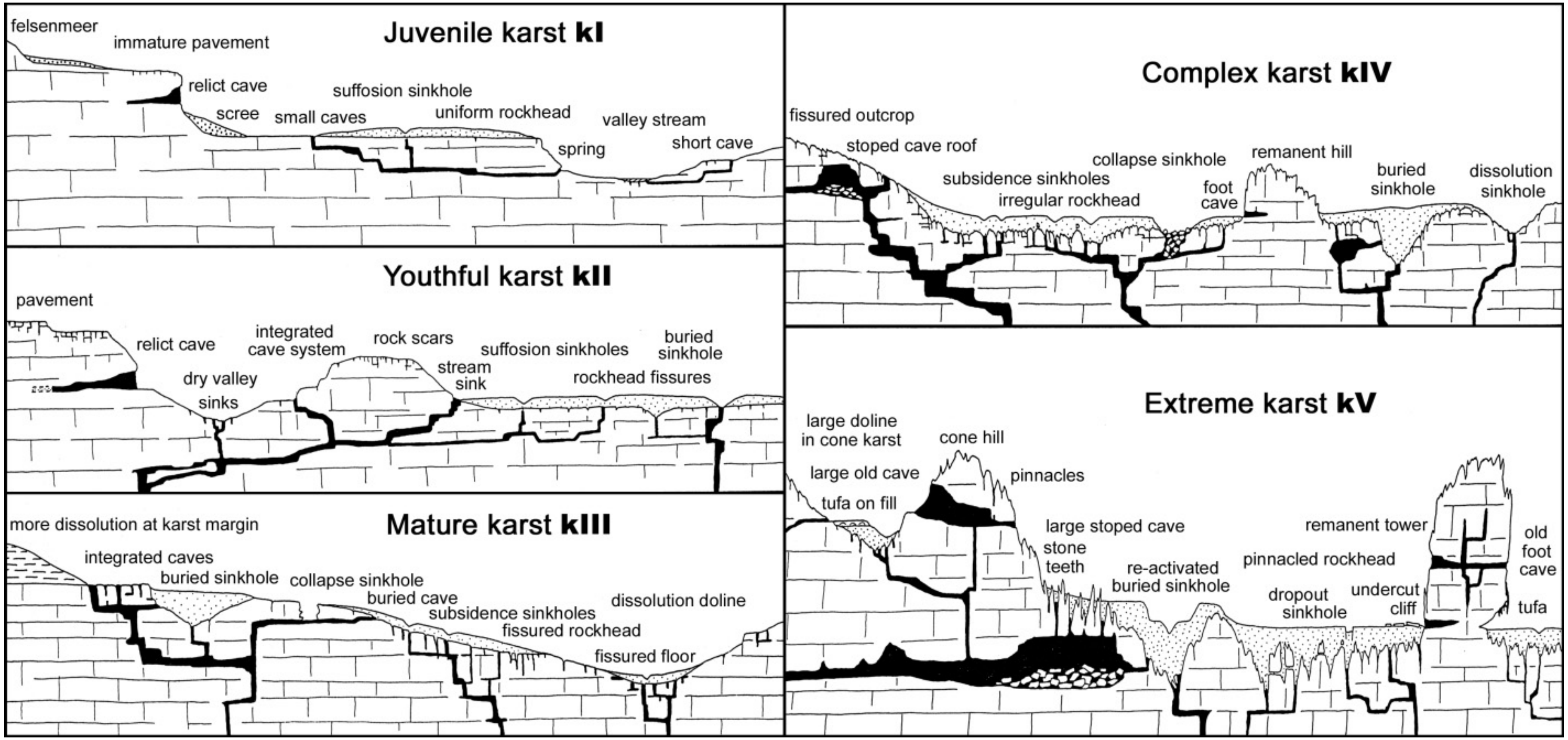

Fig. 9. Typical morphological features of karstic ground conditions within the five classes of the engineering classification of karst. These examples show horizontal bedding of the limestone; dipping bedding planes and inclined fractures add complexity to most of the features, and also create planar failures behind steep cliff faces. The dotted ornament represents any type of clastic soil or surface sediment.

