



Karst Hazards Beneath Expanding Cities and the Limits of Conventional Site Investigation

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Abstract

Cities built on limestone, dolomite, gypsum and salt are spreading onto ground where the main hazard is a void that cannot be seen from the surface. Sinkholes, irregular rockhead and soil-filled cavities damage buildings, roads and buried services, and urban development itself makes them more likely by altering groundwater levels and concentrating drainage. This narrative review of the published literature considers how well the usual tools of site investigation cope with karst. It outlines the processes that form sinkholes and the classifications used to describe karst ground, examines the ways in which urban activity triggers collapse, and then assesses boreholes and probing, surface geophysics, satellite radar interferometry and susceptibility mapping in turn. The central difficulty is one of sampling: a routine pattern of boreholes examines a minute fraction of the ground, and the features that matter are small, irregularly distributed and often change with time. Geophysical and remote sensing methods narrow the gap but each has conditions under which it fails, and urban settings supply many of those conditions. The review argues that investigation in karst must be staged, model-led and continued through construction and operation, and it identifies the main gaps in knowledge and practice.

Keywords: *Karst, Sinkholes, Site investigation, Urban geohazards, Engineering geophysics, Ground subsidence*

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1. Introduction

Soluble rocks crop out or lie at shallow depth beneath a substantial part of the ice-free land surface, and many large cities stand on them (Ford and Williams, 2007). As these cities grow, new districts are built on ground that earlier generations avoided or used only for farming. The geohazards of karst terrain have been reviewed comprehensively by Gutiérrez *et al.* (2014), who place sinkholes first among those that cause economic loss, and the engineering response is set out in the standard text by Waltham *et al.* (2005).

Site investigation as normally practised was developed for layered soils and for rock whose properties vary gradually. Codes describe a sequence of desk study, reconnaissance, boreholes at a spacing related to

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the structure, and laboratory testing (Clayton *et al.*, 1995; CEN, 2007). The approach assumes that conditions between boreholes can be interpolated. In karst that assumption breaks down, and the consequences are met during construction or, worse, after it.

This review examines where and why conventional investigation falls short in urban karst and what the literature offers to supplement it. It concentrates on sinkhole and void hazards to buildings and infrastructure. Groundwater contamination and flooding, which are equally characteristic of karst, are outside its scope.

2. Scope and Approach

The article is a narrative review. It is based on the principal textbooks and review papers on karst geomorphology and engineering, on widely cited papers describing investigation methods and their application to cavities, and on published accounts of sinkhole problems in urban and mining areas. The selection reflects the writer's judgement of which sources have shaped practice, and no systematic search or screening was undertaken. Carbonate and evaporite karst are both considered, since cities are built on each and the hazards differ mainly in rate.

3. Karst Ground and How Sinkholes Form

Karst develops where circulating water dissolves rock along fractures and bedding planes, enlarging them into conduits and caves. The upper, most weathered part of the rock mass, the epikarst, is typically cut by fissures and pinnacles and stores and redirects infiltrating water (Williams, 2008). Where the rock is mantled by soil, the buried surface may have a relief of many metres over short distances. In gypsum and salt the same processes run far faster than in limestone, because the minerals are much more soluble, and cavities can enlarge appreciably within the life of a structure (Cooper, 1998).

Sinkholes are the surface expression of these processes. Waltham *et al.* (2005) distinguish six types: dissolution, collapse, caprock, dropout, suffosion and buried sinkholes. Gutiérrez *et al.* (2008) proposed a genetic scheme that names subsidence sinkholes by the material affected, whether cover, bedrock or caprock, and by the mechanism, whether collapse, suffosion or sagging. For engineering purposes the important distinction is between failure of rock roofs over caves, which is rare on a human time scale, and failure within the soil cover, which is common. Cover-collapse or dropout sinkholes form when soil is washed down into fissures in the rock, leaving an arched void that migrates upward until the roof gives way. Sharp (1999) analysed the mechanics of this upward propagation and showed how changes in pore pressure around the void promote it.

The variability of karst ground was put on an engineering footing by Waltham and Fookes (2003), who defined five classes from juvenile to extreme according to the frequency of sinkholes, the relief of rockhead, and the size and number of fissures and caves. Their classification is explicit that the appropriate method and density of investigation depend on the class, and that in mature and complex karst no affordable pattern of boreholes will find every void.

