DEALING WITH GYPSUM KARST PROBLEMS: HAZARDS, ENVIRONMENTAL ISSUES AND PLANNING

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Gypsum dissolves rapidly underground and at the surface forming gypsum karst features that include caves, subsidence areas and sinkholes. Mapping these landforms, understanding the gypsum karst and local hydrogeology, and producing sinkhole susceptibility and hazard maps are crucial for development and public safety. Situations that change the local hydrogeology, such as dams, water abstraction or injection/drainage, can accelerate dissolution and subsidence processes increasing the severity of the problems; dams and canals built on gypsum karst can leak or fail catastrophically. Gypsum karst problems can be mitigated by careful surveying and scientific investigation followed by phased preventive planning, ground investigation and construction incorporating sinkhole-proof designs. Towns and cities, including parts of Paris (France), Dzerzhinksk (Russia), Madrid and Zaragoza (Spain), Birzai (Lithuania) and Ripon and Darlington (UK), are developed on such ground requiring local planning guidelines and special construction methods. Roads, railways, pipelines and bridges are particularly vulnerable to such subsidence and require special consideration.

Introduction

Gypsum, hydrated Calcium Sulphate ($CaSO_4.2H_2O$), is attractive as satin spar, beautiful as carved alabaster, practical as plasterboard (wallboard), but the cause of geological hazards capable of swallowing houses (Figure 1), collapsing dams and violently flooding mines and tunnels. These and other hazards are reviewed in this chapter with some of the measures that can be used to mitigate them. Gypsum karst poses problems of subsidence to construction and development. However, with appropriate geomorphological mapping, investigation and hazard avoidance, allied with careful planning, many areas can be successfully developed.

DEALING WITH DISSOLUTION AND SUBSIDENCE HAZARDS

The main types of hazards

Because of its high solubility (2.531 g/l at 20°C in distilled water: Klimchouk, 1996) and rapid dissolution rate, karst developed in gypsum can evolve on a rapid timescale. Laboratory and field measurements, summarized by James (1992 p174), indicate that fresh water flowing at 1 meter a second can dissolve 1.7 meters of gypsum in a year; a maximum figure of 1.8 meters a year with extremely fast water flow is given by Dreybrodt (2004). Underground, lower dissolution rates of 0.001 to 0.025 meters a year produced by calcium sulfate-rich water are not unusual (Klimchouk, 1996; Klimchouk et al., 1996). Where saline water is present the solubility of gypsum may increase by up 4 times. In this situation, or where turbulent flow of fresh water enters the underground gypsum karst, greatly enhanced rates of rock removal can occur. In addition to dissolution, hydrological changes in the system such as the lowering of the water table may accelerate the internal erosion of cavity fills and deposits mantling the karst. Where this occurs it can lead to rapidly evolving gypsum karst and a surface scenario of continuing sinkhole formation. The sinkholes form across the wide spectrum of styles described by Gutiérrez et al. (2008a) and summarized by Gutiérrez and Cooper (this volume). The subsidence processes range from gentle sagging to sudden collapse that can cause severe damage to buildings and infrastructure (Gutiérrez et al., 2008b).

Cities and towns

Many cities and towns are partly or wholly underlain by gypsum including Paris (France), Dzerzhinksk (Russia), Zaragoza, Calatayud and the outskirts of Madrid (Spain), Birzai and Pasvalys (Lithuania), Ripon and Darlington (UK). In all these places, and many more, the soluble and unstable bedrock is a geological hazard that poses a problem for planning and construction.

Paris gives its name to plaster of Paris, made from gypsum mined and processed there for centuries. However, in addition to extensive problems related to underground mining, Paris also has natural gypsum karst that has resulted in collapses and the destruction of property (Soyer, 1961; Arnould, 1970; Toulemont, 1984). Within the Paris Basin the geological setting encountered is a gentle syncline where groundwater flows through the Middle Eocene (Lutetian) gypsum towards the River Seine. Gypsum karstification and collapses tend to occur in areas where high groundwater gradients and the presence of gypsum of the Brackish Marl and Limestone coincide, but the subsidence hazard is reduced in areas of thick overburden (Thierry et al., 2009).