Table 1. *An engineering classification of karst. This table provides outline descriptions of selected parameters; these are not mutually exclusive and give only broad indications of likely ground conditions that can show enormous variation in local detail. It should be viewed in conjunction with Figure 9, which shows some of the typical morphological features. The comments on ground investigation and foundations are only broad guidelines to good practice in the various classes of karst. NSH = rate of formation of new sinkholes per* km^2 *per year.*

Karst class	Locations	Sinkholes	Rockhead	Fissuring	Caves	Ground investigation	Foundations
kI Juvenile	Only in deserts and periglacial zones, or on impure carbonates	Rare; NSH <0.001	Almost uniform; minor fissures	Minimal; low secondary permeability	Rare and small; some isolated relict features	Conventional	Conventional
kII Youthful	The minimum in temperate regions	Small suffusion or dropout sinkholes; open stream sinks; NSH 0.001–0.05	Many small fissures	Widespread in the few metres nearest surface	Many small caves; most <3 m across	Mainly conventional, probe rock to 3 m, check fissures in rockhead	Grout open fissures; control drainage
kIII Mature	Common in temperate regions; the minimum in the wet tropics	Many suffosion and dropout sinkholes; large dissolution sinkholes; small collapse and buried sinkholes; NSH 0.05–1.0	Extensive fissuring; relief of <5 m; loose blocks in cover soil	Extensive secondary opening of most fissures	Many <5 m across at multiple levels	Probe to rockhead, probe rock to 4 m, microgravity survey	Rafts or ground beams, consider geogrids, driven piles to rockhead; control drainage
kIV Complex	Localized in temperate regions; normal in tropical regions	Many large dissolution sinkholes; numerous subsidence sinkholes; scattered collapse and buried sinkholes; NSH 0.5–2.0	Pinnacled; relief of 5–20 m; loose pillars	Extensive large dissolutional openings, on and away from major fissures	Many >5 m across at multiple levels	Probe to rockhead, Prove rock to 5 m with splayed probes, microgravity survey	Bored piles to rockhead, or cap grouting at rockhead; control drainage and abstraction
kV Extreme	Only in wet tropics	Very large sinkholes of all types; remanent arches; soil compaction in buried sinkholes; NSH $\geqslant 1$	Tall pinnacles; relief of >20 m; loose pillars undercut between deep soil fissures	Abundant and very complex dissolution cavities	Numerous complex 3-D cave systems, with galleries and chambers >15 m across	Make individual ground investigation for every pile site	Bear in soils with geogrid, load on proven pinnacles, or on deep bored piles; control all drainage and control abstraction

to climatic environments. The types therefore reflect karstic maturity, greater in the wet tropics than in colder or drier regions, and form the background to this classification that is concerned with the degrees of karstification. The first engineering classification of karst (Fookes & Hawkins 1988) was later modified (Fookes 1997) and is replaced by this classification. It was based largely on doline karst, with little reference to pinnacled rockheads, and was not comprehensive as mature forms of tropical karst were omitted; its five classes all fall within the first four classes of the classification in Figure 9 and Table 1.

A classification of karstic dangers to Russian railways uses the frequency of recorded collapses to guide engineering maintenance measures and hazard warning systems (Tolmachev *et al.* 1999). A significant engineering hazard is recognized where the new sinkhole failure rate exceeds 0.1 per km^2 per year, and this is incorporated into unpublished classifications used in Florida, USA. However, sinkhole collapse frequency cannot be a sole guide to karst classification as it increases in areas of thin soil cover and water table drawdown. Ground conditions over the pinnacled dolomites of South Africa are ascribed to one of three classes based only on the thickness of soil cover between the pinnacle tops and the ground surface (Wagener 1985). The classification of weathered rocks excludes karst as a special case, and current engineering classifications of rock masses do not refer to karst (Bieniawski 1973; Barton *et al.* 1974; Anon 1995).

The new full engineering description of karst

A description of the karst ground conditions by a single class label may be helpful in creating concepts of the scale of anticipated foundation difficulties, but the variations that are typical of karst demand a more specific and more detailed definition. A full description of karst ground conditions should therefore state whether it is on limestone or gypsum, and then embrace four terms, so that it becomes '*Karst class + sinkhole density + cave size + rockhead relief*'.

Karst class is an overview figure in the range I to V, as defined in the classification within this paper (Fig. 9 and Table 1).

Mean sinkhole density may be a simple number per unit area, based on field mapping, available maps or air photographs. It should be noted if densities are low because the sinkholes are large. Ideally, this descriptor is a rate at which new sinkholes occur (NSH), expressed in events per km^2 per year. In practice, the data can only be derived from local records, which are rarely adequate for anything better than a broad generalization. Inevitably the NSH is higher in karst areas with thin soil cover in which subsidence sinkholes are most easily formed. It should also be noted if the NSH rate is temporarily enhanced by engineering activities.

