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THE ENGINEERING CLASSIFICATION OF KARST WITH RESPECT TO THE ROLE AND INFLUENCE OF CAVES

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ABSTRACT

The engineering classification of karst defines various complexities of ground conditions, in terms of the hazards that they provide to potential construction. Karst is divided into five classes (from immature to extreme). The three key parameters within the classification are caves (size and extent), sinkholes (abundance and collapse frequency) and rockhead (profile and relief). As one component of karst, caves are a hazard to foundation integrity, though natural surface collapses over caves are extremely rare. A cave roof is normally stable under engineering loading where the roof thickness is greater than 70% of the cave width. Construction can proceed over or around caves that are known. The main difficulty is finding unseen voids; ground investigation in mature karst may require extensive borehole probing, and microgravity is the most useful geophysical technique.

KEYWORDS: engineering classification of karst, subsidence hazard

1. Engineering and ground conditions

A classification of ground conditions - that is usable and useful for the civil engineer - identifies the degree to which any feature or group of features is present. Designation of a class for a particular site can present a useful concept of the scale and complexity of difficult ground conditions or geohazards that may be anticipated. It can also provide a first-pass guideline to design parameters that may be appropriate to a site; and it semi-quantifies any site description that may otherwise be very subjective in communications between engineers. The divisions within a classification should be recognisable, even though their differences relate to the geological and geomorphological history of the site that may be outside the understanding or background data of the non-specialist engineer.

With these premises in mind, an engineering classification of karst was prepared as part of a review of ground conditions on carbonate rocks by a Technical Committee of the International Society of Soil Mechanics and Geotechnical Engineering.

2. The engineering classification of karst

Karst ground conditions are divided into a progressive series of five classes. These are represented in Fig.1 by typical morphological assemblages, and are further

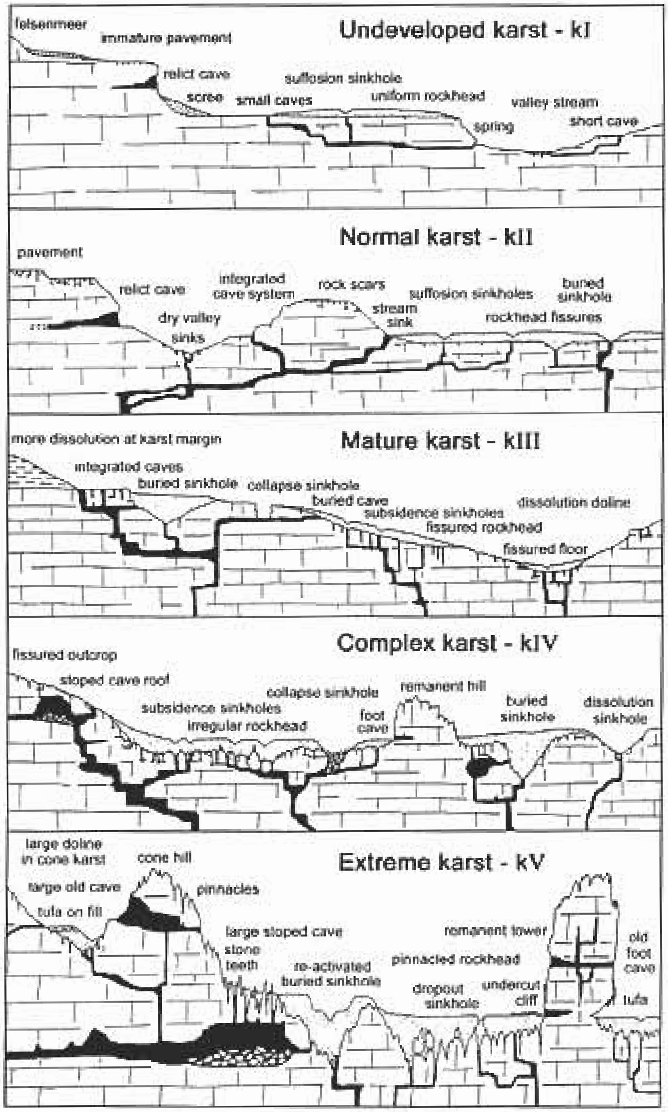

Fig.1 - Typical morphological features of karstic ground conditions within the five classes of the engineering classification of karst. These examples show horizontal bedding of the limestone; dipping bedding planes and inclined fractures add complexity to most of the features, and also create planar failures behind steep cliff faces. The dotted ornament represents any type of clastic soil or surface sediment.

