Sinkhole hazard case histories in karst terrains

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Abstract

With few exceptions, the ground collapses that constitute the karst geohazard in engineering activity in limestone terrains are induced by human activity. Subsidence sinkholes, formed entirely within the soil profile, constitute the most widespread karst geohazard, but are largely induced by engineered works, either directly or accidentally. Water table decline (as a result of pumped abstraction or quarry de-watering) and uncontrolled surface drainage input are the two key factors that induce subsidence sinkholes, especially where both are involved. Collapse sinkholes, formed by failure of bedrock over a cavity, are rare in natural karst landscapes, but may be induced by excessive loading imposed on limestone that lies above an open cave; the risks associated with this geohazard should be eliminated by implementation of an appropriate site investigation that includes proof drilling. Case studies to demonstrate the karst geohazard concern: (1) homes damaged by new sinkholes around a de-watered limestone quarry in Pennsylvania; (2) problems with sinkholes for a railway across dolomite karst in South Africa; (3) collapse of ground in pseudokarst in Guatemala; (4) failure of a viaduct pier into an unseen cave in Florida; (5) estimation of potential sizes of collapse sinkholes along a pipeline route over gypsum karst in Turkey. As hazardous new sinkholes in karst are almost entirely induced by either uncontrolled drainage or excessive loading, they should be largely eliminated by appropriate engineering design and works. These need to be based on a proper understanding of karst ground conditions.

For civil engineering and construction projects in karst terrains, the major geohazard is ground collapse related to voids. The surface expression of such collapse lies in the closed depressions that are collectively known as sinkholes (or dolines). Caves or caverns, opened up by dissolution of rock, are diagnostic of karst terrains, where natural drainage is all or partly underground. Whereas these initial cavities are created within the bedrock, subsequent downward migration of soil cover creates secondary cavities that are inherently more unstable within the soil profile. Most caves and sinkholes are in the rocks and soils of limestone or gypsum terrains, but smaller numbers are related to other rocks, and the multiple natural processes create a suite of features with various sizes and morphologies (Waltham *et al.* 2005).

As geohazards, there are enormous contrasts, in scale, process and event frequency, between rock collapses and soil collapses. One feature they share is that the great majority are induced by some form of engineering activity. Although both are features of karst terrains that occur on outcrops of a limited number of water-soluble rock types, they have to be considered as two separate geohazards. The threat of new and destructive subsidence sinkholes, formed within the soil profile, requires an engineering response very different from that posed by potential rock failure.

Subsidence sinkholes

By definition, subsidence sinkholes lie entirely within the soil profile, although their formation relies on open fissures and caves in the underlying bedrock, into which down-washed soil can be lost. They have a spectrum of morphologies between suffosion sinkholes in non-cohesive sand and dropout sinkholes in cohesive clay (Fig. 1); most are of intermediate form, with some elements of sudden collapse over voids in soil that has some cohesion (Fig. 2). They are the most common cause of ground failure in karst terrains, and constitute an active geohazard, because soil movement by flowing or seeping water may be rapid. Open voids can develop within time scales of days or months, and subsequent failure of the soil arches above them can be instantaneous and without warning. However, subsidence sinkholes still occur with very low frequencies in natural, undisturbed environments; new sinkhole frequencies only reach 1 km^{-2} year^{-1} (a rate often known by the index NSH = 1) in extreme situations (Waltham & Fookes 2003).

The vast majority of new subsidence sinkholes are induced by ground disturbance, notably in the form of engineering activity (Newton 1987; Waltham & Fookes 2003; Waltham *et al.* 2005). Their development is a function of suffosion, whereby seepage water washes soil into open voids in the underlying limestone or gypsum (which remains stable). Increased rates of suffosion are largely caused by increased drainage input or by a decline of the water table (or by a combination of both).

Increased drainage into the soil is most often due to poorly designed drainage systems on and around built structures, or to inadvertent inputs that are temporary during construction activity. In other cases, slow soil movement under natural drainage conditions may fracture a water line or drain, whose leakage then triggers a larger ground failure, as at the Guatemala site in pseudokarst (case study below). Water table decline

