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Photographic Feature

Subsidence caused by gypsum dissolution at Ripon, North Yorkshire

Anthony H. Cooper[1] **& Antony C. Waltham**[2]

[1]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK (e-mail: a.cooper@bgs.ac.uk)
[2]Civil Engineering Department, Trent University, Nottingham, NG1 4BU, UK

In the afternoon of Wednesday 23 April 1997, a large subsidence crater opened up in front of a house on Ure Bank Terrace, on the northern outskirts of Ripon in North Yorkshire. Overnight its sides collapsed inwards, so that the hole had doubled in size by the next morning (Fig. 1). The subsidence crater was then 10 m in diameter, and 5.5 m deep to a choke of debris overlain by water 1 m deep. Its sudden appearance was the cause of considerable concern to the occupants of the adjacent house, and the event was widely reported in the national press and media.

A subsidence hollow was mapped at this site by the 1856 Ordnance Survey and documented by Cooper (1986). More subsidence had occurred at the Ure Bank site in previous years, but this latest collapse had rather more impact. Creeping movement of the soil towards the new hole meant that the adjacent house was destined for demolition. The event was the latest of a series of ground collapses that have occurred, at an average rate of about one per year, in and around the city of Ripon. While they are little more than an inconvenience in farmland, they have the potential to cause serious damage when they occur in built-up areas.

The immediate cause of the Ure Bank subsidence was the downward movement of soil, drift and recent fill into actively expanding voids within the ground. Ultimately, it was caused by the partial collapse of a cave developed in Permian gypsum, which at this site lies at depths of about 13 to 45 m below ground level. There are two main beds of gypsum in the Ripon area contained within the Edlington and Roxby formations (formerly called the Middle and Upper marls). The gypsum extends from outcrop to a depth of around 80–120 m before passing down-dip into anhydrite. The gypsiferous formations are sandwiched within a Permian sequence of dolomite and limestone aquifers (Fig. 2), and these are overlain by the mainly Triassic Sherwood Sandstone, which is the major aquifer in the region. All the Permo-Triassic bedrock units are cut through by the deeply entrenched, drift-filled, buried valley of the River Ure. This buried valley breaches the gypsum beds and the associated carbonate aquifers providing a potentially higher permeability pathway for the groundwater flow.

Gypsum can dissolve very rapidly in contact with flowing water, and a normal river flow of about 1 m/s can dissolve up to about one metre of gypsum per year. This rate of dissolution has been verified by many years of observation of the low cliffs (Fig. 3) along the River Ure at Ripon Parks, 3.5 km north of Ripon (James *et al.* 1981). Here around 6 m of undercutting of the cliff took place within nine years, before the face collapsed into the river. With respect to cave development, the dissolution rate measured at the surface next to the River Ure probably represents the maximum dissolution rate achievable near a point of aquifer recharge. The progressive increase in gypsum content in cave waters will result in lower dissolution rates. Klimchouk *et al.* (1996*a*,*b*) measured dissolution in gypsum for a confined aquifer and recorded dissolution rates of between one fiftieth and one quarter of that recorded adjacent to the River Ure. These gypsum dissolution rates are much higher than any dissolution rate that can occur in limestone.

These high rates of dissolution can create a significant potential for the rapid development of cave systems where there is through-flow of groundwater within the beds of gypsum. The occurrence of caves in gypsum has been recorded at a number of locations world-wide (Klimchouk *et al.* 1996*a*,*b*). Under saturated (or phreatic) conditions, maze caves develop in gypsum (and to a lesser extent in limestone) where it is in contact with a homogeneous porous aquifer such as the underlying and interbedded dolomite at Ripon. Maze caves are normally formed by slowly moving water that dissolves along the numerous intersecting joints producing cave systems with a rectilinear plan. Passage widths in these caves are generally only 1–3 m, but in some systems the gypsum bed has been removed across more than half of its area, in the manner of a pillar-and-stall mine. Larger linear cave passages are formed where groundwater flows are higher (Fig. 4). In karst terraines of low relief, this can occur where melting glaciers provide massive flows of subglacial water (Waltham & Cooper 1998). Gypsum solubility and dissolution rates are slightly reduced by low temperatures, but remain high (James 1992) and karst development can proceed rapidly in a subglacial environment.

