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AVOIDING GYPSUM GEOHAZARDS: GUIDANCE FOR PLANNING AND CONSTRUCTION

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Front cover illustration : Subsidence hollow at Ure Bank Terrace, Ripon, North Yorkshire, UK. The hole formed during 23-24 April 1997 and measured 10m in diameter and 5.5m deep. It was caused by collapse over a cave formed in gypsum of Permian age. Four garages were initially destroyed and further failure of the hole sides have damaged the adjacent house. (Photo Paul Tod, BGS negative no. MN27923)

Keyworth, Nottingham, British Geological Survey, 1998

SUMMARY

This information details the occurrence and characteristics of the rock and mineral gypsum, its highly soluble nature and the types of problems associated with it. These include subsidence, which can affect all construction including buildings, roads, railways and canals. Water leakage beneath dams is also described along with the aggravation of dissolution and subsidence caused by water abstraction. The financial losses caused by gypsum geohazards can be large and considerable cost savings can be generated by avoidance planning and the use of protective construction measures such as those detailed.

This report is has been prepared for planners, geologists and geotechnical engineers, throughout the world, to raise their awareness of gypsum geohazard problems and to help with local and national planning.

BOXES

1. GYPSUM GEOHAZARDS

1.1. INTRODUCTION

This information is aimed at planners, geologists and geotechnical engineers, throughout the world, to raise their awareness of gypsum geohazard problems. It details the occurrence and characteristics of the rock and mineral gypsum, its highly soluble nature and the types of problems associated with it. These include subsidence, which can affect all construction including buildings, roads, railways and canals. Water leakage beneath dams is also a major concern as is the aggravation of dissolution and subsidence caused by water abstraction. The financial losses caused by gypsum geohazards can be large and considerable cost savings can be generated by avoidance planning and the use of protective construction measures such as those detailed.

This planning advice is the result of research financed by, and undertaken for, the British Government, Department for International Development under Technology and Development Research (TDR[1]) project R6490 to investigate and report on the mitigation of "Gypsum geohazards: their impact on development". The project was part of theme G3 to "Improve geotechnical hazard avoidance strategies in national planning".

1.2. WHAT IS GYPSUM AND HOW IS IT RECOGNISED?

Gypsum is hydrated calcium sulphate $CaSO_4.2H_2O$, the raw material for making plaster. The mineral is generally white, translucent, pale grey or grey; it is commonly pink where it is associated with red mudstone strata and may also be brown and yellow. It is a soft mineral (hardness 1.5-2) and can usually be scratched with a finger nail. It occurs in several forms including crystalline, fibrous and alabastrine. The specific gravity of pure crystalline gypsum is about 2.3. Further details are shown in Box 1.

The most commonly recognised, but not the most abundant gypsum type, is fibrous gypsum or satin spar. This is generally white and composed of fine gypsum fibres mainly sub-perpendicular to veins, but also commonly sigmoidally bent across the vein; mudstone inclusions are also common. In this form it tends to survive and be easily identified even in open borehole chippings samples. Its ready identification, and common, but not ubiquitous association with the other forms of gypsum, makes it a good pointer to the presence of other gypsum forms in a sequence.

The most abundant form of gypsum encountered in the largest deposits of gypsum is alabastrine gypsum or alabaster. This is commonly mis-identified as limestone in boreholes and outcrops, a mistake that can lead to disastrous engineering problems. It generally has very fine anastamosing veins of fibrous gypsum giving it the alabaster effect. It is soft, but may be harder to scratch with a finger nail than the crystalline versions. The alabastrine variety commonly has secondary crystals of gypsum up to a few centimetres. Alabastrine gypsum is mainly secondary after

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[1] The TDR programme is part of the UK provision of aid and technical assitance to developing and emerging countries.

anhydrite ($CaSO_4$) which is largely produced by the burial dehydration of primary gypsum. The rehydration of the anhydrite to gypsum is accompanied by volume changes and the generation of fibrous gypsum veins. In many places the hydration is incomplete and central masses of anhydrite surrounded by gypsum can occur.

Anhydrite is the dominant mineral at depths of burial of more than 100-500m depending on the geological situation. Compared with gypsum, anhydrite is more dense and harder (hardness 3-3.5), it scratches slightly with a piece of soft annealed copper (such as found in domestic wiring) whereas gypsum scratches very easily with the same copper. Further details are given in Box 1. Commonly anhydrite has a laminated or chicken wire mesh structure that is often partially destroyed during hydration to gypsum.

Box 1. The characteristics of gypsum and anhydrite

Gypsum:

Chemical name:	calcium sulphate dihydrate
Chemical formula:	$CaSO_4.2H_2O$
Specific gravity:	2.3-2.37
Hardness, Mohs' scale:	1.5-2
Main varieties:	fibrous, alabastrine, crystalline
Colour:	white, pale grey, pink, yellow-brown
Porosity:	typically fairly low around 4-7%
Compressive strength:	moderately strong, unconfined compressive strength, 24-35 MPa
Tensile strength:	2.2-3.6 MPa (Brazilian tensile strength)
Schmidt hammer hardness:	8-23

Anhydrite:

Chemical name:	calcium sulphate
Chemical formula:	$CaSO_4$
Specific gravity:	2.9-3
Hardness, Mohs' scale:	3-3.5
Main varieties:	crystalline and nodular
Colour:	grey and pale bluish grey
Porosity:	typically low around 3%
Compressive strength:	strong to very strong, unconfined compressive strength, 66-123 MPa
Tensile strength:	7.1-8.2 MPa (Brazilian tensile strength)
Schmidt hammer hardness:	35-37

Based on information from Deer Howie and Zussman, 1966 and Bell, 1994.

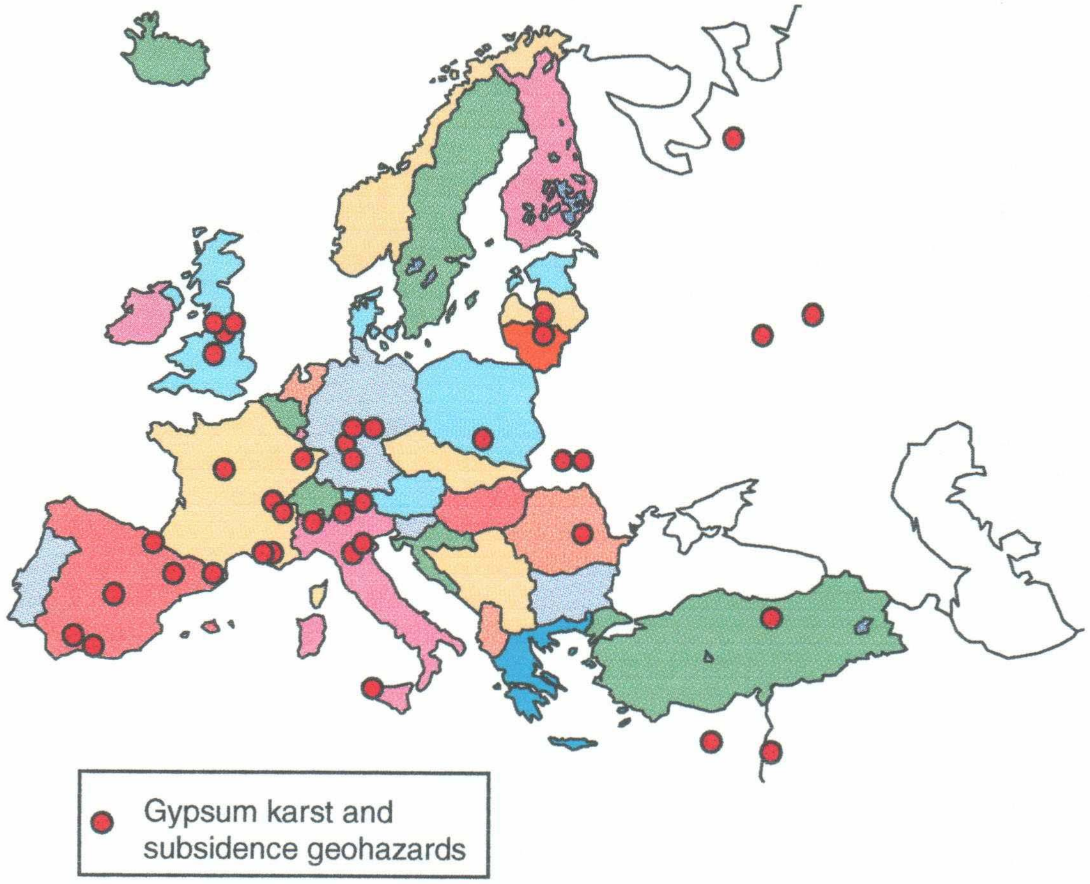
The crystalline form of gypsum can occur in small to enormous crystals (up to 1m long), the larger ones commonly arranged twinned fan or blade-like shapes. These forms tend to occur more often in the younger gypsum deposits that have not been deeply buried and transformed into anhydrite. In recent deposits gypsum commonly also occurs as gypsum sand and in algal laminated and nodular sequences.

1.3. WHERE DOES GYPSUM OCCUR ?

Gypsum has been recognised throughout the world and in all the geological sequences from the Cambrian (570 million years ago) to recent deposits. It is especially prevalent associated with former evaporitic seas and is thus commonly associated with salt and dolomite deposits. It is also often associated with limestones and very commonly occurs in red mudstone and sandstone sequences deposited in inland lakes and enclosed basins. Examples of its distribution in Europe and China are given in Boxes 2 and 3. Gypsum is also present in many of the recent coastal deposits of places such as the Gulf States.

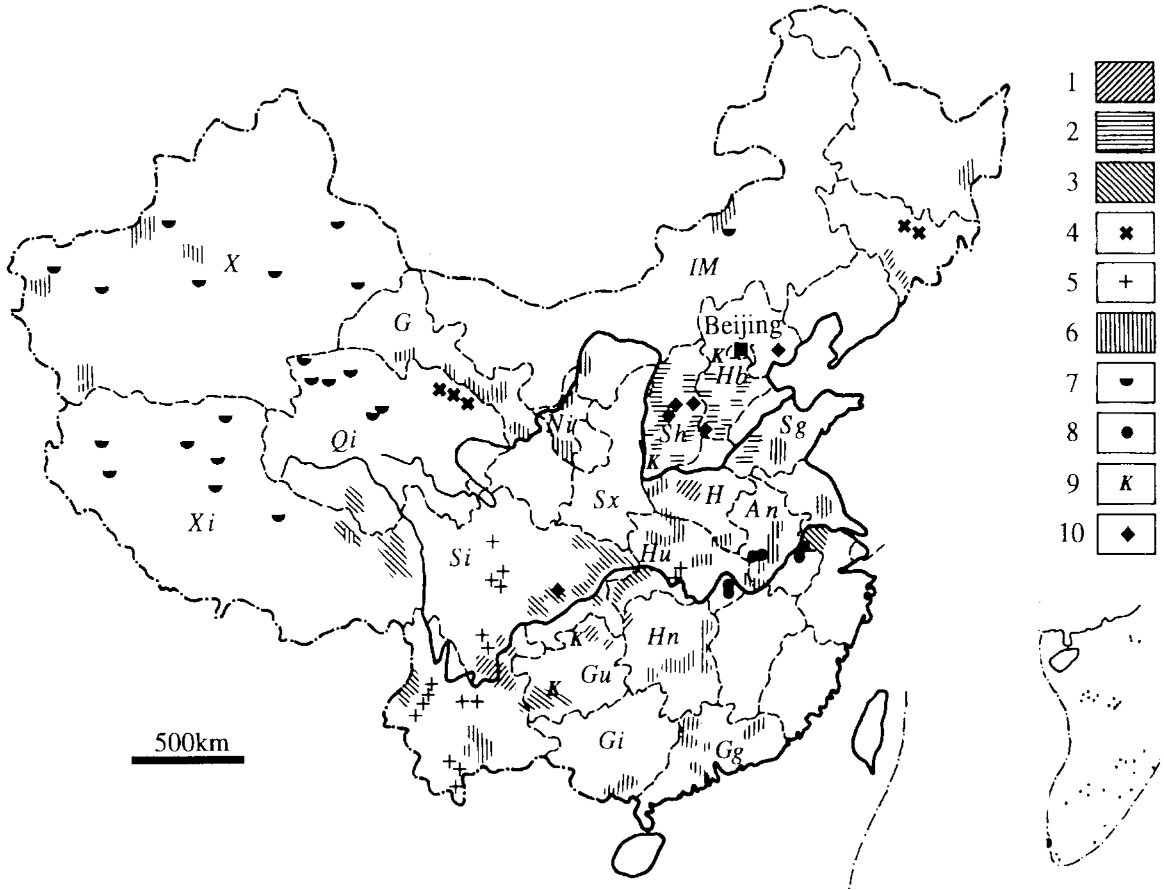
In descending order, the major world produces of gypsum (1990-4 data) were: USA, China, Canada and Iran (8-17 million tonnes each); Thailand, Spain, Mexico, France, UK, Germany, Australia, India, Russia, Italy and Egypt (1-8 million tonnes each). In addition to these countries another 66 are listed as producing less than 1 million tonnes of gypsum a year, these countries are: Greece, Irish Republic, Portugal, Austria, Azerbijan, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Latvia, Macedonia, Moldova, Poland, Romania, Serbia and Montenegro, Slovakia, Switzerland, Turkey, Algeria, Angola, Ethiopia, Kenya, Libya, Mauritania, South Africa, Sudan, Tanzania, Tunisia, Cuba, Dominican Republic, El Salvador, Guatemala, Honduras, Jamaica, Nicaragua, Argentina, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Afghanistan, Bhutan, Cyprus, Iraq, Israel, Jordan, Laos, Lebanon, Mongolia, Myanmar, Oman, Pakistan, Philippines, Saudi Arabia, Syria, Taiwan, Tajikistan, Turkmenistan, Vietnam, Republic of Yemen. Many more countries have gypsum deposits, but do not exploit them. Gypsum is a very widespread rock and problems related to it are underestimated.

Box 2. Areas in Western Europe with gypsum karst geohazards



In many countries gypsum karst constitutes a geological hazard responsible for subsidence and difficult engineering conditions. It is responsible for subsidence and collapse (sometimes sudden and catastrophic) in urban areas around Paris (France), Madrid and Zaragoza (Spain), Stuttgart (Germany), Ripon and Darlington (England), Pasvalys and Biržai (Lithuania), and the Perm area (Russia). It is also responsible for leaking reservoirs (French Alps) and difficult tunnelling conditions (Switzerland and Germany). The construction of railways has been affected in Spain and Turkey. The construction of roads have been adversely affected in Great Britain, Germany and France. Throughout the world, gypsum karst is a little known hazard that should be borne in mind especially in the siting of dams and reservoirs. It has been responsible for leakage or failure in more than 24 dams world-wide.

Box 3. Areas of gypsum in China where gypsum geohazards may occur.



In all locations in China where gypsum occurs there are likely to be gypsum geohazards. These can include subsidence caused by natural dissolution, gypsum-polluted groundwater, subsidence caused by the abstraction of groundwater, and hazardous coal-mining conditions. In addition to these hazards, the location of dams on gypsum is particularly dangerous; leakage and dissolution of gypsum can cause dams to fail catastrophically. By using maps such as this, but on a larger scale, it is possible to plan for the avoidance of gypsum geohazards on a national and regional basis.

The map shows the age and distribution of the main genetic types of gypsum in China. 1. Cambrian marine gypsum; 2. Ordovician marine gypsum; 3. Triassic marine gypsum; 4. Carboniferous marine gypsum; 5. Cretaceous lacustrine gypsum; 6. Tertiary lacustrine gypsum; 7. Late Tertiary-Quaternary lacustrine gypsum; 8. Thermal and metamorphic gypsum (typical localities); 9. Secondary deposits of gypsum produced by karstification (typical localities); 10. Coal mining areas affected by collapse columns caused by gypsum dissolution. Abbreviations for province names: *An*-Anhui, *G*-Gansu, *Gg*-Guangdong, *Gi*-Guangxi, *Gu*-Guizhou, *H*-Henan, *Hb*-Hebei, *Hn*-Hunan, *Hu*-Hubei, *IM*-Inner Mongolia, *Ni*-Ningxia, *Qi*-Qinghai, *Sg*-Shandong, *Sh*-Shanxi, *Sx*-Shaanxi, *X*-Xinjiang, *Xi*-Xizang (Tibet).

1.4. HOW FAST DOES GYPSUM DISSOLVE, AND WHY IS IT A HAZARD?

Gypsum dissolves about one hundred times faster than limestone (the rock in which most caves form) and about one thousand times slower than salt (halite). Under natural conditions, adjacent to a river or in a cave, it can easily dissolve at a rate of 1m a year with a water flow rate of about 1m per second across the rockface (Box 4). Such a fast rate of dissolution can enlarge cavities to cave passages in a relatively short time. As a consequence of this gypsum caves can enlarge rapidly and become unstable resulting in subsidence. In many situations the collapse can block the cave system and cause enhanced dissolution in the adjacent ground resulting in further collapse and subsidence.

In the foundations of dams or adjacent to canals, water leakage can cause severe dissolution. The amount of dissolution can accelerate rapidly and small initial flows can quickly become major leakages that can threaten the integrety of the structure.

Box 4. Dissolution rates of gypsum

At Ripon Parks in North Yorkshire, a large cubic block of gypsum detached itself from the gypsum cliff and fell into the river. It measured about 3m along each edge and dissolved away completely in about 18 months. The water flow rate past it was about 1m per second. Calculations show that approximately 1m of gypsum a year can be removed from a gypsum face by a water flow of about 1m per second

In Spain, dissolution experiments were conducted using balls of gypsum suspended in irrigation canals. In canals with a water flow of 0.35m per second 0.393 m of gypsum was removed per square metre of surface per year. In canals with a water flow of 0.99m per second 0.853m of gypsum was removed per square metre of surface per year.

Laboratory experiments conducted using water passed through holes in gypsum blocks yield similar dissolution rates.

Other factors affect the rate of dissolution, especially the presence of turbulent water flow. Large concentrations of dissolved gypsum can slow the dissolution rate, however, the presence of dissolved sodium chloride (salt) or magnesium carbonate (from dolomite) can considerably increase the dissolution rate.

