Geohazards explained 1

Sinkhole geohazards

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'Small but deadly' could describe sinkhole failures that can be both destructive and frightening where terra firma becomes very unfirm. These very localized ground collapses may be unpredictable but they are among the more avoidable of geohazards.

Where water erosion does not converge on surface rivers, but is directed underground, surface lowering forms not a valley but a closed depression around its central downward outlet. This is a significant process only in terrains where the bedrock has voids large enough to swallow input drainage, so is largely (but not entirely) restricted to outcrops of limestone, where the landscape is then known as karst. The closed depressions are known as sinkholes (especially to ground engineers and Americans), though many geomorphologists know them as dolines—after the Slovene word for a valley, in a land where there are no true valleys on the limestone of Slovenia's classical karst (Fig. 1). Sinkholes may or may not have a stream sinking into them, but they are named as such because the ground has sunk; and rainwater does normally sink in them. Sinkholes and dolines are the same, and they are diagnostic of karst ground conditions—along with caves, underground drainage, spectacular landscapes and the geohazard of ground collapse.

Sinkholes can be just a metre across, or more than 100 m wide and deep. They come in various forms, which can be grouped into about six main types (Fig. 2). Solution and collapse sinkholes are formed in solid rock, with the solution sinkhole forming so slowly (over geological timescales) that it is a landform and not a geohazard, and the caprock sinkhole is just a collapse where a void in the limestone has undermined a cover rock. Far more common are the two types of subsidence sinkhole that are formed entirely in the soil cover; soil fails a lot more easily than rock. The buried sinkhole may not have much to show, but can be a major inconvenience for a construction engineer trying to place foundations on

Fig. 1. A classic sinkhole in the Classical Karst of Istria, Slovenia, where it is known as a doline. Soil that has accumulated on the floor provides a patch of better farmland, and natural rainwater drainage is not causing ongoing subsidence.

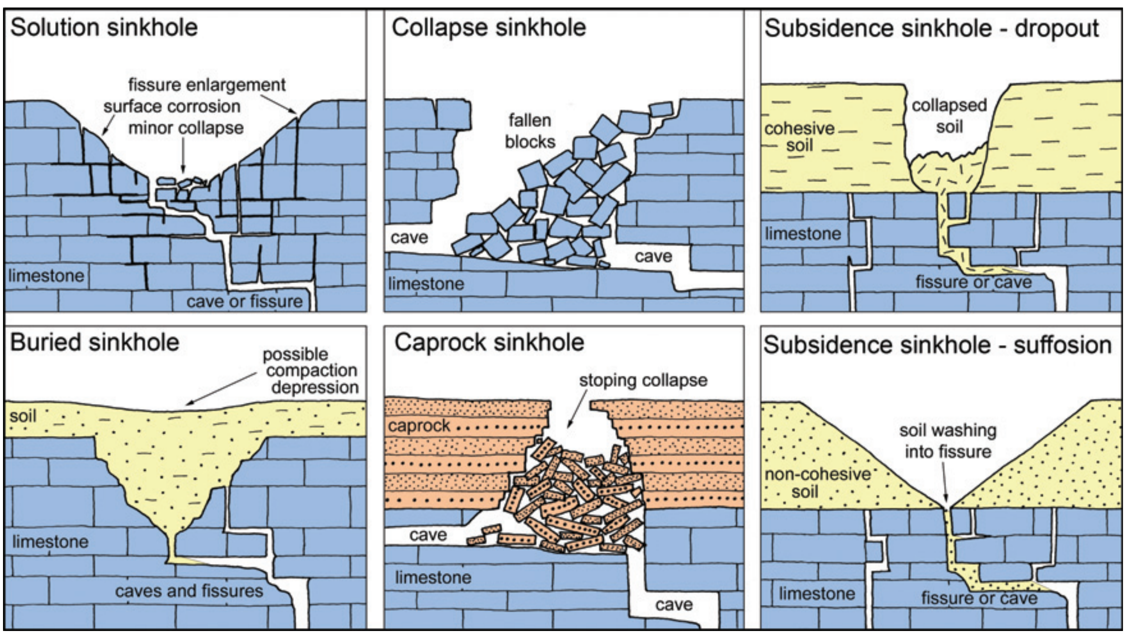

Fig. 2. Diagrammatic profiles through the six main types of sinkholes.

Fig. 3. Close to the Yangtze Gorges in the karst of southern China, the giant sinkhole of Xiaozhai Tiankeng is more than 600 m deep and wide. This viewpoint on the midway ledge is reached by a path with 1000 stone steps winding through the trees from the low point on the far rim. Reached by another flight of 1800 steps, the cave river is just visible emerging from a cave portal 100 m tall.

Fig. 4. A destructive sinkhole at Ripon in England's Vale of York formed by the failure of soil and rock over a cave in gypsum.

rockhead beneath a weak soil.