defined in Table 1 by their major identifiable parameters. These five classes provide the basis of an engineering classification of karst, that characterises karst environments in terms of the complexity and difficulty that the ground presents to the foundation engineer. The number of classes is limited to five in order to make the classification accessible and useable. Further subdivision would render the system complicated and cumbersome, and progressively less applicable due to the spectacular variations that can occur within karst. A full engineering description of the ground conditions on a site does demand more detail, and the karst class may then be qualified by defining specific parameters, as described below.

The engineering classification of karst is based largely on the three features that are most relevant to engineers concerned with the integrity of structural foundations in karst terrains - sinkholes, rockhead and caves. Any other parameters of karst morphology are generally less significant, though it should be possible to relate them to the established karst classes.

Sinkholes as labelled by most engineers are the same features as dolines labelled by most geomorphologists. They constitute a major karst geohazard with respect to their nature, size, spatial frequency and rate of new occurrences. The karst classification recognises the six main types of sinkholes/dolines (as defined in Lowe and

Table 1. The engineering classification of karst. This table provides outline descriptions of the three key parameters; these are not mutually exclusive, and give only broad indications of likely ground conditions that can show enormous variation in local detail. The table should be viewed in conjunction with Fig. 1, which shows some of the typical morphological features. NSH = rate of formation of new sinkholes per km2 per year

Karst class	locations	sinkholes	rockhead	caves
kI Undeveloped	Only likely in deserts and periglacial zones, or on impure carbonates	Rare NSH* <0.001	Almost uniform; minor fissures	Rare and small; some isolated relict features
kII Normal	The minimum in temperate regions	Small suffusion sinkholes or dropout sinkholes; open stream sinks NSH 0.001 - 0.05	Many small fissures, notably in the top few metres; significant depressions	Many small caves; most <3m across
kIII Mature	Common in temperate regions; the minimum in the wet tropics	Many suffosion sinkholes and dropout sinkholes; large dissolution sinkholes NSH 0.05 - 1.0	Extensive fissuring, with secondary opening; relief of <5m; some loose blocks in cover soil	Many caves <5m across, at multiple levels
kIV Complex	Localised in temperate regions; normal in tropical regions	Many large dissolution; many subsidence sinkholes NSH 0.5 - 2.0	Pinnacled relief of 5-20m; loose pillars, extensive fissures	Many caves >5m across at multiple levels; isolated larger chambers
kV Extreme	Only in the wet ,tropics	Very large sinkholes of all types; remnant arches; NSH >>1	Tall pinnacles, relief of >20m; loose pillars undercut between deep soil fissures complex dissolution cavities	Complex 3-D cave systems, with passages >10m wide and chambers >20m across

Waltham, 2002), though the most important are the subsidence sinkholes (both suffosion and dropout types) that form in cover soils over a fissured limestone (Table 1).

Rockhead relief is critical to engineering design where foundations have to transmit structural loads to solid rock beneath an unstable soil cover. The scale of rockhead relief increases to the pinnacled rockheads of the more mature karst in the higher classes.

Caves represent ground where engineering strength and bearing capacity are significantly reduced. The critical dimensions are the width of the void and the thickness of the rock cover, and these factors are further considered below.

Intact rock strength is not a part of the classification. Most carbonates that are eroded into cavernous karst are strong rocks (with unconfined compressive strengths greater than 50 MPa). Most of the weaker carbonates tend to have fewer and/or smaller caves, so minimising the impact of lithological variations. Chalk is a special case that warrants specific attention and has its own classification (Ward et al, 1968). Gypsum karst must be classified independently in order to acknowledge both the material weakness of bedded gypsum and also its potential for cavity development within engineering time-scales.