The city of Zaragoza in Spain has a population of about 700,000 people, making it one of the largest urban areas affected by gypsum and other evaporite dissolution problems (Gutiérrez et al., 2007, 2008c; Galve et al., 2009a). Sinkholes here are a major constraint on development; they have collapsed buildings, affected roads, and caused the derailment of a train. Nearby, numerous buildings including historical monuments in the small town of Calatayud (Figures 2 and 3) have been severely affected by subsidence (Gutiérrez and Cooper, 2002). Here, in 2003, a collapse sinkhole occurred causing the demolition of a five-storey building and direct losses of around 5 million euros (Gutiérrez et al., 2008c). Parts of the Madrid metropolitan area are also underlain by gypsiferous and other evaporitic rocks causing stability problems in buildings and infrastructure (Gutiérrez et al., 2008c).

Karstified gypsum is widespread in the United States, but to our knowledge it has only caused problems in small developments and towns (Johnson, 2003). In the Dzerzhinksk area of Russia the Permian sequence includes karstified gypsum that results in severe subsidence problems that have affected more than 250,000 people and a major industrial center (Reuter et al., 1990; Tolmachev et al., 2003; Koutepov et al., 2008). In the Biržai – Pasvalys area of Lithuania, the karstic collapse is commonly aggravated by groundwater abstraction from the gypsiferous sequence (Paukstys et al., 1999; Satkunas et al., 2007). Mosul in Iraq has suffered accelerated subsidence due to increasing water use and the drainage from septic tanks infiltrating into the gypsum karst (Jassim et al., 1997). There are extensive evaporite and gypsum sabkha deposits in the Middle East and karst hazards affect many of the new development areas including parts of Saudi Arabia, the United Arab Emirates and Quatar (Abdulali and Sobhi, 2002).

To manage gypsum karst problems affecting urban areas it is important to understand the bedrock geology, superficial geology, geomorphology, hydrogeology and the way they interact to produce karst features (Figure 4 sections A and B). These features can be mapped producing an inventory of items such as dolines, evidence of subsidence and building damage (Gutiérrez and Cooper, 2002; Nisio et al., 2007; Farrant and Cooper 2008; Cooper, 2008a and b; Galve et al., 2009a). Analysis of the spatial and temporal distribution of the features and the controlling factors can then permit the designation of planning control areas (Figure 5). The Ripon area in the UK, for example, is zoned on the basis of the distribution of subsidence features, the up-dip limit (Figure 4, section A, west side) of the gypsum and the down-dip transition from gypsum to anhydrite (Figure 5, contact between zones C and B; Thompson et al., 1998; Paukštys et al., 1999). Where good datasets are available, independently tested susceptibility models based on statistical analysis, the density of sinkholes or the proximity of each point to the existing sinkholes permits more precise and objective delineation of the subsidence-prone and safe zones (Galve et al., 2008, 2009b).

Dams, canals and pipelines

Dams are costly structures whose failure can lead to disaster, large scale mortality and financial liability. In 1926 the collapse of the St Francis Dam, California was partly attributed to dissolution of gypsum veins beneath the dam foundations (Ransome, 1928; James, 1992); more than 400 people were killed and damage cost millions of dollars. The Quail Creek Dam, Utah, constructed in 1984 failed in 1989, the underlying cause being the unappreciated existence and consequent enlargement of cavities in the gypsum rocks beneath its foundations (Johnson, 2008).

Water leakage from reservoirs through ponors, sinkholes and karst conduits can lead to costly inefficiency, or even project abandonment. The unnaturally high hydraulic gradients induced by the impounded water may flush out of the sediment that blocks karst conduits. It can also produce the rapid dissolutional enlargement of discontinuities, which can quickly reach break-through dimensions with turbulent flow. These processes may significantly increase the hydraulic permeability of the dam foundation on an engineering time scale (Milanovic, 2000; Romanov et al., 2003).

Numerous dams in the USA either have gypsum karst problems, or have encountered gypsum-related difficulties during construction. They include the San Fernando, Dry Canyon, Buena Vista, Olive Hills and Castaic dams in California; the Hondo, Macmillan and Avalon dams in New Mexico; Sandford Dam in Texas; Red Rock Dam in Iowa; Fontanelle Dam in Oklahoma; Horsetooth Dam and Carter Dam in Colorado and the Moses Saunders Tower Dam in New York State (Brune, 1965; James, 1992; Johnson, 2008). Up to 13,000 tonnes of mainly gypsum and anhydrite were dissolved from beneath a dam in the Middle East in only six months causing concerns about the dam stability (Guzina et al., 1991). In China, leaking dams and reservoirs on gypsum include the Huoshipo Dam (Lu and Cooper, 1997) and others in the same area. The Bratsk Dam in eastern Siberia is leaking (Eraso et al., 1995) and in Tajikistan the dam for the Nizhne-Kafirnigansk hydroelectric scheme was designed to cope with active gypsum dissolution occurring below the grout curtain (Lebdev, 1997). Gypsum karst in the foundation trenches of the Casa de Piedra Dam, Argentina and El Isiro Dam in Venezuela, caused difficult construction conditions and required design modifications (Marriotti et al., 1990; James, 1992).