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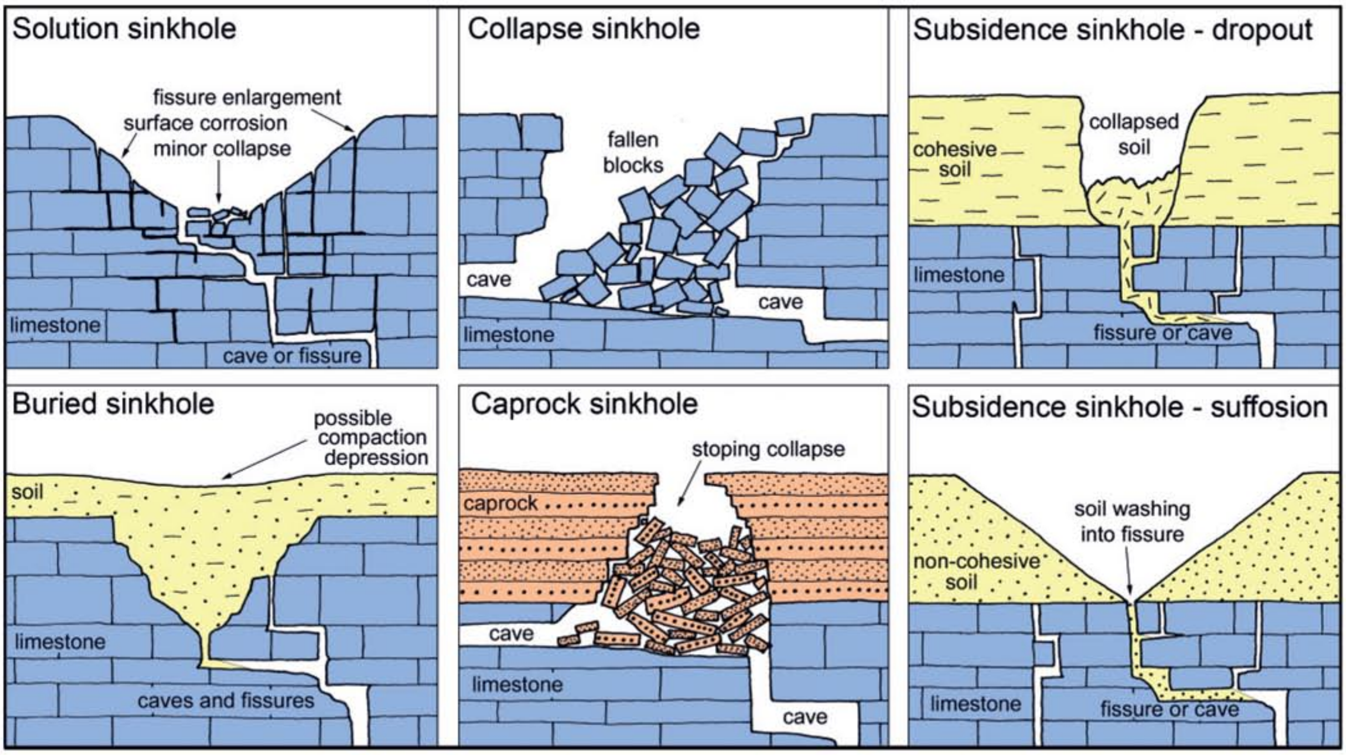

Fig. 1. Subsidence sinkholes and collapse sinkholes within the classification of these karst features. Most sinkholes are 2–50 m wide and deep, although larger examples do occur.

Fig. 2. A small subsidence sinkhole that was a dropout in the front lawn of a house in Pennsylvania affected by de-watering of a nearby quarry.

may be by regional over-abstraction for water supply, or by de-watering around a mine or quarry, as at the Pennsylvania site (case study below).

Prediction of new sinkhole events is fraught with difficulties. Locations cannot be predicted because void distribution in the bedrock is invisible beneath a soil cover, except that a sinkhole is more likely to occur at any point with a new drainage input. Timing cannot be predicted, except that most new sinkholes will occur short-term during or immediately after a major rainfall event, and long-term during or soon after poorly controlled construction activity; too many sinkholes are induced by engineers with damaging impact on their own new structures. The size of a new sinkhole may be roughly predicted by inference from local records of past events, as in the South Africa project (case study below), with implications for appropriate structural design.

At many sites, the complex geology, geomorphology and hydrogeology makes it difficult to apportion blame among contributory causes, but drains are invariably high on the list of suspects. Subsidence sinkholes are better avoided by due precaution than remediated afterwards, but risks can never be totally eliminated. Simply backfilling new sinkholes, with truck-loads of spare soil, as they occur on a construction site is never appropriate; ground movement will inevitably be reactivated at some later date unless the throat of the sinkhole is properly choked or sealed (Waltham *et al.* 2005).

Rock collapse

Failures of strong bedrock limestone are rare. Collapse sinkholes (Fig. 1) are orders of magnitude less common than the subsidence types; they do exist, but are components of landscapes that have developed on geological time scales (Fig. 3). Even China's tiankengs, giant collapse sinkholes that are hundreds of metres deep and wide, have developed by progressive multiple collapses over many thousands of years (Zhu & Chen 2005). Collapsed caverns may have been high on the school geography agenda, but, as a rule, limestone gorges are not collapsed caverns (most of them are subaerial fluvial features).

Fig. 3. Large and small collapse sinkholes, which have not been induced by man, at Koonalda, in South Australia, both with drops of 20 m to the same block-strewn floor.

Limestone collapse is rare and limestone dissolution is slow. New caves take anything from 10 ka to 1 Ma to form. Natural collapses of rock spans over old limestone caves have clearly happened in geological time, but none has been recorded in historical time; on nearly all construction projects, they present a hazard that is ignorable by both geologists and engineers. New caves cannot form in limestone within the lifetimes of built structures, which are of the order of a few hundred years.