Key references: James, 1992; James, Cooper and Holliday, 1980; James and Lupton, 1978; Navas, 1990; Kemper, Olsen and deMooy, 1975: Klimchouk, Lowe, Cooper and Sauro, 1997.

1.5. SUBSIDENCE CAUSED BY GYPSUM DISSOLUTION

The rapid dissolution of gypsum in subsurface conditions can result in caves and cavities that rapidly expand. Several geological situations exist in which gypsum-related subsidence can occur.

In many of the gypsum sequences cave development is controlled by the jointing in the rock and the adjacent strata, especially if it is an aquifer. When the caves form they tend to follow the master joints. As a result of this the caves commonly have a reticulate plan. Dissolution of the gypsum is enhanced at the intersections of the joints, and large cavities tend to form at these locations. The high dissolution rate of gypsum means that these cavities can rapidly expand, become unstable and start to collapse. When this happens the roof of the cavity collapses and works its way towards the surface leaving a column of brecciated rock beneath it; these are breccia pipes or collapse columns. If the rock overlying the gypsum is soft, or becomes soft when wetted, the collapsed material does not expand much in volume and the breccia pipes can work their way up through a considerable thickness of strata, eventually breaking through at the surface as a subsidence hollow. In soft strata it is possible for the breccia pipe to propagate up through up through strata with a thickness in excess of ten times that of the collapsed cavity. Where the collapsed rock is hard and resistant the material may bulk up considerably more and it is unlikely that such a breccia pipe will propagate up through more than eight times the height of the collapsed cavity. The sizes of the collapsed areas is also dependent on the rock that overlies the gypsum. Where competent rocks are present the breccia pipes and collapse areas are commonly 10-30m or more in diameter. Where soft mudstones are present above the gypsum the collapse areas are more typically 3-5m in diameter. The depths of the holes is dependent on the amount of gypsum removed and the depth and the bulking factor for the collapsed material. In the Ripon area, Lithuania and Germany the holes are commonly 10-20m deep.

Not all gypsum sequences develop distinct cave systems. Gypsum dissolution can occur on the top surface of the rock, especially where it is in contact with overlying water bearing deposits. In Spain, around Zaragoza, much of the dissolution appears to be taking place at the contact of the gypsum and the overlying gypsiferous fluvial deposits. Some cavities are reported in the gypsum itself, but dissolution at the contact and in the overlying deposits appears to be more intensive. Many of the holes are of similar dimensions to those found in the older deposits noted above.

Another mode of subsidence that occurs over gypsum is the failure of the overlying deposits and the washing, or collapse, of them into cavities or caves within the rock. This can especially occur where there are thick deposits of unconsolidated fluvial deposits resting on the gypsum.

In all the situations mentioned above, water abstraction and the incorrect disposal of surface waters may all aggravate the subsidence situation.

1.6. WHY IS IT IMPORTANT TO AVOID GYPSUM GEOHAZARDS?

Because gypsum is widespread throughout the world and because it dissolves so rapidly, it poses a threat to any development that encounters it. More than one metre of gypsum per annum can be easily dissolved by moderate river action on natural exposures. Where this dissolution occurs underground at similar rates, caves can develop, expand rapidly and suddenly collapse. By this mechanism holes, commonly up to 20m deep and 40m or more across, continue to appear suddenly in gypsiferous terranes throughout the world.

Examples include the towns of Ripon (UK), Pasvales and Biržai (Lithuania) where 45,000 people are currently affected by catastrophic subsidence caused by gypsum. In Ripon the recorded costs of the subsidence damage is estimated to be around £1,300,000. Half of the city of Darlington (UK) is affected by less severe, gypsum-related, subsidence. In Spain, parts of the city of Zaragoza and the surrounding areas are affected; the town of Calatayud has suffered severe subsidence and the new village of Puilatos had to be abandoned and demolished. Around Paris in France, and around Stuttgart and towns peripheral to the Hartz Mountains in Germany, gypsum dissolution caves have caused problems for road and building construction. In China large subsidence features, caused by gypsum dissolution, have occurred in the Taiyuan and Yangquan regions of Shanxi Coalfield and in the adjacent Hebei Coalfield. Wherever there is groundwater movement and gypsum together, dissolution and subsidence occur. Subsidence caused by gypsum dissolution is reported from many parts of Europe (Box 2) including the UK, Lithuania, France, Germany, Italy, Spain, Switzerland, Cyprus, Poland, Rumania, Lithuania, Turkey and Russia. Similar problems are also recorded in China, the USA and Canada; gypsum geohazards are a world-wide problem.

Gypsum dissolution makes dam construction hazardous; water leakage causes dissolution in the foundations leading to abandoned projects, costly and potentially ineffective grouting programmes, or even catastrophic failure. At least 24 dams have been affected by gypsum dissolution problems including 14 in the USA, 3 in China, and others in Switzerland, Argentina, Siberia, Venezuela, Guatemala and Peru.

Water supply is affected by gypsum dissolution problems. Abstraction from gypsum aquifers can yield excessively hard water, accelerate dissolution and cause aggravated subsidence. Where the abstracted water is of potable quality, precautions are required to prevent the pollution of gypsum and associated aquifers. This is because gypsum aquifers can transmit pollutants as fast as rivers. Poor agricultural practices can also cause severe problems in gypsiferous terranes.

In all the places where gypsum occurs there are natural or induced geohazards associated with the rock, but awareness of them is low. Throughout the world, little has been written about gypsum geohazards and scant consideration has been given to them in the planning and development process.

2. INVESTIGATION TECHNIQUES FOR GYPSUM PROBLEM AREAS

The investigation of areas with potential geological problems requires a phased approach leading from desk study through investigation to a development plan. Integration of the various datasets into a Geographic Information System (GIS) allows multiple layers of inforamtion to be overlain or merged to generate hazard maps or maps of engineering characteristics. These can be ustilised for planning and development. A suggested course of action is:

1: Desk study
2: Assessment of air photographs
3. Geological mapping
4. Building damage survey
5: Geophysical site investigation
6: Borehole investigation
7: Assessment and design

2.1. DESK STUDY

The first part of any site investigation should be the desk study. This should be designed to identify the basic geology and any geological problems, including the presence of gypsum in an area. The geological map is the logical first starting point and the initial approach is heavily dependent on what information already exists. On a regional scale this might involve a broad understanding of the basin configuration and regional geology, the presence of red beds, dolomites and salt deposits may also indicate the presence of other evaporites such as gypsum. Other indicators of potential gypsum can come from groundwater quality and the presence of sulphate-rich or saline springs. In intercontinental areas enclosed drainage basins are likely candidates for the presence of evaporites including gypsum. In coastal areas, marginal evaporitic sabkha situations can be expected to contain gypsum.

On a continental basis stratigraphical information about the occurrence of gypsum can commonly be extrapolated throughout a sedimentary basin. For example, gypsum subsidence affects much of the Zechstein sedimentary basin in Europe and similar sequences in England, Germany, Poland and Russia all suffer from the same gypsum subsidence geological hazards even though they are thousands of kilometres apart. The Messinian gypsum of the Mediterranean is similarly widespread occurring in both southern and northern Italy, southern Spain, Cyprus, Greece, Turkey and the Ukraine.

In many countries reports about mineral deposits can help to indicate the formations that contain gypsum. Similarly the presence of a gypsum extraction industry can help to identify areas which may have potential problems.

If the country maintains borehole records for the area of interest these form an invaluable source of information. As well as the presence of gypsum or anhydrite in the geological sequence, the assessment of boreholes should look to see if there is evidence for the gypsum being dissolved away at outcrop. The presence of gypsum in any geological sequence, that is the site of development, should be viewed as potentially problematical. This is especially so if the gypsifeous sequence is associated with aquifers. Many of the largest gypsum caves and most severe subsidence problems appear to occur where limestones, dolomite or sandstone aquifers feed water into gypsum deposits. Potentially difficult situations with gypsum deposits also occur in semi-arid areas, such as around Zaragoza in Spain. Here tributary valleys to the River Ebro, draining the gypsum highlands have formed gypsiferous alluvial fans deposited in the low ground. These areas appear to be more prone to subsidence and may have a concentrated underground water flow related to the drainage system that deposited them. A knowledge of situations such as these helps target the most hazardous parts of gypsiferous areas.

2.2. AIRBORNE SURVEY

One of the primary methods for gathering information about areas where some subsidence is suspected is to use airborne survey data. Stereographic air photographs, especially those taken at large scales with a low angle of lighting, are particularly useful. In places with a severe subsidence problem the subsidence hollows can form distinctive patterns. In many places they form badly drained areas and show especially well because of the different vegetation or because they are water-filled. The production of scale-true Ortho-photographs can produce a distortion-free image that can be annotated then used as a base map for the construction of a subsidence pattern map. Airborne multispectral scanning has some promise, but demands the use of high resolution scanners running at 1-2m resolution per pixel on the ground. Thermal imaging also shows some promise as a tool for locating cavities. These techniques have promise, especially with the modern advances in computer power. However, electronic imaging (either satellite or airborne) does not yet yield cheap stereographic cover at high resolutions.

2.3. GEOLOGICAL MAPPING

A record of the local subsidence history is also an invaluable tool in the investigation process of new sites. Few places have this information written down, but local farmers and local Government officers can often help to pinpoint susceptible areas. When an area suspected of subsidence is mapped by a field geologist, that person should question the local land-owners about any unusual events, such as subsidence, in the area. The field techniques of mapping subsidence-prone areas will vary, but the recording of detailed morphological information is the most useful, especially if air photographs or comparable imagery is available. The geologist should look for enclosed hollows and places where the local drainage sinks below ground. Because of the solubility of gypsum it is generally poorly exposed in northern latitudes (such as Britain and Germany). However, in countries like Spain and Italy it is seen more frequently. In order to integrate subsidence information into a geological and hydrogeological framework it is important to map all the surrounding rocks and to identify the aquifers as well as the gypsiferous sequences.

2.4. BUILDING DAMAGE SURVEY

In urban areas, mapping of building damage can complement the production of geological information. One technique used in the UK has been to classify the visible damage to buildings using the classification developed for the assessment of subsidence in coal-mining areas. Five categories of building damage have been recognised (Box 5). Once these have been mapped out it is possible to produce the subsidence damage data as a contoured map or as a layer in a GIS system. The pattern of subsidence so identified can then be compared with and integrated with the visible pattern of subsidence hollows identified by the geological survey and air photograph study.

Box 5 Building damage classification for subsidence-damage surveys

In the UK the National Coal Board devised the following system for classifying structural damage to properties. This approach has been applied to areas prone to subsidence caused by gypsum dissolution. The scale of damage ranges from 1 which is slight to 5 which approaches the point where the property needs either demolition or extensive refurbishment. Typically much subsidence manifests itself by extension, but in the sagged areas within subsidence features the structures may also suffer compressive damage. The classification (NCB, Subsidence Engineers Handbook, 1975) is based on the damage and gives an indication of the change of length of the structure. This is largely independent of the length of the structure because commonly the damage is not absorbed by the structure but concentrated in one, or a few, damage zones.

Change of length of structure	Class of damage	Description of typical damage
Up to 0.03m	**1** **Very slight or negligible**	Hairline cracks in plaster, perhaps isolated slight fracture in the building, not visible from the outside.
0.03m - 0.06m	**2** **Slight**	Several slight fractures showing inside the building. Doors and windows may stick slightly. Repairs to decoration probably necessary
0.06m - 0.12m	**3** **Appreciable**	Slight fracture showing on outside of building (or one main fracture). Doors and windows sticking: service pipes may fracture.
0.12m - 0.18m	**4** **Severe**	Service pipes disrupted. Open fractures requiring rebonding and allowing weather into the structure. Window and door frames distorted: floors sloping noticeably. Some loss of bearing in beams. If compressive damage, overlapping of roof joints and lifting of brickwork with open horizontal fractures.
More than 0.18m	**5** **Very severe**	As above, but worse, and requiring partial or complete rebuilding. Roof and floor beams loose bearing and need shoring up. Windows broken with distortion. Severe slopes on floors. If compressive damage, severe buckling and bulging of the roof and walls.

2.5. GEOPHYSICAL INVESTIGATION TECHNIQUES

If an area with gypsum and subsidence problems is to be developed it requires a comprehensive site investigation. This has traditionally been done by drilling numerous boreholes, but this approach is expensive and with out very closely-spaced boreholes it is very easy to miss areas of instability. Geophysical techniques can help to identify anomalies and allow a focused borehole programme to be undertaken. Two techniques have been successfully used, microgravity and resistivity tomography. In addition to these ground probing radar has been applied in some areas. Once the geophysical results have been processed and analysed they can be followed by a drilling programme. This programme can be more focused than "wild" drilling and planned to investigate anomalous areas and potentially good areas. The use of geophysics can considerably reduce the cost spent on drilling a site.

Microgravity

Microgravity investigations measure the minute changes in gravity caused by the underlying rocks and deposits, or the minute lack of gravitational pull caused by the presence of a cavity. The technique uses a very sensitive gravity meter. It demands careful levelling of the measurement points to allow the calculation of the gravity anomalies. The technique is completely non invasive and can work within buildings and on concrete, however, it does not like vibration. Gravity stations are arranged in a grid across the site and can typically be arranged with spacings of 2-4m. The technique is affected by the moon and tides so careful calibration and calculation of the results are required with repeat measurements and returns to a base station designated on the site. The processing is undertaken using computers.

The resolution of microgravity is dependent on the size of anomaly being imaged and the depth at which it exists. An approximate rule is that the depth at which a cavity can be detected is approximately the same as its diameter. A one metre cavity should show at one metre, but would be difficult to image at ten metres. Breccia pipes associated with subsidence commonly image very well and have large anomalies. However, there are situations that can fool microgravity. For example, if there is a vertical contact between two deposits with a strong density contrast, then even a large anomaly relating to a cavity or breccia pipe could be swamped out and not show.

Resistivity tomography

Resitivity tomography involves the use of electrode arrays placed into the ground. It works well on agricultural land, but does not work well where there is considerable cultural noise, buried pipes, concrete foundations, wire fences and overhead cables. It does not require accurate levelling and is thus quicker and cheaper to undertake that microgravity. Long cables with spaced electrodes are set out on the ground, the electrodes are driven into the ground and connected. The process of taking the resitivity readings is now computerised and the machine scans between different electrodes building up the dataset. The site can be crossed at intervals of 2-10m with electrode spacings of 5-10m. The closer the electrodes and lines of measurement the better the resolution. Once the measurements have been taken they are processed by computer to produce vertical and horizontal "slices" through the area of interest. The sides of the vertical "slices" slope inwards with depth so the area covered at depth is less that a the surface. Consequently, it is useful to be able to go about 40m outside the area of interest. The resolving power of resistivity tomography is good and it can image bedrock, cavities and breccia pipes very well. It currently has a depth range limit of about 40m.

Ground probing radar

Ground probing radar (GPR) has been used successfully along a railway line in Spain to locate the surface of the underlying gypsum and sites of potential cavities. The technique has very limited depth penetration, typically 2-5m in dry granular deposits. However, even this limited penetration is considerably curtailed by the presence of clay or water. In Spain the GPR results showed a reasonable correlation with about half of the anomalies identified by microgravity along the same route. It might detect near-surface cavities and breccia pipes.

2.6. DRILLING

Drilling is the traditional site investigation technique. On some subsidence-prone sites the ground has been drilled on a grid basis in an attempt to locate subsidence features; this is very expensive. The use of geophysical techniques, as described above, allows the anomalous and normal areas on a site to be defined. In this way potential subsidence areas can be easily targeted for drilling and avoided for construction. If sites are investigated by drilling alone, the size of the subsidence features demand closely spaced boreholes (at around 10m intervals) drilled to the base of the gypsum; commonly this can be quite deep. One potential problem with site investigation by drilling is the likelihood of penetrating a breccia pipe, or cave at shallow depth, and thereby triggering a subsidence event, either by vibration or circulation of drilling fluids. This must be borne in mind when designing site investigations and the insurance cover related to them.

Drilling can be undertaken using open hole (chippings) or rotary coring methods. The former is much cheaper, but the chippings can be difficult to identify. If open hole investigation is undertaken then a careful record of the drilling rate should be recorded either manually or using an automatic penetration rate logger. The rate of drilling gives a good indication of the amount of cavitation in the area. If cores are obtained they should be carefully examined for the presence of dissolution features and cave deposits washed in from above. In some cores the scalloped surfaces of cave walls have been identified. One problem that is very common, especially with chippings, but also with cores, is the misidentification of gypsum as limestone. In many places within the UK sites have been identified as having solid limestone beneath them, when in fact they are situated on cavernous gypsum.

The use of geophysics in boreholes can help with the identification, but near surface gypsum and anhydrite can be difficult to distinguish from limestone. Around Paris gamma ray geophysical logging has been used to identify the amount of brecciation in the gypsum sequence as a precursor to grouting programmes. Other techniques that can be used in boreholes include cross-hole seismic surveys which show promise for defining cavities. If fairly small cavities are encountered in boreholes it may be possible to image them on borehole television. If large cavities or caves are penetrated down-hole sonar could be used to define them. This technique has been used in old mine workings and dissolution mining chambers in salt.