The difficulties of building hydraulic structures on soluble rocks are re-iterated by Brune (1965), James and Lupton (1978), James and Kirkpatrick (1980), James (1992) and Milanovic (2000). Milanovic (2000) provides a thorough review of the strategies that can be applied to reduce water losses from reservoirs, either by preventing infiltration or sealing underground karst conduits. Dissolution beneath damsites has been modeled allowing prediction of performance to be calculated (Romanov et al., 2003). Gypsum dissolution at the Hessigheim Dam on the River Neckar in Germany has caused settlement problems with sinkholes nearby (Wittke and Hermening, 1997). Site investigation showed cavities up to several meters high and grouting from 1986 to 1994 used 10,600 tonnes of cement. The expected life of the dam is only 30-40 years with continuing grouting required to keep it serviceable. Grouting costs can be very high and may approach 15 or 20% of the dam cost reaching US$ 100 million in some cases (Merritt, 1995). In karstified limestones grouting is difficult, yet in gypsum it is even more difficult due to the rapid dissolution rate of the gypsum. Grouting may also alter the underground flow routes translating and focusing the problems to nearby areas. In the Perm area of Russia, gypsum karst beneath the Karm hydroelectric power station dam has been successfully grouted using an oxaloaluminosilicate gel that hardens the grout, but also coats the gypsum slowing its dissolution (Maximovich, 2006). The Mont Cenis Dam, in the French Alps, is not itself affected by the dissolution of gypsum. However, the reservoir is leaking and photogrammetric study of the reservoir slopes showed doline activity over gypsum and subsidence in the adjacent land (Deletie et al., 1990).

Canals that leak, in gypsum karst areas, can trigger subsidence, which can be severe enough to cause failure. In Spain, the Imperial Canal in the Ebro valley (Gutiérrez et al., 2007), and several canals in the Cinca and Noguera Ribagorzana valleys (Lucha et al., 2008), which irrigate parts of the Ebro basin, have on numerous occasions failed in this way. Similarly, canals in Syria have suffered from gypsum dissolution and collapse of soils into karstic cavities (Swan, 1978). Canals excavated in the ground may also alter the groundwater flow accelerating internal erosion, dissolution processes and collapse of cover materials. In the Lesina Lagoon, Italy, a canal was excavated to improve the water exchange between the sea and the lagoon. It was cut through loose sandy deposits and highly cavernous gypsum bedrock, but has created a new base level distorting the groundwater flow. The canal has caused the rapid downward migration of the cover material into pre-existing conduits producing a large number of sinkholes that threaten an adjacent residential area (Fidelibus et al., 2009).

Pipelines constructed across karst areas are potential pollution sources and some may pose explosion hazards. The utilization of geomorphological maps depicting the karst and subsidence features allied with GIS and karst databases help with the routing and management of these structures (Gibson et al., 2005). In some circumstances leaking water supply pipelines can trigger severe karstic collapse events similar to those recorded by McDowell (2005). Where hazards are identified, such as a major oil and gas pipeline crossing the Sivas gypsum karst in Turkey, the maximum size of an anticipated collapse can be determined and the pipeline strength increased to cope with the problems (Waltham, 2008).

Water and drainage

Drinking water

Surface and underground water in gypsum karst areas may contain large amounts of dissolved calcium sulfate (Klimchouk and Andrejchuk, 1996); this can reach in excess of 2400 Mg/l. The World Health Organization (2008) suggests concentrations of no more than 250 Mg/l of SO_4 for potable water and indicates that health authorities should be informed if it is greater than 500 Mg/l; though for animals much higher concentrations are permissible. Despite being of poor quality, waters from gypsum karst may locally be the only potable supplies. This is the situation in the Birzai area of Lithuania, where water with very high sulfate concentrations (up to 1655 Mg/l) is found in the local aquifer, though water with much lower levels are used for the potable supply (Paukštys and Velo, 1998; Paukštys et al., 1999). The natural dissolution of gypsum by groundwater can also lead to increased levels of dissolved solids in water courses and reservoirs. Large-scale groundwater abstraction from gypsum karst for water supply from one borehole in the UK effectively removed 200 cubic meters of dissolved gypsum per year from beneath Ripon (Cooper, 1988). Not all gypsiferous groundwater is problematical as it is naturally ‘Burtonised’ (Cooper, 1988), a process of using naturally sulfate-rich water (originally in Burton upon Trent) for brewing beer (or adding gypsum to water – 400 Mg/l for bitter, 100 Mg/l for porter) to give it a bitter taste – hence the name of English beer – “bitter”.