Typical cave size is a dimension in metres, based on available local data, to represent the largest cave width that is likely to be encountered. This is larger than the mean cave width, but may reasonably exclude dimensions of the largest cave chambers that are statistically very rare (though these should be noted, where appropriate).

Rockhead relief is a measure in metres of the mean local relief in the karst rockhead, including depths encountered within buried sinkholes. Where possible, a note should distinguish between pinnacled rockheads and more tabular, fissured surfaces that are buried pavements.

Though this four-element description may appear cumbersome, any lesser qualification is incapable of reasonable representation of the vagaries of karstic ground conditions.

Where it is helpful to design concepts, the engineering classification of ground conditions may be applied to small units of ground, though rarely down to the scale of applying rock mass classification metre by metre within a tunnel heading. A single residual pinnacle of massive limestone may offer conditions of class kI to found a single column base within a region of pinnacled karst of class kV [i.e. kI (in kV)]. Conversely, a deeply fissured zone of fractured limestone with a large underlying cave in the same fracture line may represent immediate, shallow ground conditions of class kV within a glaciokarst terrain that is regionally of class kI [i.e. kV (in kI)].

Engineers and ground investigators must recognize that karst ground conditions are immensely variable, and always demand thorough investigation and site-specific comprehension. A face cut with a wire-saw on a building site (Fig. 10) within a karst (class kIV; few sinkholes; caves 5 m across; rockhead relief 10 m) in Sicily revealed many small cavities and one larger buried sinkhole adjacent to areas of sound rock. It is near to Palermo airport, where a cavern up to 20 m wide was found under a runway extension. Every site on karst should be regarded as unique. Classification provides a broad indication of the engineering difficulties of a karst site, and offers guidance on approaches to overcoming the ground difficulties, but it can apply only an approximate label to a medium as variable as karst.

The processes and landforms of gypsum karst (Klimchouk *et al.* 1996) are broadly comparable to those on limestone, except that gypsum is dissolved more rapidly in natural waters and is mechanically weaker than most limestones. The engineering classification of karst is applicable to gypsum terrains, though extreme karst of class kV does not develop. Caves in gypsum collapse before they reach very large dimensions, surface crags are degraded, and denudation totally removes gypsum before it can mature into the extreme karst landforms. Rapid dissolution and low strength favour development of large collapse sinkholes, and some

Fig. 10. A sawn face 10 m high on a construction site sections limestone just below rockhead in a karst of class kIV in northwestern Sicily. Small caves and dissolutional-opened fissures are mainly aligned on dipping fractures, and a buried sinkhole is exposed on the left after its fill has been removed. Note person at lower left of image for scale.

gypsum karsts of classes kIII and kIV are distinguished by a scatter of large, isolated collapses (Waltham 2002).

Ground investigation on karst

Some of the most difficult ground conditions that have to be investigated in civil engineering are found in karst. Conventional practices are generally adequate to investigate sites in karst of classes kI and kII, but sites in more mature karst (classes kIII–kV) demand more rigorous ground investigations managed by a team that fully appreciates the complex characteristics of karst. Adaptation and re-assessment are critical on karst, where many ground conditions cannot be foreseen from any reasonable programme of investigation.

A major difficulty in karst investigations is finding underground cavities. There may be little alternative to closely spaced probes, but a density of 2500 per hectare is needed to have a 90% chance of finding one cavity 2.5 m in diameter. Probes beneath every pile foot and column base are a better option, and are essential at many sites on mature, cavernous karst. Exploration of pinnacled rockhead in a karst of class kIV or kV may demand extensive probing, but there is no answer to the question of how many probes are needed. Construction of a viaduct on class kIII karst in Belgium initially had 31 boreholes for five pier sites; these missed two caves revealed only during excavation for foundations. A second phase of investigation checked the ground with another 308 probes, but found no more caves (Waltham *et al.* 1986). Investigation by 31 boreholes was inadequate; drilling 339 holes was over-cautious. At many karstic sites, the true ground conditions are discovered only when foundations are excavated.

The depth probed should be a function of likely cavity size. In karst of classes kI – kIII, caves more than 5 m wide are unusual, and probing 3.5 m should therefore confirm rock integrity. Engineering practice varies considerably, by proving 5 m of rock beneath pile tips in cavernous Florida karst (Garlanger 1991), 4 m under foundations in South Africa (Wagener & Day 1986), 2.5 m under caissons in Pennsylvania (Foose & Humphreville 1979), and only 1.5 m under lightly loaded bridge caissons in North Carolina (Erwin & Brown 1988). The limestone in Florida is weaker than at the other sites, but there is no consistency in empirical data from engineering practice on karst.

