Engineering Geology 65 (2002) 205–215

ENGINEERING GEOLOGY

www.elsevier.com/locate/enggeo

A decision-logic framework for investigating subsidence problems potentially attributable to gypsum karstification

John Lamont-Black[a,*], Paul L. Younger[a], Richard A. Forth[a],
Anthony H. Cooper[b], Jason P. Bonniface[c]

[a]*Department of Civil Engineering, University of Newcastle upon Tyne, Newcastle, NE1 7RU, UK*
[b]*British Geological Survey, Kingsley Dunham Centre, Keyworth Nottingham, NG12 5GG, UK*
[c]*Babtie GeoEngineering, 95 Bothewell Street, Glasgow, G2 7HX, UK*

Abstract

Karst regions, especially gypsum ones, are prone to subsidence; this can cause severe problems in urban areas. However, this subsidence may have causes other than active karstification. A decision-logic framework designed to tackle this issue is presented. It comprises subsidence description identification of causal mechanisms; construction and evaluation of conceptual models; evaluation and parameterization of fundamental processes and development of a management strategy. This framework is applied to an area of active subsidence in the UK underlain by gypsiferous rocks. In this example, particular attention is paid to the evaluation of gypsum dissolution using four criteria: presence of evaporite; presence of undersaturated water; energy to drive water through the system; and an outlet for the water. Gypsum palaeokarst was identified from borehole evidence and contemporary karstification is indicated by groundwaters containing up to 1800 mg/l of dissolved sulphate. Strontium/sulphate ratios enabled the discrimination of gypsum and non-gypsum-derived sulphate ions and correlation with the hydrostratigraphy. Continuous measurement of groundwater levels showed differential potentiometric surfaces between stratigraphical horizons and indicated a complex pattern of groundwater movement. Integration of these data in a physically and chemically based groundwater model, incorporating a void evolution capability, is suggested.

Keywords: Decision-logic framework; Gypsum karstification; Subsidence

---

1. Introduction

Ground subsidence is a frequently encountered geological hazard. It can result from one or a combination of processes. These include: removal of fluids; shrinkage of organic or clay-rich materials; hydrocompaction of sediments; creep or catastrophic collapse of materials into voids created by mining activities; or natural processes like karstification and periglaciation. Subsidence classification schemes (e.g. Prokovich, 1978; Waltham, 1989) can be a useful first step in identifying possible causes. However, given the diverse settings and variety of processes at work, adopting a general classification scheme can lead to assumptions that limit applications or fail to take full account of potential hazards.

As in the more widespread limestone karsts, the most obvious and profound surface manifestations of gypsum karst are collapse sinkholes or dolines. These have been recorded in many parts of the world

---

[*] Corresponding author.
E-mail addresses: john.lamont-black@ncl.ac.uk (J. Lamont-Black), p.l.younger@ncl.ac.uk (P.L. Younger), r.a.forth@ncl.ac.uk (R.A. Forth), a.cooper@bgs.ac.uk (A.H. Cooper).

PII: S0013-7952(01)00130-2

(Cooper, 1995; Benito et al., 1995; Johnson, 1996; Paukštys et al., 1997; Yaoru and Cooper, 1997; Martinez et al., 1998). In the UK, cover collapse sinkholes related to gypsum karst are present around the city of Ripon (Cooper, 1986, 1998). However, gypsum dissolution need not lead to a sudden collapse, and a sinkhole can form by a more gradual subsidence process. Gradual subsidence can have origins other than bedrock dissolution and these must be considered in any long-term management strategy. The rate of gypsum dissolution in water is approximately from 30–70 (Klimchouk et al., 1996) to 100–150 (Martinez et al., 1998) times that of limestone. Therefore, it must also be recognised that changes in groundwater circulation (which may be caused by groundwater abstraction) may initiate dissolution or increase existing dissolution (Paukštys et al., 1998; Cooper, 1988).

The research results discussed below are drawn from a study of an area in the UK that suffers from subsidence problems. It is underlain by 40–50 m of Quaternary till and a substantial thickness of Permian gypsiferous strata. The surrounding areas contain limited indications of gypsum dissolution and the area has hitherto been classified as one of low-subsidence risk. Owing to an agreement of confidentiality, we are not able to divulge the precise location of the site.

To develop an effective long-term hazard management strategy, it was considered that a thorough process-based understanding of subsidence mechanisms should be sought. It was realised that it is a mistake to assume automatically that an area in which karstification is known will have subsidence that is caused by karstification. This is especially so in areas with a complex hydrogeological and geomorpholog-

Table 1
Possible causes of subsidence that may be present in an area underlain by gypsiferous rocks