In gypsum karst areas, the number of sinkholes connecting the surface directly to the aquifers gives a measure of the vulnerability of the aquifer to pollution (Figure 6). Consequently, the gypsum karst areas of Lithuania are zoned by way of the number of sinkholes with the strictest agricultural controls implemented in the most sinkhole-prone areas. The controls include ‘organic’ agriculture, restrictions on the use of fertilizers and the construction of earth barriers and exclusion zones around sinkholes; these regulations are locally controlled by the Tatula Board (Paukštys et al., 1999).

Water abstraction, dewatering and irrigation.

In common with all karstic areas, gypsum karst is also prone to subsidence induced by fluctuations in the local groundwater levels. These can be changed dramatically by groundwater abstraction and local groundwater recharge, both of which can cause subsidence. Consequently, the effective management of karstic aquifers should also try to control the rapidity and amount of the fluctuations in the piezometric surface.

Large-scale abstraction for industry or irrigation can cause subsidence. Irrigation of fields is also proven to cause an increase in subsidence features in geologically susceptible areas such as zones irrigated by sheet-flooding from ditches in the Ebro valley, Spain (Gutiérrez et al., 2007). Local injection of water into the ground should also be avoided on karstic areas as point recharge can cause internal erosion of detrital material through underground cavities and the failure of cavity roofs; this is the sort of anthropogenic trigger that has caused subsidence in Mosul city, Iraq (Jassim et al., 1997). Because of the subsidence risk, natural urban drainage (or sustainable urban drainage – SUDS- Woods-Ballard et al. 2007) should not generally be encouraged on karstic rocks and drainage should be routed away from buildings and the sides of roads.

Mining

Mining in gypsum karst can be difficult; cavities complicate the excavations and reduce the productivity, while phreatic conduits filled with sediment or water under pressure can cause dangerous inrushes and mine flooding (Milanovic, 2000; Sharpe, 2003; Bonetto et al., 2008; Wang et al., 2008). Underground flood events are commonly accompanied by sharp drops in the local piezometric level, the development of sinkholes and the eventual disruption of the surface drainage. In 2006 the Nanjing Gypsum Mine in China broke into a phreatic cavity, flooding the entire mine in about three days. The groundwater level in a deep well at Huashu village dropped 90 m, disrupting the water supply; ground subsidence cracked numerous roads and buildings (Wang et al., 2008). For safe mining, dewatering of the mine area is a prudent step, but like groundwater pumping, it can trigger subsidence and accelerate dissolution. In the Ukraine, dewatering of gypsum karst associated with sulfur mining has increased the rate of dissolved gypsum removal by a factor of 80 times and favored the occurrence of sinkholes (Sprynskyy et al., 2009). In China, coal mining is affected by palaeo-karst collapse pillars (breccia pipes) which have propagated upwards from cavities in the underlying Ordovician gypsum and limestone (Lu and Cooper, 1997; He et al., 2009). Some of the breccia pipes have penetrated hundreds of meters though the coal sequence, posing a hazard of unpredictable sediment-laden water inrushes. Between 1975 and 2005, over 50 mines were flooded and three mining disasters occurred, however, the risks are reduced by drilling ahead of the advancing excavations and grouting (Li and Zhou, 1999; Lu and Cooper, 1997;Yin and Zhang, 2005; He et al., 2009).

Surveying, sinkhole susceptibility, GIS and planning

Geomorphological and geological surveying is required to identify the subsidence features that constitute the basis for making sinkhole susceptibility and hazard maps. Multiple tools can be used to produce the best possible cartographic sinkhole inventory. Historical maps and multiple temporally-spaced sets of monoscopic or stereoscopic aerial photographs are essential starting points for a survey. These can be complemented by multispectral scanning (Cooper, 1989) and geodetic techniques like LiDAR (Light Detection and Ranging) surveys or radar interferometry from aircraft or satellite (DInSAR - Castañeda et al., 2009). Field surveying is indispensable and verbal information from farmers, residents and local government officials can add considerably to the data on subsidence features. A complete karst inventory including subsidence features gives an indication of the spatial distribution and severity of the problem (Cooper, 1998; Galve et al., 2009a). This type of information can then be