3. DEALING WITH GYPSUM GEOHAZARDS

3.1. BUILDING CONSTRUCTION TO AVOID GYPSUM GEOHAZARDS

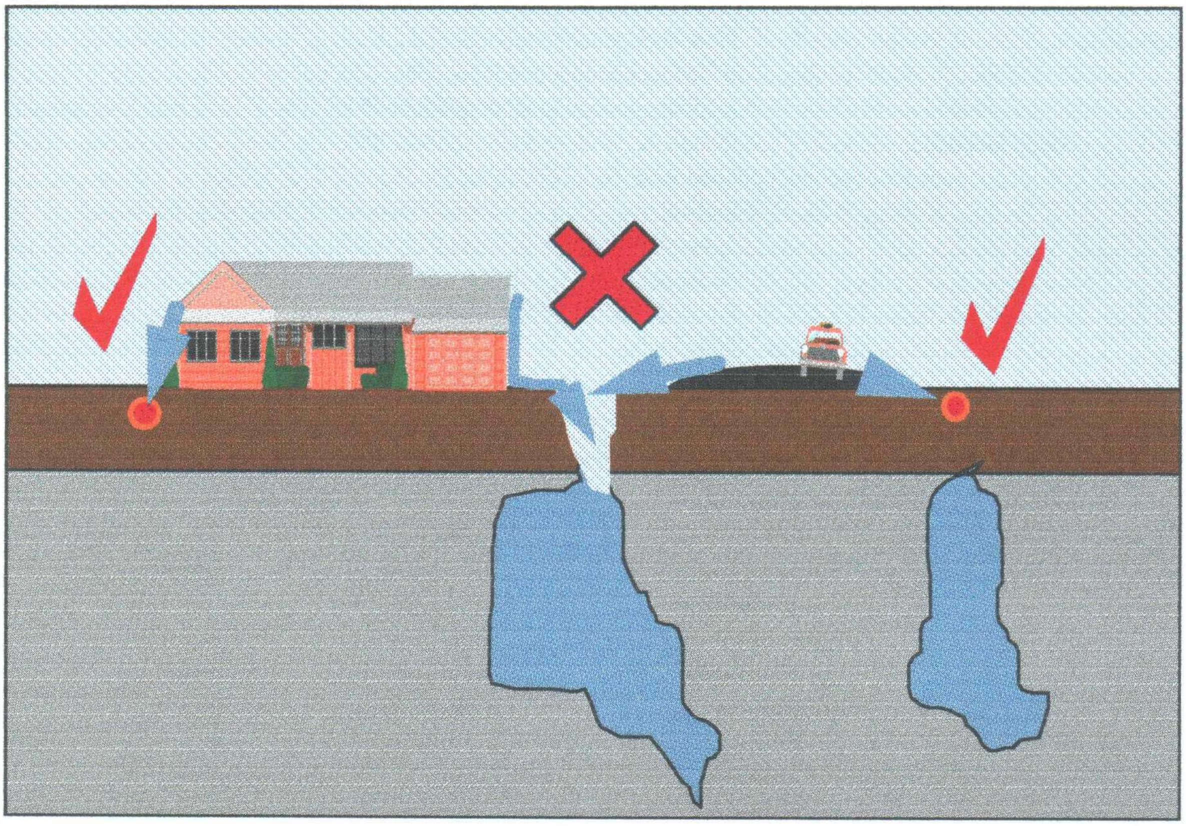
The construction of buildings within gypsum karst requires special measures. Construction options for the types of foundations suitable for use in subsidence-prone areas include raft foundations, jackable foundations, reinforced strip and special antikarst foundations (Box 5). Difficulties and hazards are present when piling into gypsum karst, or of trying to improve the ground by grouting. The cost of piling to 50m through gypsum on the outskirts of Paris was considered prohibitive, and a major multi-storey car park was designed with foundations that would span the 10m predicted size of any new collapses. In addition to these measures, microgravity surveys were carried out and the known cavities were filled; injection tubes were also placed in the foundations to allow for further filling of cavities should they appear. A similar approach to development is the use of extended foundations, or the construction of properties on linked foundations to prevent individual houses collapsing into subsidence hollows (Box 6). Further precautions, which include measures to protect services such as gas, water, electricity and sewerage, are also desirable since water leakage can cause severe subsidence (Box 7). These could include protected and flexible pipe work, flexible connections, and protection such as reinforced plastic grid geotextile materials or reinforced supports.

In Great Britain, leakage of water from power station cooling ponds has also resulted in gypsum dissolution and probable degradation of foundation rock quality, a problem highlighted during cooling tower improvements (Seedhouse and Sanders, 1993).

3.2. ROAD AND RAILWAY CONSTRUCTION TO AVOID GYPSUM GEOHAZARDS

Sudden failure of roads over natural and man-made cavities have led to collapses in which vehicles have fallen into the resultant cavity. It is largely impractical to engineer roads with design parameters of sufficient strength to span the larger subsidence features. Even if this could be done, the removal of support from beneath such structures could ultimately result in subsidence features migrating, and the structures themselves failing catastrophically in a much larger way than non-protected structures. One practical approach that was adopted for a new bypass at Ripon was to incorporate several layers of high tensile heavy duty reinforced plastic mesh geotextile material into the embankments of the road (Box 8). If a subsidence hollow develops beneath the road, the area of the subsidence will sink, but should not fail catastrophically. When subsidence occurs, its location will be obvious and some remedial measures can be undertaken. The use of geotextile materials is also a proven method of protecting car parks and public spaces.

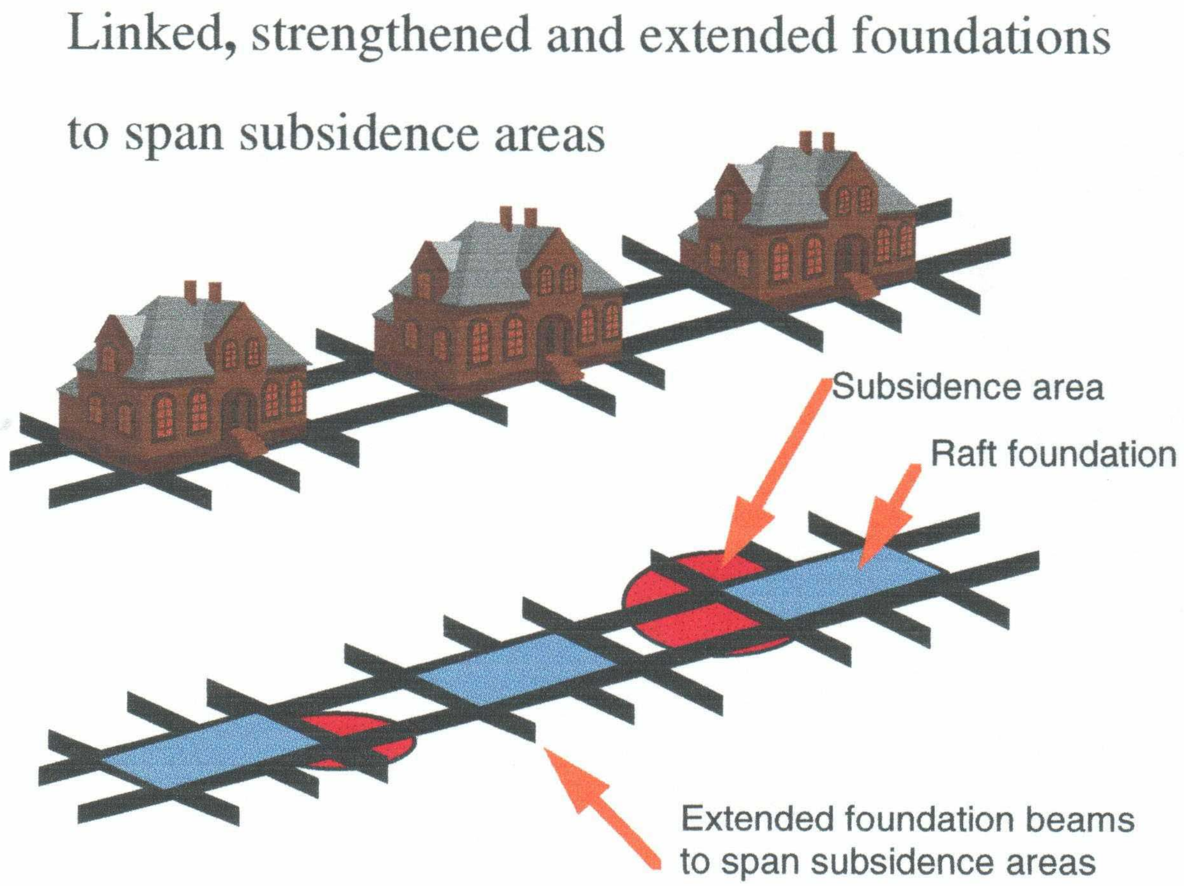
Box 7. Planning to avoid surface water seepage can prevent subsidence in gypsum and limestone karst areas



In all karst areas, both gypsum and limestone, the prevention of surface water seepage into the ground is important. Surface water from houses, other developments and roads should be piped away to established surface water drainage. If surface water is allowed to soak away it can promote the rapid subsidence of metastable deposits over cavities in the karst system. It also increases the possibility of polluting the karst aquifer. Karst collapses of the drainage ditches adjacent to roads are particularly common and commonly affect the stability of the road. These problems can be largely overcome by the installation of waterproof drainage ditches alongside the roads.

Box 6. Planning to avoid surface subsidence in new constructions.

In subsidence-prone gypsum karst areas, housing and other developments can be protected from subsidence by using reinforced and extended foundations. For small structures the sizes of the potential collapses can be similar to the sizes of the proposed developments. In this situation a possible solution is to link the foundations to form a ladder which is capable of spanning the collapses. In addition to this sort of foundation, the main services (water, electricity, drainage and gas) to the developments should be protected by running on reinforced parts of the foundation structure and by being of flexible construction. It is particularly important to prevent the leakage of water into the karst below as this can also promote subsidence (Box 7).



Linked, strengthened and extended foundations to span subsidence areas

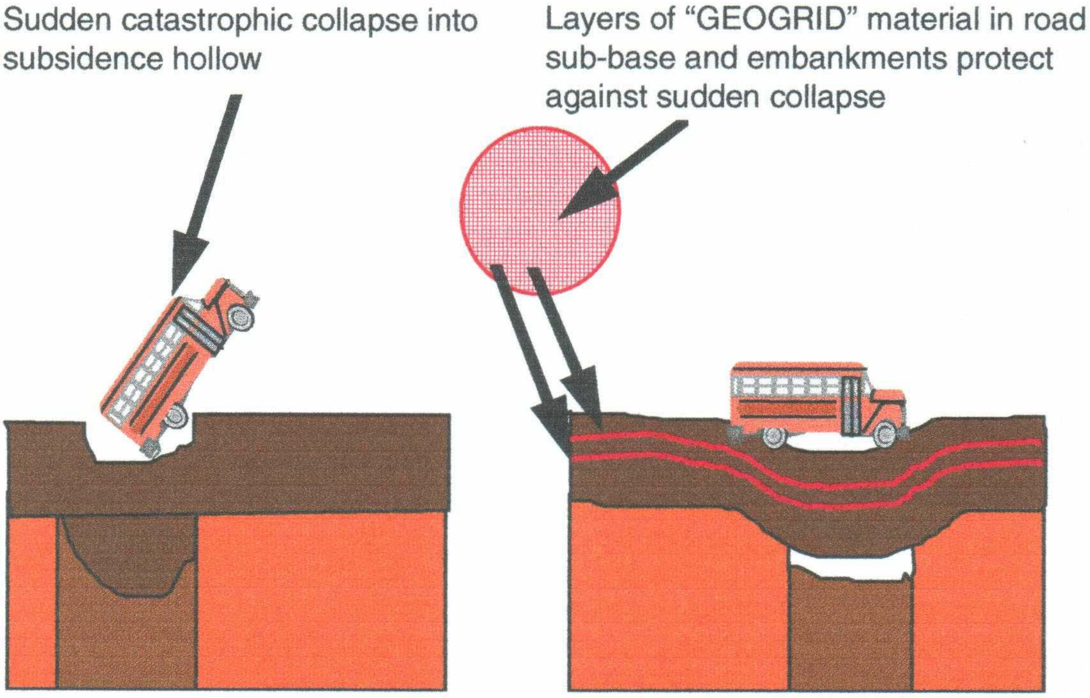
The construction of bridges and viaducts over actively dissolving gypsum karst is problematical. Viaducts around Paris have been constructed with foundations that will span the likely size of collapse, and benchmarks to monitor movement have been installed and surveyed regularly; in addition, a network of clinometers and extensometers are automatically monitored and linked to a warning system which is activated if the settlement exceed 6cm. At Ripon, the new road bridge has been built on the principle of having sacrificial supports (Box 9). The deck of the bridge has been strengthened and built as a continuous structure, so that the loss of support of any one upright will not cause the deck to collapse. A monitoring system to measure the loads on each support has been built into the bridge, and a system installed to warn of any pier failure. In addition to these measures, an added degree of security could be obtained by extending the foundations of each pier laterally to an amount which could span the normal-sized collapses.

Grouting has been suggested as a method of overcoming the problems of subsidence caused by gypsum dissolution. However, the filling of the cavities may induce groundwater level changes and accelerate the dissolution of the gypsum adjacent to the grouted area, in the same way that a collapse commonly causes dissolution in the adjacent ground and the development of subsidence hollows in groups. Furthermore, in places such as Ripon, where there is a strong artesian groundwater flow and the cavities are large, grouting becomes a very problematical technique. To ensure additional protection, a sulphate-resistant grout will be required to avoid interaction of the sulphate-rich groundwater with the cement-based grout. In contrast to the Ripon area, grouting has been used extensively around Paris for the stabilisation of the gypsum karst along the line of major roads. As a precursor to the grouting, geophysical logging of boreholes has been undertaken using γ-ray logging to estimate the degree of cavitation. The success of such grouting schemes is very dependent on the contemporary dissolutional activity and the sizes of the cavities being grouted. All these costs can add a considerable amount to any development; for example, the cost of grouting represented 12 percent of the foundation costs for a new road viaduct around Paris. However, not taking precautions can not only be costly to property and construction, but possibly also to life.

3.3. CANAL CONSTRUCTION AND GYPSUM GEOHAZARDS

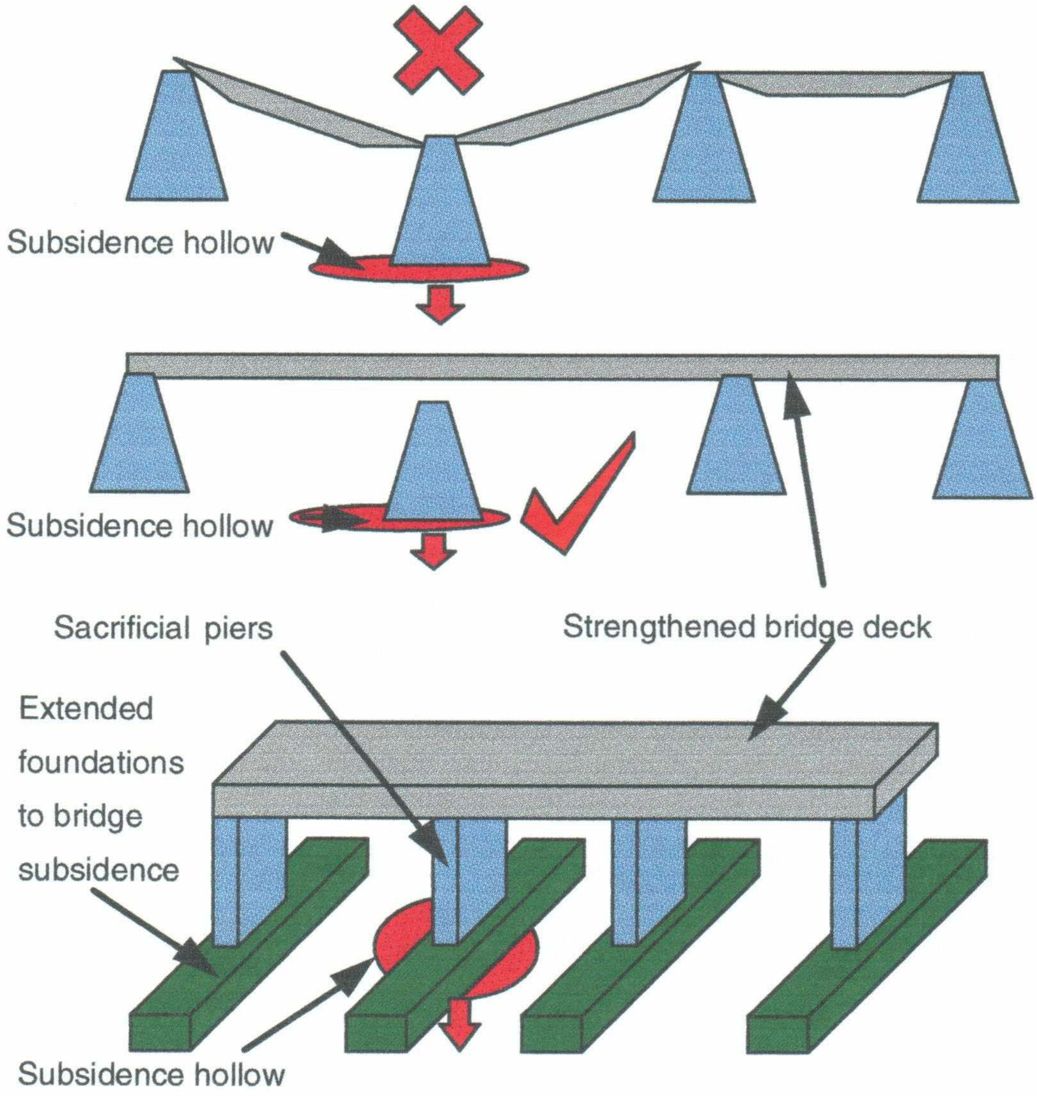
All structures that place water and gypsum together are potentially problematical. Leaking irrigation canals in the Zaragoza area of Spain have generated subsidence along their routes. Here 90 percent of the failures, resulting in the loss of irrigation and hardship to the local farming community, have been attributed to gypsum dissolution problems. In 1996, one failure of the main canal bringing water to Zaragoza cost about £40,000 to repair (F Gutiérrez, pers comm.). The additional cost to the local community caused by the interruption of their water supply was not estimated. In one place near Zaragoza the canal has been re-rooted and numerous small collapses have caused failure of the distributory system. In Syria gypsum dissolution, and the additional problem of sulphate attack on concrete canal linings, have also resulted in the failure of canal structures.

Box 8. Planning to protect roads against sudden subsidence failure.



In subsidence-prone gypsum karst areas, roads are also susceptible to collapse with potentially dangerous results. One method of protecting roads is by the incorporation of a high tensile heavy duty reinforced plastic mesh geotextile material as layers within earth embankments. Failure of the ground beneath the road then results in a less severe collapse, the position of the failure is obvious and remedial work can be undertaken. The use of a flexible material is preferable to a rigid construction which will span a cavity until the cavity is so large that a large catastrophic collapse occurs.

Box 9. The use of sacrificial piers and extended foundations in bridge construction to protect against sudden subsidence failure.



In areas prone to subsidence, structures such as bridges should be constructed to withstand possible subsidence. On method that has been used is that of construction with sacrificial piers. The bridge is designed with a very much strengthened bridge deck so that the loss of support by any one pier will not cause the collapse of the whole structure. In addition to this type of design it is possible to incorporate load monitoring and extensometer devices in the bridge piers to warn of potential loss of support. Further to these measures extended foundations may give added security to the bridge foundations. These should be designed to span the *largest* size of subsidence hollow in the area of construction.