The classes of karst are defined and recognised by typical assemblages of morphological features (Fig.1, Table 1). These cannot be absolute, as karst is too variable to lend itself to complete quantification, but they are guidelines to the ground conditions. The classes can be recognised in a climatic context. A geomorphologist may equate the immature classes kI and kII with glaciokarst or desert conditions, and the very mature classes kIV and kV with karst of the wet tropics, but these concepts would not be familiar to an engineer. Most of the dissolutional features of the lower classes of karstic ground conditions also appear as components within the more mature karsts. The parameters in Table 1 are not exclusive; a desert karst may have almost no active dissolutional development, and therefore appear to be of class kI, whereas it may contain unseen caves remaining from phases with wetter palaeo-climates.

The extreme local variability of karst ground means that there are limits to how successfully karst can be classified. Whereas the scale of rockhead relief may lend itself to quantifiable classification, the distribution of individual sinkholes and underground cavities is so diverse, chaotic and unpredictable that a classification provides only broad concepts of their likely abundance. 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 (Fig.2). 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 is valid, but the local variations that typify karst mean that any small site sample may fall into a higher or lower class.

Fig.2 - A rare example of a large collapsed cavern in karst in Nepal. Though the collapse is indicative of karst class kIV or kV, it is one of only three collapse features in a small limestone outcrop whose otherwise minimal karst landforms indicate a lower class of karst. This anomaly is largely due to very rapid landform development in limestone that is less than 500 years old.

3. The full description of karst ground conditions

A single class label may be helpful in creating concepts of the scale of anticipated foundation difficulties at a particular site, but it is not a full description of the karst ground conditions. The variations that are typical of karst may demand a more specific and more detailed definition. In such cases, a description of karst ground conditions should embrace four parameters, 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 and recognisable within Fig.1 and Table 1.

Mean sinkhole density may be a simple number per unit area, based on field mapping, available maps or air photographs. Ideally, it should be a rate at which new sinkholes failures (NSH) are occurring, expressed in events per km^2 per year. In practice, the data could only be derived from local records, which are rarely going to be adequate for anything better than a broad generalisation. An NSH rate $>0.1/km^2/y$ would normally be expected in a karst of class kIII or higher. The NSH rate may be temporarily enhanced by engineering activities, in which case this variation should be noted.

Typical cave size should be a dimension in metres, based on available local data, which represents the largest cave width that is likely to be encountered. It would be larger than any local figure for mean cave width, but may reasonably exclude dimensions of the largest cave chambers that are statistically very rare (though mention of both those in an appended note would be appropriate if the data were available).

Rockhead relief should be a measure in metres of the local relief in the karst rockhead. This figure should include depths encountered within buried sinkholes. A distinction between pinnacled rockheads and those that are buried pavements (with a more tabular and perhaps fissured morphology) would be a helpful qualifier, if the data are available.

Though the four-parameter description may appear to be rather cumbersome, it can be reasonably argued that any lesser qualification is incapable of representing the vagaries of karstic ground conditions.

Every engineer must recognise that karst ground conditions are immensely variable, and always demand thorough site-specific investigation. Because of the local variability of karst ground conditions, every site on karst should be regarded as unique. The classification of karst provides only a broad indication of the engineering difficulties of a site, and therefore offers guidance on suitable approaches to elucidating and overcoming the ground difficulties; but it can be no more than an approximation when applied to a medium as variable as cavernous limestone.

4. Caves within the karst classification

Cave dimensions vary from those of impenetrable fissures upwards to vast caverns. In temperate regions, cave passages are generally less than 10m in diameter, but caves 30m in diameter are more common in the wet tropics. This distribution of typical cave sizes does correlate with the five classes of karst (Table 1). Both surface landforms and cave passages are larger and more mature in wet tropical regions, where dissolution rates have been high for long periods without interruptions or temporary reductions in cold stages of the Pleistocene. Karst of classes kI and kII is therefore typified by cave passages normally only a few metres across, though scattered larger chambers can occur. Karst of class kV typically has trunk passages more than 10m in diameter, with even larger chambers, though many tributary passages may be much smaller.