In more highly soluble gypsum, these time scales may be reduced to only a tenth (therefore perhaps as low as 1000 years) and any cave roof has to survive in a rock weaker than most limestones. However, risks of ground collapse are still extremely low, as in the gypsum karst of Turkey (case study below). Dissolution of rock salt is even more rapid and provides a separate and special case of geohazard that is fortunately not widespread (Johnson & Neal 2003).

The significant karst geohazard related to bedrock is the potential for collapse induced by loading of a thin rock span over an unseen cave. This is extremely difficult to analyse, because the major risk is from rock at depth, beneath structural foundations, with rock mass characteristics barely assessable from a few borehole cores, over caves of unseen dimensions. The only engineering precaution is prior drilling to prove adequate sound rock over any unknown void, and inadequate probing depth leaves open the possibility of a failure under load, as beneath a viaduct in Florida (case study below). Geophysical surveys (by microgravity, seismic or resistivity cross-hole tomography, or ground penetrating radar) can usefully accompany a programme of boreholes; their results normally require confirmation by drilling, and may not be worth while where a borehole is required beneath each point loading, as for example beneath large piles or caissons. Recent research has suggested a guideline of proving sound rock to a depth that exceeds 70% of the likely cave width (Waltham & Lu 2007). This generalization comes with many caveats, and can only be applied after a careful study of the local karst. It awaits case histories of practical experience that might confirm it or instigate modifications.

Case 1: induced subsidence sinkholes in Pennsylvania

New sinkholes have destroyed houses and road bridges near Tatamy, in the Lehigh Valley karst of eastern Pennsylvania, USA. Folded Palaeozoic limestones have narrow outcrops aligned roughly east–west, where many streams sink underground for short distances. Bushkill Creek has a surface course past the large Stockertown limestone quarry and the small community of Brookwood, before sinking north of Tatamy (Fig. 4). The quarry is now worked to a depth of 65 m below the adjacent creek, which has become a losing stream with water sinking at various sites. The same water cascades out of at least two open cave passages in the quarry's northern wall, and feeds strong artesian flows from boreholes in the western quarry floor. The quarry is kept dry by pumping water at a mean rate of 2 $m^3 s^{-1}$; this water is piped from sump pools on the quarry floor up to outfalls into a section of the creek that is now lined to prevent the same water returning to the quarry (Fig. 5).

The quarry's pumping has created a cone of depression that has been mapped over 36 km^2 (Risser 2006). It extends largely east–west along the limestone outcrop, and is distorted to the south by the regional groundwater gradient (Fig. 4, where only its deepest part, within the 90 m water table contour, is indicated). This