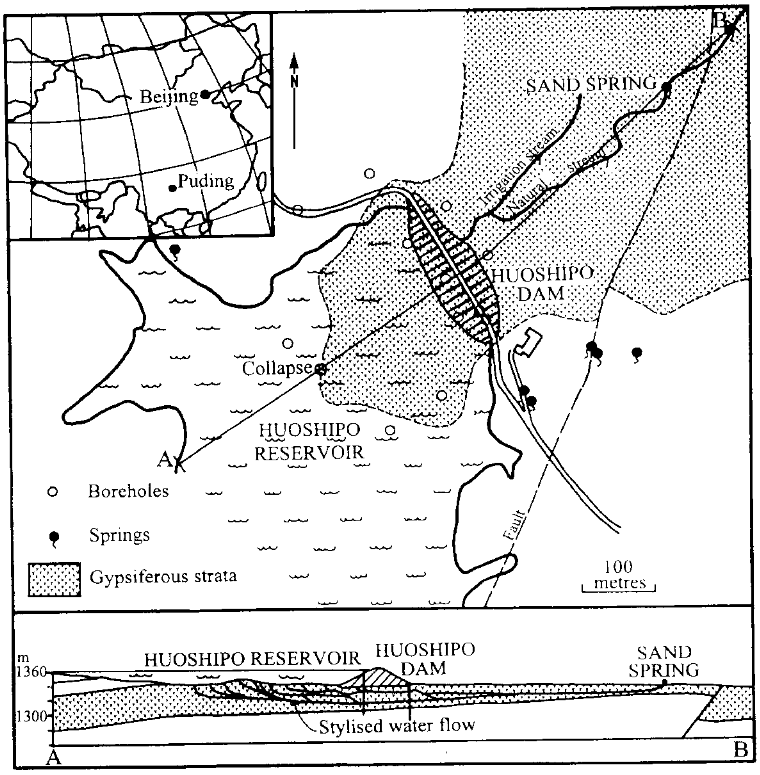
3.4. DAM CONSTRUCTION AND GYPSUM GEOHAZARDS

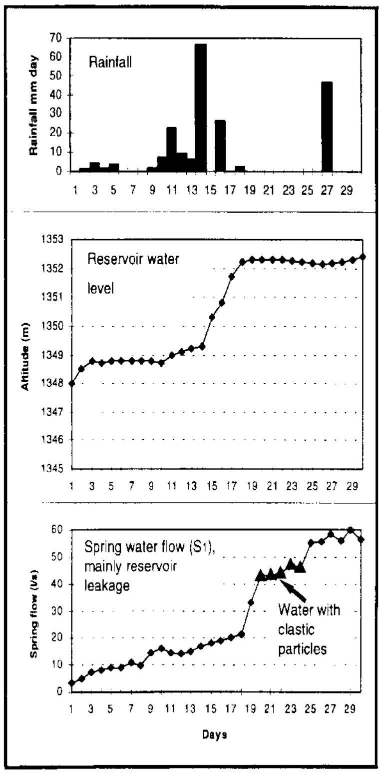
Dams are costly structures whose failure can lead to disaster and large scale mortality and a great financial liability. Foundation failure has been cited as the major cause of dam failure accounting for 40% of all incidents. The failure, in 1926, of the St Francis Dam in California was partly attributed to gypsum dissolution. More than 400 people were killed in the disaster and millions of dollars worth of damage was caused. The Quail Creek Dam, Utah, constructed in 1984 failed in 1989, the underlying cause being the dissolution of gypsum in its foundations. The associated costs of dam failure can also be very high, for example, the failure in 1976 of the Teton Dam (built on a rhyolitic tuff, not gypsum). This collapse killed 11 people, left 25,000 people homeless and generated US$ 400 million of damage claims (at 1978 prices). The cost of the French Malpasset Dam in 1959 caused an estimated £22 million of damage at (1959 prices). There are more than 30,000 dams world-wide; 1242 were being constructed in 1994 with 79 of them in excess of 100 metres high. Of the major dam-building nations, China was constructing 311, Turkey 190, Japan 140, Republic of Korea 125, India 76 and the USA 55. Other countries building significant numbers of dams were Spain 55, Romania 39, Italy 37, Tunisa 28, Algeria 24, Iran 22, Thailand 17, Greece 14, France and Brazil 12 each.

Less serious than complete failure, the construction of dams on gypsum (and limestone) karst can lead to serious leakage and inefficiency. This reduces the cost-effectiveness of the structures and in some places has caused the complete abandonment of the project. Numerous dams in the USA either have gypsum dissolution problems, or encountered gypsum problems during construction. They include the San Fernando, Dry Canyon, Buena Vista and Castaic dams in California; the Hondo, Macmillan and Avalon dams in New Mexico; Sandford Dam, Texas; Red Rock Dam, Iowa; Fontanelle Dam, Oklahoma; Moses Saunders Tower Dam, New York State and the Olive Hills Dam.

Other dams elsewhere in the world have caused concern because of gypsum dissolution. These include the El Isiro Dam, Venezuela and the Alloz dam in the Spanish South Pyrenees. Gypsum dissolution problems have affected the pressure tunnel of the Peuble de Pava Dam, Guatemala and the foundations of other dams here. In China, leaking dams and reservoirs on gypsum include the Huoshipo Dam (Box 10) and others in the same area; the Bratsk Dam in eastern Siberia is leaking and in Tajikistan the dam for the Nizhne-Kafirnigansk hydroelectric scheme has active gypsum dissolution occurring below the grout curtain. Gypsum karst in the foundation trenches of the Casa de Piedra Dam, Argentina, caused difficult construction conditions and required design modifications. Gypsum in the foundations of the wier, locks and powerhouse of the Hessigheim Dam on the River Neckar in Germany has dissolved and caused settlement problems. Sinkholes have also occurred near the dam, one hole being 8m in diameter. During the remedial site investigation cavities up to several metres in height were encountered in the boreholes. The underlying rock has now been grouted in an eight-year scheme (1986 to 1994) involving the use of about 10,600 t of cement. Further work still needs to be completed and the expected life of the remedial measures is 30-40 years. 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 side shows doline activity over gypsum and lowering of the adjacent land. The costs associated with remedial grouting measures to prevent severe dam leakage can be very high. The cost of grouting a site can approach 15 or 20% of the cost of a dam; on some recent projects it has reached US$ 100 million. In karstified limestones grouting is difficult, in gypsum it is very difficult and prone to failure, or expensive repeated grout programmes.

Box 10. Gypsum geohazards associated with dam construction near Puding, Guizhou Province, China





The Huoshipo dam and reservoir were constructed, without any site investigation, on gypsum and limestone. Soon after the reservoir was filled, the flow of water from "Sand Spring" increased followed by a collapse of the reservoir floor. When this happened the clastic material was washed out of the spring and the reservoir lost considerable amounts of water. The reservoir is still leaking, and the water emerging from the spring has considerably more gypsum in solution than that in the reservoir. The gypsum is being actively dissolved by the leakage and could ultimately cause further collapses or possibly threaten the stability of the dam. Geological hazard maps incorporating information about gypsum geohazards would warn about the problems of developing dams in such areas.

The most serious problem with dams on gypsiferous rock is leakage through gypsum beneath the dam site. Such leakage might destabilise the structure and result in its failure. Not as catastrophic, but almost as serious is the total leakage of a dam so that it is completely ineffective. Large-scale leakage through conduits in gypsum karst is recorded at many sites. Also of great importance, is slow leakage of water through the gypsum. Because of the great solubility of gypsum, a slow initial flow can quickly become a flood. Any amount of water flow is critical where there is gypsum or anhydrite in the foundations of a dam.

Because remedial measures are difficult, the early avoidance of gypsiferous strata for dam and reservoir sites is likely to be the most cost-effective approach to the geohazard.

3.5. WATER ABSTRACTION AND GYPSUM GEOHAZARDS

The abstraction of water from gypsiferous sequences has a two-fold effect that can cause subsidence - enhanced dissolution and water table draw-down.

Because of its high solubility, gypsum in close proximity to water abstraction boreholes can be locally dissolved; this has happened in Ripon, England. Subsidence problems have been associated with a site that once extracted large volumes of water. It was calculated that annually the volume of gypsum being removed by one food processing factory was about 200 cubic metres. The factory itself suffered severe subsidence problems suggesting probable dissolution in the immediate vicinity, but subsidence also occurred for a considerable distance around the factory.

The other effect that water abstraction has (both in gypsum and limestone karst) is to lower the groundwater table level. This has the effect of removing some of the buoyancy induced by the groundwater. If there are metastable cavities, such as those over gypsum subsidence pipes, the removal of the hydraulic support makes the capping material effectively more dense sometimes causing it to collapse. Another factor of groundwater abstraction is the washing out of fine material and passage of it downwards into the cavernous rock below. Many site investigation boreholes in gypsiferous rocks encounter cave fill deposits washed in from above and this mechanism has been suggested as the control in the widespread, but slight subsidence that affects Darlington in Northern England.

In Pasvalys, Lithuania, the most recent major collapse of the gypsum karst early, in 1997, occurred close to the local water boreholes and treatment plant; it is probable that these are connected. As more pressure is placed on the use of underground water for supply the water table may be expected to continue its decline with the risk of further subsidence. In situations such as these consideration could be given to trying to find an alternative supply or spreading the abstraction over a larger area to try to limit the amount of water table drawdown.

The presence of pollutants in the groundwater may also enhance the rate at which the gypsum can dissolve. It has been shown that some fertilisers can result in faster gypsum dissolution.

4. PLANNING FOR GYPSUM GEOHAZARDS

4.1. NATIONAL PLANNING TO AVOID GYPSUM GEOHAZARDS

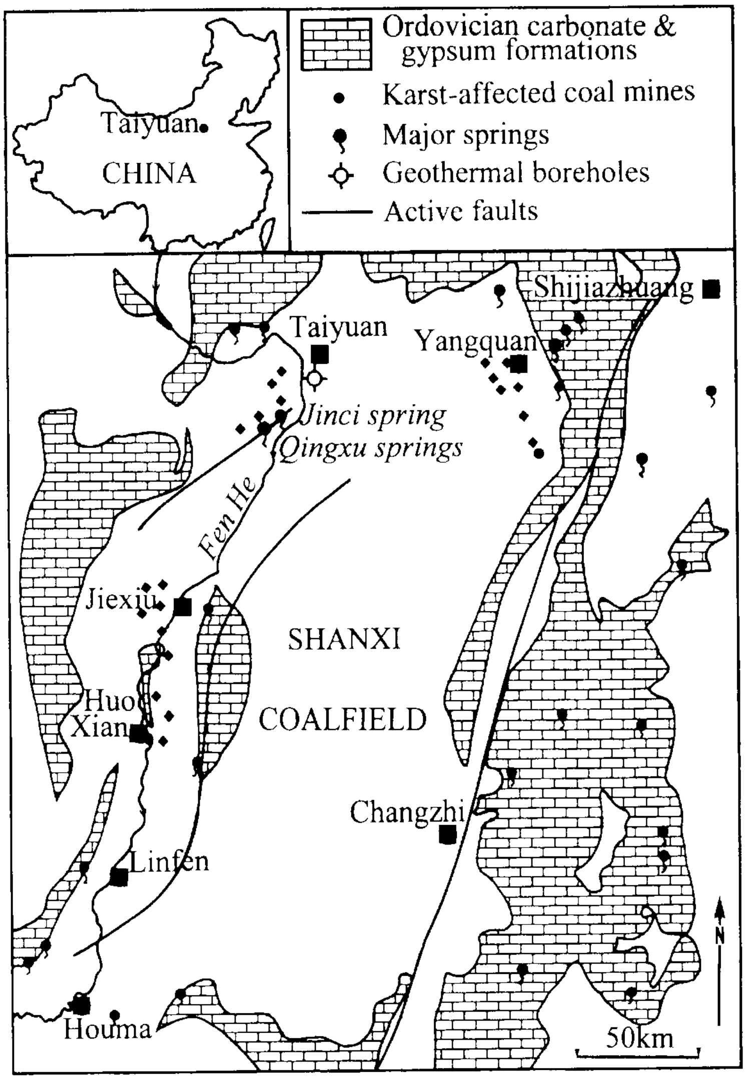
Strategic or national planning to avoid gypsum geohazards requires a recognition by geologists and engineering geologists that these geohazards constitute a problem that it is necessary and cost-effective to avoid. This paper goes some way to highlighting the problem and will hopefully be acted upon. Once the problem is appreciated, the best way forward for national planning is by the compilation of maps showing the distribution of gypsum and gypsiferous sequences. Commonly, these have already been compiled at a large scale for the assessment of mineral resources, or the interpretation of karst geology, thus very basic maps exist for countries like Great Britain and China (Boxes 3 and 11). A logical step forward from this initial mapping is the incorporation of gypsum data in general geological hazard maps or engineering geology maps. Depending on the scale of presentation, such maps could also indicate the susceptibility of the gypsum sequences to dissolution, a function largely controlled by the local hydrogeology, the thickness of the gypsum and the presence or absence of aquifers associated with the gypsum. The use of maps such as these may allow the worst areas to be avoided, or at least considered in more detail. Detailed maps showing the presence of gypsum for planning railway construction have been used in Turkey.

Items of national planning that can benefit most from taking gypsum problems into account include dams and reservoirs, any major construction such as roads, railways and canals, and the location of new towns. A framework for the assessment of the cost-benefit analysis of producing gypsum geohazard avoidance information in geological hazard mapping is presented in Section 5.

4.2. LOCAL PLANNING FOR THE AVOIDANCE OF GYPSUM GEOHAZARDS

Local planning for gypsum subsidence can be of great benefit to the local population and avoid costly and potentially harmful development. However, the seriousness with which the situation is approached is also dependent on the local will to comply, the pressure on land use and the finances available for developing alternative sites or for constructing in problematical ones. There is a local balance between the risk that the population will tolerate and the amount both the public authorities and developers can afford to pay to avoid the problems. Thus solutions suitable for Great Britain may be completely unsuitable for other countries. The one approach that is usually universally cost effective is the avoidance of the hazard by careful local planning.

Box 11. Gypsum geohazards peripheral to the Shanxi Coalfield, China.



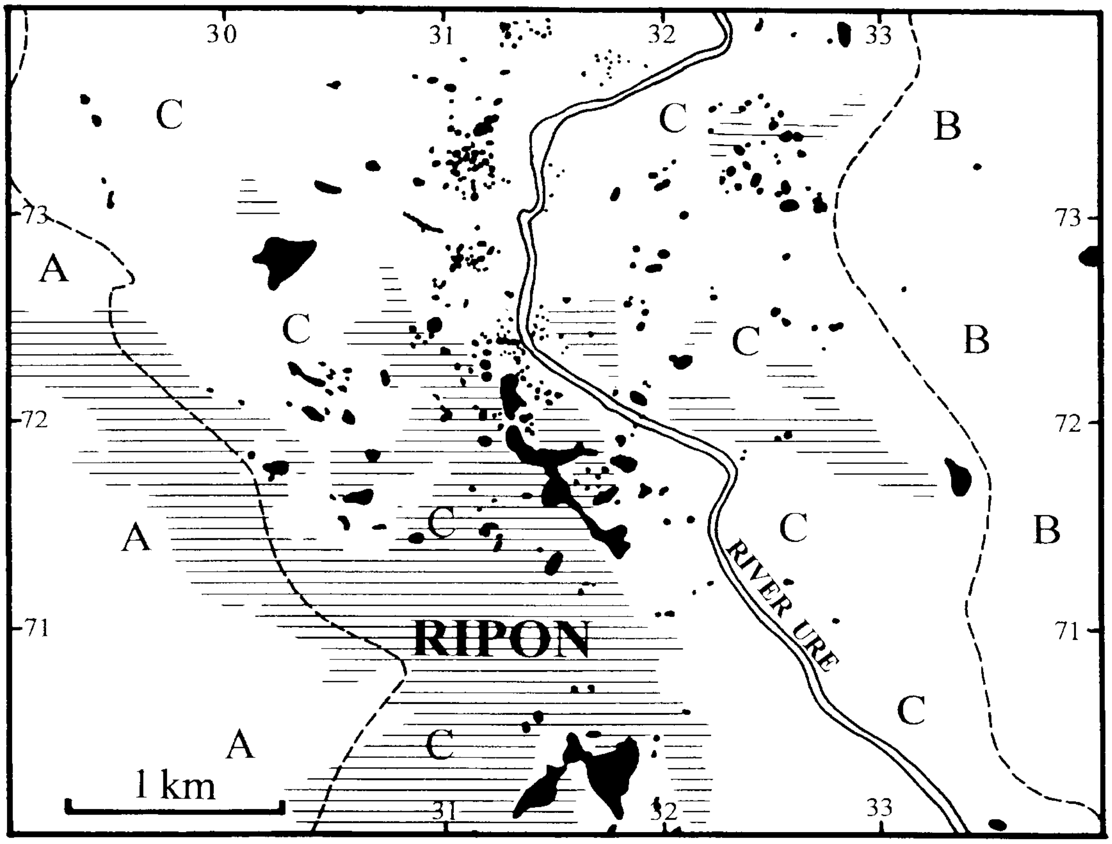
In the Shanxi Coalfield, gypsum karst underlies the coal-bearing sequences and many coal mines are affected by collapse columns that emanate from the underlying gypsum. These collapse columns lead to difficult mining conditions and act as potentially dangerous pathways allowing water to enter the mine workings. The karstic coal mines are located towards the margins of the coalfield and it is in these areas that surface subsidence associated with this gypsum karst can also occur. The presence of sulphate-rich springs and boreholes may aggravate the amount of gypsum dissolution and result in subsidence. The Shanxi Coalfield is an example of an area that would benefit from the production of a geohazard map incorporating information about gypsum karst.