Action or group of processes	Subsidence mechanisms	Examples
Removal of ground fluid	loss of buoyant support for soil particles; compaction of sediment; possible failure of material bridging a void, thus, causing catastrophic collapse	sinkholes overlying gypsum karst in Lithuania (Paukštys et al., 1997)
Shrinkage of organic or clay-rich materials	loss of moisture; consolidation of sediment; net loss of organic material	shallow depressions from desiccated swelling clays (Biddle, 1983; Driscoll, 1983); subsidence of peat in subsidence hollows (Cooper, 1998)
Hydrocompaction of sediments	softening and yield of metastable interparticle bonds by the introduction of water	building subsidence caused by compaction of gypsiferous silt in alluvial fan, e.g., Calatayud Spain (Gutiérrez, personal communication)
Fluvial karstification of gypsum bedrock	loss of mechanical support—syn- and post-sedimentary subsidence of alluvial deposits into depressions forming at the alluvium/gypsum contact	subsidence depressions on alluvial flood plains, Calatayud Graben, Spain (Gutiérrez, 1996), river valley ‘subrosion’ (Ford, 1997)
Downwashing of unconsolidated sediments	downward movement of sediments into existing voids or breccia pipes resulting in gradual growth of shallow depressions	sinkholes in Lithuania (Paukštys et al., 1997); sinkholes in Ripon (Cooper, 1986)
Gradual collapse of unconsolidated materials overlying gypsum karst	sagging of materials overlying a void leading to concomitant lowering of the cover/gypsum interface, and growth of a surface depression	sinkholes in West Ripon (Cooper, 1998)
Catastrophic collapse of unconsolidated sediments into existing voids (may be preceded by a period of gradual subsidence)	collapse that probably requires a triggering mechanism; ravelling of a void upwards through unconsolidated sediment possibly accompanied by removal of sediment by rapid water flow through the void	sinkholes in Ripon (Cooper, 1986, 1998); sinkholes in China (Yaoru and Cooper, 1997); sinkholes in glacial drift overlying gypsum karst, Nova Scotia (Martinez and Boehner, 1997)
Catastrophic collapse of competent strata into voids (breccia pipe propagation)	failure of material bridging void; development of sinkhole generally requires a triggering mechanism	sinkholes in Ripon (Cooper, 1986), New Mexico (Martinez et al., 1998), NW territories, Canada (Ford, 1997)

ical history. However, to assume that if karstic voids have caused few problems in the past, they are unlikely to do so in the future is equally mistaken. This paper presents a working framework for identifying and evaluating a variety of component processes responsible for subsidence in areas underlain by gypsiferous strata. The results are drawn from an EC-funded study entitled Risk of Subsidence due to Evaporite Solution (ROSES).

2. Decision-logic framework

Subsidence over gypsiferous strata can have a number of different causes including some that may not be related to dissolution. Klimchouk (1996) classified gypsum karst into eight speleogenetic types. In the UK at Ripon, Cooper (1998) illustrated 16 sinkhole variations that fall within the subjacent, entrenched and, possibly, mantled categories of Klimchouk (1996). Thus, it is seen that gypsum karst is complex. In addition, numerous subsidence mechanisms (Table 1) can be present within a given setting. A decision-logic framework was developed to enable the characterisation and classification of the observed gypsum karst and the design of a monitoring strategy. The framework follows the six steps listed below. These are followed by an example of its application to a UK site.

1. Describe the observed subsidence accurately.
2. Identify the possible causal mechanisms, making reference to local geology and Table 1.
3. Construct conceptual ground models incorporating the processes driving the above mechanisms.
4. Collect data to evaluate the different fundamental processes.
5. Parameterize the important fundamental processes.
6. Develop a management strategy based on understanding these parameters.

3. Description of the observed subsidence (site in the north of England)

Prior to the 1970s, the recorded subsidence around the northern England site was limited to a few shallow closed depressions and a group of four sinkholes. These sinkholes yield sulphate-rich water and were formed by a catastrophic collapse during the 12th century. In recent years, however, subsidence has been experienced on a much wider scale. It takes the form of shallow ground depressions with maximum widths of a few tens to approximately 100 m and has mostly affected residential properties. Although building subsidence rarely exceeds 300 mm, the total cost of remedial work over recent years has been in excess of £1 million.

4. Identification of possible causal mechanisms

To identify the possible mechanisms involved, an initial desk study of the area's geology, hydrogeology and land-use history was made. Geological data were established from British Geological Survey maps and boreholes. The area is gently undulating, and the sequence comprises 40–50 m of glacial till (boulder clay) and laminated clay overlying Permian dolomites, dolomitic limestones, gypsum and marl (Fig. 1). From previous investigations, it was known that the glacial sequence was likely to contain a variety of materials including lenses of soft, water-saturated, silty and sandy material.