Some of the most widespread difficulties with any engineering classification of karst are created by an immature modern karst that contains ancient large cave passages. A modern desert or polar environment may inhibit current dissolution processes. A mature karst may have evolved during wetter and/or warmer stages of the Pleistocene (or Tertiary). The old surface landforms may progressively be destroyed by the modern weathering, but the caves may survive. Observation of the surface may indicate a karst of class kI, but caves commensurate with classes kIV or kV may be present. Karsts in northern Greenland and in the Australian Nullarbor demonstrate the case where a simple karst classification is inadequate, and a fuller description (as above) is required.

Cave systems can also be of spectacular complexity. Surface lowering and valley entrenchment over long periods of time mean that most limestone masses have evolved through an earlier phase when they were saturated beneath a water table and a subsequent phase when they were largely free-draining into adjacent valleys. Most cave systems are therefore multi-phase, with an early network of tubular phreatic caves modified and entrenched by later phases of vadose canyon caves. The older passages are generally modified by roof breakdown debris and partly or completely filled by allogenic clastic sediments or the deposition of stalagmites and flowstones. Such variety further complicates any engineering classification of the karst that has to relate to the size and extent of the voids. Most caves are however stable in their natural state; conventional engineering would require little or no roof support in excavated tunnels or caverns of comparable sizes (Fig.3).

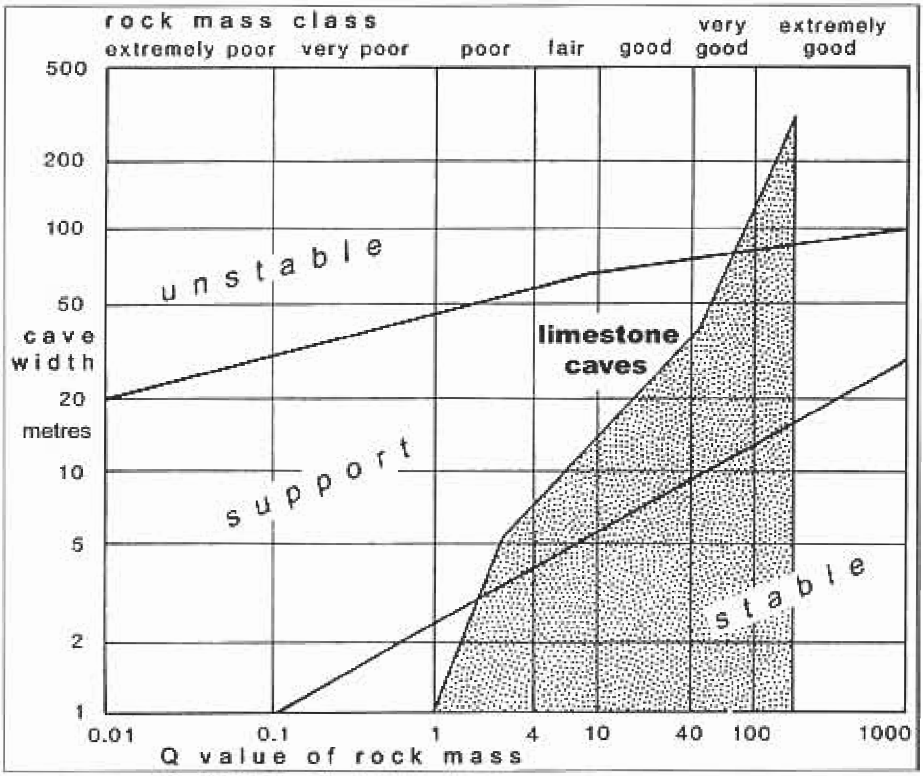

Fig.3 - Cave stability related to cave width and rock mass quality (Q value after Barton et al, 1974). The envelope of the limestone caves field is derived from observations of caves around the world. The labelled fields of stable, support and unstable are those applied in guidelines for the Norwegian 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, in the Mulu caves of Borneo; 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

On both small and large scales, the patterns, shapes and profiles of cave passages are determined by the structural and lithological features of the host limestone; the overall patterns are also influenced by the past and present hydrology. Though the guiding features can be recognised in all mapped caves, the locations of unknown caves cannot be predicted, except in the broadest of terms. Limestones have too many structural elements to consider, and fissures may develop on any or all of them, so that there are too many choices for subsequent cave development from only some of the fissures. The distributions of inception horizons, shale beds, past water tables and mixing zones are generally only understood after a detailed geomorphological study of the karst, underpinned by a large database of cave surveys. These are not available to most engineering investigations, and unknown cave locations remain a major problem on construction projects.