Caves have not yet been directly observed at Ripon, where most of the gypsum is beneath drift and below the water table. Interconnected cavities have been

Fig. 1. The new sinkhole at Ure Bank Terrace, Ripon, looking northeast. The hole formed in April 1997, and measured 10 m across and 5.5 m deep. It was caused by collapse over a cave formed in gypsum of Permian age. Photograph by Tony Waltham.

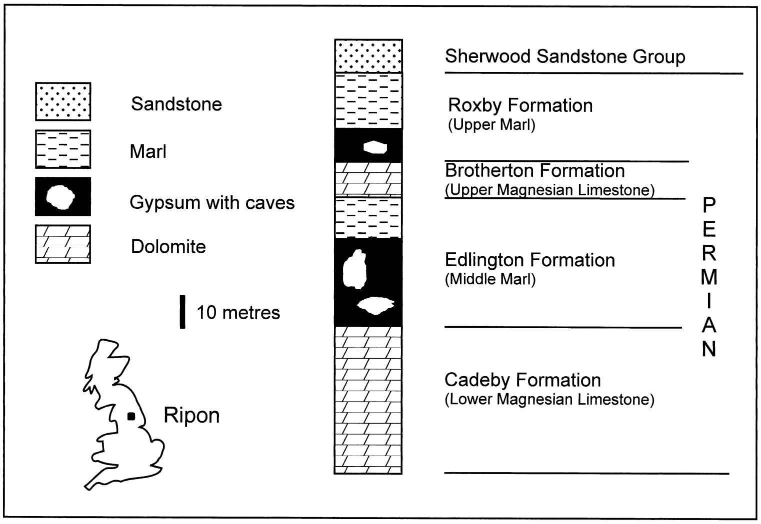

Fig. 2. Diagrammatic profile of the approximate sequence of beds in the vicinity of the sinkhole site at Ure Bank Terrace.

penetrated in boreholes, a situation proved by air flush escaping from boreholes some distance away from a hole being drilled. Small caves have been recorded in the Permian gypsum of Cumbria (Ryder & Cooper 1993) where the gypsum is mainly confined between mudstone sequences. Water flow through the gypsum beds at

Fig. 3. River cliff developed in the Edlington Formation gypsum at Ripon Parks, 3.5 km north of Ripon. This photograph was taken in 1980 when the face was undercut by about 1.5 m. By August 1989 the undercut measured about 6 m, and the full flow of the river passed through it, before the face collapsed some time later that year. Photograph by Tony Cooper.

Fig. 4. Cave passage within a bed of Permian gypsum at Pinega, Russia. The cave was enlarged partly by subglacial or proglacial meltwater in an environment which may be compared to that of the Ripon area during the Devensian. Photograph by Tony Waltham.

Ripon is within the saturated zone. It is likely that any caves here will have the form of a reticulate maze following the jointing pattern, this pattern is also reflected in the subsidence pattern (Cooper 1986). An additional factor at Ripon is the location of the site near to the marginal lateral ablation zone of the Vale of York glacier during the Devensian (Powell *et al.* 1992; Cooper & Burgess 1993). This may have encouraged larger cave passages to be formed by meltwater during the Devensian.