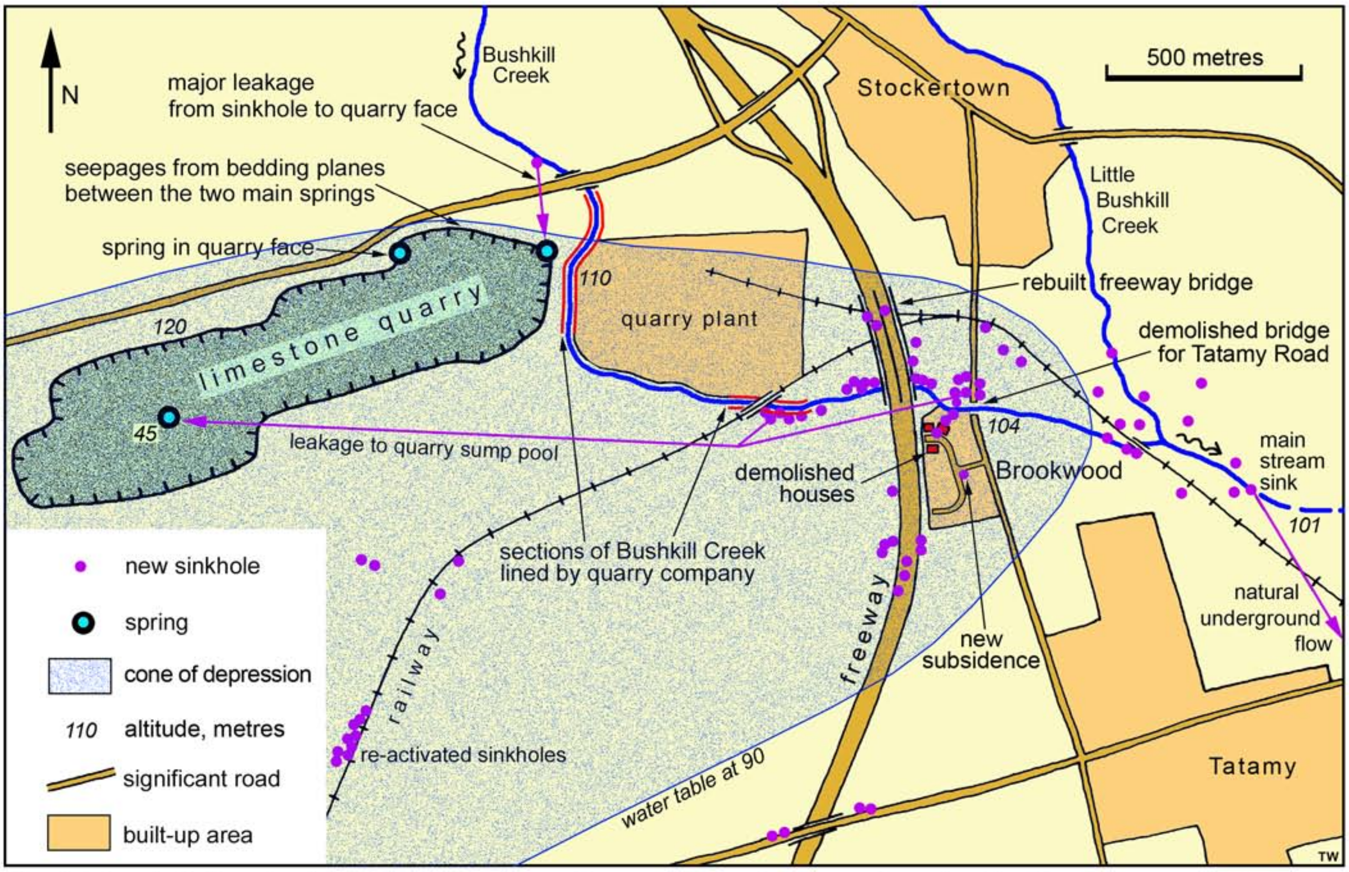

Fig. 4. New sinkholes related to de-watering the Stockertown Quarry in eastern Pennsylvania. The 90 m water table contour surrounds only the deeper part of the cone of depression. The long leakage trace in the centre of the map is shown bent for clarity, but is probably along a single straight line from both sets of sinkholes to the quarry.

Fig. 5. Installing the liner along the creek bed downstream of Stockertown Quarry (photo: Brookwood Group).

area, with more than about 10 m of drawdown, encompasses about 100 new sinkholes, all subsidence sinkholes formed within the soil profile. Quarrying towards the 45 m level started in 1993. After a few abnormally dry years, pumping was increased to the current rate early in 2000, and, later the same year, it was observed that water flowing into the quarry was carrying sediment. The first new sinkhole had appeared in 1999, beside the Tatamy bridge, and the autumn of 2000 saw many more new sinkholes in and around Brookwood.

One sinkhole in the creek bed below the railway bridge swallowed a large part of the creek flow, which then emerged in the far quarry floor. This input was greatly reduced when the creek bed was sealed by the quarry company. Subsequently, the creek began to lose about half of its flow into sinkholes between the freeway bridge and the Tatamy bridge, downstream of the lined section. An injection of brine confirmed that this also emerged near the far end of the quarry floor. Both these underground flows may pass largely along a zone 100 m wide of heavily fissured limestone (described as deeply weathered), which is aligned on an east–west fault and lies beneath a buried valley filled with 30 m of alluvial sediment and soil. This zone was recognized in boreholes drilled to rebuild the bridges that carried the carriageways of the north–south freeway, after footings under both had subsided in 2004 (Waltham *et al.* 2005). By then, the northern approach to the Tatamy bridge had already been destroyed by very active sinkholes (Fig. 6) that swallowed up to 1 $m^3 s^{-1}$ of the creek's flow; the last span of the bridge was demolished early in 2007 to create space for sinkhole remediation. All the bridges over Bushkill Creek originally stood on pads founded in the alluvial soils that have since been washed into the limestone.

Fig. 6. The approach to the Tatamy bridge, destroyed by active sinkholes.

Fig. 7. The basement floor of 29 Babbling Brook Road, which collapsed into an expanding group of subsidence sinkholes (photo: Brookwood Group).

Away from the creek bed, sinkholes developed at many points over the cone of depression, but the most destructive are the active cluster within the north end of the Brookwood residential area. Worst hit was 29 Babbling Brook Road (the Sarkady house), with its first sinkholes developing in 2000. Late that year, these were filled with 1000 tonnes of soil and rock and 100 m^3 of concrete, but they kept reopening and expanding (Perlow 2003). A resistivity survey indicated the presence of a buried sinkhole, with a soil-filled throat 5 m across, in the rockhead beneath about 10 m of soil. More subsidence sinkholes opened in the front lawn in 2003 (Fig. 2), and again in 2006, when the basement floor collapsed into yet another sinkhole (Fig. 7); this rendered the house uninhabitable, although the owners had long since moved out. Four more adjacent houses were also damaged by sinkholes within the same period, and three of their owners subsequently moved out. Residents in 16 neighbouring houses were justifiably concerned.

