Natural and anthropogenic rock collapse over open caves

T. WALTHAM[1] & Z. LU[2]

[1]*Civil Engineering Department, Nottingham Trent University, Nottingham NG1 4BU, UK (e-mail: tony@geophotos.co.uk)*

[2]*School of Civil Engineering, Nottingham University, Nottingham NG7 2RD, UK*

Abstract: Natural rock collapse that reaches the ground surface to form a collapse doline is relatively rare in limestone karst. The anthropogenic karst geohazard is posed by the possibility of rock collapse when additional loading is imposed by engineering works directly over a known or unknown cave. An intact rock-cover thickness that exceeds half the cave width appears to be safe in most karst terrains formed in strong limestone. Guidelines suggest that drilling or probing prior to construction should prove sound rock to depths ranging between 3 and 7 m in most of the various types of karst.

Conduits are a ubiquitous feature of karst (and pseudokarst) terrains, and many (but not all) reach dimensions whereby they are accessible by man and are then known as caves. The potential for gravitational collapse of rock and/or soil into them, either naturally or under induced load, therefore renders them a notable karst geohazard. As a real hazard to the construction industry, this primarily concerns the larger conduits (i.e. the caves), but soil failure into the smaller conduits (i.e. smaller than caves) can cause significant ground subsidence. The dominant hazard occurs on strong limestones, but assessment of cave instability can be extended to sites in chalk, gypsum, salt, basalt and some unconsolidated sediments (generally known as soils by civil engineers). Karst is distinguished by its formation in soluble rock terrains, so caves in basalt and soil are considered as features of pseudokarst.

Natural collapse and doline development

Rock that constitutes the roof span over a natural cave has an element of inherent instability. Some caves are cylindrical tunnels that have developed slowly over geological timescales, so that they have equilibrium roof arches in sound and massive rock, but even these may become unstable when surface lowering reduces their roof thickness. Far more caves are developed in fractured rock, whose rock mass integrity is locally variable, and progressive roof failure on small or large scales is a natural process within the evolution of a cave that was initiated by dissolutional processes (Fig. 1). Repeated failures in a cave roof constitute natural stoping and upward cavity migration. Where this propagates as far as the ground surface, it generates a collapse or caprock doline.

The surface depressions that are diagnostic of karst landscapes are known to geomorphologists as dolines, but in the American and engineering literature are generally known as sinkholes (Sowers 1996; Waltham *et al.* 2005). These may be classified into six main types, distinguished by their genetic processes and morphology (Fig. 2). Collapse dolines are formed by single or multiple collapses of cave roof spans; these are not common, and new events of rock collapse without imposed load are extremely rare. Where cave roof stoping migrates to the ground surface through a covering insoluble rock, a cap-rock doline is formed; these are similar to collapse dolines except that they form in an insoluble outcrop, and new events are equally rare.

The mechanisms and rates of cave roof failure, and ultimately surface collapse, are dependant largely on rock structure, most significantly on the bedding and jointing densities and attitudes within the rock mass. In roughly horizontal, and minimally disturbed, strong limestones, individual beds across a cave roof fail when the cave's unsupported span exceeds between 10 and 20 times the bed thickness (but such figures are major generalizations across greatly variable situations and processes; see Waltham *et al.* 2005, fig. 3.5). Joints across beds of rock clearly reduce their ability to survive in cantilever or in unconstrained beams across cave roofs, but the joint influence is greatly reduced where potential displacements are restrained within the zone of ground compression that naturally develops as an arch over a void. Consequently, many large caves have stable arched roof profiles that follow the shapes of their compression zones; these have developed by beds falling away from the tension zone beneath the compression arch. Although their geometry is not perfect, some cave roofs in heavily fractured rock can approach the stability of a voussoir arch in uncemented masonry (an arch formed of shaped blocks designed to be stable in compression). However, heavily shattered rock or intersecting sets of inclined fractures can

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Fig. 1. Collapse of strong, well-bedded limestone in a chamber within the Sof Omar cave system in Ethiopia; the metre-thick bed above the man's head height has fallen away from the chamber roof, to form the breakdown floor, but the same bed still spans the narrower passage beyond the man.

produce serious instability, so that some caves are heavily collapsed when only a few metres wide.