The relatively low mechanical strength of gypsum and its potential for rapid dissolution along joint intersections combine to accelerate roof collapse within gypsum caves. Boreholes, and exposures of similar rocks on the Durham coast and in Cumbria (Ryder & Cooper 1990), suggest that progressive upward stoping causes cavity migration above growing piles of debris. This process ultimately creates breccia pipes that progress upwards to reach rockhead; collapse of the drift cover then creates surface depressions (Fig. 5). Subsidence hollows similar to these have been classified as subsidence sinkholes (Culshaw & Waltham 1987), except that they differ from such sinkholes over limestone by being underlain by pipes of failed rock. These breccia pipes are well known in the Ripon area (Cooper 1986, 1988, 1989). Whether individual pipes occur over joint intersections within caves or over larger passages within linear caves is open to debate. Both situations are recorded in

Fig. 5. Subsidence sinkhole that formed on 1 February 1982 at Sharow, near Ripon. The hole was 12 m in diameter and up to 9.7 m deep. Photograph by Tony Cooper.

comparable Russian gypsum caves in the Urals though the dissolution here is currently occurring by downward percolation of water in the unsaturated zone (Andrejchuk *et al.* 1997).

The breccia pipes commonly reach through considerable thicknesses of solid rock above buried gypsum horizons, to create subsidence hollows and craters in outcrops of effectively insoluble rocks. One hole formed near Ripon station in 1834 and remains open today; it is 14 m across, and exposes solid Sherwood Sandstone in its sides down to a depth of at least 15 m (Fig. 6). A borehole near Ripon penetrated undisturbed drift and then solid rock to a depth of 24 m, before descending through 4 m of unconsolidated cave sediments containing housebricks. There is no doubt that some of the gypsum caves are active, and are continuing to swallow material from above.

The presence and threat of these subsidence collapses is significant for urban development in the Ripon area, and provides special problems in site investigation. For example, the drilling of a typical site investigation borehole close to the rim of the station sinkhole (Fig. 6) would prove solid red sandstone to a depth of over 15 m. However, only a few metres away there is a catastrophic subsidence. Complete assessment of the subsidence hazard for a site in Ripon could demand large numbers of closely spaced boreholes. In some areas these may have to reach depths of 60 or 70 m. This is clearly an uneconomic proposition for many forms of development. Geophysical surveys by microgravity (Patterson *et al.* 1995) or resistivity tomography have potential to identify anomalies in such areas and reduce the dependence on boreholes. However, these techniques have limitations in their depth penetration, their decreased resolution with depth, and the interference

Fig. 6. Vertical shaft that formed by a drop-out collapse in July 1834 near Ripon railway station. The cylindrical sinkhole is 14 m in diameter and 15 m deep with red Sherwood Sandstone exposed in its sides. Photograph by Tony Cooper.

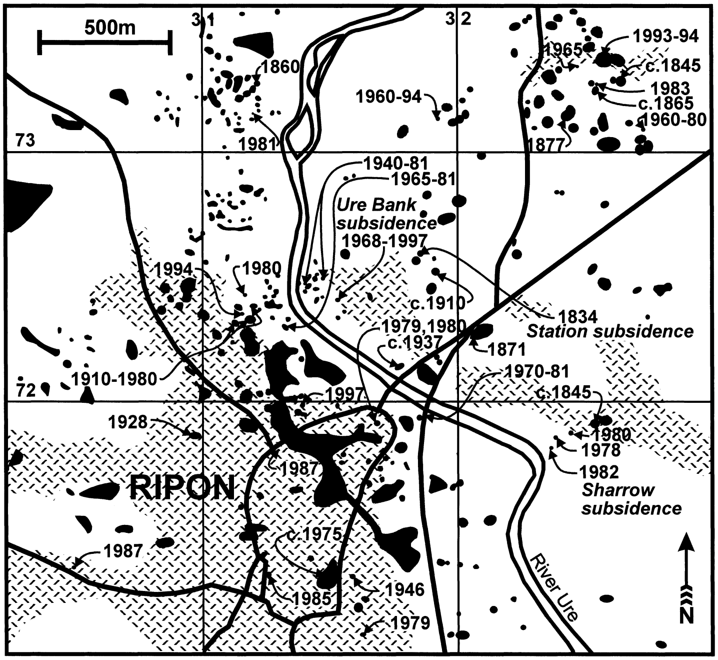

Fig. 7. The distribution of subsidence hollows and craters (shown in black) in the Ripon area (built up area is shown stippled). Dates of the subsidences are given where known, and the named sites are referred to in the text.

caused by the edge of the River Ure buried valley and anthropomorphic disturbance.