Help for the home-owners was slow to come while responsibilities were disputed. The state authorities were directly concerned with only the highways and bridges. They deemed Hercules Cement Company, owners of the quarry, responsible, but only for contributing to the sinkhole development and not for causing the sinkholes in a geologically complex situation. They suggested that residents should move out if they were not happy with living there, and should contact Hercules about compensation; vague and unhelpful advice in a legally grey area. Meanwhile, Hercules blamed, with some justification, the increased urbanization since the 1970s, construction of the freeway in the late 1960s, and the realignment of stream channels, as significant contributors to the rash of new sinkholes. Subsequently, Hercules has accepted that its quarry contributes to the sinkhole problem, without being the primary cause, and has responded appropriately.

Continuing repair and filling of sinkholes has been carried out by Hercules personnel, but such work is only ever a stop-gap and can cause lateral expansion of an active sinkhole. One sinkhole in the southern bank of the creek has been filled and repaired eight times in 7 years. Permanent remediation is extremely difficult, and nearly impossible in practice, because the deep profile of soil and weathered rock hides the throats of sinkholes, where the bedrock fissures must be sealed to be effective. Major grouting would be excessively costly and could still not guarantee success in ground that is a mix of limestone blocks, residual soil, in-washed sediment and open voids.

Early in 2007, Hercules bought four of the houses in Brookwood, thereby allowing their previous owners to relocate without financial loss. Three of the houses have since been demolished, so that the ground can be more effectively patched. Stability might be better achieved if lateral water input was reduced by sinkhole remediation, but the stream sinks at the demolished Tatamy bridge are kept open by filling the surface collapses with permeable granular fill. This is because the freeway bridges stand on micro-piles within the weathered profile (where sound bedrock is found only at depths of more than 100 m), and the state fears destructive soil compaction as a result of any change to the groundwater regime. For the same reason, the state has opposed Hercules' proposal to extend their lining of Bushkill Creek to beyond Brookwood, and thereby shift any induced sinkholes further downstream, and away from houses and structures. However, a creek lining may be the only safe option to protect totally the houses that remain occupied in Brookwood. New slow subsidence of a garden south of the demolished houses may indicate a site with future problems.

Future development of the quarry will expand horizontally towards the north, where the existing road will be realigned, so that the destructive cone of depression should grow no larger. Hercules also wants the quarry to reach more than 15 m deeper at the eastern end, where the geological structure currently precludes major groundwater inflows; the impact on the cone of

Fig. 8. A new sinkhole that is continuing to enlarge some months after its first failure over the buried dolomite south of Pretoria.

depression is uncertain. The company would also shift the creek channel 200 m to the east past the quarry (through the plant area); this may help quarry drainage and environmental restoration of the stream, but would have no impact on distant sinkholes. Closing the quarry has not been considered good for the local economy, and would also remove the teams who currently repair the new sinkholes. The current situation is a compromise, but it does appear to be as good as is possible in an area where sinkholes have clearly been induced by man's own activities.

Fig. 9. Pinnacled rockhead exposed in a large dolomite quarry south of Pretoria.

Case 2: sinkholes over pinnacled rockhead in South Africa

The dolomite karst of South Africa has an unusually long and complex geomorphological history, which has created difficult ground conditions with a variety of sinkhole hazards (Brink 1979; Wagener 1985). The dolomite is a very strong rock, but its rockhead has been fretted into forests of buried pinnacles with local relief of 3–10 m, which are superimposed on larger and broader variations in rockhead elevation. The overlying soils, 10–100 m thick, are a mixture of relatively stable chert gravels and collapsible, silty, residual wad. A new railway between Johannesburg and Pretoria has to cross 15 km of buried dolomite outcrop without inducing sinkholes, either by disturbance during its construction or by the impact of its continuing existence.

Within the dolomite karst, very old buried sinkholes are up to 100 m deep and 1000 m across with no surface expression. They are famous for the series of huge dropout sinkholes that developed within their old and varied fills along the Far West Rand outcrops; during the 1960s and 1970s, these were induced by major water table decline consequent on massive dewatering of the underlying gold mines (Waltham *et al.* 2005). Large and destructive compaction sinkholes also developed where the fills in the buried sinkholes contained deep profiles of unstable wad. Similar large buried sinkholes have been found along the railway corridor; but they are not considered a significant hazard, because their wad fills are capped by thick chert gravels, and the water table is stable and protected by existing legislation against dewatering.

Smaller subsidence sinkholes are perceived as the major hazard. Records of 300 past events in and around the railway corridor show a direct correlation with drainage disturbance, mainly in the urban areas, and also show that new sinkholes develop by expanding slowly from initial failures that are only a few metres across. Very strict control of all runoff and drainage, along and adjacent to all structures for the new railway, is intended to minimize this sinkhole risk, but it cannot eliminate the hazard. Some sections of the line lie on concrete slabs that are designed to span 15 m over any new collapse. Existing records suggests that this exceeds the maximum size of an initial failure; subsequent expansion takes months or years (Fig. 8) and can be restrained by filling and grouting after the initial event is revealed by regular monitoring.