Parameters for natural cave roof collapse

The great variability of structures within limestone means that cave stability is equally variable. Numerical modelling of cave roof failure under imposed load (see text below and Fig. 5 later) has provided peripheral data on unloaded cave failures. These suggested that a rock roof 2 m thick would be marginally stable across caves 10–25 m wide, depending on the quality of the limestone (indicated by rock mass strengths that are representative of cavernous karst ground). Similarly, rock 8 m thick would fail where caves reached widths of 20 m in weak rock or well over 50 m in strong rock. A different method of numerical modelling indicated that a cave 130 m wide in strong and massive limestone in Slovenia would fail when the roof was thinned to about 6 m (Kortnik 2002). Observations of cave chambers, both surviving and failed, confirm a huge range of values in stability parameters, dependant largely on the immediate patterns and densities of rock fractures.

Cave collapse events may be induced by increased water input. In the short term, enhanced rock dissolution is not normally significant, but greatly increased water flow could reduce stability by washing out fissure fills that had been contributing to the integrity of a compression arch within the roof rock. In the long term, the accelerated opening of fissures within the drainage zone beneath the floor of a solution doline is recognized as contributing to major rock failure over cave chambers to form the giant collapse dolines known as tiankengs (Zhu & Chen 2005). At a recent collapse event in Kentucky, rock failure appears to have been induced by impact loading created when soil arches collapsed over voids that had developed within the soil profile over fissures in the limestone (Kambesis & Brucker 2005), but this cave roof was already very thin (Fig. 3).

There is a shortage of data on cave roof stability in weaker rocks. Gypsum may be analogous to the weakest limestones, and roof spans of more than about 25 m do not appear to survive; the many larger collapse dolines in gypsum have evolved by multiple collapses. Salt is even weaker and is also subject to plastic flow at low stress levels; large caves in salt are rare and ephemeral. Both gypsum and salt are so rapidly soluble in flowing water that contemporary rock dissolution is a significant factor in ground stability over caves within them;