Only when a potential site has been fully investigated for subsidence hollows, breccia pipes and near-surface cavities can any form of development planning and design be considered for planning approval. This practice has been adopted by the local authority for development in the Ripon area using a ‘ground stability declaration form’ signed by a competent person for each new development (Thomson *et al.* 1998). Difficulties can be caused when developers ‘plan and design’ their structures before doing the ground investigation and are then unwilling to make changes in location or layout. Some ground in the Ripon area is just not suitable for development, and this can be inconvenient when the land has already been purchased speculatively. Though subsidence hollows have been mapped in the Ripon area, there is no clear pattern recognizable enough to be useful in the prediction of future new sites and instability (Fig. 7). Throughout the city, the risk of subsidence must be accepted; individual events can be catastrophic, but the risk at most sites is extremely low. In a region prone to subsidence hollow formation, where event prediction is normally impossible, and sufficient site investigation may sometimes be ruled out by cost, development should perhaps best proceed where risk is dispersed by an umbrella of adequate insurance. Sinkhole insurance is mandatory for all buildings in the Florida karst. It may need to be specified for land and structures within a specially defined zone around Ripon, where appropriate premium weighting, not refusal to provide cover, can reflect the risk. Currently, many companies charge increased premiums, or have higher excesses for Ripon, but the cover offered does not include the liability associated with the land and cover may be refused.

Within the subsidence-prone area of Ripon, one practical precaution is to avoid development on sites of known current or historical instability (Fig. 7). Another precaution is to put exclusion zones around unstable features. These zones may need to be 20 m or wider, because once a collapse has occurred dissolution can continue in the adjacent gypsum to cause another collapse. Furthermore, in areas of thick drift, subsidence craters can enlarge laterally as soils slump into narrow pipes. Because of the problems of liability it is also important not to leave known sites of potential instability within private gardens. House insurance covers the properties, garages and structures, but does not include the land; householders with subsidence hollows on their land could be held responsible for peripheral damage or threat to neighbouring property. Since these holes may be difficult, expensive or impossible to remediate, they are very undesirable to own.

There is no simple remediation for a major sinkhole collapse like that in Ure Bank (Fig. 1), it has been there for more than 140 years. Filling the subsidence crater merely creates temporary support for the sides of the collapse; long-term stability of the fill cannot be guaranteed, and many older holes that have been filled in this way have collapsed again. A subsidence sinkhole over limestone may be repaired by excavation to rockhead, placing chunkrock too large to enter the bedrock fissures, and backfilling to ground level. Many of the Ripon subsidences are in drift too deep to excavate to bedrock economically, and breccia pipes of large diameter can render this approach inapplicable. Geogrid mattresses sunk within the collapse zone or placed across at ground level can offer only temporary respite in an active sinkhole, before it is ultimately undermined.

Ground cavities associated with subsidence features in an active gypsum karst may expand by dissolution at rates that are significant on an engineering time scale. Dissolutional removal of gypsum is generally at rates about 50–100 times faster than it is for limestone. A fissure, breccia pipe or cave in gypsum, blocked by chunkrock, grout or a geogrid mattress, may be replaced by new dissolution voids within tens of years, causing renewed collapse and ground subsidence. Gypsum dissolution may even be enhanced where groundwater flow is concentrated around the margin of an engineered plug, thereby propagating and spreading subsidence. Complete prevention of collapse in gypsum may only be possible by sealing from contact with groundwater, and this is probably impossible at Ripon where water circulates into and from the buried valley of the Ure. Furthermore, any interruption of the natural groundwater flow may aggravate dissolution in the adjacent ground. An effective engineered response to subsidence and collapse in active gypsum karst terraines, at Ripon or elsewhere, remains elusive.

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