A viaduct carries the line through an urban area, with all its piers founded on bedrock beneath soil cover that is 5–50 m deep. The nature of the rockhead means that piers have to bear on pinnacles of the strong dolomite, each of which has its integrity proven by drilling to 10 m beneath socket level (Fig. 9). The piers are also designed to survive lateral stresses that could be induced should the soil cover be lost on one side into an adjacent new subsidence sinkhole.

Ground investigation for the new railway has included very thorough study and assessment of each and every karst hazard, followed by appropriate and conservative design, so that risks have been reduced to acceptable and very low levels. The railway is still under construction, and should perform well across this very complex karst terrain.

Case 3: dropout sinkhole in pseudokarst in Guatemala

Early in 2007, a sinkhole collapse in the San Antonio suburb of Guatemala City provided the ultimate nightmare of a large unpredictable hole that instantly swallowed houses and people in the middle of the night. The new sinkhole was a little over 20 m in diameter at the surface with overhanging walls to a depth of 60 m (Fig. 10); the collapse killed three people, and destroyed one street and five buildings.

The sinkhole was caused by rock collapsing into a large void, but the rock is so weak that the site is better described as a large dropout sinkhole (Fig. 11). It developed in weak Quaternary volcanic deposits, mainly pumice and ash, which are very weak, crumbly and easily eroded. However, they have a degree of cohesion that allows them to stand in vertical faces, and also allows subterranean caverns to be opened up in them. The void that this sinkhole collapsed into was created by soil piping, whereby seepage water had washed the fines out of the poorly consolidated sediment, progressively taking coarser material and eventually creating an open pipe that developed headwards towards its water input. Eventual failure of the undermined roof was an inevitable continuation of the piping process. No rock dissolution was involved, and it is therefore a pseudokarst feature. Comparable large piping failures and sinkhole collapses are well known in the loess lands of China (Waltham *et al.* 2005).

Fig. 10. The large dropout sinkhole in the suburbs of Guatemala City.

Fig. 11. Weak pyroclastic sediments that are prone to piping failure, exposed in the new sinkhole in Guatemala City.

Collapse of the sinkhole was triggered by a major sewer failure after a period of heavy rains. Residents of the area reported that they had heard noises underground for a month prior to the final breakthrough to the surface; piping wash-out is noisier than rock dissolution when large chunks of wall material fall away in the later stages of a large pipe's expansion. Storm-water continued to flow through the base of the open sinkhole. Although piping failures do occur naturally in these sediments, the scale of this event was largely induced by failure of a storm drain that had been installed 50 years ago. The outlet of the soil pipe was not observed, but appears to have been into one of the nearby, steep-walled, fluvial canyons, where heavy flows of muddy water were seen; at least part of the pipe was created in the backfill that was poorly compacted after the drain's construction.

The size of the open sinkhole showed how huge amounts of material can be lost into networks of voids, in either limestone karst or piping pseudokarst. At this site, the right cohesion levels within the soil profile, and with a fortuitous input of uncontrolled drainage, led to unknown soil cavities growing to large size before the roof collapsed with little or no warning.

Case 4: collapse induced by loading in Florida

Across the south side of Tampa, in Florida, USA, an extra three lanes for tidal-flow traffic along the Lee Roy Selmon Expressway has been added as a viaduct 9 km long, elevated over the original central reservation. Deck sections, each 18 m wide and 43 m long, reach between single central piers (Wilson 2004). The piers extend as caissons 1.8 m diameter in bored holes that reached to rock 20 m or more below ground surface. However, the elevated expressway stands on limestone, and, during construction, one of the piers failed. Preceded by a sound like a thunderclap, it dropped 5 m straight down, aligned in its bored shaft. The road deck on either side tilted down to the failed pier (Fig. 12).

The failed pier had reached to a depth of 19.2 m, through 11.3 m of sand and clay soils, then through 0.9 m of what was described as weathered limestone, and

Fig. 12. The failed expressway viaduct after its pier had dropped into a void in the limestone beneath Tampa (photo: S. O'Rourke).

then 7 m into sound limestone. The entire pier appeared to have dropped into a void that lay at some depth below the pier toe. Later boreholes indicated that the pier had been bearing on a ledge of limestone, a situation not unusual in mature karst. The sudden drop suggested that this had failed under the pier's end-load, and skin friction down the soil profile had been instantly overcome; the accompanying sound effect was probably created by fracture of the bedrock. There were claims that this was not a sinkhole; and there was certainly no surface feature before or after the failure. However, it was a rock collapse into an underlying solution cavity that was either open or filled with soft clay. As such, it was a buried version of a collapse sinkhole that had been induced by imposed load.