Collapse sinkholes are spectacular and obvious, but are rare. Scattered cases of rock collapse into open caves can be identified in most karst terrains (Hull Pot is the well known example in the English Pennines), and a modest proportion of rock collapse contributes to the evolution of many sinkholes formed essentially by dissolution. But even worldwide, only a handful of cases have been observed or recorded in historical times where massive rock collapse has occurred. As a geohazard, collapse sinkholes rate fairly low.

Within the last 15 years or so, a variety of giant collapse sinkhole has been recognized, mainly in China, from where they therefore take their name—tiankengs, roughly meaning 'sky holes'. These are defined as being at least 100 m wide and deep, though some are much larger than that (Fig. 3), and there are less than a hundred tiankengs known in the whole world. They are formed by roof collapse of large cave chambers traversed by cave rivers large enough to dissolve and remove the steady supply of breakdown debris produced as the chamber enlarges upwards and then breaks out to the surface. They form by multiple phases of progressive wall and roof breakdown, probably over time spans of a million years or more. So they are limited to areas of very mature karst (parts of China, New Guinea, Slovenia and Croatia have the best examples). A tiankeng can be large enough to swallow a small town, but there is no evidence that any could develop or could have developed to do so in a single gulp. They add a dimension to geomorphological concepts of major collapse and perhaps gorge evolution in karst, but tiankengs can be ignored as a geohazard.

Rather smaller sinkholes can be a geohazard in terrains on rocks other than limestone. Gypsum is soluble, and may produce karst terrains similar to those on limestone, where all types of collapse and subsidence sinkholes can develop (Fig. 4). A special feature of gypsum karst is that the rock is dissolved very much faster than is limestone, so new voids and potential rock collapses can be developed within the lifetime of built structures (say 200 years) instead of taking the tens of thousands of years required to create a significant new ground cavity in limestone. Basalt is totally insoluble, but may contain caves where lava has flowed out through the core of a flow that has crusted over with chilled rock. In some volcanic terrains lava caves (or lava tubes) are both long and numerous, old and new collapses into them are common, and the thin roof over them poses a significant hazard where roads and buildings are constructed (Fig. 5). Sinkholes can also develop through headward internal erosion by groundwater that creates 'piping failures' in silty or loessic soils; these are generally small, but a piping sinkhole swallowed five buildings and killed three people in Guatemala in 2007. These are all in addition to sinkholes in rocks underlain by limestone, such as the many on the Millstone Grit plateaux of Llangynidr and others in South Wales.

The main hazard—subsidence sinkholes

On limestone and any other karst, the huge majority of sinkholes are of the subsidence type—where unstable soil is washed down into quite small voids in bedrock that itself remains stable. The process of soil down-washing is known as suffosion, and purely suffosion sinkholes are formed very slowly in sandy soils as the sand drops away below egg-timer-style (go boil an egg, and watch a succession of sinkholes develop and then slump in during the three minutes). At the opposite end of the scale, cohesive clay soils can be undermined to create large soil voids above narrow bedrock fissures, and these can collapse to form instantaneous ground failures known descriptively as dropout sinkholes (Fig. 6). Most subsidence sinkholes involve a combination of these processes. Their depths can be no more than the soil thickness and their widths are rarely more than treble that. But they are numerous. There are thousands in the cover of glacial till that lies on the benches of Great Scar Limestone in the Yorkshire Dales karst—where they are locally known as 'shakeholes' (Fig. 7).

In any soil-mantled karst, whether on limestone, dolomite, chalk or gypsum, subsidence sinkholes are the major karst geohazard. Catastrophic sinkhole events can occur in any soil that has some clay content and therefore some cohesion. They can occur with no warning, where groundwater slowly washes away the soil, so that a void steadily grows totally unseen, until its weak arch roof collapses and undermines any farmland, road or building that may lie on the ground surface. These collapses are almost totally unpredictable. They depend on water, so more occur during or soon after rainstorms. But the locations of new sinkholes depend on the distribution of bedrock fissures hidden beneath the soil. In some areas of high sinkhole density (Fig. 8), an alignment of existing sinkholes may indicate a major bedrock fissure where a new sinkhole is more likely to occur, but event predictions are so vague and unreliable that they are useless to engineers concerned for the integrity of roads and buildings. A rate of one new sinkhole per square kilometre per year is a remarkably high event rate in a natural environment, but can have a massive impact in residential areas such as those in Florida and Pennsylvania, where every year sees a handful of houses damaged or destroyed.

Fig. 5. A sinkhole in basalt in Hawaii, caused by collapse during a small earthquake of the thin rock roof over a large lava tube.

A geohazard that is natural or induced?

It is very clear that huge numbers of all types of sinkholes have developed purely by natural processes where they are recorded in the great karst regions of

Fig. 6. A small new dropout sinkhole formed entirely in the soil cover over fissured chalk near Portsmouth.

Fig. 7. A large subsidence sinkhole, known locally as a 'shakehole', in glacial till on a limestone hill in the Yorkshire Dales. At present, this one is well choked with soil, so it frequently fills with water after heavy rain.