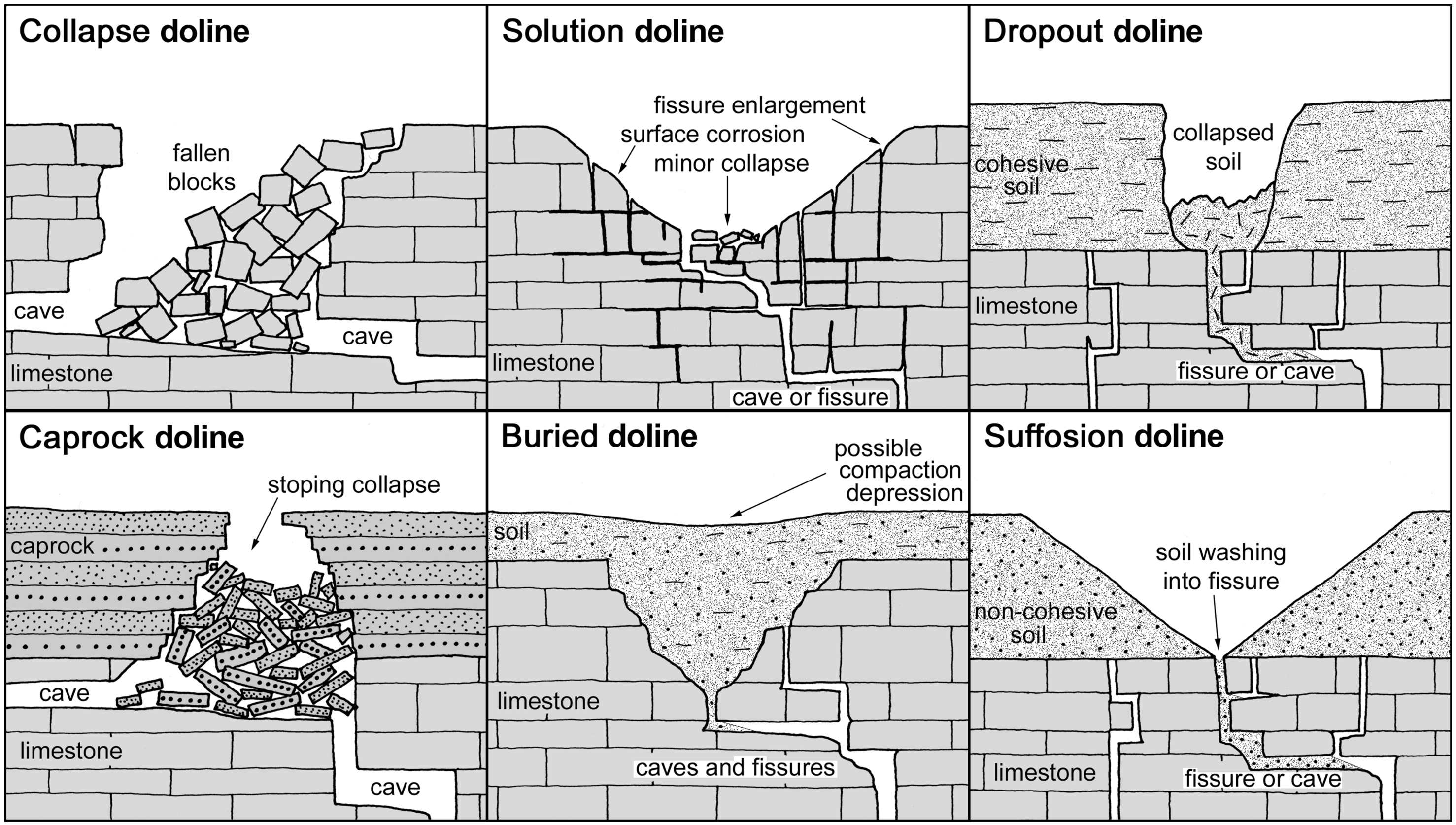

Fig. 2. The six main types of dolines; the two on the left are those involving rock collapse; the two on the right are together known as subsidence dolines, developed entirely by failure of the soil mantle. (After Waltham *et al.* 2005.)

Fig. 3. The edge of the collapse doline that destroyed a road in Kentucky in 2002, viewed when remediation was under way; the broken edge shows the wide cave chamber spanned by a very thin roof, of which the upper half was a zone of soil-filled fissures between rockhead pinnacles.

groundwater flows that are enhanced, either naturally, accidentally or by mismanaged engineering works, may modify cave profiles enough to induce collapse within engineering timescales but without any imposed loading. Chalk is only slowly soluble in water, but accelerated drainage can induce liquefaction of material previously weakened by Pleistocene frost shattering and its consequent loss into any underlying void; most recorded cases of liquefaction failure in Britain have been over old mines, and are therefore more allied to crown hole failures (surface holes that open up when progressive mine roof stoping failures reach rockhead), but comparable new collapse dolines are known in the chalk of France (Waltham *et al.* 2005).

The development of new cap-rock dolines is a function of the rock mass strength of the cap-rock. Gritstone capping the interstratal karst of Wales is analogous to the strongest limestone, whereas clays over some buried karst in Russia are so weak that collapse events mimic the mechanisms of subsidence dolines within soils. Large cavities in salt, formed rapidly by dissolution that is either natural or enhanced by brine drainage, have been known to migrate to the ground surface by stoping through hundreds of metres of weak cover rocks within periods of just months or years. These events have implications for ground stability over any soluble rock, but risks are reduced by their extreme rarity.