analyzed with respect to other parameters using GIS techniques to produce susceptibility and hazard models (Galve et al., 2008, 2009b).
Yilmaz (2007) working in the Sivas gypsum karst, Turkey, considered multiple parameters related to the topography, geology, hydrology, human structures and vegetation to calculate a susceptibility map. In the Paris area, using topographical and geotechnical data, 3D geological modeling and probability analyses in a GIS environment, Thierry et al. (2009) determined three probabilities as GIS layers: 1. Probability of the presence of gypsum; 2. Probability of dissolution; 3. Probability of collapse and damage. By combining the data from these three layers they improved the Paris regulation map for gypsum problems and identified additional areas that were previously not thought to be problematic (Figure 7). In the Ebro Valley, Galve et al. (2009b) have produced multiple sinkhole susceptibility models by applying different methodologies including probabilistic analyses, a heuristic approach, sinkhole density analysis and the proximity to nearest sinkhole. The independent evaluation of these models reveals that the most reliable susceptibility maps are based on the simplest methods without requiring data on the causal factors; the density of sinkholes and the proximity to the nearest sinkhole have proved the best. Furthermore, in a sector of the Ebro valley near Zaragoza, Galve et al. (2008) have produced a sinkhole hazard model from two temporal populations of sinkholes that express the probability of sinkhole occurrence in quantitative terms (number of sinkholes per hectare per year). A susceptibility model was produced using the sinkholes from the older sample. The sinkholes of the younger sample were then used to validate the susceptibility model and transform it into a hazard model considering the frequency of the sinkholes occurring in each susceptibility class and their mean diameter. Combinations of topographical and geotechnical parameters have also been used in the Dzerzhinsk area to assess sinkhole susceptibility (Koutepov et al., 2008). In the UK, GIS has been used to zone the country into five categories of karst problem susceptibility. The zones were calculated using datasets that included: digital geological maps, terrain (slope) models, information about buried karst, runoff zones from areas of semi-impervious cover and superficial deposit thickness (Cooper, 2008b; Farrant and Cooper, 2008). These zones have been validated by independent information held in the UK National karst database.

In places that have already been developed, mapping the damage caused to buildings and infrastructure can reveal patterns of subsidence that complement the more obvious subsidence features (Gutiérrez and Cooper 2002; Cooper 2008a). Airborne surveys using laser altimetry (LiDAR) can pick up subsidence on buildings (Waltham et al., 2005). Satellite monitoring using DInSAR, which provides precise measurement of surface deformation, can be used to identify structures affected by subsidence, to measure the rate of settlement and probably to detect precursor displacements of catastrophic collapse events (Castañeda et al., 2009). If the worst areas can be avoided during this early planning stage the project can become safer and more cost-effective. The production of local planning guidance and rules for development is the most practical way of ensuring that local subsidence hazards are taken into account (Thierry et al., 2009; Thompson et al., 1998). The implementation of formal signing off procedures completed by a ‘competent person’ also help to reduce the possibility of collapse problems (Thompson et al., 1998; Paukštys et al., 1999).

Construction and site investigation

Civil engineering works including building development and the construction of linear structures across gypsum karst prone to subsidence can be very problematical. However, a phased approach of desk-study, surveying, geophysical investigation and site investigation followed by mitigation measures and monitoring technology can reduce the risks.

Geophysical investigation

Once the provisional route, site or layout has been identified, geophysical investigation can be applied. Depending on the local geology, ground probing radar (GPR: Benito et al., 1995) and microgravity (Lakshmanan, 1973; Patterson et al., 1995) techniques have both proved effective. Ground probing radar works well in dry rocks and can image down to about 20 m, but water and clay severely attenuate the signal (Matthews et al., 2000) and may limit penetration to as little as 1 m (Fenning and Hasan, 1995). In bare gypsum it has detected caves at a depth of 3 m and found adjacent cave passages 8 m away when used underground in gypsum karst (Prokhorenko et al., 2006). The microgravity technique can resolve small cavities near surface, but with greater depth only the larger cavities can be detected (McCann et al., 1987). The detection of small near surface cavities is very dependent on the spacing of the microgravity stations. As a general rule, for an anomaly beneath a measurement point, microgravity will detect a 2m diameter spherical cavity at 2m depth and a 10m cavity at a depth of 10m (Kaufmann and Romanov, 2009), it is however very good at detecting breccia pipes and subsidence features that reach the surface (Patterson et al., 1995; Styles et al., 2005). Resistivity tomography can help to delineate near surface cavities down to a depth of around 30 m – depending on the electrode spacing and array used (Roth et al., 2002; Epting et al., 2009) and is particularly effective when combined with GPR and trenching (Gutiérrez et al., 2009). Seismic techniques have been applied to gypsum karst in the UK and have resolved the sequence down to a depth of about 70 m (Sargent and Goulty, 2009).