Fig. 8. Closely packed sinkholes cut in both the soil cover and the limestone bedrock of the Sinkhole Plain, near Mammoth Cave in Kentucky. Trees remain in the deeper sinkholes that have not been cleared, and ponds stand in sinkholes that are choked with soil. This terrain is now fairly stable as farmland, but new sinkholes would develop if the ground was disturbed by development.

the world that lie in a natural state. China's tiankengs have taken a million years to form, and even the thousands of shakeholes in the Yorkshire Dales karst have developed over the 12 000 years or so since the last Ice Age—at a mean event rate that is extremely low.

New collapse sinkholes in bedrock are extremely rare (Fig. 9), but rock failure can occur where excessive loads are placed by foundations onto thin arches of rock above unknown caves. A cave roof in strong limestone is stable under most imposed loads if its thickness exceeds about 70 per cent of the cave width. Good engineering practice is therefore to drill beneath proposed foundations to ensure that there is solid rock to a depth appropriate for the largest cave likely to occur in the local karst environment. A viaduct pier in Tampa, Florida, recently collapsed into an unknown cave during its construction, but the cave was only unknown because the prior drilling had not gone deep enough.

High rates of new sinkhole development are always of subsidence sinkholes, within the soil cover, and are all associated with human activity. These sinkholes form by water moving downwards through the soil, so any increased flow raises the process rate and very effectively induces new ground failures. Increased flows of water, from the soil into the bedrock fissures, are caused either by a rainstorm, the input of additional drainage, or a water table decline that increases the drawdown. The rainstorm is natural, and repeated events achieve some form of equilibrium. Drainage input and water table decline are both by human activities, especially by poorly planned engineering works: the sinkhole geohazard is largely self-induced.

New drainage input can be by increased runoff from roads, badly planned drainage around buildings, inappropriate soakaway drains, and leaking or overflowing pipelines. Dozens of new sinkholes formed in a few days on the downs near Portsmouth (Fig. 6) when flow from a broken water main washed the soil down into fissures and caves within the underlying chalk. Pipelines need to be repaired, but drains, runoff and drainage can be safely managed by sound engineering work. Most buildings damaged or destroyed by sinkholes can trace their demise back to some form of inadequate drainage, and too many sinkholes develop along unlined roadside ditches that are unsuitable in karst terrains.

Fig. 9. Collapse of a very thin roof over a small cave in the side of a wadi in Jordan. The cave appears to have formed in weak limestone beneath a thin crust of stronger caliche, and the undermined roof then failed under its own weight.

Water table decline can affect larger areas and induce great rashes of new sinkholes. The worst case

Fig. 10. One of 1200 new subsidence sinkholes that developed in the alluviated valley floor of Shuicheng, amid the splendid cone karst of Guizhou, China. This one was only 100 m from the black pumphouse standing over the over-abstracted borehole that induced the sinkholes by lowered the local water table.

Fig. 11. A road in Pennsylvania destroyed when it dropped into a new subsidence sinkhole that had been largely induced by drainage of a deep quarry more than a kilometre away.

is when the water table declines past the rockhead, so that groundwater flow that was largely lateral at rockhead is replaced by downward flow from soil to bedrock, or rather into the bedrock fissures. The decline may be due to groundwater abstraction, for local supplies. When new boreholes were sunk into limestone beneath an alluvial plain, to supply the new town of Shuicheng in China's karstlands, 1200 new sinkholes developed within less than ten years (Fig. 10). Most of these were in the cones of depression around over-pumped boreholes, and there was massive damage to farms, villages, fields and roads. Water table decline is also caused where a limestone quarry creates its own cone of depression merely by pumping out enough water to stay dry on the quarry floor. A large quarry in Pennsylvania has recently been the major cause of nearly 100 new sinkholes that have destroyed roads and houses in a nearby community (Fig. 11).

Stopping a quarry or groundwater supply scheme may not be economical or practical, so a level of induced sinkholes may have to be tolerated in some developed karst terrains. Individual sinkholes can be repaired with ground restoration based on choking the sinkhole with stone blocks (Americans call these 'chunk rock') too large to drop into the bedrock fissures (Fig. 12). This is much better than a simple granular backfill, which is the best way to ensure that the sinkhole will develop again in exactly the same place. There is little excuse for most of the scatter of new subsidence sinkholes that are induced by new flows of water entering the soil cover on top of fissured limestone. Such inputs are usually the result of poorly planned or executed engineering works. Controlling the drainage is critical to good ground engineering. Sinkholes are largely a controllable geohazard, and those involved in construction in limestone terrains are well minded to properly appreciate the processes of karst geomorphology.

Suggestions for further reading

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Fig. 12. Bulldozing chunk rock into the throat of a large subsidence sinkhole after it had collapsed to undermine a residential street in a small town in Pennsylvania (Photo: P. Dougherty).