Fig.4 - Evolution of a cave roof by large block-fall in massive limestone, in Yordas Cave, England. Flowstone high on the cave walls indicates that the roof profile has remained almost unchanged for >100,000 years.

5. Natural cave collapse

The roof of a limestone cave may collapse either in its natural state or under an imposed load from engineering activity. Natural collapse is by progressive failures of roof rock units (Fig.4), which may eventually reach the ground surface. Wall or pillar failures (which are alternative collapse mechanisms in mines) rarely occur in natural caves that are isolated voids within large rock masses. Imposed loading may either accelerate or precipitate the natural processes of cave roof failure. Whether natural or induced, cave failure is a rare event in strong limestones, but the geohazard is created because the distribution of natural caves is notoriously unpredictable. A single cave was found, purely by chance during routine maintenance, just a few metres beneath the main runway of Palermo airport, on Sicily. It was 25m wide, and though there were no signs of breakdown, the consequence of even partial failure was so severe that it was filled with concrete (Jappelli and Liguori, 1979). The site is on a coastal platform of young limestone, where wide cavities are notably prone to development by dissolution at the interface between salt and fresh water at either current or past sea levels.

Cave roof breakdown is normally a progressive failure of individual beds or blocks, that develops upwards as a process known as roof stoping or cavity migration (Fig.5). It is rapid (on a geological time-scale) in thinly-bedded limestones. It may stop where a single bed is thick enough to resist failure by acting as a stable beam or cantilever over the cave void. A stable compression zone develops as an arch within a roof mass, and its arch profile rises typically to about one third of the cave width. Within this compression zone fractured rock may become very stable. Rock can fall away from the tensile zone beneath it, while the arch retains its integrity. Most large cave chambers have roofs that are compression arches with very low pro-

Fig.5 - Progressive bed failure in the roof of a passage in Agen Allwedd, Wales. The breakdown process causes upward void migration of the void over an increasing pile of rock debris; in this case, the original dissolution cave was 12m below the present roof, but this migration has probably taken more than 100,000 years

files in fractured rock (Fig.6). The process can be seen in the entrance chamber, 150m wide, in Tham En, Laos (Waltham and Middleton, 2000), and the giant Sarawak Chamber in the Mulu caves is similar.

Arch development relies on lateral compressive stress to maintain integrity, and such stress is normally present in deeply buried limestone. Lateral stress may be inadequately low near to the ground surface, and particularly in caves that lie parallel to an open cliff face or valley side. In these situations, the rock mass may relax towards the unconfined surface and a stable compression arch cannot develop within it. Progressive stoping failure of a cave roof may then continue unhindered. The end result is a breccia pipe (Fig.7) and/or a surface collapse (Fig.8). Open karstic fissures also permit greater deformation of an arch and accelerated failure of a cavern roof.

Cave roof collapse is also a natural consequence of ground surface lowering until a rock roof is so thin that it fails under its own load. A Slovenian cave, Brezno pri Medvedovi Konti, has an almost circular chamber, 130m across, beneath a gently domed roof that is 45m thick. This was modelled numerically, with a roof progressively thinned as if by surface lowering (Kortnik and Sustersic, 2000; see also paper by Kortnik in this volume). Massive failure (with no imposed load) started only when the roof at its thinnest part was down to just 15m thick. Reducing the strength of the modelled roof rock did not affect this thickness, though re-failure deformation was greater. Though difficulties were recognised in modelling the limestone fractures, the

Fig.6 - A stable roof with a roughly arched profile has developed in structurally complex limestone to span 40m in the entrance chamber of Tham Nathan, Laos.

Fig.7 - A breccia pipe in thinly bedded limestone, created by upward stoping within a small cave. It is now exposed in a sea cliff in Halong Bay, Vietnam. The open cave is less than 5m below the ground surface in the cliff section, and nearly 20m of breccia pipe is exposed above sea level.