Trenching, borehole investigation and probing.

Borehole investigation of a karstic site by drilling on a grid pattern is expensive and has a high probability of missing cavities and buried sinkholes; a borehole in solid rock may be just centimeters away from a significant karst feature (cave or potentially large collapse). By utilizing geophysical techniques the potentially subsidence-prone and potentially stable areas can be identified and investigated by focused drilling reducing the number of boreholes. Further savings can be made by drilling open holes and collecting chippings instead of coring; this method can be very effective if automated or manual recording of the drill penetration rate is made (Cailleux and Toulemont, 1983; Patterson et al., 1995). However, experience and skill is needed to interpret the drilling rate figures with the identification of the chippings material. Downhole geophysics, cross-hole geophysics and downhole optical and acoustic cameras can also help to understand the local karst geology (Yuhr et al., 2008). Trenching involves the detailed study of the sediments and deformation structures exposed in the walls of trenches excavated in sinkholes, in combination with the application of dating techniques (Gutiérrez et al., 2009). This technique can provide information on the precise limits of the sinkholes, subsidence mechanisms, cumulative displacement, kinematic regime (gradual vs. episodic), age of the sinkholes and rates of subsidence. This information can be used as an objective basis to forecast the future behavior of problematic sinkholes.

Building and construction

In addition to careful planning and the avoidance of the most subsidence-prone areas, further protection can be afforded by reinforced foundations (rafts, slabs, reinforced strip, piles), which can be required and specified by the local planning regulations (Thompson et al., 1998). In areas where there is thick superficial cover over the bedrock, piles may not be practical and strengthened foundations such as rafts are preferable. If a ground collapse occurs beneath a corner of a raft, there is a possibility that the building may cantilever over the hole. Further support for the structure can be afforded by the adding extension beams extending outwards from the foundation to span any potential collapse (Reuter et al., 1990; Cooper and Calow, 1998).

Roads, bridges, railways and pipelines

Railways are particularly prone to damage by karstic collapse and gypsum dissolution has affected the Moscow to Nizhny Novgorod Railway in the Dzherzhinsk area. This has resulted in collisions and disruptions of the train service. Management of the problem involves monitoring of the track conditions, engineering solutions and alarm systems (Tolmachev et al., 1999). The recent construction of high-speed railway lines across gypsum karst areas have necessitated the assessment of the likely collapse sizes along proposed routes through Southern Germany (Molek, 2003). Guerrero et al. (2008) propose a sinkhole susceptibility zonation for a 24-km-long stretch of the high-speed Madrid-Barcelona railway in the Ebro Valley based on the type and distribution of the dissolution and subsidence features exposed in the adjacent cuttings, some of which reveal the presence of cavities beneath the railway right-of-way. Where bridges are constructed they can be reinforced to cope with the loss of a supporting pillar and the pillars can be supported on extended foundations. Roads can also be reinforced with geogrids; these approaches were applied at Ripon (Cooper and Saunders, 2002). Sensitive structures such as bridges and viaducts can be equipped with monitoring and warning systems such as those installed in the Paris road viaducts (Arnold, 1970) and the bridge at Ripon (Cooper and Saunders, 2002).

Conclusions

Because of its high solubility and dissolution rate, gypsum karst can evolve on a human time scale rather than a geological time scale. In gypsum karst, underground drainage through interconnected dissolutional conduits is prevalent allowing groundwater and pollutants to circulate much faster than in aquifers with granular or fracture permeability. These factors are important for construction, the integrity of hydraulic structures and sustainable water management. The most widespread hazard associated with gypsum karst is subsidence, which can vary from widespread gentle sagging to the catastrophic development of collapse sinkholes. These ground movements can be particularly damaging to buildings and linear infrastructures including roads, railways, bridges, canals and pipelines. Dams and canals are very susceptible to the dissolution of gypsum in their foundations. Leakage through conduits can be excessive and accelerate rapidly leading to complete and disastrous failure. Water abstraction, like dewatering in mining areas, may lower the groundwater levels and lead to subsidence. Groundwater in gypsum karst areas may be the only drinking water supply. Such groundwater is also highly vulnerable to pollution requiring careful protection of the karstic systems whose limits commonly do not coincide with the surface drainage divides. Understanding the geomorphology, hydrology and underlying geology are prerequisites for developing and managing gypsum karst areas. Local or national planning policy guidelines and mitigation measures, based on careful investigation, can permit safe development of gypsum karst areas and the protection of the groundwater resources.