The Permian dolomitic limestones and dolomites form an important regional aquifer, which is in a confined state beneath the area. Increased exploitation of this resource in recent years may be influencing gypsum karst genesis. Consideration of the above ground conditions, the genetic types of sinkholes and the broad types of subsidence mechanisms listed in Table 1, led to the following mechanisms being postulated:

- Clay shrinkage including:
    - ◦ clay shrinkage owing to localised desiccation by large trees
    - ◦ clay shrinkage owing to climatically driven desiccation
    - ◦ localised lowering of the water table in the till and consolidation of lacustrine clays
- Gypsum karst including:
    - ◦ gypsum dissolution by groundwater

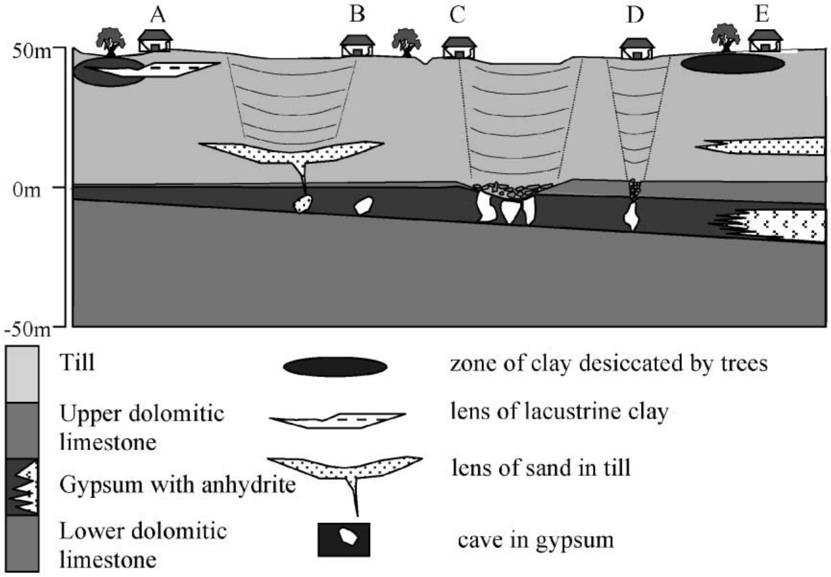

Fig. 1. First conceptual model of subsidence mechanisms: (A) desiccation of lacustrine clays in dry periods (amplified by trees); (B) Downwashing of sand and silt in the till into karstic voids in the gypsum; (C) gradual lowering of till/gypsum interface; (D) upward migration of karstic voids in the gypsum; (E) localised desiccation and shrinking of clays due to large trees. Not to scale.

- ◦ upward migration, through the till, of karstic voids originating in the gypsum
- ◦ localised enhanced dissolution at the till/gypsum interface and sagging of overlying till
- ◦ downwashing of saturated sands or clays in the till towards voids in gypsum, with consequent surface depression growth

Mining activity is completely unknown in the area, so mining-related subsidence was discounted. Therefore, the above mechanisms were used to construct conceptual models of the observed subsidence (Fig. 1), thus providing a number of hypotheses to be tested.

5. Conceptual model construction

5.1. Clay shrinkage as a conceptual model

Localised building subsidence damage can be caused by clay shrinkage due to tree roots removing soil moisture (type E, Fig. 1). Biddle (1983) and Driscoll (1983) examined the effects of different tree species on soil moistures in the UK. They noted that elm, oak, willow, and in particular, poplar, have the greatest effect in reducing soil moisture. They also noted that for a given set of environmental conditions, clay type has little effect on the degree of desiccation that will occur, but it is very important in terms of the amount of shrinkage that can occur. The Building Research Establishment (1996) highlighted the importance of stress history (degree of overconsolidation) in calculating the degree of desiccation from observations.

Clay shrinkage, caused by climatically driven soil desiccation, is a well-known British phenomenon that has occurred widely on clay soils following very dry summers such as those in 1976 (Driscoll, 1983) and 1990. The worst damage generally occurs on soils rich in swelling clays, in areas where soil moisture deficits are highest. This effect is linked closely to the effects of trees. A dry period with gradual lowering of the water table could also give rise to consolidation of deposits, such as glacio-lacustrine clays, and cause subsidence (type A, Fig. 1).

5.2. Gypsum karst as a conceptual model

The first stage in evaluation is to decide the genetic type of karst. Klimchouk's (1996) classification includes every type of karst (not necessarily gypsum) within a complex multi-stage development framework. This classification provides an important framework for understanding the processes involved and the physical types of karst that can be expected. Northern England potentially contains subjacent, mantled and buried karst (Klimchouk, 1996). If the karst is buried, it could suggest that karstic processes are no longer active. Johnson (1996) and Martinez et al. (1998) list four conditions that must be met for evaporite karstification to be considered active. These include:

1. an evaporite deposit in the subsurface
2. water that is unsaturated with respect to the evaporite mineral
3. an outlet for the escape of solvent water
4. energy to cause water to flow through the system

It is important, first, to evaluate whether the above conditions were met, and then if any of the conditions had been altered (e.g., increased groundwater heads resulting in higher rates of water flow through the system). Only if these conditions exist is it sensible to consider the mechanisms that might be operating in the overlying deposits. All these mechanisms are shown in Fig. 1 (constructed from desk study data) and include slow upward migration of a void such as a breccia pipe in limestone overlying the gypsum (type D, Fig. 1), downward illuviation of loose saturated sediments (type B, Fig. 1), and gradual lowering of the till/gypsiferous unit interface (type C, Fig. 1).