Where there are long-established communities on gypsum subsidence-prone terrane the most practical approach is to try to limit the impact of the hazard. Failure to do this can result in developed areas becoming blighted with falling property prices and an unwillingness to invest in those areas. In England, Thomson and others (1996) reviewed the problems of gypsum dissolution subsidence and how it affects the town of Ripon. They approached the matter on two fronts, construction and planning. From their work, the local authorities now have guidance for development whereby the main thrust of avoiding the problem is through the planning regulatory process. They divided the Ripon area into three development control zones: A, B and C (Box 12). Within Zone A there is no gypsum and no special planning constraints would be imposed. In Zone B, where the risk of subsidence is small, a ground stability report prepared by a competent person would usually be required and the problem should be considered in local planning. The Zone C area, with gypsum subsidence problems, would be potentially subject to significant constraints on development, and local planning should take these into account. Also within this zone, development is subject to controls. A ground stability report prepared by a competent professional person would normally be required before planning applications for new buildings, or change of use of buildings, are determined. In most cases this report would need to be based on a geotechnical desk study and a site appraisal, followed by a programme of ground investigation designed to provide information needed for detailed foundation design (unless this information, such as from boreholes, exists from a previous study). Where planning consent is given, it may be conditional on the implementation of approved foundation or other mitigation measures, designed to minimise the impact of any future subsidence activity.

One key to the implementation of this approach is the use of a proforma checklist to be completed and signed by a competent professional person. For Great Britain, a competent person is defined in the report as a Geotechnical Specialist who is "A Chartered Engineer or Chartered Geologist, with a postgraduate qualification in geotechnical engineering or engineering geology, equivalent at least to an MSc, and with three years of post-Charter practice in geotechnics; or a Chartered Engineer or Chartered Geologist with five years of post-Charter practice in geotechnics". In addition to these qualifications, it is also desirable that the practitioner has experience of the problems though this is not formally stated. This procedure has been adopted by the local council, but is likely to be subject to minor changes with experience of its use.

On a local basis it would be possible to refine further the planning process by the use of detailed subsidence and engineering geology/geohazard maps. This would enable the avoidance of subsidence hollows and actively subsiding areas as part of the planning process, rather than as part of the investigation and regulatory process. However, this approach may put more responsibility on the local authority, whereas the regulatory process puts the responsibility on the developer to show that the site is suitable.

Box 12. Local planning for gypsum geohazards at Ripon, North Yorkshire, UK.



A,B,C denote the Ripon development zones with their margins shown as pecked lines. Subsidence hollows are coloured black. Existing urban areas are shown with a horizontal ornament.

Like many towns built on gypsum, Ripon suffers from natural catastrophic subsidence caused by gypsum dissolution. The subsidence is ongoing and causes difficulty with planning. The areas of the individual subsidence hollows are of very high risk of further subsidence. The areas between and adjacent to individual hollows are of high risk of subsidence. The Ripon district has been zoned for planning purposes. The area of Zone A is outside of the subsidence belt and no gypsum is known to be present. Zone B has gypsum present at depth, but is largely outside of the subsidence area. Zone C has gypsum susceptible to dissolution present. Zone C is subject to stringent planning controls to enable development to proceed. These include the requirement that a detailed geotechnical report prepared by an officially recognised "competent person" is produced. Only when it can be shown that the risk of subsidence has been considered, and that the site investigation and structural design have taken this into account, will the development get planning permission and be allowed to proceed.

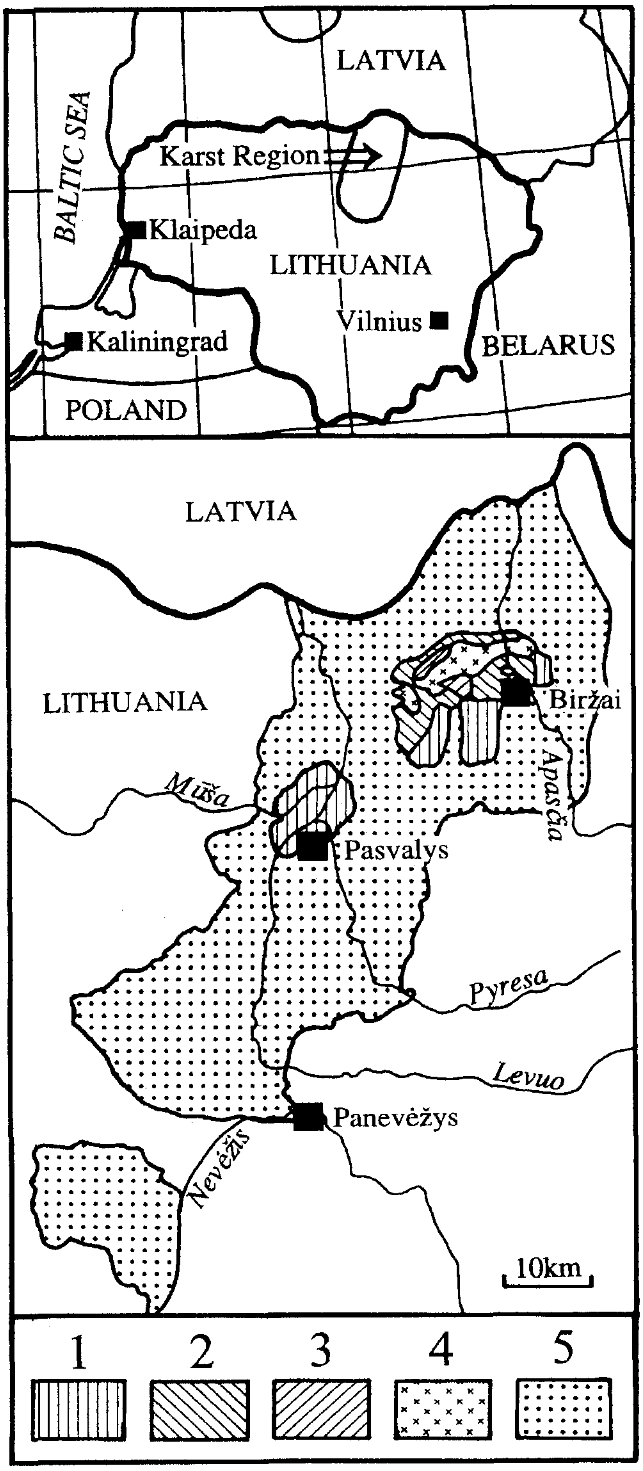
4.3. LOCAL PLANNING FOR THE PROTECTION OF GROUNDWATER

In Lithuania, groundwater in the gypsum karst areas is such a valuable resource that it is protected from pollution. The measures introduced here form a workable model for planning to avoid pollution in other gypsum karst areas. Firstly, the susceptibility of the gypsum karst to pollution was analysed by looking at 19 geological, hydrogeological and hydrological variables, then each area was given a susceptibility grading. The grade marking allowed the land to be divided into classes with varying susceptibilities to pollution and requirements for protection. The most important controlling factor was found to be the concentration of sinkholes or subsidence hollows which allow rapid runoff into the gypsum karst. As a consequence of this work, the land has been divided into areas for protection by agricultural regulation (Paukštys, 1996). By government decree, 27,600 hectares (276 sq km) of intensive karst are delineated with strict agricultural limitations, and 166,000 hectares (1,660 sq km) are defined as a karst protection zone. Four divisions of agricultural land use have been defined based mainly on the number of sinkholes per square kilometre. The categories and restrictions imposed are shown in Box 13.

In addition to these measures, it is illegal to apply ammoniacal solutions to the soils of all four categories. It is also prohibited to use aircraft for spraying chemicals and mineral fertilisers. For the area around each sinkhole, in all four agricultural categories, the law is that there must be a 25m zone of exclusion to agriculture, and around some an earth barrier to prevent runoff entering the hole. Ecologically sound agricultural plans have been designed for each land group, and organic agriculture is being introduced to the region. Thus, the protection of karst water from pollution and the reduction of human impacts on vulnerable karst groundwater is official Lithuanian Government policy. The protection of the gypsum karst and its groundwater is monitored by the Government-funded Tatula Board, named after the local karst River Tatula. In addition, the Board supports training courses, gives loans to encourage environmentally-friendly (organic) agriculture and provides assistance with antipollution measures including the installation of effluent treatment plants.

In contrast to the protection of the karst water in Lithuania, some unsuitable practices have been noted in England. These include the piping of surface water run off from roads into sinkholes to drain it away (Box 7). In addition, during the 1970s, some large sinkholes in the Ripon area were filled with domestic refuse. Any leachate from this will have drained directly into the gypsum karst water system and may threaten local springs and wells supplying farms.

Box 13. Planning for groundwater protection in the gypsum karst area of Lithuania.



To protect the gypsum karst groundwater in Lithuania a classification based on the number of sinkholes per square kilometre (100 ha) has been introduced. Within the karst area the categories and restrictions imposed by law are:

1. Land Group 1 (up to 20 sinkholes/100 ha). Grain crops should compose at least 50% of arable lands, perennial grass 40% and root crops (potatoes and sugar beet) not more than 10%. Fertilizers are limited to a maximum of 90 kg/ha of nitrogen/phosphorus/potassium (NPPt active ingredients) and 80 t/ha of manure. Triazinic herbicides and Chloroganic insecticides are prohibited..

2. Land Group 2 (20-50 sinkholes/100 ha). Grain crops should compose 43% or arable lands and perennial grass 57%. Root crops (potatoes and sugar beet) are prohibited as is the setting up of new orchards and gardens. Fertilizers are limited to a maximum of 60 kg/ha of NPPt and 60 t/ha of manure.

3. Land Group 3 (50 - 80 sinkholes/100 ha). Perennial grass and pastures only are allowed. Fertilizers are limited to a maximum of 60kg/ha NPK. Mineral nitrogen fertilisers are prohibited as are pesticides (except for fungicides).

4. Land Group 4 (80 - 100 sinkholes/100 ha). Only grass meadows and forests are allowed. All fertilizers and pesticides are prohibited. 5. General karst protection area.

Reference: Paukštys, 1996.

4.4. LOCAL PLANNING TO AVOID SUBSIDENCE CAUSED BY GROUNDWATER ABSTRACTION

In many countries including Great Britain and Lithuania the abstraction of groundwater from the gypsiferous sequences, and those in hydrological continuity with them, has caused drawdown of the water table and local subsidence. The risk of subsidence can be reduced by the careful exploitation of the local water resources and the avoidance of this excessive drawdown, but in some areas this has an additional cost in the provision of an alternative supply. Similarly, the avoidance of water table drawdown associated with mining can be of benefit to the community, but the cost may be the lack of economic and social benefit related to the non-development of a valuable resource.

4.5. SITE SPECIFIC PLANNING FOR THE AVOIDANCE OF GYPSUM GEOHAZARDS

The development of individual sites on gypsum karst areas will be very variable dependent on the local geological conditions. However, some of the experience from places such as Ripon in Great Britain may be of use elsewhere. The first procedure adopted at Ripon is a desk study to compile all the previously known information about the site and the subsidence problem. The published 1:10,000 scale geological map shows the distribution of the subsidence hollows, most of which must be regarded as potentially very unstable. In many instances, subsidence has occurred on several occasions in the same subsidence hollow. In addition to the hollows, the areas between them, or in line with other hollows, is also potentially at risk. This is because once a collapse has occurred, the cavity becomes choked and the dissolution can then continue in the immediately adjacent ground; in this way areas of amalgamated subsidence hollows can develop. The dates of collapse of the surrounding subsidence hollows and a knowledge of the local groundwater flow can also indicate the areas that are best avoided. Some areas will be deemed to be unsuitable for development; this is one of the costs of safe development.

The desk study should also report on the preferred scheme for site investigation, and the parameters that need to be addressed. In many places including Ripon, Paris and Northern Spain, geophysics, including microgravity and resistivity tomography, have proved worthwhile tools for finding the most subsidence-affected parts of a site and for delineating hidden subsidence features such as cavities or filled breccia pipes with no surface expression. The geophysics survey can then be followed by a limited amount of drilling. In Ripon, Thomson and others (1996) recommended the use of cored boreholes, but as these are prohibitively expensive for most sites. Cost effective investigation can be made using chippings samples, but these must be examined by a competent geologist. One of the major problems in the gypsum karst areas is the misidentification of gypsum as limestone (even in cores), and the resulting reports may imply that in the absence of gypsum there will be no problems on the site. Once the nature of any underlying subsidence features have been defined, foundations appropriate to the planned construction can be designed.

5. THE ECONOMICS OF GYPSUM GEOHAZARD AVOIDANCE

5.1 BACKGROUND

The presentation of information about gypsum geohazards, for example through hazard and planning maps, can improve land use planning. Better informed decision-making can limit or prevent hazard costs, especially where large capital investment projects such as dams are concerned.

While such a conclusion is reasonable, few studies have tested the hypothesis in cost-benefit terms. There are good reasons for this: firstly, there are methodological difficulties associated with cost-benefit analyses of hazard avoidance; secondly, few scientists have had to justify their work in economic terms. This situation is changing with the need to justify expenditure and demonstrate its benefits to society.

Here we show how some of the principles of cost-benefit analysis can be applied to the avoidance of gypsum geohazards. Firstly, we present the general nature and distribution of costs and benefits, and how they might be valued. This is followed by an overview of some of the basic principles of cost-benefit analysis and how they might be applied in the present context. The discussion is illustrated with reference to cost-benefit case studies, and some generic issues and procedures are identified.

5.2 COSTS AND BENEFITS OF GEOHAZARD AVOIDANCE

The benefits of accounting for gypsum geohazards in planning decisions can be defined in terms of economic costs avoided when the hazard is minimised, or avoided. This is because new, or more detailed information on the geological hazard, can provide a better database for planning decisions. Vulnerable areas can then be avoided, or engineering modifications made to structures to prevent damage occurring within them. This approach to benefit estimation, identifying benefits as costs avoided, is widely used in hazard planning. It has also been used to estimate the societal value of regional geological mapping programmes (eg ISGS, 1991; USGS, 1993).

Cost sources

Here, a simple distinction is made between personal costs, direct costs and indirect costs. The broad range of costs associated with gypsum subsidence damage are detailed in Box 14. These are costs which might potentially be avoided, or reduced, with improved geological information and land use planning. The costs of gypsum subsidence damage will vary with the severity of the event and its location in relation to people and infrastructure. Some of these costs will be more easily valued than others, they fall into three main categories: personal costs, direct and indirect costs.

Box 14. Personal, direct and indirect costs of gypsum subsidence.

When comparing costs a distinction has been made between different cost types. Personal (health) costs, which include items such as stress, injury and loss of life, might be caused by a catastrophic subsidence events, such as a building collapse. Direct costs are those associated with damage repair/replacement (eg repair to buildings, or their replacement) and other responses to the event itself, such as evacuation and cordoning off the area. Indirect, or secondary costs, may be incurred by third parties such as road users, inconvenienced by repair work, or farmers who find their fields flooded following damage to a canal. Indirect costs may also arise some time after the event, in terms of rising insurance premiums, and possible legal actions and public enquiries.

Adapted from NAO (1992)

Damage costs	Cost sources	Potential cost distribution
Personal costs	• Fatal accidents • Injuries • Psychiatric problems caused by stress	⇒ Private individuals; health services
Direct costs	• Mobilisation of relief workers and emergency services	⇒Public bodies (eg local authorities)
	• Evacuation and provision of temporary or replacement housing and other buildings	⇒As above
	• Loss of land and property	⇒Private individuals and firms; public bodies
	• Construction delays	⇒Private firms, public bodies
	• Costs of investigation to determine appropriate response	⇒ As above
	• Cost of repair to damaged buildings and structures	⇒Private individuals and firms; public bodies
Indirect costs	• Loss of agricultural or industrial production	⇒Private individuals and firms; public bodies
	• Transport delays and inconvenience	⇒Transport uses - public and private firms; public bodies
	• Increased insurance premiums or withdrawal of cover	⇒Private individuals and firms; public bodies
	• Depreciated property or land values	⇒As above
	• Costs of legal actions	⇒As above
	• Costs of public enquiries into causes and responsibilities	⇒Public bodies

The personal costs identified in Box14 are difficult to quantify. What value, if any, should be placed on someone's death, serious injury, or stress, following collapse of a building or dam? Although there are no market prices for these effects, attempts have been made to place monetary values on them, particularly in relation to injury which can be viewed in terms of loss of an individual's earnings and the resource cost of medical treatment. In the UK, for example, the Department of Transport have estimated average injury costs resulting from road accidents at around £46,000 per person (Department of Transport, 1996).

More often, gypsum subsidence costs will arise as the direct and indirect costs identified in Box 14. The direct costs of infrastructure damage are most readily quantified, as most are registered in market prices. For example, where a building is destroyed or damaged, repair and replacement costs can be estimated, respectively. These estimates are likely to provide a minimum impact estimate, as subsidence events may incur many other indirect, or 'knock-on', costs. In the UK, for example, a recent gypsum-related subsidence event outside a house led to the loss of the building, investigation costs, enactment of a council disaster plan, and other direct costs. However indirect costs, which are still increasing, include a court case, and the possibility of higher insurance premiums and deflated property values in the surrounding area. In this instance, total costs may reach over £200,000 of which only about £90,000 actually relates to the value of the property. Similarly in Zaragoza, Spain, damage to irrigation canals has incurred direct repair costs *and* imposed secondary costs on farmers left with reduced water supplies (see Section 2.3). The larger the development the larger the liability. Damage to a dam, or worse still its collapse, may endanger life and incur millions of dollars worth of direct and indirect costs (see Section 2.4 and Box 10).

Although subsidence damage can be very costly, it does not necessarily mean that all measures to reduce or eliminate risk are economically justified. A critical issue is risk, and the probability of subsidence occurring at a specific site within a project's lifespan. Clearly a balance needs to be struck between the risk and potential impact of collapse, and the cost of risk avoidance. This evaluation is not always easy: risk analysis is data intensive, and historical records on the incidence and severity of subsidence events may not be available. In addition, it may be difficult to quantify all costs, and identify clear links between cause and effect, particularly for indirect costs. In many cases, this uncertainty is sufficient cause for a precautionary approach to decision-making, in which hazards are avoided if possible, or engineered for if necessary, especially where safety is a concern. The treatment of risk and uncertainty in cost-benefit analysis is considered in more detail below.