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Illustrations for:

DEALING WITH GYPSUM KARST PROBLEMS: HAZARDS, ENVIRONMENTAL ISSUES AND PLANNING

By **Anthony H. Cooper** and **Francisco Gutiérrez**

Figure 1. Cover collapse sinkhole at Ure Bank Terrace, Ripon. The collapse occurred on the 23-24 April 1997 and measured 10m in diameter and 5.5m deep. BGS reference no P526866 Photo P Tod BGS© NERC.

Figure 2. Cover collapse sinkhole 600 m3 in volume formed in 2003 next to and beneath a five storey building in Calatayud city. The five-storey building was finally demolished involving direct losses of ca. 5 million euros. Photo © F Gutiérrez.

Figure 3. Damage to a historic building in Calatayud city. Photo A H Cooper BGS © NERC.

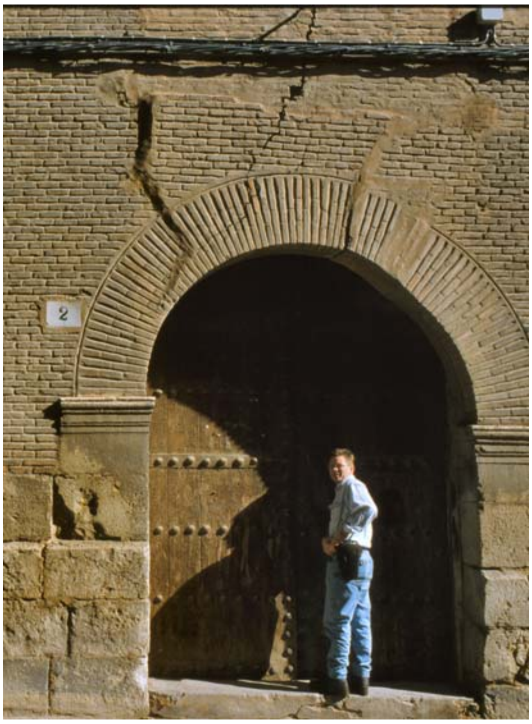

Figure 4. Cross sections through the Permian sequence and gypsum karst in the Ripon area of North Yorkshire, UK, based on boreholes and geomorphological mapping. Section A shows the easterly dipping strata intersected by the valley fill of the River Ure. Water flows from both the west and east pass through the gypsum causing dissolution and sulfate rich springs along the River Ure. Section B shows the size and character of the subsidence features in the eastern area.