6. Evaluation and development of conceptual models

6.1. Clay shrinkage as a conceptual model

Clay soils of different types underlie the whole of the study area. Subsidence was recorded in a variety of locations overlying different soils with different tree types and planting densities. There was no systematic correlation between incidence of subsidence and either extended dry periods or proximity to trees. Moreover, many of the buildings affected were built in the 1950s, but did not begin to experience subsidence until the late 1970s. Similar housing stocks on similar Quaternary deposits with similar tree densities, but with no underlying gypsum, have not suffered subsidence. Although the indications are that clay shrinkage is not the main cause of the subsidence, this can only be confirmed by a systematic analysis of the trees with respect to their species, proximity to buildings and maturity. The results must then be related to the underlying geology, particularly the presence or absence of gypsum.

6.2. Gypsum dissolution as a conceptual model

The desk study showed that additional information was required to allow a full evaluation of the possible effects of gypsum dissolution. This information comprised detail of the solid and drift geology and the hydrogeology, including water levels and water quality. In one of the areas most severely affected by subsidence, four boreholes were drilled to a depth of

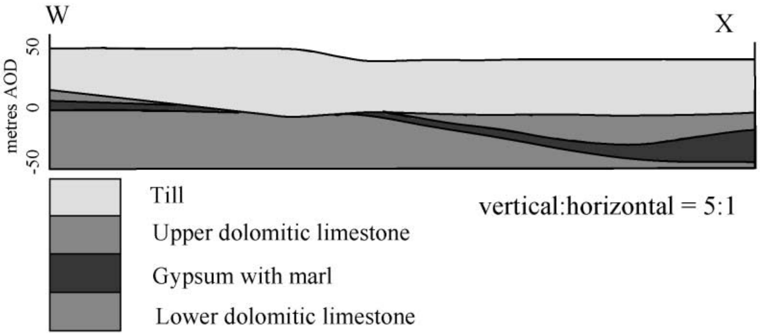

Fig. 2. Geological cross-section along line W–X (see Fig. 4 for location).

approximately 100 m. Data from these boreholes and data from the British Geological Survey borehole archive were used to construct a series of digital elevation models (DEMs) describing the geological surfaces, and data from the Ordnance Survey were used to construct a DEM of topography.

Groundwater levels were monitored in all four boreholes by installing standpipe piezometers at specific points related to the stratigraphy. This was done in order to measure seasonal variations and differential pressure heads in the strata. Falling head permeability tests were performed to estimate the hydraulic conductivities of the strata. Water quality analyses for major ions and strontium were performed on all the samples to determine mineral saturation indices. In addition, records of borehole logs, water quality and piezometric data for the surrounding area were obtained from the British Geological Survey and the Environment Agency. These data allowed the four essential conditions for gypsum karstification to be considered.

6.3. Is gypsum present?

Figs. 2 and 3 are geological cross-sections constructed from the archive and ground investigation data (for locations see Fig. 4). The gypsiferous horizon, present under much of the area, attains a maximum-penetrated thickness of 19.6 m. It comprises alabastrine gypsum with marl horizons near the top and base. Farther to the east, where the unit is thicker and deeper, gypsum is replaced by anhydrite. The unit may be absent from part of the area (Fig. 4) which is coincident with a depression in the rockhead surface where the gypsum may have been removed by dissolution or other erosion mechanisms. However, this idea cannot be validated without additional borehole data.

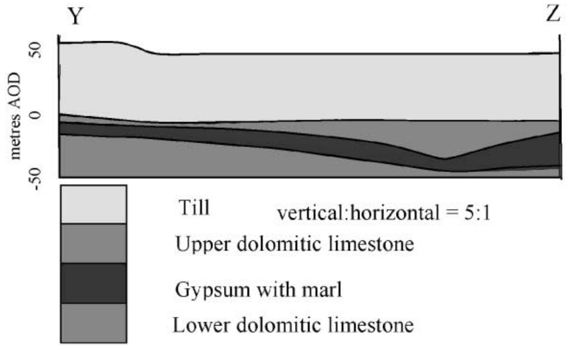

Fig. 3. Geological cross section along line Y–Z (see Fig. 4 for location).

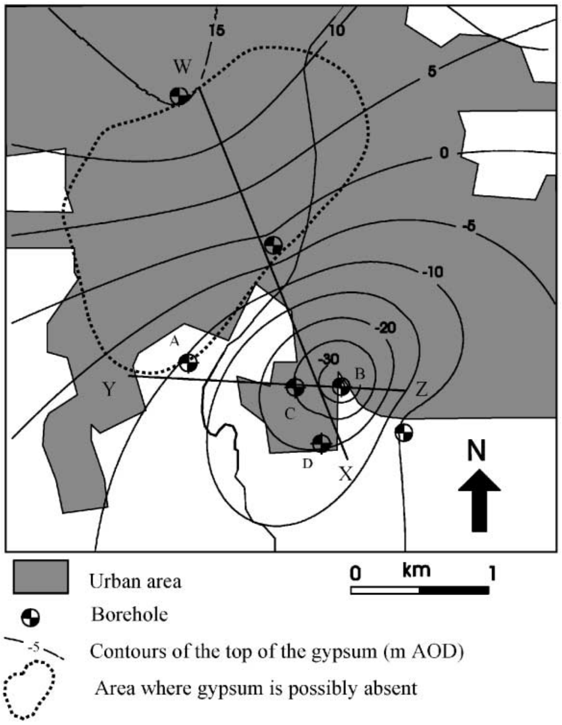

Fig. 4. Contoured interpolated upper surface of the gypsum unit. Note the depression overlying Borehole B and the zone where the gypsum is absent.