This brief review of the karst geohazard owing to natural, unloaded, rock collapse is more fully explored by Waltham *et al.* (2005). As a karst geohazard, rock collapse is totally overshadowed by the

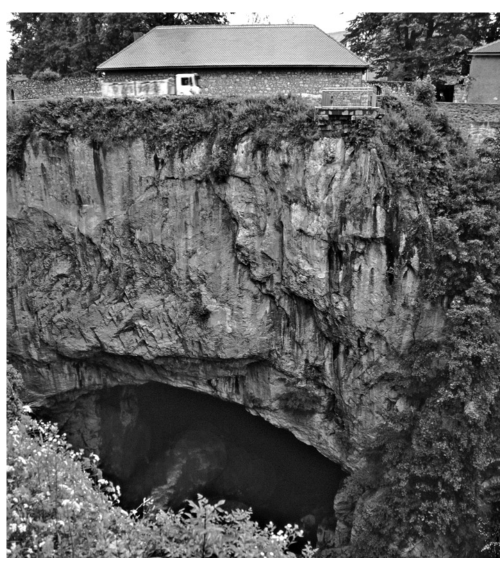

Fig. 4. Houses in the town of Ogulin stand in complete safety atop a thick arch of massive limestone that spans a wide cave passage in the inland karst of Croatia.

hazard of dolines that form by downwashing of unstable soil into fissures within underlying, stable limestone; these are dropout dolines (formed rapidly, and widely known as cover-collapse dolines in North America) or suffosion dolines (evolving slowly), which are together known as subsidence dolines. The high rates of new doline appearances reported from some karst terrains (exceeding one per km^2 per year) all refer to new subsidence dolines that develop in the soil mantle over cavernous limestones, notably during periods of high rainfall.

Cave roof collapse under imposed load

Collapses that are induced by man's activities in karst terrains (thereby anthropogenic collapse) is a long-recognized hazard where increased loading is imposed in construction works. The great majority of caves lie at depths that are irrelevant to engineering loading on the surface because they lie beneath thicknesses of stable rock far greater than the cave widths. However, there is a potential hazard in caves at shallow depth, where the rock roof is thin in comparison to the underlying cave width.

A critical value, for the ratio of roof thickness to cave width needed to ensure stability under construction loading, has long been questioned, but rarely concluded. It is clearly a function of the thickness and rise profile of the compression arch within the ground that is needed both to span the cave and to support the load, ameliorated by an added thickness of rock that allows stress distribution above the notional arch. The concept that collapse is unlikely where the imposed load is less than about 10% of the existing overburden stress (Sowers 1996) relies on stress distribution within the bulb of pressure, but takes no account of stress concentration (and bulb distortion) in fissured karst over an open cave. It is more realistic to assess cave roof stability in terms of the cover ratio (t/w, where t is roof thickness and w is cave width) that is appropriate for any limestone (or other cavernous rock) of given rock mass quality. The popular 'rule of thumb', that a limestone cave is stable and can be ignored when its cover thickness exceeds its width, is very convenient, although it does appear to be rather conservative.

Some very thin rock spans have been inadvertently loaded and yet have survived. A large cave was found under the main runway at Palermo, Sicily, after it had been in use for many years; with a cover ratio of about 0.1, this was deemed unsafe and is now full of concrete (Jappelli & Liguori 1979). The survival of the open cave, and the runway, may have relied on stress distribution within the reinforced concrete of the runway. There are numerous sites in the populated karsts (notably in Croatia and China) where houses and villages stand directly over caves with rising or sinking rivers, but most of these rock arches are comfortably massive (Fig. 4).

In contrast, there are records of structural collapse into unseen caves inadvertently loaded by engineering works. A large column supporting a freeway, and heavily loaded during construction, dropped 5 m into a cave in Tampa, Florida, in 2004; the cave dimensions were not seen, but the rock below the column base had been probed for only 3 m, which was clearly inadequate for the properties and morphological conditions locally well known in the local karst limestone. An entire five-lane road collapsed into a cave in Bowling Green, Kentucky, in 2002 (Kambesis & Brucker 2005), and this cave was known and mapped before the road was built only a few years previously; the road lay over the widest part of the cave where the cover ratio was less than 0.2 (Fig. 3), so it was a collapse waiting to happen, although the failure process was probably complicated by collapsing soil voids between the rockhead and the roadbed.