Fig.8 - A zone of collapsed blocks of limestone in Penyghent Gill, England. The original cave (that still continues behind the collapse) was over 15m wide, but the rock roof had been thinned by erosion to less than 2m, and may have been loaded by a Pleistocene glacier.

data confirm that a very thin rock arch can be stable. Cave collapse still can and does occur, but the statistical chance of a natural cave roof collapse at any one point, within an engineering time-scale of a few hundred years, is extremely low. The geohazard exists but is essentially irrelevant, unless or until a failure is induced by imposed structural loading.

6. Cave collapse under imposed load

Loadings imposed on a cave roof by engineering works have the potential to precipitate natural failures that may have taken thousands of years to develop in the unloaded state. Total structural loads are mostly small in comparison to the loads imposed by rock and soil overburden, but they are commonly concentrated to stresses of >1 MPa (equal to a rock column 40m high) on small foundation pads, column bases or pile tips.

An informal guideline to the stability of the natural rock roof over a cave is that the ground is stable (for normal engineering activity) 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 appears to be conservative in most situations. For typical limestone karst where the rock mass is of fair quality, in rock mass class III, with a Q value of 4-10 (Barton et al, 1974), a cover thickness of intact rock that is 70% of the cave width ensures integrity (Fig.9). This applies under foundation loading that does not exceed 2 MPa, which is half the SBP appropriate for sound limestone. The concept covers limestone with a normal density of fractures and bedding planes; local zones of heavy fissuring may reduce cave roof integrity. It covers normal limestone with a degree of dissolutional widening of fissures, and is therefore independent of the engineering classification of karst (except with respect to the anticipated cave width).

This guideline is based on a scatter of documented experience at individual sites and correlation with data on failures of mined cavities. There is almost no reliable data on the loads required to cause the failure of a limestone cave roof. Physical and numerical modelling of artificial caves in sandstone under Nottingham, UK, (Waltham and Swift, in prep) has confirmed the critical parameters:

- failure loads increase over thicker roof rock;

- failure loads decrease over wider caves;

- failure loads increase sharply where only a small part of the loading footprint extends over intact rock beyond the cave walls;

- minimum failure load is not over the centre of a cave but is over the edge of the cave where stress concentration develops.

The modelling results for the sandstone were calibrated to a full-scale test of a cave roof loaded to failure, but that type of data is rarely available. Caves 5m wide in the sandstone are routinely built over, with heavy structures on 5m of rock roof and lighter structures on 3m of rock. Many older structures (that pre-date modern building codes) stand on very much less rock thickness and over wider caves. The