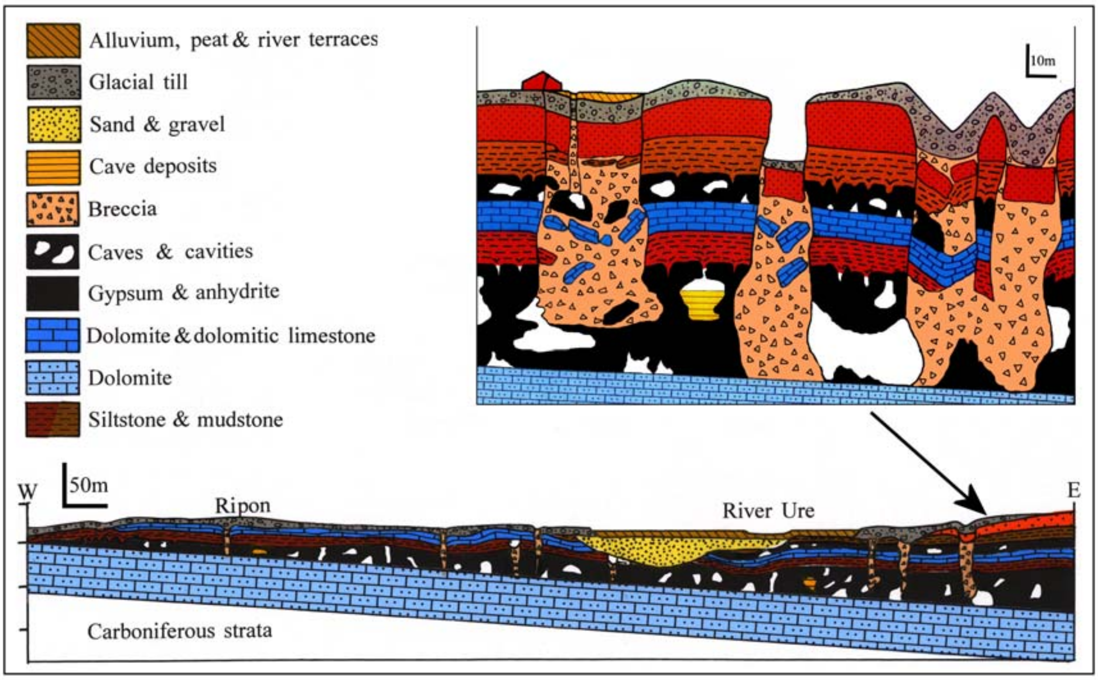

Figure 5. Gypsum dissolution planning areas in Ripon, North Yorkshire, England. The yellow area is zone C where special planning constraints are in force. The red areas are subsidence features including sinkholes with the dates of their collapse shown where known.

Reproduced from Cooper, A.H., 1998. Subsidence hazards caused by the dissolution of Permian gypsum in England: geology, investigation and remediation. In: Maund, J.G., Eddleston, M. (Eds.), Geohazards in Engineering Geology. Engineering Special Publications, 15. Geological Society, London, pp. 265–275, and with additions from Thompson, A., Hine, P., Peach, D., Frost, L., Brook, D., 1998. Subsidence hazard assessment as a basis for planning guidance in Ripon. In: Maund, J.G., Eddleston, M. (Eds.), Geohazards in Engineering Geology. Engineering Special Publications, 15. Geological Society, London, pp. 415–426, with permission from Geological Society.

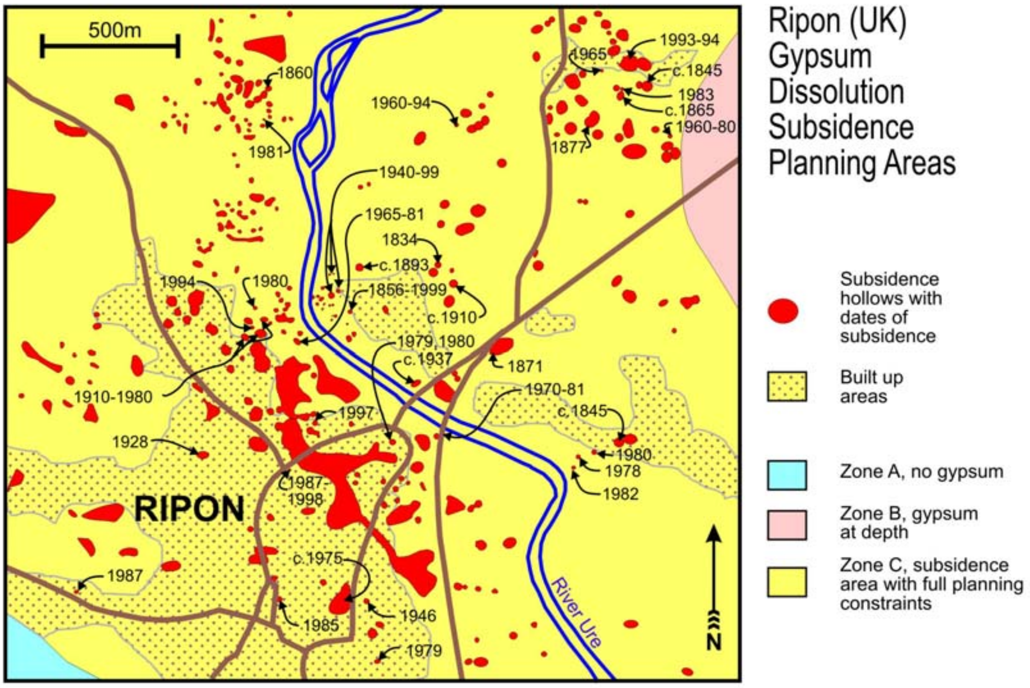

Figure 6. Sinkholes developed by dissolution of Devonian gypsum near Birzai, Lithuania. The area is within the agricultural control zone where, based on the density of sinkholes, the amount of fertilizer use is limited to protect the groundwater. Photo A H Cooper BGS© NERC.

Figure 7. Areas of Paris, France, that were recently calculated to have geological conditions prone to gypsum dissolution and subsidence problems - compared with the city planning regulation map areas established in 1977 and 2000.

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