The gypsiferous unit is significantly thinner in the central south-eastern parts of the area (Figs. 2 and 3) and this is coincident with a depression in its top surface (Fig. 4). However, this depression is not reflected in the rockhead surface. If the thinning of the gypsum here is due to dissolution, it appears likely to have dissolved prior to the erosion of the present rockhead surface during the Pleistocene. The borehole records consistently recorded deposits of cave-fill type (up to 3.7 m thick) in the basal part of the gypsiferous unit where it is in contact with the underlying dolomitic limestone aquifer.

6.4. Is there water which is undersaturated with respect to gypsum?

The typical water chemistry of the lower dolomitic limestone is of a Ca–Mg–HCO_3 type with typical values for HCO_3^-, Ca^{2+}, Mg^{2+} and SO_4^{2-} of 34, 85, 28 and 75 mg/l, respectively. These data indicate groundwater saturation with respect to calcite, aragonite and dolomite, but undersaturation with respect to gypsum (saturation index $\cong -1.7$). However, water sampled from piezometer tips sealed off close to the gypsiferous unit provided samples with sulphate concentrations of 1700 mg/l and a corresponding saturation index of -0.05, i.e. almost fully saturated with respect to gypsum, thus indicating that gypsum dissolution has occurred.

6.5. Is there energy to drive water through the system?

The energy required is generated by regional groundwater gradients and differential piezometric heads between different lithological units. In the simplest terms, the groundwater hydrostratigraphy comprises the Quaternary till overlying the confined lower dolomitic limestone aquifer. Falling head permeability tests, performed in the piezometer tubes, indicated hydraulic conductivities of 1–10 m/day for the lower dolomitic limestone and 0.01–0.0 4 m/day for the till. In reality, the till is likely to have a more variable hydraulic conductivity than the dolomitic limestone. This is because of its inherent heterogeneity, including lenses of water-lain clay, silt, sand and gravel. In all four boreholes, the lower dolomitic limestone aquifer exhibited a lower piezometric level than the till.

Klimchouk (1996) showed that the most common and rapid development of gypsum caves occurs in the interstratal setting, when water under artesian pressure is driven through a layer of gypsum in a direction roughly perpendicular to the bedding. Such conditions were obtained in Borehole A (Fig. 5), where a head difference of 0.2 m was present across the gypsum layer. This head difference has reduced with the onset of water quality sampling in July 1998. This reduction could be a response to well development as large quantities of water have been removed during purging operations. There appears, however, to be some divergence in the hydrograph levels of the blue and brown piezometers in Borehole A, indicating that the initially observed head difference was real and this was disturbed by the sampling; a longer period of observation will be required to assess this.

In contrast, Borehole B yielded piezometric head data that showed almost zero head difference across the gypsiferous unit, but higher water pressures in the till above and in the dolomitic limestone aquifer beneath (Fig. 6). This can be interpreted as the gypsiferous unit acting as a drain to the system. If this is the case, then it is reasonable to assume that gypsum dissolution is ongoing and that the water containing high levels of dissolved gypsum is not sampled because it is confined within the gypsiferous unit. It is important to note that Borehole B is located in the area where the gypsiferous unit thinned markedly and there is a depression in its upper surface (Figs. 2–4). The draining activity may be related, therefore, to reactivation of the paleokarst interpreted from the lithostratigraphy.

The hydrograph of Borehole A (Fig. 5) shows a difference in potentiometric level between the brown piezometer (situated at the base of the gypsiferous unit) and the yellow piezometer (lower dolomitic limestone). The absence of any significant clay strata in

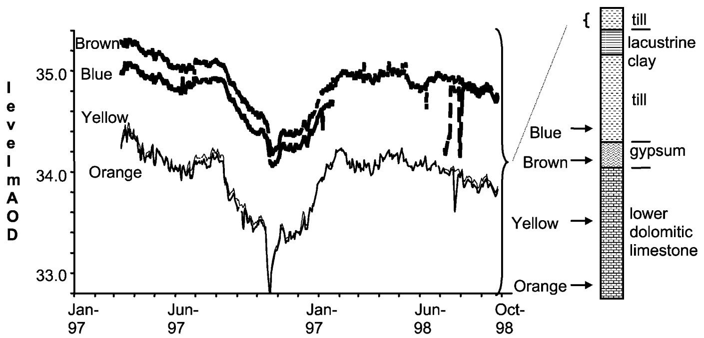

Fig. 5. Groundwater levels from standpipe piezometer tubes in Borehole A. In this figure, the curled bracket indicates the zones of fluctuation of piezometric levels within Borehole A (represented by the stratigraphic columns).