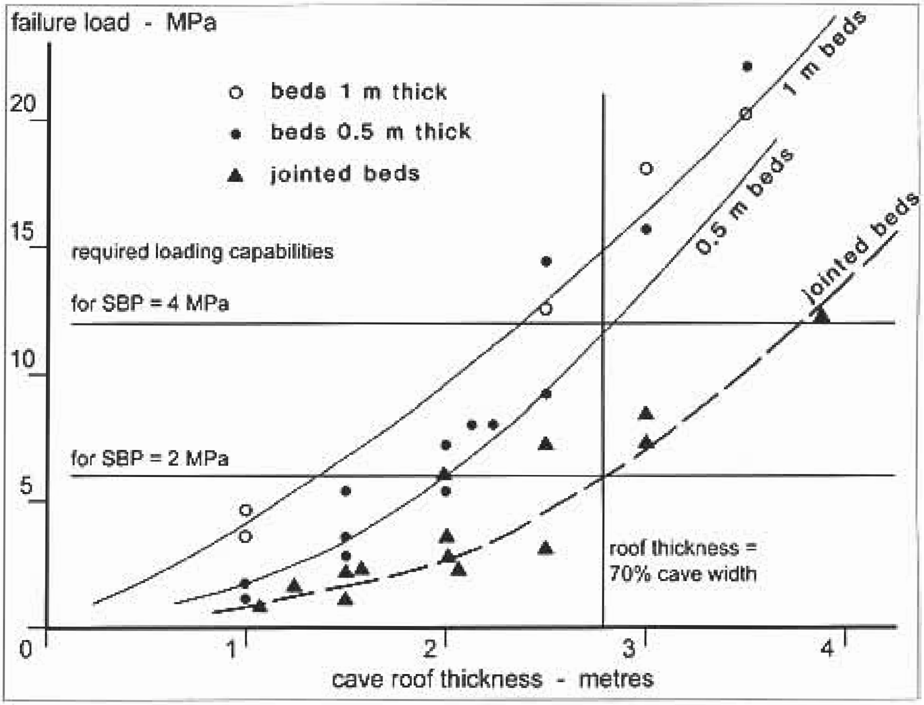

Fig.9 - The stability of cave roofs in limestone under engineering imposed load, with respect to the thickness and structural morphology of the roof rock. Data points are derived from destructive tests of scale models of caves all 4m wide in limestone with UCS of 80 MPa, loaded on foundation pads of 1m2. The required loading capabilities are for Safe Bearing Pressures of 2 and 4 MPa multiplied by a Factor of Safety of 3.

Nottingham sandstone has a Safe Bearing Pressure of 1 MPa.

Quantification of modelled or theoretical failure loads over limestone caves fails through lack of data on the *in situ* rock mass properties (notably with respect to fracture patterns and fissure development). Physical modelling was extended from the Nottingham sandstone to karst limestone that is much stronger as intact material. This showed the relative strengths of cave roofs of different bed thicknesses and with inherent fractures (Fig.9). Numerical modelling did not adequately represent the greater fracture densities in the strong limestone, and calibration of the physical models is only possible by a tenuous link to the one real test on sandstone. The available data concur with the guideline that the limestone roof thickness should exceed 70% of the cave width. Any but the softest of recent limestones would be stronger than the sandstone, and the test data imply that a guideline demanding roof thickness greater than cave width is conservative in karst. At any site, inspection of an individual cave roof may indicate variance from the guideline ratio to ensure stable ground.

Most karstic caves lie at depths within the limestone rock mass, where they constitute no hazard to civil engineering works with conventional foundations on the surface (Fig.10). The potential hazard in civil engineering works is the large cave that lies at shallow depth, where it may threaten foundation integrity. Caves may commonly reach widths of 10m in karst of class kIV, where borehole proving to 7m would therefore be appropriate. Caves of even larger sizes are common in class kV karst, and can occur in karst of less mature classes.

Fig.10 - A stable cave passage 100m below the ground surface in Mammoth Cave, Kentucky, USA. Stability of the cave is also enhanced by the flat arch profile of the ceiling carved by dissolution in a singularly unbroken bed of limestone

7. Construction over caves

Where caves are found at critical locations under planned foundations, the normal remedy is to fill them with mass concrete. Grout injection through boreholes may incur considerable losses by flowage into karstic cavities that extend far off site, and perimeter grout curtains may therefore reduce total costs. Alternatively, creating access to a cave may allow installation of shuttering and removal of any weak floor sediment before filling, as a concrete fill would lose its load-bearing capacity where placed over a soft fill. A lean-mix fill is however satisfactory on top of soft sediment where its only purpose is to prevent blockfall from the roof. Relocation of footings is usually an expensive option, but can prove essential over complex caves (Waltham et al, 1986). Bored piles can be placed through a cave to sound footing in the rock below; geotextile sleeves can be used to cast the concrete through the cave (Heath, 1995), but total cave filling is often preferred for its simplicity, at costs that may be little different.

It is impossible to predict both the number and the size of caves beneath any given karstic site. Each site has to be assessed individually within the context of its geomorphology, and engineering works must respond to the local conditions. Local records and observations may indicate the typical and maximum cave sizes previously encountered. The cave size determines the engineering philosophy whereby a defined minimum of sound rock should be proven by drilling beneath every foundation pad and pile tip (see below). Experience in Slovenia (Sebela et al, 1999) indicates the major variations that may be represented within a mature cavernous karst; cave discoveries and collapses have both been common during road construction, but subsequent cave collapses directly under operational roads have not occurred.