Tampa is well known for its karst with active subsidence sinkholes developed over extensive limestones that lie beneath a thick soil cover. Sinkholes are recorded close to the expressway corridor, and one had been found earlier in the same project where the new road was built at grade. In that terrain, karst voids can reasonably be expected to exist, with or without any surface expression. The small footprints of the viaduct's piers reduced the area to be covered by prior ground investigation, but void locations could only be proven by boreholes. Each and every pier site was drilled, but only to depths of 3 m below the intended pier toe. This was inadequate.

The pier had a design load in normal use of about 5.6 MN, but was carrying 7.35 MN at the time of failure, when it was supporting the massive steel truss that was used to assemble the deck segments. The use of the truss had been perceived as a style of load test for each pier, and it certainly revealed bad ground under this pier. In limestone terrains, such an end-bearing column gains its integrity from an adequate thickness of sound rock over any potential unseen cave. There is rarely any alternative to proving this by an appropriately deep borehole. The Tertiary limestones beneath Tampa are not as strong as most, older, cavernous limestones, and a suitable depth for probing may be compared with the guideline figure of 5 m that is cited for chalk (Waltham & Lu 2007). A probing depth of 4.9 m has previously been suggested for use in the Florida karst (Garlanger 1991). For such heavily loaded piers in this weak limestone, it would probably be more appropriate to prove sound rock for 7 m beneath each pier toe. Any extra probe depth could also offer an economical alternative to drilling arrays of three or four boreholes to the depths of nearly 30 m.

Aftermath expressions of surprise that such a failure could occur, and claims that such an isolated cavity could not be identified, simply lacked justification. Void locations within the limestone could not be predicted, but sound rock could have been proven. Following the pier collapse, all other pier sites were re-investigated. A second pier was found to have subsided by 33 mm, probably over a clay fill within the complexly weathered limestone just below a highly irregular rockhead. Of the 206 viaduct piers, 155 were then retrofitted with additional micro-piles, or parallel bored piles, tied to a pile cap around the original pier. The expressway's extra lanes were opened to traffic in 2006, but the retrofit had added about a third to the total cost of the project. This could have been largely avoided if the prior "soil tests" had properly investigated the rock integrity.

Case 5: collapse sinkholes in gypsum karst in Turkey

The pipeline from the Baku oilfields in Azerbaijan to the Turkish Mediterranean port of Ceyhan, which carried its first crude oil in 2005, has nearly 70 km of its route across mature gypsum karst near Sivas, in eastern Turkey (Waltham 2002). This provided risk of sinkhole development that could undermine the pipeline, with severe consequences in the cost of temporary shutdown and possibly in impacts on the environment. An initial terrain evaluation subdivided the gypsum karst into a series of geohazard models, each of which described the major geological, geomorphological and ground engineering features of particular types of karst. It was recognized that sinkhole hazards emanated from small subsidence sinkholes within the soil profile, and also from large collapse sinkholes developed within the gypsum bedrock.

Field observations and available records showed that most new subsidence sinkholes in the Sivas karst are likely to be <5 m across, and features larger than 15 m across could be regarded as almost inconceivable. These develop wherever and whenever there is increased water flow into the soil, and new sinkholes have been seen to form in agricultural land on the Sivas karst after the spring snow melt. As the pipeline is capable of spanning at least 20 m between supports, these subsidence sinkholes offer no threat to its integrity. Any new features

Fig. 13. The large old collapsed sinkhole of Kizilcam in the gypsum karst of Turkey.

that happened to undermine the buried pipeline could be sealed and backfilled to prevent continuing enlargement. They would have been most likely to develop during disturbance by the construction operations, but none occurred that caused significant inconvenience or delay.

In contrast, potential collapses of large caverns in the gypsum represent a more significant geohazard. Although they appear to be lacking in the youthful polygonal karst, large collapse sinkholes that formed by comparable events in the past are scattered across the older mature karst. Among the largest is the Kizilcam sinkhole, which contains a lake 220 m in diameter surrounded by steep rock slopes that rise 30–50 m to a rim about 350 m in diameter (Fig. 13). This is a textbook collapse sinkhole, except that its sides are now degrading so that it has already matured into a well-rounded shape. The scale of the collapse event or events that formed these large sinkholes may be indicated by processes in an active collapse sinkhole that lies close to the Kizilcam site. This feature is about 200 m across, floored partly by a chaos of breakdown blocks and a small lake, at the level of the adjacent river, only 10 m below the surrounding terrain. One wall of the sinkhole is a cascade of gypsum blocks each about 4 m across, whereas the opposite wall has larger blocks of gypsum that appear to have dropped into a cave perhaps 25 m across (Fig. 14). Dissolution at water level, undercutting and block collapse are clearly active. It therefore appears that the largest sinkholes did not develop as single collapse events, but evolved through a succession of collapses, each of which might have undermined a piece of ground 20–40 m across.