Investigation of a safe cover ratio over caves

Clearly, some form of guidelines for safe cover ratios for engineering loading over caves would be useful in the construction industry, especially as the vagaries of cavernous karst morphology are so little understood by engineers normally more concerned with settlements on soils. Most of the worldwide geohazards databank on mine collapses is barely relevant to caves, as it is concerned with pillar failure or with crown hole development in mainly weak rock sequences.

The artificial sandstone caves under the city of Nottingham have been investigated with respect to the extensive new construction on top of them (Waltham & Swift 2004). This included the full-scale test loading of a cave roof, when failure was induced by a load of 340 kN on a small bearing pad on moderately weak sandstone with a cover ratio of 0.13 over a cave 4 m wide. Numerical modelling was calibrated with these test data, but was based on rock that was homogeneous except for a few defined fractures, and it could not model the fractured and fissured rock mass that pertains in karst limestone. The stability assessment of a karst cave roof depends on adequate evaluation of the rock fracturing. This could be based on direct observation so that it is very detailed but site-specific, but this does not help where the potential hazard posed by an unseen cave has to be assessed prior to engineering construction.

Numerical modelling has therefore been advanced by defining fractured rock masses in terms of their 'rock mass ratings' (RMR). The geomechanics system derives RMR by summing rating values ascribed on the basis of RQD (rock quality designation, based on fracture intersections in borehole core), mean fracture spacing, fracture conditions, fracture orientation, unconfined compressive strength of the intact rock and groundwater state (Bieniawski 1973). RMR values range from more than 80 for very good rock of rock mass class I to less than 20 for very poor rock of rock mass class V; they may be correlated with Q values derived from the alternative Norwegian classification scheme (Barton *et al.* 1974). For application in numerical modelling, packages of strength and deformation values have been created for each of various values of RMR; these have been developed through extensive research, and their realism has been confirmed by empirical correlation with various measurable situations (Asef *et al.* 2000).

By installing these definitions of rock mass properties, the second author has modelled the effects of loading over cave roofs in two dimensions, using the finite-difference code Fast Lagrangian Analysis of Continua (FLAC). Caves, 3–50 m wide with flat roof profiles at depths of 2–10 m, have been modelled under loads applied to pads of 1 × 1 m at the ground surface above the centre-line of the caves. Loads were increased until failures were defined by settlements of 25.4 mm, a value that indicates loss of integrity and is likely to precede total collapse, besides causing significant damage to built structures. The caves were modelled in materials with RMR values of 20–50, which are considered to encompass the ground conditions to be found in most types of cavernous karst in limestones.

Results from this numerical modelling effectively indicate ultimate bearing pressures in terms of cave width, roof thickness and rock mass strength (Fig. 5). For any design load, selected factor of safety, estimated RMR and known or inferred cave width, a safe roof thickness can therefore be estimated from these nomograms. Cave dimensions at failure loads of 5 MN can be extracted from these FLAC models to define safe conditions for the single case of 1 MN loading (at 1 MPa bearing pressure on a pad of 1 m^2) pad, with a factor of safety of 5 in any given rating of rock mass (Fig. 6). If RMR for typical cavernous karst in strong limestone is taken conservatively as between 30 and 40, a cover ratio of 0.5, where the roof thickness is at least half the cave width ($t = w/2$), appears to be adequate for most engineering practice where bearing pressures greater than 1 MPa are rarely invoked. In karst terrains on chalk and some other weak or thinly bedded limestones, RMR may be estimated as nearer 20, and a cover ratio of 1, where roof thickness equals cave width ($t = w$), may be required for safe construction. It is notable that these data are derived from purely two-dimensional modelling, and failure loads are likely to be higher where some roof support is provided in the third dimension; this would increase the factor of safety in any interpreted results.