8. Engineering exploration of cavernous karst

The greatest single difficulty in ground investigations on karst is the detection of underground cavities. Local data are the only guide to local cave passage widths, and also to the extent of caves with respect to the statistical chance of one lying under a given point. Ultimately, there is little alternative to closely spaced probing (non-cored drilling) of the rock; however, it needs 2500 boreholes per hectare to have a 90% chance of finding one cave 2.5m in diameter. On any site, an appropriate number of exploratory probes can only be defined in terms of the known local conditions (including the geomorphological history), the sensitivity of the structure to be built, and the results achieved as the investigation proceeds in stages. Belgium's Remouchamps Viaduct provided a classic example of the unpredictable nature of karst (Waltham et al, 1986). On the initial ground investigation 31 boreholes found no caves. Subsequent excavation of the pier footings found two unknown caves. A second phase of investigation was therefore instigated, but 308 new boreholes found no more caves.

Probes beneath every pile foot and column base are frequently the sensible option, and are essential at many sites on mature, cavernous karst. Site-specific risk assessment can indicate whether a typical or a maximum cave width is used to determine drill hole probing depths beneath foundation sites. If the concept of a cave being stable where its rock cover exceeds its width (see above), the depth to be probed is the likely cavity size, but this is very conservative, and probing to lesser depths is satisfactory except for the most heavily loaded structures. In karst of classes kI - kIII, caves more than 5m wide are unusual, and drilling 3.5m should therefore confirm integrity for most purposes. Engineering practice varies considerably, by proving 5m beneath pile tips in Florida (Garlanger, 1991), 4m under foundations in South Africa (Wagener and Day, 1986), 2.m under caissons in Pennsylvania (Foose and Humphreville, 1979), and only 1.5m under bridge caissons in North Carolina (Erwin and Brown, 1988). It is significant that the Florida proving was for small-diameter piles in a karst where large caves are known to exist, whereas the caissons in North Carolina were lightly loaded on a weak limestone.

Large caves at shallow depths constitute the major geohazard, and they commonly have open entrances nearby, so that they are best assessed by direct exploration. Small shallow cavities may be collapsed by dynamic compaction (with drop weights), and this may be appropriate on karst of classes kIII or kIV, particularly in weak limestones.

Geophysical identification of ground voids has not produced consistently reliable interpretations, and there are many reports of it producing no useful data for engineering purposes. However, technology is advancing rapidly, and there are new geophysical techniques that can produce useful results in certain situations (Cooper and Ballard, 1988).

Some of the best data come from microgravity surveys, which continue to improve in value with increasing sophistication of their data analysis. Gravity survey data provide a direct measure of the extent of voids within a rock mass. Individual caves can be identified by negative anomalies, whose amplitude relates to the cave size and whose wavelength is a function of the cave depth. Fourier analysis of data from a grid with spacing of 2m can identify caves only 1m across at various depths; this is directly applicable to engineering investigation (Butler, 1984; Crawford et al, 1999; McDonald et al, 1999; Styles and Thomas, 2001). There is the prospect that bands of gravity values and anomaly relief could be applied to the classification of karst, but this awaits the accumulation of gravity data from a range of sites as the technique becomes more widely employed.

In a single rock type, seismic velocities decrease in a rock mass that is more fissured and cavernous; seismic data have already been correlated broadly with engineering classifications of the rock mass, and this could offer a second geophysical tool with which to characterise the karst classes. Three-dimensional cross-hole seismic tomography (3dT) is newly developed with the improved computer analysis of massive banks of data (Simpson, 2001). Though invaluable for tunnel projects and sites with available deep boreholes, it is limited in application to surface investigations of greenfield sites.

All types of electro-magnetic geophysical surveys have serious limitations in cavity searches. A cave full of clay produces a positive conductivity anomaly, whereas an empty cave produces a negative anomaly, while both are potential engineering hazards. A mixture of both filled and empty caves provides spectacularly confusing data. Ground-probing radar suffers similar difficulties, and is limited to shallow depths. Three-dimensional resistivity tomography is time-consuming and expensive, but can be combined with microgravity to identify rockhead and so distinguish caves from any buried sinkholes that create similar gravity anomalies.

Cavernous karst can constitute seriously difficult ground for engineering works. The chances of a cave lying undetected beneath a foundation and causing a structural failure (except by sinkhole development within a cover soil) are statistically very small. But the impact of a total ground collapse can be very high. Proving that there is no cave within a given block of limestone can be difficult and/or expensive. A better option is commonly to design foundations that can survive total roof collapse of a predictable but unknown cave.

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