Hazard mitigation

Before we can determine whether gypsum hazard planning is economically justified, we must first consider the costs of hazard mitigation. The types of hazard mitigation costs are listed in Box 15. Here, a distinction is made between hazard assessment and hazard prevention costs. The former includes data collection, dissemination and planning costs, such as those associated with hazard mapping programmes and the formulation of planning guidelines. The latter includes the costs of engineering measures to limit or prevent infrastructural damage in vulnerable areas. The two are linked; before measures can be taken to reduce or eliminate subsidence damage,information and guidance are needed on the nature and severity of the hazard. Also included are potential land value losses. This is because geohazard mapping may identify new or additional 'at risk' zones which may reduce the value of land and property. Thus, one potential avoidance cost in urban areas is land blight, which may be reflected in the difference in land values between land with and without the benefit planning permission. However, the counterbalance to this is that where land use planning becomes highly regulated with a very precautionary stance to risk, hazard mapping may actually reduce planning blight by reducing uncertainty in new developments. In this situation land values could rise.

Box 15. Hazard mitigation costs.

Hazard assessment includes the costs of data collection dissemination and planning costs. The hazard prevention costs include the costs of the engineering solutions, additonal land where unstable land is unsuitable for development and the costs of monitoring potentially unstable areas or structures.

Adapted from NAO (1992)

Hazard mitigation costs	Cost sources	Cost distribution
Hazard assessment	• Research into nature and extent of gypsum hazard problems	⇒Public bodies
	• Formulation of planning policies related to development on unstable land	⇒Public bodies
	• Public consultation	⇒Public bodies
	• Dissemination of planning guidance	⇒Public bodies
Hazard prevention	• Site Investigation	⇒Private individuals and firms; public bodies
	• Design and construction of preventative measures, including reinforced and extended foundation structures	⇒Private individuals and firms; public bodies
	• Costs of monitoring potentially unstable ground conditions	⇒Public bodies
	• Cost of possible 'planning blight' in areas identified as being particularly vulnerable	⇒Private individuals and firms; public bodies

The costs of geohazard mapping that underlies basic hazard avoidance are typically borne by central or local government, perhaps through a geological survey organisation. Such studies may include field mapping (either primary or revision), desk studies and compilation (Box 16).

Box 16. Hazard mitigation costs incurred at Ripon, UK.

The town of Ripon, North Yorkshire, UK, suffers from subsidence caused by gypsum dissolution (Box 12). A recent study of gypsum subsidence here illustrates how hazard avoidance costs may be incurred. The study included:

- Data collection in the field (including subsidence information, geological and hydrogeological data)
- Archive data collection and interpretation
- Data presentation, including digitising maps and database development
- Formulation of planning guidance
- Printing and publication
- Distribution and dissemination of information
- Regulation of the planning process

A geological resurvey of the town was undertaken at a scale of 1:10,000 and included approximately 25 square kilometres of the area. It was based heavily on modern geological mapping reinterpreted with newly gathered commercial borehole information and supplemented with some additional boreholes. The basic geological study cost around £14,500 at 1995 prices. The boreholes, hazard assessment and planning guidance study for the area, which was designed to assess risk and formulate draft planning guidelines (Thompson et al., 1996), cost about an additional £230,000.

As a result of this study, detailed site investigation procedures have been recommended and some preventative foundation measures suggested for the identified subsidence-prone areas. Site investigation costs will clearly vary with the site area and level of detail required. As a general rule, however, costs are normally around 1-3% of construction costs.

The extra costs of reinforced and/or extended foundations are generally around 2-5% of constructions costs, though costs will vary with the size of the structure, its intended use, and perceived risk.

The most obvious way of dealing with a gypsum hazard is to simply relocate the proposed project. Alternatively, structures may be strengthened to reduce or eliminate subsidence risk within the hazardous area (Boxes 6, 8 and 9). This latter course of action may be attractive where (a) cost-benefit analysis indicates that engineering measures can be cost-effectively employed, perhaps in less vulnerable areas; and (b) where there are few alternative project sites, and relocation would have a detrimental impact on the deselected site (eg where large land areas are involved and land is scarce or where the line of a road cannot be changed). It is likely that additonal site investigation costs and additional foundation costs could add about 8% to the cost of development, more in some places.

In any cost-benefit analysis, it is important to consider the distribution as well as the magnitude of costs and benefits. In Boxes 14 and 15, an attempt has been made to show how costs may fall on different parties, both public and private. For example, damage to a building may incur repair costs which a private insurance company meets. However, the home owner may also experience considerable, and uncompensated, inconvenience costs. Some costs (eg fencing off the area) may also fall on a local authority. In an alternative mitigation scenario, the nature and distribution of costs might be quite different. For example, a public body might fund a hazard assessment study which identifies vulnerable areas. A planning authority might then decide that no houses should be built within these zones. Alternatively, detailed site investigations and engineering modifications might be called for, with additional costs met by developers and, ultimately, house buyers.

5.3 COST-BENEFIT ANALYSIS

The costs of hazard mitigation, including hazard assessment and preventative costs, have to be balanced with the risk and potential impact of subsidence. This can be done using cost-benefit analysis (CBA); here it is used to evaluate alternative courses of action.

Cost-benefit analysis is used as a decision-making method in project appraisal. In essence, cost-benefit analysis is a very simple method for comparing, over time, the predicted costs and benefits of a line of action, such as the adoption of a particular policy or project. To assess the worth of a course of action, two scenarios are compared: one 'with' the project, and one 'without'. The 'without' scenario is used as a baseline, or benchmark, against which the effects of a project or policy are measured. The present value of cost and benefit streams is then determined by a process known as discounting, in which future amounts are multiplied by a discount factor[2] to determine the value today of amounts received or paid out in the future. Benefit cost ratios can then be calculated, or the net present value (NPV) of an investment determined by discounting the net benefits. Decisions can then be made on the basis of whether a positive or negative value is obtained. [3]

In the present context, we can view the 'with' and 'without' project scenarios in terms of alternative site selection and construction decisions. Thus, we can compare subsidence damage costs in a 'without' project scenario, in which land use and construction decisions are made *without* the benefit of new or improved geohazard information, with subsidence costs in a 'with' project scenario, in which decisions are made *with* the benefit of improved information. The difference in costs - after accounting for additional expenditures on hazard assessment and prevention - then gives us an estimate of the benefits (costs saved) attributable to the availability and use of improved hazard data. It is important to note that this approach does not consider the benefits of projects themselves, in terms of reduced travel times for a new road, for example.

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[2] The economic rationale for discounting is twofold: firstly, capital tied up in any project has a potential value, or 'opportunity cost' in other projects. The scarcity of capital should therefore be reflected as a discount rate applied to the project in question. Secondly, the notion of time preference suggests that people prefer to have money now rather than in the future, with the result that future amounts are 'worth less' than present ones. This reflects the commonplace observation that real interest rates are generally positive, so that £1 received now can be invested to yield more than £1 at a future date, even after allowing for inflation (ODA, 1988). Advice on the appropriate discount rate to use should be sought from the national planning authority. In many countries, a discount rate of 8-12% applied to costs and benefits in constant prices is a useful operational guide (ODA, 1988).

[3] The project selection criterion is to accept projects with a net present value of zero or greater when discounted at a suitable discount rate.

Rather, it is the application of geohazard information to land use planning and cost reduction that is being evaluated.[4]

Two case studies are presented in Boxes 17 and 18 to illustrate how this approach can be applied in practice. The case study in Box 17 considers a hypothetical housing development in a gypsum zone, drawing on data from the town of Ripon in northern England (Boxes 12 and 16). The case study in Box 18 summarises a detailed investigation into the benefits of geological mapping by the United States Geological Survey (USGS) who considered the use of updated geological data in land use planning. In each case, benefits arising from the use of geological data take the form of damage costs avoided, through on-site engineering and site relocation, respectively. The USGS example is not concerned specifically with gypsum hazards, but looks at landslip instability along the line of a road and pollution from a landfill site. The approach and procedures followed in these studies are applicable to road and develoment planning in gypsiferous terranes.

Sensitivity analysis can be used to determine how appraisal results are affected by changes to key assumptions (see end of section). Sensitivity analysis relating to the study detailed in Box 17 indicates the result is significantly affected by changes to assumptions. For example, if the risk factor for a major subsidence event is doubled, benefits increase to around £91,000. A similar effect is achieved if the size, and thus land area, of the housing development is increased. Conversely, if only one house is considered in the analysis, risk becomes negligible and mitigation becomes uneconomic. The appraisal is also very sensitive to the timing of subsidence events. For example, a major event in Year 1, substituting for two events averaged out over 50 years, brings discounted cost savings up to about £114,000.

So far, the analysis has assumed that site selection for each scenario is the same. However, if the hazardous area is avoided altogether, additional engineering costs can also be avoided. The sensitivity analysis indicates that a development of 500 houses at an alternative risk-free site would realise discounted cost savings of approximately £127,000, compared with £48,000 for a similar sized development, with countermeasures, in the gypsum zone. Moreover, the £127,000 is assumed to be net of a £250,000 hazard assessment and planning guidance report, similar to the one produced for Ripon in 1996 (see Box 16), which might inform such a decision.

Is relocation always the best option when subsidence risk appears to have a significant impact on the proposed use of a site? Where there are many alternative project sites to choose from, and land is not scarce, relocation is the obvious choice. However, where 'subsidence-proofing' is economic, few alternative sites are available, and land blight on a deselected site is a possibility, relocation is likely to be less attractive.

Several important issues emerge from these illustrations, and from previous discussion, particularly in relation to the treatment of risk and uncertainty:

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[4] For many social projects (roads; housing; education; health; etc), where outputs are not traded and benefits difficult to measure, cost-effectiveness evaluations are commonplace (ODA, 1988). In the present context, it is also assumed *project* benefits in 'with' and 'without' scenarios are the same, and that cost differences can be attributed to hazard mitigation.

Box 17a. Cost-benefit illustration for a housing development

In this illustration, the cost-effectiveness of engineering modifications to house foundations is evaluated for a hypothetical development of 100 houses. Cost-effectiveness is tested by comparing subsidence damage costs in two scenarios: one in which no mitigation measures are taken (the 'without' project scenario), and one in which measures - in the form of detailed site investigations and reinforced foundations - are taken (the 'with' project scenario). The difference in costs then gives an indication of benefits (or otherwise), of mitigation. The benefits of the housing project itself are assumed to be identical in each case.

The analysis draws on subsidence and cost data from the Ripon area in northern England, and is conducted using a spreadsheet. Spreadsheet models can be easily manipulated, allowing users to test how appraisal results may be affected by changes to data and assumptions. The table below presents a summary of the analysis; the full spreadsheet, including a detailed sensitivity and key, is presented in Box 17b.

	Year 1	Yr 2	Yr 3	Yr 4	Yr 5	Yrs 6-50
- Costs without mitigation	3,00944	9440	9440	9440	9440	9440
- Costs with mitigation	3,09000	0	0	0	0	0
- Damage costs saved	-80,56	9440	9440	9440	9440	9440
- Discount factor (@10%)	0.90	0.826	0.751	0.683	0.621	6.124
- Discounted costs saved	-73,22	7797	7089	6448	5862	57,811

Result: net present value of costs saved £11,778

The general procedure adopted in the analysis is as follows:

1. *Annual construction and subsidence damage costs for the 'no mitigation' scenario are estimated.* Construction is assumed to end in year one. Damage costs are estimated by multiplying annual risk factors with an appropriate cost factor. Risk and cost factors for the housing area are based on historical records from the Ripon gypsum belt. A category 5 event is assumed to incur demolition and house replacement costs, as well as other indirect costs (see Box 14) amounting to £200,000/house.

2. *Annual construction and subsidence damage costs for the mitigation scenario are estimated.* Constructions costs in year one are higher than in the 'no mitigation' scenario, as houses are built with reinforced foundations following detailed site investigation. However, these measures are assumed to prevent future subsidence, and thus damage costs throughout the appraisal period are zero.

3. *A discounted net benefit stream (annual discounted costs saved) is obtained* by multiplying cost savings by the appropriate discount factor. Discounted costs saved are then summed to give an estimate of the present value of costs saved.

4. *A sensitivity analysis is conducted* to see how sensitive the appraisal outcome is to changes in key assumptions. These include changes to the discount rate, the timing of subsidence events, risk and cost factors, and the size of development (see Appendix A for details)

The appraisal indicates that hazard mitigation is the least cost option, realising benefits (costs saved) of around £12,000. However, the result is a marginal one, as this figure is low in relation to total damage and mitigation costs. The effects of inflation on costs and benefits are ignored, as relative prices are assumed to remain unchanged over the appraisal period. The use of constant prices is standard practice for most cost-benefit analyses.

Box 17b Cost Benefit Illustration:

THE BENEFITS OF GYPSUM HAZARD AVOIDANCE FOR A HOUSING DEVELOPMENT

	Year	1	2	3	4	5	6_50
	A. Costs without countermeasures						
1	Number of houses built/year	100	0	0	0	0	0
2	Construction costs (excluding reinforcements) (£)	3000000	0	0	0	0	0
3	Risk factor: category 5 damage	0.04	0.04	0.04	0.04	0.04	0.04
4	Cost factor: category 5 damage (£)	200000	200000	200000	200000	200000	200000
5	Damage cost: category 5 (£)	8000	8000	8000	8000	8000	8000
6	Risk factor: category 4 damage	0.042	0.042	0.042	0.042	0.042	0.042
7	Cost factor: category 4 damage (£)	30000	30000	30000	30000	30000	30000
8	Damage cost: category 4 (£)	1260	1260	1260	1260	1260	1260
9	Risk factor: category 3 damage	0.18	0.18	0.18	0.18	0.18	0.18
10	Cost factor: category 3 damage (£)	1000	1000	1000	1000	1000	1000
11	Damage cost: category 3 (£)	180	180	180	180	180	180
12	Total damage cost/year: category 3, 4 and 5 (£)	9440	9440	9440	9440	9440	9440
13	Total cost of development with no countermeasures (£)	3009440	9440	9440	9440	9440	9440
	B. Costs with countermeasures						
14	Construction costs (inc. reinforcements) (£)	3060000	0	0	0	0	0
15	Extra SI costs (£)	30000	0	0	0	0	0
16	Risk factor: category 5 damage	0	0	0	0	0	0
17	Cost factor: category 5 damage (£)	0	0	0	0	0	0
18	Damage cost: category 5 (£)	0	0	0	0	0	0
19	Risk factor: category 4 damage	0	0	0	0	0	0
20	Cost factor: category 4 damage (£)	0	0	0	0	0	0
21	Damage cost: category 4 (£)	0	0	0	0	0	0
22	Total damage cost/year: categories 4 and 5 (£)	0	0	0	0	0	0
23	Total cost of development with countermeasures (£)	3090000	0	0	0	0	0
	C. Damage costs saved (benefits)						
24	Costs saved/year (£)	-80560	9440	9440	9440	9440	9440
25	Discount factor @ 10%	0.909	0.826	0.751	0.683	0.621	6.124
26	Discounted costs saved (£)	-73229.04	7797.44	7089.44	6447.52	5862.24	57810.56
27	*Net Present Value (NPV) of costs saved (benefits)*	*£11,778*					

Sensitivity Analysis

Present value of costs saved (benefits) if:

a	Category 5 event occurs in Year 1	*£114,266*
b	Category 5 event occurs in Year 50	*-£65,727*
c	Risk of category 5 event doubles	*£91,090*
d	Risk of category 5 event halved	*-£27,878*
e	Discount rate reduced to 6%	*£63,923*
f	Discount rate increased to 14%	*-£11,604*
g	One house only, with cost of countermeasures increased from 2% to 5%	*-£428*
h	Development of 500 houses over 5 years	*£48,498*
I	Alternative land use decision: 500 houses built in different location in years 2-6, following £250000 planning guidance study in Year 1	*£126,571*

Subsidence classification:

Based on NCB damage classification (Box 10)

Category 5	Major structural damage - rebuilding or demolition required
Category 4	Very severe damage - extensive repair work required
Category 3	Some damage - inhabitable, but work to repair cracks, service pipes etc

KEY

A. Costs without countermeasures

1 Houses built/year, each with total plot area (buildings and immediate area) of 300m²

2 Construction cost @ £30,000/house; no special foundations

3 Risk factor based on historical subsidence data from Ripon gypsum belt, giving average of 0.040 category 5 events/30,000m² housing area/year

4 Cost factor based on demolition and replacement cost, plus legal, temporary accommodation and other indirect costs

5 Risk factor 3 multiplied by cost factor 4 above

6 Risk factor based on historical subsidence data from Ripon gypsum belt, giving average of 0.042 events/30,000m² housing area/year

7 Cost factor based on cost of major work to house @

8 Risk factor 6 multiplied by cost factor 7 above

9 Risk factor based on historical subsidence data from Ripon gypsum belt, giving average of 0.18 events/30,000m² housing area/year

10 Cost factor based on cost minor repair work to house @

11 Risk factor 9 multiplied by cost factor 10

12 Total subsidence-induced damage cost/year: sum of 5, 8 and 11

13 Total construction and subsidence-related damage costs/year:

B. Costs with countermeasures

14. Construction costs @ £30,000/house, including extra foundation work @ 2% construction cost

15. Site investigation costs @ 1% construction costs

16 - 22. Risk of subsidence damage assumed to be zero with gypsum hazard prevention measures in place

23. Total construction and subsidence-related damage costs/year

C. Damage costs saved (benefits)

24. Equivalent to 13 subtract 23

25. Discount factor applied to incremental benefit figures (24) at discount rate of 10% (from compounding and discounting tables)

26. Discounted costs saved/year (24 multiplied by 25)

27. Sum total of discounted costs saved over 50 years

Risk analysis

A key consideration in any analysis is the risk, or probability, of subsidence. The first step in evaluating risk at a particular site is therefore a statistical analysis of subsidence occurrence. This requires a valid database[5] on modern subsidence events (Beck, 1991). Compiling such a database can be difficult: systematic recording of subsidence events is rare, and data may need to be compiled from a variety of sources, including local residents, government agencies, newspaper reports, insurance reports and consulting engineers' records. If historical data are available for a sufficiently large area, a risk factor for a specific site can be calculated, in the form of the number of expected events/unit area/unit time. Risk factors will vary from place to place, depending on geological, geomorphological and hydrological controls. Beck (1991) suggests that high incidence rates are of the order of 1 event/3-4 years/km^2, though these figures are for sinkhole collapses in a limestone karst area. Higher rates may be expected in active gypsum dissolution subsidence areas if both minor *and* major subsidence events and damage (Box 10) are considered in the calculations.