Guidelines for construction over caves

Combined with an estimation of likely cave width in a given karst, the above results allow definition of the depth to which rock should be proof-drilled to eliminate the hazard of rock failure over caves with respect to the stability of engineered structures. The widths of potential caves that remain unseen beneath any given construction site can only be estimated as 'most likely values'. Such estimates are best made after perusal of local records of observed caves in that particular karst environment; alternatively, failing the existence of a useable cave database, estimates can be derived from the engineering classification of the karst, which may be assessed from broad visual inspection (Waltham & Fookes 2003). More conservative values for generalized safe cover ratios may then be taken as 0.7, to make due allowance for poor data on likely cave dimensions, even more local variation within the fissured karst bedrock and higher imposed loads from engineering works.

Values for the required safe cover thickness then become the guidelines for the minimum depths of exploratory drilling or probing that should prove sound rock beneath foundation levels in engineering works (Table 1). At most sites on strong cavernous limestone (typical of most major karst terrains), drilling is required to depths that varies between 3 and 7 m, depending on the karstic maturity and, hence, the cave size. The most common weaker cavernous rocks are chalk and gypsum; although they would both require higher values of safe cover ratios, they require roughly comparable depths of drilling to ascertain ground integrity under the lower loading stresses that building codes normally set as maxima on these weaker rocks (Table 1). Basalt is commonly very strong and also structurally massive in the types of lava flows that may contain tubes or caves (Waltham *et al.* 2005), and proof drilling within basalt may therefore be less, based on a safe value of 0.5 for the cover ratio.

A survey of available drilling guidelines, that have been applied in various ground investigations on karst (Waltham *et al.* 2005, table 7.2), reveals values that range from 1.5 to 5.0 m. Although these encompass considerable variety in limestone lithologies, karst morphologies and engineering requirements, some appear rather conservative and others may be open to question. Collapse of the Florida freeway viaduct, as referred to earlier, followed exploratory drilling that could not be regarded as appropriate. The freeway's support column stood on a large-diameter pile that reached 19 m below ground level