Although the risk of ground collapse was perceived as small, and the pipeline corridor was selected to avoid the most hazardous parts of the karst, searches were made to identify any large voids within the gypsum that could potentially collapse beneath the active pipeline. As it was considered possible that an open cave 30 m across could lie within the gypsum, ground investigation extended to a depth of 30 m, using non-invasive geophysics followed by core and probe drilling of significant anomalies (Arthur *et al.* 2004).

Fig. 14. Progressive small-scale rock failure within an active collapse sinkhole in the gypsum karst of Turkey.

The distribution of existing collapse sinkholes suggested that surface collapses occur at a rate of less than one event per 100 km^2 per 10 ka. This implied a chance of about 1 in 2000 of an event affecting the pipeline somewhere along its course across the gypsum karst within a design lifetime of 200 years. Any rock collapses into unknown caves were most likely to be triggered by imposed dynamic loads from construction traffic, and the risk to the completed pipeline (with its low imposed load when buried) is therefore further reduced. Although the likelihood of a large collapse was considered to be very small, the consequence of such an event would be very serious, both economically and environmentally. Consequently, no chances were taken, and the pipe, a metre in diameter, was increased to a steel thickness of 22.6 mm for the entire route across the karst, so that it could safely span 44 m, even with a worst-case soil wedge balanced on the exposed pipe. Although the sinkhole hazard could not be eliminated, the risks were reduced to an acceptable minimum by conservative engineering that responded to thorough investigation of the local karst environments and processes.

The sinkhole geohazard

A successful engineering response to the sinkhole geohazard requires a thorough understanding of karst processes. Collapses in soil are largely induced, and may be minimized by proper drainage control. The risk of new subsidence sinkholes can never be totally eliminated, but it can be reduced to acceptable levels, and small initial ground failures can generally be remediated before they expand into large features. Collapses of rock are invariably reduced, and can be reduced to ignorably low levels, by adequate ground investigation.

A note of caution may be sounded with respect to the sabkha environments of hot semi-arid coastal terrains, which are underlain by beds of soluble limestone, dolomite and gypsum that are young, poorly consolidated, weak and unstable. Such conditions are notably common in the Persian Gulf region, where urban development is currently rapid. There is as yet no large database on these conditions, and sinkhole hazard recognition is still low on the learning curve in these environments.

Sabkha excepted, karst ground conditions are now well documented. If sinkholes are caused by poor engineering practice, they can equally well be stopped by good engineering practice.

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References

ARTHUR, J.C.R., HAAS, C., SHILSTON, D.T. & WALTHAM, A.C. 2004. The Sivas karst, from terrain evaluation to ground truth. *In:* SWEENEY, M. (ed.) *Proceedings of International Conference on Terrain and Geohazard Challenges Facing Onshore Oil and Gas Pipelines.* Thomas Telford, London, 311–323.

BRINK, A.B.A. 1979. *Engineering Geology of Southern Africa,* **1**. Building Publications, Pretoria.

GARLANGER, J.E. 1991. Foundation design in Florida karst. *Concrete International,* **13**, 56–62.

JOHNSON, K.S. & NEAL, J.T. 2003. *Evaporite karst and engineering/environmental problems in the United States.* Oklahoma Geological Survey Circular, **109**.

NEWTON, J.G. 1987. *Development of sinkholes resulting from man's activities in the eastern United States.* US Geological Survey Circular, **968**.

PERLOW, M. 2003. An overview of recent Lehigh Valley, Pennsylvania, sinkhole problems. *In:* BECK, B.F. (ed.) *Book title.* American Society Civil Engineers Geotechnical Special Publications, **122**, 644–651.

RISSER, D.W. 2006. *Simulated water budgets and ground-water/surface-water interactions in Bushkill and parts of Monocacy Creek watershed, Northanpton County, Pennsylvania.* US Geological Survey, Open-File Reports, **2006-1143**.

WAGENER, F.v.M. 1985. Dolomites; problems of soils in South Africa. *Civil Engineer in South Africa,* **27**, 395–407.

WALTHAM, T. 2002. Gypsum karst near Sivas, Turkey. *Cave and Karst Science,* **29**, 39–44.

WALTHAM, A.C. & FOOKES, P.G. 2003. Engineering classification of karst ground conditions. *Quarterly Journal of Engineering Geology and Hydrogeology,* **36**, 101–118.

WALTHAM, T. & LU, Z. 2007. Natural and anthropogenic rock collapse over open caves. *In:* PARISE, M. & GUNN, J. (eds) *Natural & anthropogenic hazards in karst areas: Recognition, Analysis, Mitigation.* Geological Society, London, Special Publications, **279**, 13–21.

WALTHAM, T., BELL, F. & CULSHAW, M. 2005. *Sinkholes and Subsidence: Karst and Cavernous Rocks in Engineering and Construction.* Springer, Berlin.

WILSON, B. 2004. Everybody wants in—and out. *Roads and Bridges,* **42**, 30–33.

ZHU, X. & CHEN, W. 2005. Tiankengs in the karst of China. *Cave and Karst Science,* **32**, 55–66.

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