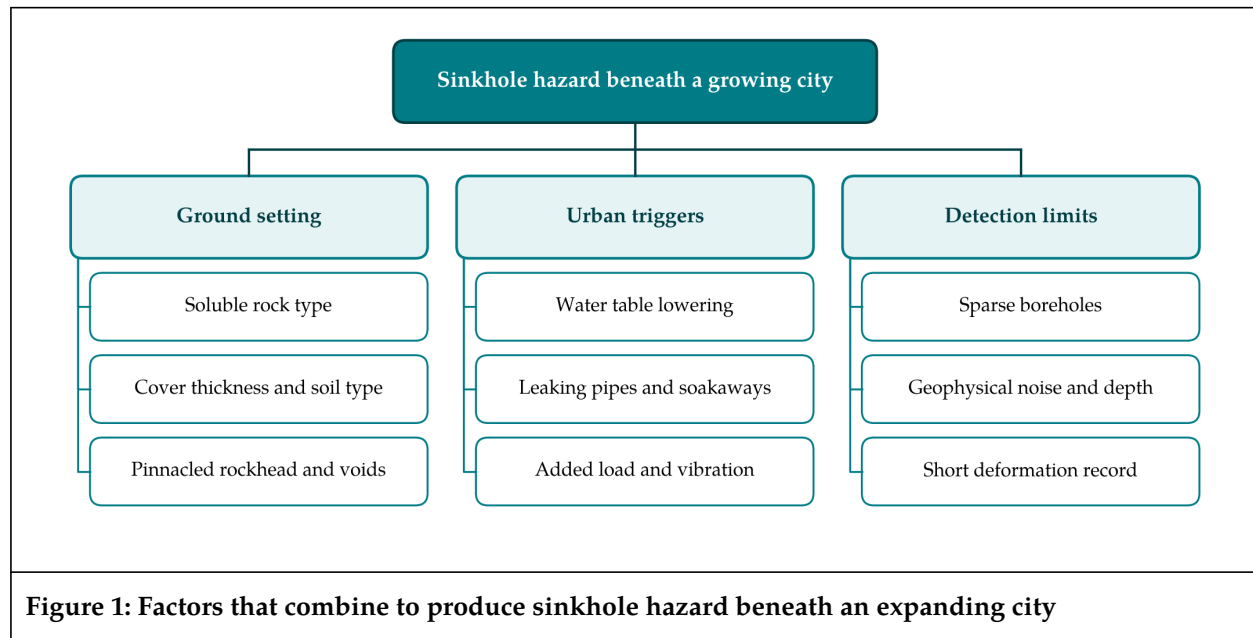
4. How Urban Growth Raises the Hazard

A large proportion of sinkholes in settled areas are induced by human activity. In a study of the eastern United States, Newton (1987) attributed most new sinkholes to two causes: decline of the water table through pumping, and construction practices that divert or impound surface water. Lowering the water table removes buoyant support from soil arches, increases downward seepage gradients and may dry and crack cohesive cover. The best-documented example is the dolomite of the Far West Rand in South Africa, where dewatering of groundwater compartments for gold mining in the 1960s was followed by catastrophic sinkholes and subsidence, and where a formal method of hazard assessment was later developed for dolomite land (Buttrick and van Schalkwyk, 1998).

Cities reproduce these triggers at a smaller scale and in great number. Water mains, sewers and storm drains leak; soakaways and detention basins concentrate infiltration at points; paved surfaces shed runoff to the edges of sites. Each provides the flow needed to carry soil into the rock. Loading by buildings and

embankments, vibration from traffic and piling, and excavation that thins the cover add to the effect (Zhou and Beck, 2008). Brinkmann *et al.* (2008) examined the distribution of sinkholes in the rapidly urbanising Tampa Bay area of Florida. In such settings depressions are filled and built over, so the record of past events is incomplete. The factors involved are grouped in Figure 1.

The implication for investigation is that the hazard is not fixed at the time a site is studied. Ground that has been stable under farmland may become unstable once it is drained, loaded and plumbed.



5. Limits of Boreholes and Probing

A borehole samples a cylinder of ground a few centimetres across. Even a closely spaced grid examines a tiny fraction of the volume beneath a building, and the chance that it intersects a given fissure or small cavity is correspondingly low. On pinnacled rockhead, adjacent holes may meet rock at very different depths, and a hole that strikes the top of a pinnacle gives no warning of the soil-filled slot beside it. Sowers (1996) described these difficulties from long experience of foundations in the limestone terrain of the south-eastern United States and recommended that investigation be treated as continuing through construction.

The practical response has been to probe at the position of every foundation element. Waltham and Fookes (2003) suggest that, in the more mature classes of karst, each pile or pad location should be proved by drilling to a depth related to the likely cave width. Rotary percussive probing is fast and cheap, and drilling parameters give an indication of voids and soft infill, but it yields little information on the nature of the material. Probing also has to be done with care, since the flushing water and the hole itself can open a path for soil loss.

6. What Geophysics Adds and Where It Fails

Surface geophysics offers continuous coverage between boreholes, and several methods respond to the contrasts that karst features present. Chalikakis *et al.* (2011) reviewed their use in karst and concluded that no single method is sufficient and that the choice must follow from the target and the setting. Table 1 summarises the methods most often used for void and rockhead detection.