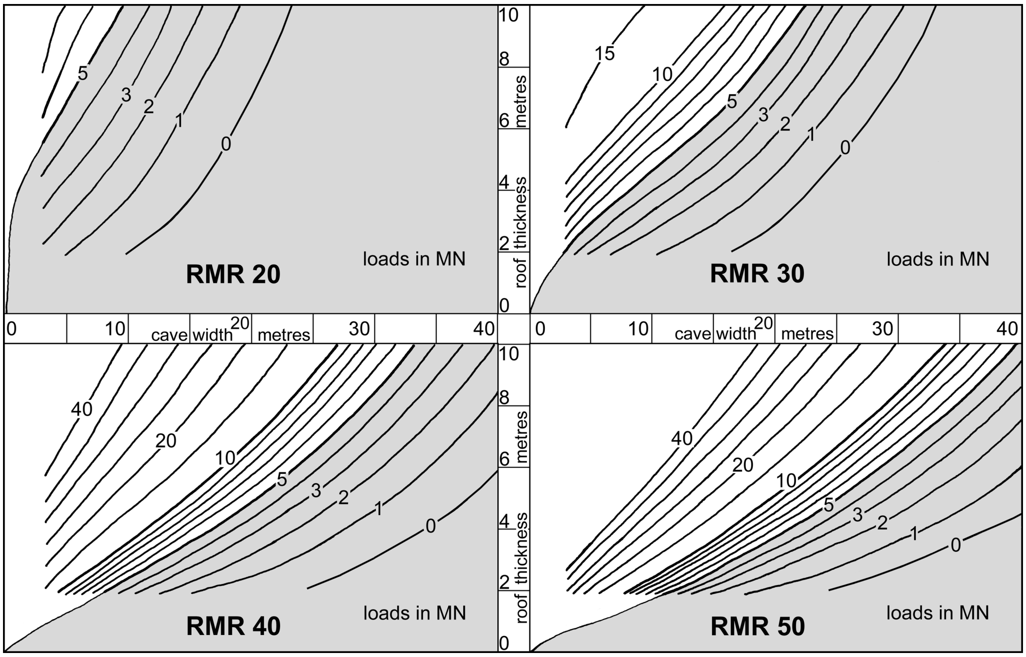

Fig. 5. Nomograms that relate failure loads to cave width and roof thickness in ground of various rock mass ratings. Numerical models were generated with incremental loads applied to foundation pads, 1 m^2, on the surface directly above the caves. The shaded areas represent situations with respect to cave width and roof thickness where a loading of 1 MN on the pad leaves a factor of safety of less than 5, and are therefore considered unsafe. (From Waltham *et al.* 2005.)

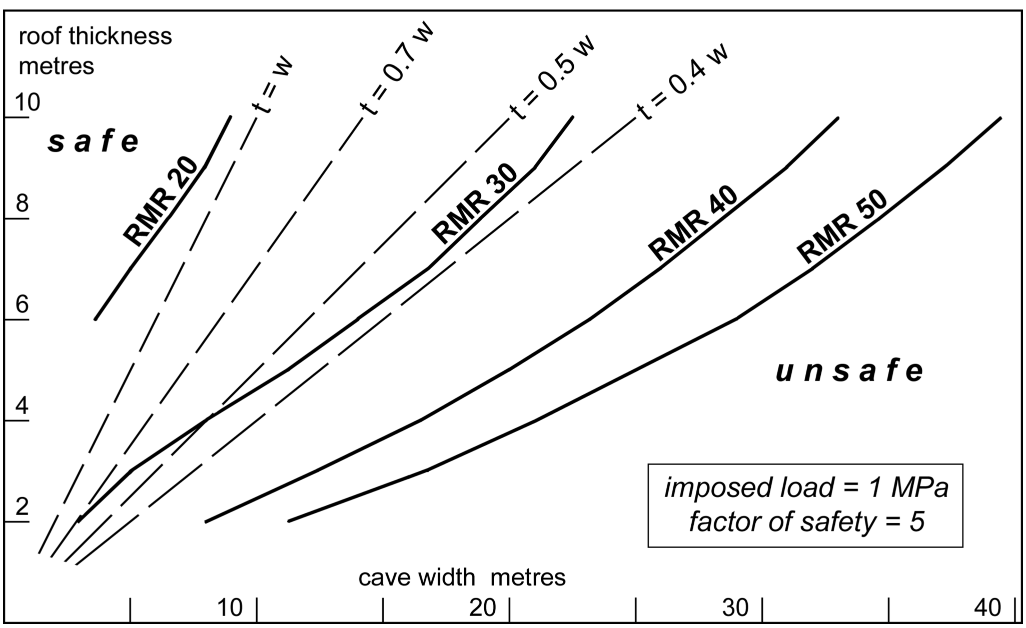

Fig. 6. Envelopes of acceptability, with respect to cave width and roof thickness, where engineering loads of 1 MN are applied, with a factor of safety of 5, to pads of 1 m^2 on the surface directly over the caves, in ground of various rock mass ratings; broken lines indicate various cover ratios, where t is roof thickness and w is cave width. (From Waltham *et al.* 2005.)

Table 1. *Safe roof thicknesses for various cave situations. The karst classes refer to the designations of Waltham & Fookes (2003)*

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

(and therefore 8 m below rockhead), but prior drilling proved only 3 m of sound limestone below the heavily loaded base of the pile. This was because the engineers' guidelines had been based on a total drilling depth from the surface, in respect of the pile's conceptual skin friction within the profile of soil and karst limestone, while the pile's high end-loading caused the rock failure in this event.