The risk of subsidence damage will increase with the size of site. Thus for an individual house, the risk of subsidence is generally negligible, and engineering modifications uneconomic, at least from the perspective of an individual homeowner (Beck, 1991). For larger developments, the risk of subsidence increases and mitigation, in terms of engineering or site relocation, becomes more attractive (see section on sensitivity analysis below).

In the housing illustration discussed in Boxes 17a and 17b, annualised (average) risk factors were computed for a 50 year appraisal period. Averaging probabilities in this way is the simplest way of dealing with risk, though sensitivity analysis (see below) should ideally be used to test how sensitive appraisal results are to alternative approaches.

Risk, vulnerability and precaution

Probability figures tell us nothing about the size or impact of subsidence events, unless historical records of this kind also exist and can be used as a guide. In built up areas, where subsidence events may only register through infrastructural damage, such information may be available, and risk factors for different magnitudes of event may be estimated and costed. Thus in the Ripon case study (Box 17), three risk factors relating to different sizes of subsidence event were computed, based on historical records of varying degrees of building damage in the Ripon area (Box 5). A cost was then attributed to each of three damage levels, and an annual (average) damage cost estimated by multiplying this figure by the appropriate risk factor. In the USA case study (Box 18), a similar approach was used to estimate avoidable damage costs attributable to geological hazards. In this instance, sophisticated GIS techniques were used to create environmental risk maps, combining geological, engineering and economic data.

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[5] Ideally, the statistical sampling area should be geologically, geomorphologically and hydrologically consistent, and large enough for a significant number of data points to be used in the calculation. As a general rule of thumb, Beck (1991) suggests that the product of the area over which subsidence events are counted (in km^2) times the number of years of record, should be at least 300. For the purposes of long term planning, such as for the design life of a building, Beck (1991) also suggests that the database encompasses a sufficient time span to include climatic extremes of rainfall and drought. Where the subsidence record is in the form of damage events (eg to buildings), the record should be compared with a 'control' outside the gypsum to ascertain how many events are related to gypsum dissolution as opposed to other conditions affecting ground stability.

Box 18. Cost benefit analysis applied to road and landfill siting

In 1993, the United States Geological Survey published a detailed report on the economic value of geological mapping (USGS, 1993). The report details a general procedure, or approach, for estimating net benefits to society from updated mapping. The approach is similar to the one described throughout this section in terms of its focus on benefits as hazard costs avoided. The analytical methods employed, particularly the use of Geographic Information Systems (GIS), illustrate how geological data can be combined with engineering and economic data to determine the costs and benefits of alternative land use decisions.

The approach described was applied to two case studies in one County: (a) selection of a road corridor; and (b) selection of a landfill site. In each case, hypothetical landuse decisions made with and without the benefit of new mapping information were compared to see if new information would be compelling enough to alter land use decisions, and to determine the economic impact of such decisions. In each case, geological map information for old and new maps was converted into a probability map of an environmental hazard using digital GIS techniques. Land use decisions made under alternative regulatory regimes were then compared, and environmental hazard costs computed by combining risk data with engineering and economic data. Thus in the road corridor example, better siting decisions reduced the probability of slope failures and thus mitigation costs. In the landfill example, improved siting was assumed to reduce the risk of contamination and any consequent reduction in property values. In each case, hazard costs avoided greatly exceeded the cost of providing new geological information.

Ideally, all the potential impacts of gypsum subsidence should be valued in a cost-benefit analysis. In practice this is often difficult, as some effects may not be registered in market prices (eg injury and stress), and some (eg transport delays and inconvenience), are both difficult to value and link directly with subsidence (see Box 14). In the USA case study (Box 18), for example, only the more readily valued direct damage costs associated with geological hazards were valued to give a partial *indication* of remapping benefits. In the Ripon case study (Box 17), an attempt was made to capture some of the indirect costs of subsidence. This was achieved by assuming that major subsidence events, leading to house abandonment, incurred direct house replacement and demolition costs *and* additional investigation, inconvenience, litigation and local authority costs, amounting to around £200,000/house.

Having examined the risk of subsidence and its potential impact, several lines of action need to be evaluated. Where risk does appear to have a significant impact on the proposed use of a site, the most obvious course of action is to redesign the project to avoid the hazardous area. This may be the preferred choice where:

- engineering measures to eliminate or reduce the risk of subsidence are not cost-effective over the intended lifespan of a project;
- site selection is not critical to the project itself, and alternatives are available which have little, if any, impact on project benefits;
- the selection of an alternative site has little opportunity cost, in terms of development value foregone, on the deselected site.

Conversely, measures to render a site "subsidence-proof", so that development in the hazardous area can proceed, may be preferred where:

- CBA demonstrates that engineering measures to reduce or eliminate risk are economically justified; and
- few alternative sites are available;
- de-selecting a site incurs a high opportunity cost on that site.

The housing development case study described in Box 17 helps shed light on the decision-making process. Here, the appraisal indicates that additional site investigation and engineering costs which eliminate subsidence risk are economically justified for larger developments. However, avoiding the area altogether (and thus the need for additional engineering) would clearly be more attractive if (a) the development could be easily relocated with no loss of housing benefits, and (b) if the value of the deselected site was unaffected. Thus, the sensitivity analysis (see below and Box 17b) reveals that a development of 500 houses at an alternative site, following a £250,000 planning guidance study, would realise a discounted damage cost saving of around £127,000, compared with £48,000 for a similar sized development requiring expensive countermeasures in the gypsum zone.

This illustration assumes that assumptions (a) and (b) are correct. In an urban context however, where there may be considerable pressure to avoid 'planning blight' on large areas of land, assumption (b) may be unrealistic. In these circumstances, relocation could still be economically justified if losses under (b) were less than the benefits, in terms of mitigation costs avoided, of relocation. In this case, mitigation costs which might be avoided amount to £79,000 (the difference between £127,000 and £48,000).

Sensitivity analysis

An important tool for dealing with uncertainty in cost-benefit appraisals is sensitivity analysis. The aim of sensitivity analysis is to test the extent to which appraisal results are affected by changes to key assumptions. This helps to establish the degree of confidence that may be placed on the results of an analysis, and highlights those variables which have a significant impact on the estimates made.

For the housing development illustration outlined in Box 17, a sensitivity analysis was carried out. This was to see how sensitive the appraisal result was to changes in risk factors, discount rates, the size of the housing development, the timing of subsidence events and other factors (full details in Box 17b). The analysis highlights several important generic issues:

Choice of discount rate and the timing of costs. The choice of discount rate can have a significant impact on appraisal results because costs and benefits are not normally spread out evenly over the appraisal period. In the housing illustration, extra site investigation and engineering costs associated with subsidence mitigation are incurred during the construction period in Year 1. However benefits, in terms of damage costs avoided, are spread evenly over the full 50 years. The result is that benefits, in terms of costs saved, are discounted more than the mitigation costs arising in Year 1 and, at high discount rates, benefits accruing towards the end of the appraisal period are negligible. Thus, while net present value of costs saved is positive at discount rates of 6% and 10%, it is negative when the rate is increased to 14%.

Similarly, changing the timing of costs has a significant impact on results. In the sensitivity analysis, this has been highlighted by substituting the annualised risk-cost approach for one in which 'whole' events occur either at the beginning or end of the appraisal period. For example, if a major subsidence event occurs in Year 1 only (compared with two events averaged out over 50 years), then discounted damage costs which might potentially be saved increase significantly, from around £12,000 to £114,000. Conversely, if this event is now assumed to occur in Year 50 only, then the value falls to around -£66,000, and mitigation becomes uneconomic. These values are illustrative only, and are not based on a statistical analysis of probabilities and confidence limits. However, they highlight the need for supplementary statistical analysis, which goes beyond the annualised risk-cost approach to look at the occurrence and impact of 'whole' subsidence events. For example, Monte Carlo simulation techniques could be used to test the impact of random events for varying levels of confidence. Alternatively, Beyesian probability theory could be used to test whether new hazard assessment evidence, when combined with existing information would be compelling enough to change planning decisions.

Size of development. The risk of subsidence clearly increases as the size of site being considered increases. Whether this realises a linear increase in damage costs will depend on the nature of development proposed. For example, a supermarket site may occupy a large area, but most may be earmarked for a car parking. Subsidence which occurs in this area is unlikely to have serious economic or safety implications. Subsidence damage to an airport runway, however, may pose a serious safety risk and cause costly delays and diversions while repair work is carried out.

For the housing development case study, the effects of different sized developments on appraisal results was evaluated. Not surprisingly, the cost of extensive additional engineering and site investigation is not justified if just one house is built, as the risk of subsidence occurring within such a small area is negligible.[6] Mitigation becomes more economic for larger developments of around 100 houses or more, when risk factors and therefore damage costs increase.

Risk factors. Where risk factors cannot be estimated precisely, or with confidence, sensitivity analysis can be used to see what effect deviations from the mean have on appraisal results. Thus in case study A, doubling the risk factor for major subsidence increased the discounted cost saving in the mitigation scenario from roughly £12,000, to £91,000.

Insurance

In areas prone to gypsum dissolution subsidence the use of insurance cover allows the liability of any one collapse to be spread between the residents of that area. Even with good site investigation the problems are very difficult to delineate and the high solubility of gypsum means that problems may change with time causing new areas of subsidence to develop. In addition to covering the value of the property and surrounding infrastructure, consideration should also be given to insuring the land around the property against the costs of stabilising any collapse which may impinge on adjacent land ownerships. Rather than exclude gypsum subsidence areas from insurance cover the insurance companies should consider them as an opportunity, but one that has an increased premium.

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[6] For a property in a gypsum area, insurance is therefore the only practical solution.

6.SYNTHESIS AND CONCLUSIONS

Because of its high solubility and rapid dissolution rate, gypsum in all its forms constitutes a geological hazard detrimental to development. Wherever it occurs, it can be responsible for catastrophic subsidence or difficult engineering conditions. The careful control of construction and water abstraction can reduce the impact of the hazard on development. The cost-effectiveness of the measures depend partly on the value of the construction and partly on the local severity of the problem and its associated risk. The measures taken will vary depending on the structures being constructed and the degree to which they can be modified or relocated. For the construction of dams and reservoirs, the severe impact of gypsum dissolution on the structures is potentially very large with catastrophic results. The total avoidance of gypsum beneath dams is likely to be the most cost-effective way to plan such structures. For housing and industrial development the avoidance of the areas with the greatest severity of subsidence and the construction of reinforced structures in the other gypsiferous areas may be the best course of action.

The initial delineation of gypsum hazard areas can be often be carried out using existing geological maps. These can be supplemented by further field studies and possibly, if funds are available, by a limited number of boreholes. Once the hazardous areas have been delineated they can be incorporated into local planning to encourage the avoidance of the problems or their mitigation. Strong local development control helps to alleviate the hardships caused by catastrophic subsidence. House and property values may be adversely affected in the worst areas, but may be enhanced away from the centres of subsidence. The cost-benefits of hazard avoidance increase in importance and effectiveness as the size or cost of the development increases. For individual houses the avoidance of the actively subsiding areas and the use of reinforced foundations may be all that can reasonably be expected; insurance covering the remainder of the risk. As the number of houses increases, or the size of the structure increases to factory proportions, then the risk of subsidence affecting a part of them increases considerably, in these circumstances it is justified in spending more on hazard avoidance and mitigation measures. Insurance is important for development in gypsum geohazard areas, the individual risk to any single property may be fairly small, but the problems to an individual can be very large. The use of insurance, with increased premiums to cover the additional hazard, is the most sensible way for the individual to guard against the dangers. In some karst-subsidence affected states in the USA the purchase of subsidence insurance is obligatory.

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8. GLOSSARY

Alabaster: The alabastrine form of gypsum comprising fine-grained granular gypsum with abundant very fine veins of fibrous gypsum.

Anhydrite: The rock or mineral composed of the anhydrous form of Calcium sulphate $CaSO_4$.

Aquifer: A rock that is water bearing, either in the pores or the joints.

Breccia pipe: A sub-vertical cylindrical pipe-like structure caused by the gravitational collapse of the overlying strata into a cave or cavity.

Calcite: The mineral composed of calcium carbonate, $CaCO_3$.

CBA: Cost Benefit Analysis.

Dolomite: The mineral and rock composed of calcium magnesium carbonate, $CaCO_3MgCO_3$.

Fibrous gypsum: The fibrous form of gypsum that occurs in veins.

GIS: Geographic Information System

Halite: Another name for the mineral form of common salt or Sodium Chloride, NaCl.

Limestone: A rock composed dominantly of the mineral Calcite or $CaCO_3$.

Karst: A distinctive terrain created by the erosion of soluble rock where the topography and landforms are a consequence of efficient underground drainage. Usually applied without qualification to limestone terranes.

Gypsum: The rock or mineral composed of the hydrated form of Calcium Sulphate, $CaSO_4.2H_2O$.

Gypsum karst: A distinctive terrain created by the erosion of gypsum where the topography and landforms are a consequence of efficient underground drainage.

Satin Spar: See fibrous gypsum

Salt: See halite

9. SELECTED REFERENCES

Arranged under topic headings

Key references:

James, A.N., 1992. Soluble material in civil engineering. Ellis Horwood Ltd, England, 433p. [This volume includes numerous other references to gypsum properties, dissolution rates, and dams, it is a standard work].

Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue. [This book reviews the physical and chemical characteristics of gypsum karst formation and its world-wide distribution].

Reuter, F. and Tolmačëv, V.V. 1990. Bauen und Bergbau in Senkungs und Erdfallgebieten, Eine Ingenieurgeologie des Karstes. Schriftenreihe für Geologische Wissenschaften, Vol 28. Academie-Verlag, Berlin. [In German: an engineering geology of karst, partly summarised in English by Reuter and Stoyan, 1993.]

Properties of gypsum: physical and dissolution

Bell, F.G. 1994. A survey of the engineering properties of some anhydrite and gypsum from the north and midlands of England. Engineering Geology. Vol. 38, 1-23.

Deer, W.A., Howie, R.A. and Zussman, J. 1966. An introduction to the rock-forming minerals. Longmans.

Fabre, D and Dayre, m. 1982. Proprietes geotechniques de gypses et anhydrites du Trias des Alpes de Savoie (France). Bulletin of the International Association of Engineering Geology, Vol. 25. 91-98.

James, A.N., 1992. Soluble material in civil engineering. Ellis Horwood Ltd, England, 433p.

James, A.N., Cooper, A.H. and Holliday, D.W. 1981. Solution of the gypsum cliff (Permian Middle Marl) by the River Ure at Ripon Parks, North Yorkshire. Proceedings of the Yorkshire Geological Society, Vol. 43, 433-450.

Kemper, W.D., Olsen, J. and DeMooy. 1975. Dissolution rate of gypsum in flowing water. Proceedings of the American Society of Soil Science. Vol. 39. 458-463.

Klimchouk, A. 1997. Dissolution and conversion of gypsum and anhydrite. 21-36 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Klimchouk, A. 1997. The typology of gypsum karst according to its geological and geomorphological evoloution. 49-60 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Klimchouk, A., Cucchi, F., Calaforra, J.M. and Forti, P. 1997. Dissolution of gypsum from field observations. 37- 48 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Lebdev. A.L. 1997. Gypsum dissolution and leaching processes: The influence on permeability and porosity of fractured-porous rock massif. 823-827 in Marinos, P.G., Koukis, G.C., Tsiambaos, G.C. and Stournaras, G.C. Engineering Geology and the Environment. Proceedings international symposium on engineering geology and the environment, organised by the Greek national group of IAEG/Athens/Greece/23-27 June 1997. A.A.Balkema, Rotterdam.

Mossop, G.D. and Shearman, D.J. 1973. Origins of secondary gypsum rocks. Transactions of the Institute of Mining and Metallurgy, (Section B: Applied Earth Sciences), Vol. 82, B147-B154.

Müller-Salszburg, L. and Götz, H.P. 1976. Heaving of invert in tunnelling. Bulletin of the International Association of Engineering Geology. No 13, 51-53.

Navas, A. 1990. The effect of hydrochemical factors on the dissolution rate of gypsiferous rocks in flowing water. Earth Surface Processes and Landforms. Vol. 15, 709-715.

Wigley, T.M.L. 1973. Chemical evolution of the system Calcite-Gypsum-Water. Canadian Journal of Earth Sciences. Vol. 10, 306-315.

Gypsum caves and karst

Andrajchouk, V. 1997. Gypsum karst of the Pre-Ural region, Russia. 285-292 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Andrajchouk, V. and Klimchouk, A. 1993. Environmental change and human impact on karst in the Western Ukraine. Catena Supplement, 25, 147-160.

Andrejchuk, V. and Klimchouk, A. 1997. Gypsum karst of the eastern-European plain. 251-261 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Arauzo, T. and Gutiérrez, F. 1995. Fenomenos recientes de subsidencia kastica sinsedimentaria en el Barranco de Torrecilla (Depression del Ebro, Zaragoza). Cuaternario y Geomorfologia. Vol. 9. 73-90.

Biese, W. 1931. Über Höhlenbildung, 1. Entstehung der Gipshölen am südlichen Harzrad und am Kyffhäuser. Abhandlung Preußischen Geologischen Landsanstalt, Vol. 71. 5-69 and 12 plates.

Calaforra, J.M. and Pulido-Bosch, A. 1997. Some examples of gypsum karst and the more important gypsum caves in Spain. 225-237 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Chardon, M and Nicod, J. 1997. Gypsum karst of France. 203-208 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Chiesi, M., Forti, P. and Panzica la Manna, M. 1989. Le esplorazioni speleologiche nell'area carsica di S. Ninfa. Istituto Italiano di Speleologia, Memoria 3, s. II, 85-92.

Cooper, A.H. 1997. Gypsum karst of Great Britain. 195-202 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Forti, P. 1987. Fenomeni carsici nei gessi dell'Emilia-Romagna. Natura e Montagna, Vol. 1. 13-22.

Forti, P. and Sauro, U. 1997. The gypsum karst of Italy. 239-250 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Gutiérrez, M. and Gutiérrez, F. 1996. Geomorphology of the Tertiary gypsum formations in the Ebro depression. International Symposium on Soils with Gypsum. Lleida. 1996. 1-20.

Johnson, K.S. Hydrogeology and karst of the Blaine gypsum-dolomite aquifer, southwestern Oklahoma. 1990. Oklahoma Geological Survey, Special Publication 90-5. 31pp.