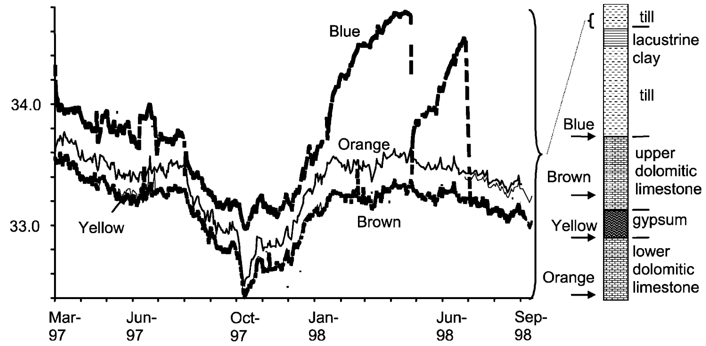

Fig. 6. Groundwater levels from standpipe piezometer tubes in Borehole B. In this figure, the curled bracket indicates the zones of fluctuation of piezometric levels within Borehole B (represented by the stratigraphic columns).

the lower dolomitic limestone aquifer, and the presence of only a 3-m-thick bentonite seal between the two packed zones, suggest that the gypsiferous unit has a low-hydraulic conductivity. However, falling head tests were unsuccessful, because the water levels fell too quickly to enable a measurement to be taken. This suggests open voids, perhaps related to the cave deposits proved by boreholes at the base of the gypsum. A possible explanation for these observations, however, might be that the clay in the cave deposits has formed an 'armour' or 'filter cake' at the base of the gypsiferous unit, thus offering an effective hydraulic barrier at the top of the lower dolomitic limestone.

6.6. *Is there an outlet for the water?*

To maintain a consistently lower pressure in the gypsiferous unit in Borehole B, water must be flowing laterally within the unit. As Fig. 2 shows, the gypsiferous unit continues with a shallow southerly dip suggesting that an outlet might exist to the south. Possible confirmation is provided by the presence of sulphate-rich waters in the sinkhole flashes, 2 km to the south and sulphate-rich springs, 3.5 km to the south. Borehole A is adjacent to a river (Fig. 4) that gains from the groundwater in the late summer and autumn. A larger river, 4 km to the south, gains groundwater from the dolomitic limestone throughout the year.

6.7. *Non-gypsum sources of dissolved sulphate*

It is important not to rely simply on sulphate levels as an indication of gypsum dissolution. Groundwater from the till in Boreholes C and D contains sulphate concentrations between 660 and 890 mg/l; ordinarily this might indicate gypsum dissolution. However, the existence of a higher potentiometric surface in the till makes it difficult to imagine a mechanism that would enable groundwater, containing dissolved gypsum, to be found 30 m above the rockhead surface. Data presented in Fig. 7 shows that strontium concentrations correlate generally well with those of sulphate. This would be expected if the sulphate is from gypsum, as strontium is concentrated progressively during the evaporation of seawater that leads to gypsum precipitation. However, Fig. 7 also shows that the sulphate and strontium levels from the till in Boreholes C and D plot on a different trend, thus indicating a different source. To the north of the area, the Coal Measures outcrop, which was traversed by the glacier that deposited the till, contains several pyrite-rich horizons. Incorporation of material from this stratum into the till and its subsequent oxidation would provide the high-sulphate levels independent of gypsum dissolution. This possibility is supported by the frequent inclusion of coal fragments in the till.

7. General conceptual model

A general model of gypsum dissolution can now be derived for the study area. All the components for gypsum dissolution exist: gypsum is present, undersaturated water is present, there is energy to drive water through the system, and there appears an outlet

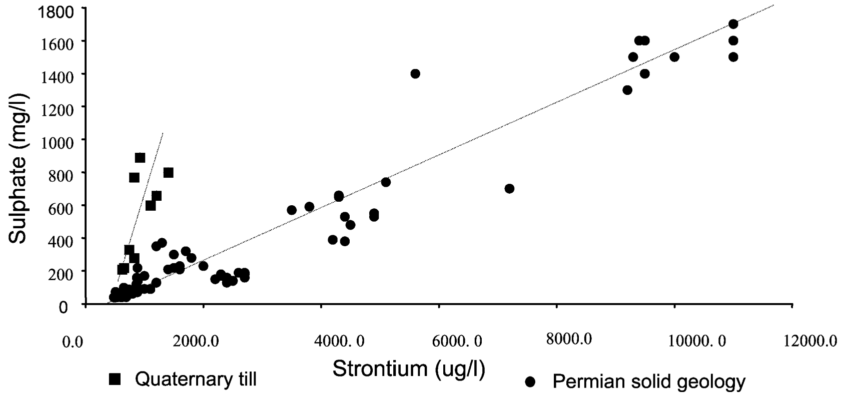

Fig. 7. Plot of strontium versus sulphate for all analyses showing two distinct trends relating to gypsum and non-gypsum sources for sulphate.

for the water. The situation, shown schematically in Fig. 8, allows for two mechanisms of subsidence at the surface, i.e. upward migration of a void developed by gypsum karstification, or downwashing of loose sediments. It has not yet been established which of these is the more appropriate.