Geophysics on karst

Geophysical identification of ground voids has not produced consistently reliable interpretations, but technology is advancing, and there are techniques that can produce useful results in certain situations (Cooper & Ballard 1988). All geophysical anomalies require verification by drilling, but a geophysical survey can reduce costs by identifying drilling targets.

Microgravity surveys identify missing mass within the ground and produce good data that improve in value with increasing sophistication of their analysis. Individual caves create negative anomalies, whose amplitude relates to cave size and whose wavelength is a function of cave depth. Fourier analysis of data from a grid with spacing of 2 m can identify caves only 1 m across at specific depths (Butler 1984; Crawford *et al.* 1999; McDonald *et al.* 1999; Styles & Thomas 2001). Wider grids cover larger areas to identify low-density fills in buried sinkholes (Kleywegt & Enslin 1973). In the

Fig. 11. A road cutting 4 m high in class kII karst in Korea, exposing two clay-filled sinkholes cut below a rockhead with minimal fissuring.

future, when data from more sites have been accumulated, gravity values and anomaly profiles could be applied to the classification of karst.

Seismic velocities decrease in more fissured and more cavernous ground; they correlate with engineering classifications of rock mass, and could perhaps be used to characterize karst classes. Three-dimensional cross-hole seismic tomography (3dT) can identify caves (Simpson 2001), but requires deep boreholes for data collection so that it is rarely applicable to surface investigations of greenfield sites.

Resistivity surveys are used for rockhead profiling (Dunscomb & Rehwoldt, 1999), but deeply pinnacled rockheads in karst of classes kIV and kV are too complex to be resolved by surface geophysics. Resistivity tomography is expensive, but can combine with microgravity to identify rockhead and distinguish buried sinkholes from caves (which have similar gravity signatures). Ground-probing radar is limited to shallow depths, but has been applied to incipient sinkhole detection (Wilson & Beck 1988). In similar situations, low-density granular soils have been identified by SPT values below 5, but these are not always indicative of active suffosion and potential sinkhole failure (Kannan 1999).

Ground engineering on karst

Limestone presents the foundation engineer with a range of difficulties that increase in scale and complexity with increased maturity of the karst morphology.

Foundations over karstic rockhead

Karst of class kI provides rockhead that is sound except for unpredictable isolated fissures or shallow caves that may require response during construction. Rockhead of class kII karst (Fig. 11) generally creates only minor problems. Installation of piles may require longer elements for some parts of a site (Statham & Baker 1986), and reinforced ground beams can be designed to span small new ground failures (Mishu *et al.* 1997).

In class kIII karst, rafts or groundbeams may bridge cavities (Sowers 1986; Clark *et al.* 1981; Green *et al.* 1995). In Florida, either rafts or preparatory grouting are preferred where new sinkholes are recorded locally at rates above 0.05 km^2/a (Kannan 1999). Heavy geogrid stabilizes soil profiles, and can be designed to span potential voids to reduce the impact of any subsequent catastrophic collapses (Kempton *et al.* 1998). Grouting of soils over highly fissured rockhead, before founding spread footings within the soil profile, may be more economical than piling to rockhead. A site of 10 000 m^2 on class kIII karst in Pennsylvania took 1200 m^3 of compaction grout through 560 boreholes to rockhead around 9 m deep (Reith *et al.* 1999).

Pinnacled rockheads of karst classes kIV and kV generally require that structures are founded on sound limestone by piling to rockhead or spanning between sound pinnacle tops (Brink 1979). Driven piles may be bent, deflected or poorly founded on unsound pinnacles (Sowers 1986, 1996); bored piles are preferred. Each pile tip is probed to ensure lack of voids beneath, and narrow unstable pinnacles may require assessment by probes splayed 15° from the vertical. As a guide for planning, adding 30% to the mean rockhead depth indicates the mean final length of end-bearing piles (Foose & Humphreville 1979). The lower strength of gypsum means that it can support neither high loads on rockhead pinnacles nor heavily loaded end-bearing piles.

A road or light structure can bear safely on the soil over a deeply pinnacled rockhead of karst class kV, where drainage is not disturbed, though geogrid reinforcement may be appropriate. Rockhead pinnacles 50 m high in some tropical karsts, offer dreadful ground conditions for heavy structures that demand founding on bedrock (Bennett 1997). Each pile location requires its own ground investigation, and designs must adapt to unique ground conditions as they are revealed by excavation.