Electrical resistivity tomography, made routine by inversion methods such as that of Loke and Barker (1996), maps rockhead relief and clay-filled depressions well, because limestone, clay and air differ greatly in resistivity. Microgravity detects the mass deficit of a cavity directly and was shown by Butler (1984) to be capable of locating shallow voids, though the anomaly of a small or deep void is close to the noise level. Multichannel analysis of surface waves (Park *et al.*, 1999) identifies zones of reduced stiffness

in the cover that may mark ravelling soil above a void. Ground-penetrating radar gives fine detail at shallow depth where the cover is sandy and is of little use beneath clay.

Table 1: Investigation methods used in karst, what each responds to and its main limits in urban settings

Method	Responds to	Main limits in a city	Source
Boreholes and probing	Material at a point	Minute sample; may trigger soil loss	Sowers, 1996
Electrical resistivity tomography	Contrast between rock, clay and air or water	Buried metal, paving, limited line length	Loke and Barker, 1996
Microgravity	Mass deficit of a void	Slow; needs corrections for buildings and basements	Butler, 1984
Surface wave methods	Low stiffness zones above voids	Traffic noise; resolution falls with depth	Park et al., 1999
Radar interferometry	Slow surface settlement	Misses sudden collapse; needs stable reflectors	Ferretti et al., 2001
Susceptibility mapping	Spatial pattern of past sinkholes	Depends on a complete inventory	Galve et al., 2009

Urban conditions degrade every one of these. Buried services, reinforced slabs and fences distort electrical and electromagnetic measurements. Buildings and basements produce gravity effects larger than those sought. Traffic and machinery raise seismic noise. Above all, the space needed to lay out a survey line long enough to reach the depth of interest is seldom available between buildings. A further limit is inherent in the physics: resolution falls with depth, so that a void capable of damaging a structure may be too small to detect at the depth where it lies. Geophysical anomalies indicate where to drill and do not remove the need for it.

7. Monitoring from Space and Mapping Susceptibility

Because the hazard evolves, methods that observe change have particular value. Satellite radar interferometry using persistent scatterers measures millimetre-scale movement of buildings and other stable reflectors over years ([Ferretti et al., 2001](#)), and cities provide reflectors in abundance. [Jones and Blom \(2014\)](#) reported that airborne radar interferometry recorded ground deformation before the Bayou Corne sinkhole in Louisiana appeared at the surface, and [Intrieri et al. \(2015\)](#) described the use of ground-based radar to monitor a sinkhole and give warning of its growth. These results show that some sinkholes have detectable precursors. Many cover-collapse events do not, since the void migrates through the soil with little surface movement until the final failure.

At the scale of a district, susceptibility maps relate the positions of known sinkholes to geological and hydrological factors and extrapolate to unaffected ground. [Kaufmann and Quinif \(2002\)](#) produced such a map for cover-collapse sinkholes in southern Belgium, and [Galve et al. \(2009\)](#) compared several mapping methods in the evaporite karst of the Ebro valley in Spain and tested their predictions against later sinkholes. Such maps are suited to planning: steering development away from the worst ground and setting the level of investigation required elsewhere. Their reliability rests on the completeness of the inventory, which is the very thing that urbanisation erodes as depressions are filled and built over.

8. Towards Investigation That Fits the Ground

The literature converges on a small number of principles. Investigation should begin from a geological model of the karst, including its type, maturity, cover and hydrogeology, and each stage of work should be designed to test and refine that model ([Fookes, 1997](#); [Waltham and Fookes, 2003](#)). Desk study carries more weight than usual: old maps, aerial photographs and records of past collapses reveal buried and

filled sinkholes that no borehole grid would find. Geophysics is used to direct drilling, with two or more methods chosen for the target, and probing is carried out at foundation positions. The design then assumes that some features remain undetected, and provides for them through foundations able to span a void of specified size, control of drainage and services, and inspection during excavation (Sowers, 1996; Zhou and Beck, 2008).

Seen in this way, the limit of conventional investigation is less a shortage of technique than a mismatch of expectation. A report that presents a karst site as characterised, in the sense in which a clay site can be characterised, overstates what any current method can deliver. Stating the residual uncertainty, and managing it through design and monitoring, is the more defensible course.

9. Gaps and Future Work

Several gaps are apparent. Few published studies compare geophysical predictions with what was later exposed in excavation, so the detection rates of the methods under urban conditions are poorly known. Sinkhole inventories are kept by different bodies in different forms, and events repaired by utility companies or private owners often go unrecorded. The contribution of leaking services to collapse is widely asserted and seldom quantified. Finally, the effect on karst hazard of changing rainfall patterns and of large shifts in urban groundwater abstraction has received little attention in the engineering literature.

10. Conclusion

Karst presents urban engineering with ground whose critical features are small, hidden, irregularly distributed and liable to change once development begins. Boreholes establish conditions at a point and cannot be relied on to find voids between points. Geophysics, radar interferometry and susceptibility mapping each extend what can be known, and each is weakened by the conditions that cities impose. The published literature supports an approach in which investigation is led by a geological model, combines methods, continues through construction and is honest about what remains unknown, with design and water management carrying the remaining risk.

Conflict of interest

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