8. Parameterization of fundamental processes

Initially, two groups of possible subsidence mechanisms were identified: clay shrinkage and mass wasting relating to gypsum karstification. The approach described above has identified several important parameters, especially those relating to the hydrogeology, which describe karstification processes. The parameters include:

- magnitude of piezometric heads in geological units
- direction of water flow in relation to the gypsiferous strata
- concentrations of dissolved sulphate and mineral saturation indices
- relationship between groundwater and surface water
- lateral variations in thickness of gypsiferous strata

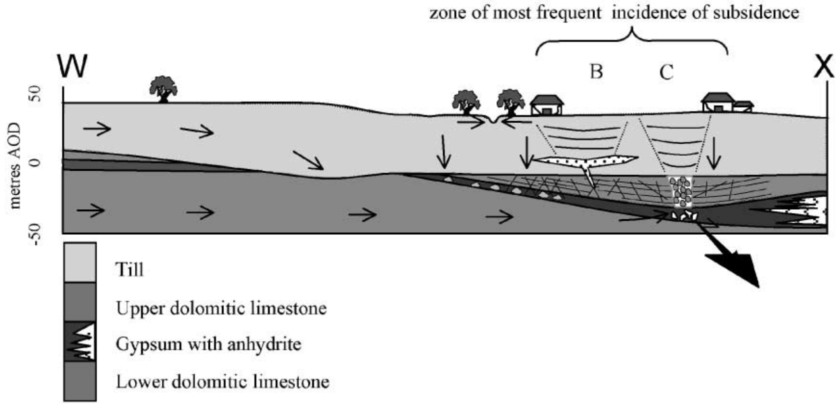

Fig. 8. Generalised conceptual model of karstification and subsidence in the study area developed along section W–X. Large arrow indicates postulated outflow of water along the gypsum unit, small arrows indicate suggested groundwater flow direction in the till and lower dolomitic limestone.

Values of all parameters will vary over different time scales. It is intended to perform continuous monitoring of the first four parameters to establish the long-term trends. However, this study has been hindered somewhat by the unusually wet summer of 1998. Therefore, neither piezometric levels nor groundwater/surface interactions have been representative, and their effect on groundwater quality is not clear.

This study shows that dissolution is occurring in the gypsiferous strata beneath the study area. Without more detailed hydrogeological work, the dissolution cannot be quantified confidently. Therefore, the process has not been related directly to the subsidence that is being observed at the ground surface. Continued monitoring of ground subsidence and a full evaluation of the subsidence data must be undertaken. The latter is necessary to test the initial conclusion of a non-systematic relationship between instances of subsidence and soil types or trees.

9. Develop a management strategy based on understanding the controlling parameters

Although it can be costly to repair the damage caused by near-surface clay shrinkage, the process has few long-term implications for buildings after their foundations have been deepened to reach below zones of high-soil moisture deficit. The long-term effects of gypsum karst, however, would be much more difficult to control. The fullest possible evaluation is needed because the consequences of long-term damage can be severe, as demonstrated in Ripon, Yorkshire (Cooper, 1986, 1998; Thompson et al., 1998).

Initial work suggests that karstification may be driving the subsidence in the present study area. If this is so, then a more detailed investigation should be planned as the first step in the management strategy. This would be necessary to improve several areas of knowledge, i.e. geological aspects such as variations in lithology, structural features and, in particular, the solid-drift interface and stratigraphy of the Quaternary deposits; groundwater flow and hydraulic conductivities. With this information, it should prove possible to construct a representative groundwater flow model using the Evaporite Void Evolution (EVE) code (newly developed under the ROSES project), which has added turbulent conduit flow and dissolution in gypsum caves to the basic capabilities of the well-known MODFLOW® code (McDonald and Harbaugh, 1988). EVE is designed to model the effects that groundwater abstraction may have on flow vectors. The present investigations indicate that some aggressive groundwater flows from the glacial deposits downwards. If the potentiometric level in the lower dolomitic limestone aquifer fell because of further groundwater abstraction, then the pressure difference across the gypsiferous unit would be increased, thus possibly accelerating gypsum dissolution rates, provoking additional subsidence.

Acknowledgements

The authors would like to thank Dr. Alex Klimchouk, Professor Mateo Gutiérrez-Elorza, Dr. Francisco Gutiérrez-Santolalla, Dr. Martin Sauter and Dr. Rudolph Liedl for their valuable discussions on gypsum karst. Dr. Dave Lowe and Tim Charsley are thanked for reviewing the manuscript. AHC publishes with the permission of the Director British Geological Survey (NERC). The research presented above is part of the ROSES project funded from under the European Commission Framework IV Programme (contract number ENV4-CT97-0603).