While construction projects in typical karst on strong and massive limestone require guidelines that drilling or probing should prove between 3 and 7 m of sound rock, gypsum is a slightly weaker rock and, therefore, requires drilling to the greater depths. Further expansion of the guidelines may be required in active karst terrains on gypsum, where dissolution by flowing water may significantly

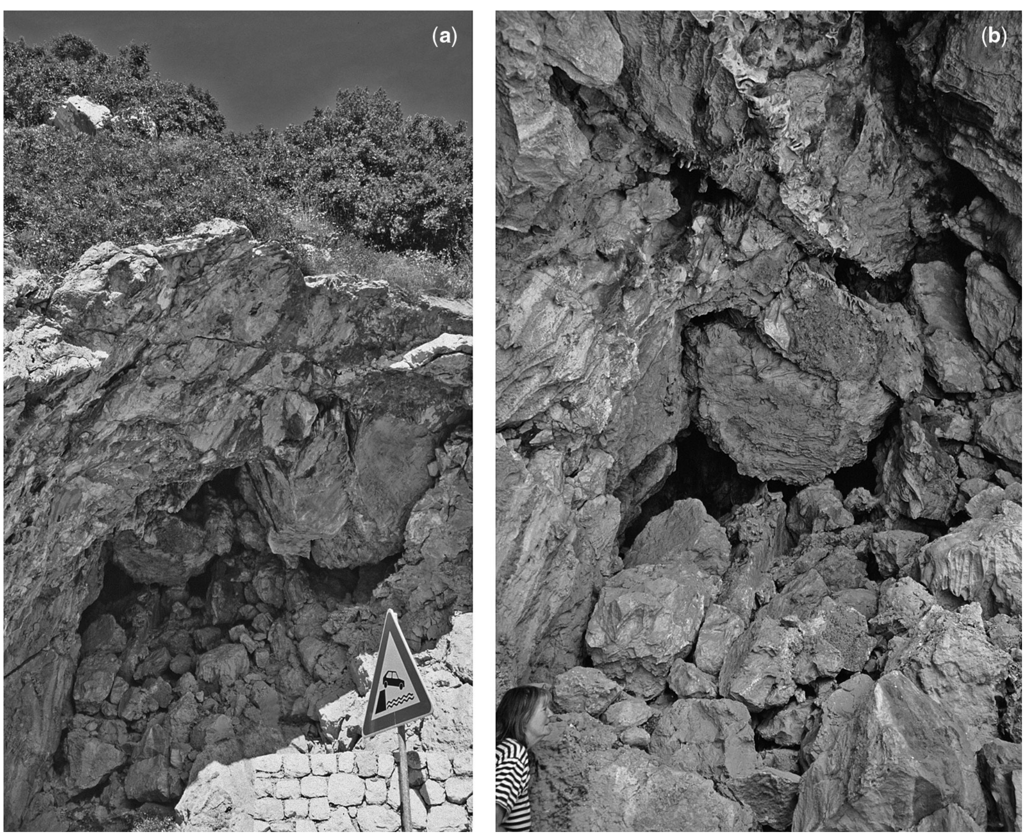

Fig. 7. A roadside cave in the limestone of Krk, Croatia, where the wider view (**a**) exposes a solid rock arch over the front of the cave, but a closer view (**b**) reveals an unstable pile of fallen blocks and debris extending upwards at the back of the cave.

enlarge or modify ground cavities within the lifetime of a built structure.

It is essential to note that the numerical modelling, with respect to cave roof integrity under imposed load (Fig. 5), is only based on generalized estimates of the strength parameters for rock masses of the various rating values. These estimates can only approximate the notoriously variable conditions in karst, where strong intact rock is broken by open or soil-filled fissures, in styles very different from those in insoluble rock masses. Whereas parts of some open caves may have structurally sound roofs within relatively intact rock, another site may have zones of broken and collapsed ground over ruckles of breakdown blocks inside what was once an open cave (Fig. 7). Such ground conditions in karst can be a nightmare to structural engineers, and do confirm that there is no substitute for careful examination of each individual site within a terrain of cavernous karst.

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