Foundations over caves

Caves are unpredictable. Every site in karst has to be assessed individually in the context of its geomorphology, and engineering works must respond to the local conditions. Local records and observations may indicate typical and maximum cave sizes, and these define the minimum of sound rock to be proven by drilling beneath structural footings (see above). Major variations occur within a mature cavernous karst; in Slovenia, cave discoveries and collapses are common during road construction, but subsequent collapses under operational roads have not occurred (Sebela *et al.* 1999).

Caves typically reach widths of 10 m in karst of class kIV, so probing to 7 m is appropriate in limestone. Larger caves are common in class kV karst, and can occur in less mature karst. Many large caves at shallow depths have open entrances, and are best assessed by direct exploration. Dynamic compaction or monitored surcharge may collapse small shallow cavities in weak limestone of karst classes kIII or kIV.

Caves at critical locations under planned foundations, are normally filled with mass concrete, or may be bridged. In Ireland, a cave 6 m wide beneath just 2.5 m of limestone, supported a railway for many years, but a concrete slab was installed to lessen the risk when a main road replaced the railway. Grout injection through boreholes may incur considerable losses by flowage into karstic cavities that extend off site, and perimeter grout curtains may reduce total costs. Access to a cave allows installation of shuttering and removal of floor sediment before filling. Relocation of footings may prove essential over complex caves (Waltham *et al.* 1986). Piles that are preformed or cast in geotextile sleeves can transfer load to a solid cave floor, but costs may approach those of simpler total cave filling (Heath 1995). Grout filling of caves in gypsum is often inappropriate because the greater dissolution rates can allow significant amounts of intact gypsum to be removed within engineering timescales. An underground stream re-routed round a concrete plug can excavate a new adjacent cave, with implications for subsequent collapse, within the lifetime of an overlying engineered structure.

Remediation and prevention of sinkhole failure

The key to minimizing sinkhole failures in karst is proper control of water flows. Design specifications for a karst site (except some of class kI) should include a ban on soakaway drains, use of flexible infrastructure lines and diversion of inbound surface flows. Dry wells are acceptable where they are sealed onto open fissures and cased below rockhead (Crawford 1986; Vandevelde & Schmidt 1988). To found a road in Puerto Rico, natural soils in class kIV cone karst were replaced with granular, permeable engineered soils with diversionary clay caps and drainage wells (Vazquez Castillo & Rodriguez Molina, 1999). Control of water abstraction is also critical, especially where the water table is close above rockhead. Florida's Disney World stands on 20–30 m of soils over limestone of class kIII, and its wells are monitored so that pumping is switched where a local water table decline is detected; sinkholes have not yet occurred on the site (Handfelt & Attwooll 1988). Dewatering by quarrying has been stopped at some sites by legal action to prevent further ground failures (Quinlan 1986; Kath *et al.* 1995; Gary 1999).

Grout sealing of rockhead fissures is problematical, but may be appropriate on any karst except that of class k1; pinnacled rockheads of classes kIV and kV require elaborate 'cap grouting' with cement slurries after plugging open fissures with viscous grouts (Kannan & Nettles 1999; Siegel *et al.* 1999). Compaction grouting (with slump <25 mm), forming within the soil a solid block that bridges over fissures, has been used to remediate sinkholes over pinnacled rockheads of classes kII – kIV, though grout flow is uncontrollable and its placement may not remedy the initial cause of a failure (Henry 1987; Welsh 1988; Siegel *et al.* 1999). In karst of classes kII–kIV, sinkhole hazards are reduced by laying a geogrid into the soil (Villard *et al.* 2000), combined with proper drainage control.

Where a subsidence sinkhole does develop, a permanent repair requires exposure of rockhead and choking of the causative fissure or cave with blocky rock, covered with graded fill, with or without a concrete slab or geogrid mat (Dougherty & Perlow 1987; Bonaparte & Berg 1987, Hubbard 1999). Whether such action is preventative before site development or remedial after failure, depends largely on how well the problems of karst are understood. It is further complicated in gypsum karst where rapid development of new voids in adjacent ground must not be instigated by blocking a natural drainage conduit.

Conclusion

Karst frequently presents 'difficult ground conditions' to engineers, and is often inadequately understood by those only familiar with insoluble rock. An improved classification is presented to provide starting points in recognizing the scale of karst geohazards in widely varying terrains. It relates to the engineering techniques appropriate to different classes of cavernous ground and offers guidelines towards more efficient ground investigation.

A proper understanding of karst is essential to good practice in ground engineering.

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