References

Benito, G., Pérez del Campo, P., Gutiérrez, F., Elorza, M., Sancho, C., 1995. Natural and induced sinkholes in gypsum terrain and associated environmental problems in NE Spain. Environmental Geology 25, 156–164.

Biddle, P.G., 1983. Patterns of drying and moisture deficit in the vicinity of trees on clay soils. Geotechnique 33, 107–126.

Building Research Establishment, 1996. Digest 412, "Desiccation in Clay Soils". HMSO, London.

Cooper, A.H., 1986. Subsidence and foundering of strata caused by the dissolution of Permian Gypsum in the Ripon and Bedale areas, North Yorkshire. In: Harwood, G.M., Smith, D.B. (Eds.), The English Zechstein and Related Topics. Geological Society, London, Special Publication, vol. 22, pp. 127–138.

Cooper, A.H., 1988. Subsidence resulting from the dissolution of Permian Gypsum in the Ripon area; its relevance to mining and water abstraction. In: Bell, F.G., Culshaw, M.G., Cripps, C.J., Lovell, M.A. (Eds.), Engineering Geology of Underground Movements. Geological Society, London, Engineering Geology Special Publication, vol. 5, pp. 387–390.

Cooper, A.H., 1995. Subsidence hazards due to the dissolution of Permian gypsum in England: investigation and remediation. In: Beck, B.F. (Ed.), Karst Geohazards: Engineering and Environmental Problems in Karst Terranes. Proceedings of the 5th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Gatlinburg, TN, 2–5 April, 1995. Balkema, Rotterdam, pp. 23–29.

Cooper, A.H., 1998. Subsidence hazards caused by the dissolution of Permian gypsum in England: geology, investigations and remediation. In: Maund, J.G., Eddleston, M. (Eds.), Geohazards in Engineering Geology. Geological Society of London, Engineering Geology Special Publications, vol. 15, pp. 265–275.

Driscoll, R., 1983. The influence of vegetation on the swelling and shrinking of clay soils in Britain. Geotechnique 33, 93–105.

Ford, D.C., 1997. Principal features of evaporite karst in Canada. Carbonates and Evaporites 12 (1), 15–23.

Gutiérrez, F., 1996. Gypsum karstification induced subsidence: effects on alluvial systems and derived geohazards (Calatayud Graben, Iberian Range, Spain). Geomorphology 16, 277–293.

Johnson, K.S., 1996. Gypsum karst in the United States of America. International Journal of Speleology 25 (3–4), 184–194.

Klimchouk, A., 1996. The typology of gypsum karst according to its geological and geomorphological evolution. International Journal of Speleology 25 (3–4), 49–60.

Klimchouk, K., Cucchi, J., Calaforra, J., Calaforra, M., Askem, S., Finocchiaro, F., Forti, P., 1996. Dissolution of gypsum from field observations. International Journal of Speleology 25 (3–4), 37–48.

Martinez, J.D., Boehner, R., 1997. Sinkholes in glacial drift underlain by gypsum in Nova Scotia, Canada. Carbonates and Evaporites 12 (1), 84–90.

Martinez, J.D., Johnson, K.S., Neal, J.T., 1998. Sinkholes in evaporite rocks. American Scientist 86, 39–52.

McDonald, M.G., Harbaugh, A.W., 1988. A modular three-dimensional finite difference ground-waterflow model. United States Geological Survey, Techniques of Water Resources Investigations, 06-A1.

Paukštys, B., Cooper, A.H., Arustienne, J., 1997. Planning for gypsum geohazards in Lithuania and England. In: Beck, B.F., Stephenson, J.B. (Eds.), The Engineering Geology and Hydrogeology of Karst Terranes. Proceedings of the 6th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Springfield, MO, 6–9 April, 1997. Balkema, Rotterdam, pp. 127–135.

Prokovich, N.P., 1978. Genetic classification of land subsidence. In: Saxena, S.K. (Ed.), Evaluation and Prediction of Subsidence. Proceedings of the International Conference on Evaluation and Prediction of Subsidence, Florida, January, 1978. American Society of Civil Engineers, New York, pp. 389–399.

Thompson, A., Hine, P., Peach, D.W., Frost, L., Brook, D., 1998. Subsidence planning assessment as a basis for planning guidance in Ripon. In: Maund, J.G., Eddleston, M. (Eds.), Geohazards in Engineering Geology. Geological Society of London, Engineering Geology Special Publications, vol. 15, pp. 415–426.

Yaoru, L., Cooper, A.H., 1997. Gypsum karst geohazards in China. In: Beck, B.F., Stephenson, J.B. (Eds.), The Engineering Geology and Hydrogeology of Karst Terranes. Proceedings of the 6th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Springfield, MO, 6–9 April, 1997, pp. 117–126.

Waltham, A.C., 1989. Ground Subsidence. Blackie, Glasgow.