Johnson, K.S. 1992. Evaporite karst in the Permian Blaine Formation and associated strata in western Oklahoma, USA. 405-420 in Back W. Herman, J.S. and Paloc, H. (Eds) Hydrogeology of Selected Karst Regions. IAH, International Contributions to Hydrogeology. Vol 13.

Johnson, K.S. 1997. Gypsum karst in the United States. 183-193 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Kaçaroğlu, F. Değirmenci, M. and Cerit, O. 1997. Karstification of Miocene gypsum: an example from Sivas, Turkey. Environmental Geology. Vol. 30. 88-97.

Kempe, S. 1997. Gypsum karst of Germany. 209- 224 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Klimchouk, A. 1992. Large gypsum caves in the western Ukraine and their genesis. Cave Science. Vol. 19, 3-11.

Klimchouk, A. 1997. Sulphate rocks as an arena for karst development. 9-20 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Klimchouk, A. 1997. Speleogenesis in gypsum. 61-82 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Klimchouk, A. 1997. Gypsum karst of the western Ukraine. 263-278 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Klimchouk, A., Forti, P. and Cooper, A. 1997. Gypsum karst of the world: a brief overview. 159-181 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Macaluso, T. and Sauro, U. 1997. Weathering crust and karren on exposed gypsum surfaces. 115-126 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Marcinkevičius V. and Bucevičiūtė. 1997 Sulphate karst of North Lithuania. 247-252 in Marinos, P.G., Koukis, G.C., Tsiambaos, G.C. and Stournaras, G.C. Engineering Geology and the Environment. Proceedings international symposium on engineering geology and the environment, organised by the Greek national group of IAEG/Athens/Greece/23-27 June 1997. A.A.Balkema, Rotterdam.

McGregor, D.R., Pendery, E.C. and McGregor, D.L. 1963. Solution caves in gypsum, north central Texas. Journal of Geology. Vol. 71. 108-115.

Nicod, J. 1992. Recherches nouvelles sur les karsts des gypses et des evaporites associées (Première partie: processus et cavernement). Karstologia, No. 20, 1-10.

Paukštys, B. and Narbutas, V. Gypsum karst of the Baltic Republics. 1997. 279-284 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Pfeiffer, D. and Hahn, J. 1972. Karst of Germany. 187-223 in Herak, M. and Stringfield, V.T. (Editors) Karst: Important Karst Regions of the Northern Hemisphere. Elsevier, Amsterdam. 551p.

Quinlan, J.F., Smith, R.A. and Johnson, K.S. 1989. Gypsum karst and salt karst of the United States of America. Le Grotte d'Italia. Vol. 13 (4), 73-92.

Ryder, P F, & Cooper, A H. 1993. A cave system in Permian gypsum at Houtsay Quarry, Newbiggin, Cumbria, England. Cave Science, 20, No. 1, 23-28.

Sauro, U. 1997. Geomorphological aspects of gypsum karst with special emphasis on exposed karst. 105-114 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Trzcinski, Y. 1997. Gypsum karst in the south of the Siberian Platform, Russia. 293-295 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Subsidence and gypsum geohazards

Benito, G. and Gutiérrez, M. 1987. Karst in gypsum and its impact on the Middle Ebro Basin (Spain). 137-141 in Beck, F.B. and Wilson, W.L. (Editors.) Karst hydrogeology: engineering and environmental applications. Proceedings of the second multidisciplinary conference on sinkholes and the environmental impacts of karst Orlando/Florida/9-11 February. A.A.Balkema, Rotterdam.

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

Cooper, A.H. 1986. Foundered strata and subsidence resulting from the dissolution of Permian gypsum in the Ripon and Bedale areas, North Yorkshire. 127-139 in Harwood, G M and Smith, D B (Editors). The English Zechstein and related topics. Geological Society of London, Special Publication. No. 22.

Cooper, A.H. 1995. Subsidence hazards due to the dissolution of Permian gypsum in England: investigation and remediation. 23-29 in Beck, F.B. (Editor.) Karst Geohazards: engineering and environmental problems in karst terrane. Proceedings of the fifth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst Gatlinburg/Tennessee/2-5 April 1995. 581pp. A.A.Balkema, Rotterdam.

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

Han Xingrui. 1991. Gypsum karst and collapse column. 94-98 in Yuan Daoxian (ed.) Karst of China. Geological Publishing House, Beijing, China.

Hundt, R. 1950. Erdfalltektonik. Wilhelm Knapp, Halle (Saale), 145 pp.

Julian, M. and Nicod, J. 1990. Catastrophes naturelles et risques afférents aux terrains gypseux (Alpes et Provence). Revue de Géographie Alpine, Vol. 78. 157-173.

Klimchouk, A. and Andrejchuk, V. 1997 Breakdown development in cover beds, and landscape features induced by intrastratal gypsum karst. 127-144 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Klimchouk, A. and Andrejchuk, V. 1997. Environmental problems in gypsum karst terrains. 145-156 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Nicod, J. 1991. Phénomènes karstiques et mouvements de terrain récents dans le Trias du Département du Var. Travaux U.A. 903 du CNRS, No. 20. 5-14.

Nicod, J. 1976. Karsts des gypses et des evaporites associées. Annales de Géographie, No. 471. 513-554.

Olive, W.W. 1957. Solution-subsidence troughs, Castile Formation of Gypsum Plain, Texas and New Mexico. Bulletin of the Geological Society of America. Vol. 68. 351-358.

Paukštys, B. 1996. Hydrogeology and groundwater protection problems in karst region of Lithuania. Geological Society of Lithuania, papers, 6, 1-72, Vilnius,

Paukštys, B., Cooper, A.H. and Arustiene, J. 1997. Planning for gypsum geohazards in Lithuania and England. 127-135 in Beck, F.B. and Stephenson, J.B (Editors) The Engineering Geology and Hydrogeology of Karst Terranes. Proceedings of the Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst Springfield/Missouri/6-9 April 1997. A.A.Balkema, Rotterdam.

Ströbel, W. 1973. Der Grundgips im Raum Stuttgart als Model für Gipsauslaugung und Bildung von Erdfällen. T1-G 1-8 in Proceedings of a symposium on sinkholes and subsidence, Hannover, Deutsche Gessellschaft für Erd- und Grundbau. Essen.

Toulemont, M. 1984. Le karst gypseux du Lutétien supérieur de la région parisienne. Charactéristiques et impact sur le milieu urbain. Revue de Géologie Dynamique et de Géographie Physique. Vol. 25, 213-228.

Wigley, T.M.L., Drake, J.J., Quinlan, J.F. and Ford, D.C. 1973. Geomorphology and geochemistry of gypsum karst near Canal Flats, British Columbia. Canadian Journal of Earth Sciences. Vol. 10. 113-129.

Distribution of gypsum

British Geological Survey. 1995. World Mineral Statistics. Keyworth, Nottingham.

Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

[The individual papers in this reference section (listed above and below) give details of gypsum problems in many countries]

Construction

Arnould, M. 1970. Problems associated with underground cavities in the Paris region. 1-25 in Geological and geographical problems of areas of high population density. Proceedings of the symposium, Association of Engineering Geologist, Sacramento, California.

Reuter, F. and Tolmačëv, V.V. 1990. Bauen und Bergbau in Senkungs und Erdfallgebieten, Eine Ingenieurgeologie des Karstes. Schriftenreihe für Geologische Wissenschaften, Vol 28. Academie-Verlag, Berlin.

Reuter, F and Stoyan, D. 1993. Sinkholes in carbonate, sulphate, and chloride karst regions: Principles and problems of engineering geological investigations and predictions, with comments for the construction and mining industries. 3-25 in Beck, B. F. (ed) Applied karst geology. Proceedings of the fourth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, Panama City/Florida/ 25-27 January 1993. A.A. Balkema, Rotterdam.

Soyer, R. 1961. Les dissolutions de gypses antéludiens dans le centre de l'Ile-de-France et leurs dangers pour les constructions. Bulletin de la Société Géologique Francais (Série 7), Vol 111, 432-436.

Dams

Brune, G. 1965. Anhydrite and gypsum problems in engineering geology. Engineering Geology (Sacramento). Vol 2. 26-33.

Calcano, C.E. and Alzura, P.R. 1967. Problems of dissolution of gypsum in some dam sites. Bulletin of the Venezuaelan Society of Soil Mechanics and Foundation Engineering, July-September, 1967.

Calvino, F., Costantino, F. and Mirri, F. 1981. Design criteria for a dam, reservoir and irrigation system on Middle East evaporite formation. Bulletin of the International Association of Engineering Geology. Vol. 24. 53-55.

Deletie, P., Haguenauer, B., Quenee, B. and Robinet, A. 1990. Étude et Surveillance de la dissolution du gypse sur deux sites d'ouvrages hydrauliques. Mémoires de la Société Géologique de France, Nouvelle Série No. 157. 33-42.

Eck, W. and Redfield, R.C. 1965. Engineering geology problems at Sanford Dam, Borger, Texas. Engineering Geology. Vol. 2. 15-25.

El Ghorfi, A and Giafferi, J-L. 1991. Galerie d'Amenee de l'Usine Hassan 1er (Maroc) Problèmes liés à la présence des gypses. 40-49 in in Les Fondations de grands ouvrages. Mémoire de la Société Géologique de France. Novelle Série. Mémoire No. 157. Volume complémentaire.

Eraso, A., Trzhtsinskij, Y. and Castrillo, A. 1995. Dolinas de colapso y karst en yeso en la plataforma cámbrica del esta de Siberia. Boletin Geológico y Minero. Vol. 106-4, 373-378.

Gruner, E. 1963. Dam Disasters. Proceedings of the Institution of Civil Engineers. Vol. 24. 47-60.

Hu Wuzhou. 1988. A study on the formation of Triassic "gypsum-dissolved-strata" in Guizhou Province and the seepage prevention for reservoirs. 1117-1126 in Yuan Daoxian (ed), Karst hydrogeology and karst environment protection; proceedings 21st IAH Conference, 10-15 October 1988, Guilin, China. IAH-AISH Publication. 176, Vol 2.

James, A.N., 1992. Soluble material in civil engineering. Ellis Horwood Ltd, England, 433p. [This volume includes numerous other references and is a standard work].

James, A.N. and Lupton, A. R. R. 1978. Gypsum and anhydrite in foundations of hydraulic structures. Geotechnique. Vol. 3, 249-272.

James, A.N. and Kirkpatrick. I.M. 1980. Design of foundations of dams containing soluble rocks and soils. Quarterly Journal of Engineering Geology, London. Vol 13. 189-198.

Lebdev. A.L. 1997. Gypsum dissolution and leaching processes: The influence on permeability and porosity of fractured-porous rock massif. 823-827 in Marinos, P.G., Koukis, G.C., Tsiambaos, G.C. and Stournaras, G.C. Engineering Geology and the Environment. Proceedings international symposium on engineering geology and the environment, organised by the Greek national group of IAEG/Athens/Greece/23-27 June 1997. A.A.Balkema, Rotterdam.

Lu Yaoru and Cooper, A.H. 1997. Gypsum karst geohazards in China. 117-126 in Beck, F.B. and Stephenson, J.B (Editors) The Engineering Geology and Hydrogeology of Karst Terranes. Proceedings of the Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst Springfield/Missouri/6-9 April 1997. A.A.Balkema, Rotterdam

Marriotti, G., Rondot, E. And Speziale, J. 1990. Le Barrage de Casa de Piedra (Argentine). Mise en évidence de conditions de fondations dangereuses au cours de la construction. Adaptation du projet. 77-85 in Les Fondations de grands ouvrages. Mémoire de la Société Géologique de France. Novelle Série. Mémoire No. 157.

Merritt, A.H. 1995. Geotechnical aspects of the design and construction of dams and pressure tunnels in soluble rocks. 3-7 in Beck, F.B. and Stephenson, J.B (Editors) The Engineering Geology and Hydrogeology of Karst Terranes. Proceedings of the Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst Springfield/Missouri/6-9 April 1997. A.A.Balkema, Rotterdam.

Ransome, F.L. 1928. Geology of the St. Francis Dam-site. Economic Geology. Vol. 23 553-563.

Redfield, R.C. 1967. Brantley Reservoir site - and investigation of evaporite and carbonate facies. Engineering Geology (Sackramento) Vol. 4. 14-30.

Waltham, A.C. 1978. Catastrophe, the violent earth. Macmillan, London. 170pp.

Wittke, W. and Hermening. 1997. Grouting of cavernous gypsum rock underneath the foundation of the weir, locks and powerhouse at Hessigheim on the River Neckar. Proceedings of the 19th Congress ICOLD (International Commission on Large Dams) Florence. Q75, R.44, 613-626.

Roads

Cadilhac, M., Poupelloz, B and Toulemont, M. 1977. Fondations d'ouvrage d'art en site karstique. Le viaduc de l'autoroute A15. Bulletin de Liaison Labo. P. et Ch. 87. janv.-févr. Réf. 1915.

Kempton, G.T., Lawson, C.R., Jones, C.J.F.P. and Demerdash, M. 1996. The use of geosynthetics to prevent the structural collapse of fills over areas prone to subsidence. 317-325 in de Groot, den Hoedt and Termaat (Eds.) Geosynthetics, Applications, Design and Construction. Balkema, Rotterdam.

Poupelloz, B. and Toulemont, M. 1981. Stabilisation des terrains karstiques par injection. Le cas du Lutetian gypseux de la region de Paris. Bulletin of the International Association of Engineering Geology. No. 24. 111-123.

Wohnlich, M. 1976. Sulphatic rocks in Switzerland. Bulletin of the International Association of Engineering Geology. No 13, 39-43.

Toulemont, M. 1984. Le karst gypseux du Lutétien supérieur de la région parisienne. Charactéristiques et impact sur le milieu urbain. Revue de Géologie Dynamique et de Géographie Physique. Vol. 25, 213-228.

Railways

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

Irfan, T.Y. and Özkaya. 1981. Engineering geological mapping of gypsiferous formation, Sivas, Central Eastern Turkey. Bulletin of the International Association of Engineering Geology. No. 24. 33-37.

Canals

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

Swan, C.H. 1978. Middle East - canals and irrigation problems. Quarterly Journal of Engineering Geology. Vol. 11, 75-78.

Power stations

Seedhouse, R.L. and Sanders, R.L. 1993. Investigations for cooling tower foundations in Mercia Mudstone at Ratcliffe-on-Soar, Nottinghamshire. 465-471 in Cripps, J.C., Coulthard, J.C., Culshaw, M.G., Forster, A., Hencher, S.R. and Moon, C. (Eds). The Engineering Geology of Weak Rock. Proceedings of the 26th annual conference of the Engineering Group of the Geological Society, Leeds, September, 1990. A.A..Balkema, Rotterdam.

Hydrogeology and Water Abstraction

Cooper, A.H. 1988. Subsidence resulting from the dissolution of Permian gypsum in the Ripon area; its relevance to mining and water abstraction. 387-390 in Bell, F G, Culshaw, M G, Cripps, J C and Lovell, M A (Editors) Engineering Geology of Underground Movements. Geological Society of London, Engineering Geology Special Publication No.5.

Claassen, J.C. 1981. Estimation of calcium sulfate solution rate and effective aquifer surface area in a ground-water system near Carlsbad, New Mexico. Groundwater. Vol. 19. 287-297.

Klimchouk, A. 1997. Hydrogeology of gypsum formations. 83-89 in Klimchouk, A., Lowe, D., Cooper, A.H. and Sauro, U. (Eds) 1997. Gypsum karst of the world. International Journal of Speleology. Vol 5 (1-2) 1996 Thematic Issue.

Klimas, A. and Paukstys, B. 1993. Nitrate contamination of groundwater in the Republic of Lithuania. Norges Geologiske Undersokelse Bulletin 424, 75-85.

Paukstys, B., Cooper, A.H. and Arustiene, J. 1997. Planning for gypsum geohazards in Lithuania and England. 127-135 in Beck, F.B. and Stephenson, J.B (Editors) The Engineering Geology and Hydrogeology of Karst Terranes. Proceedings of the Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst Springfield/Missouri/6-9 April 1997. A.A.Balkema, Rotterdam.

Pulido-Bosch, A. and Calaforra, J.M. 1993. The gypsum karstic aquifer of Sorbas (Almeria). 225-241 in Pulido-Bosch (Editor) Some Spanish Karstic Aquifers, University of Granada.

Qian Xuepu. 1988. The formation of gypsum karst collapse-column and its hydrogeological significance. 1186-1193 in Yuan Daoxian (ed), Karst hydrogeology and karst environment protection; proceedings 21st IAH Conference, 10-15 October 1988, Guilin, China. IAH-AISH Publication. 176, Vol 2.

Roje-Bonacci, T. 1997. Influence of the fluctuation of groundwater levels upon the formation of sinkholes. 997-1002 in Marinos, P.G., Koukis, G.C., Tsiambaos, G.C. and Stournaras, G.C. Engineering Geology and the Environment. Proceedings international symposium on engineering geology and the environment, organised by the Greek national group of IAEG/Athens/Greece/23-27 June 1997. A.A.Balkema, Rotterdam.

Investigation Techniques

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

Calleux, J.B. and Toulemont, M. 1983. La reconnaissance des cavities souterraines par methodes diagraphiques. Bulletin of the International Association of Engineering Geology. No 26-27, 33-42.

Cooper, A.H. 1989. Airborne multispectral scanning of subsidence caused by Permian gypsum dissolution at Ripon, North Yorkshire. Quarterly Journal of Engineering Geology (London), Vol. 22, 219-229.

Patterson, D, Davey, J C, Cooper, A H & Ferris, J K.1995. The application of microgravity geophysics in a phased investigation of dissolution subsidence at Ripon, Yorkshire. Quarterly Journal of Engineering Geology (London), Vol. 28, 83-94.

Poupelloz, B. and Toulemont, M. 1981. Stabilisation des terrains karstiques par injection. Le cas du Lutetian gypseux de la region de Paris. Bulletin of the International Association of Engineering Geology. No. 24. 111-123.

Planning

Paukstys, B., Cooper, A.H. and Arustiene, J. 1997. Planning for gypsum geohazards in Lithuania and England. 127-135 in Beck, F.B. and Stephenson, J.B (Editors) The Engineering Geology and Hydrogeology of Karst Terranes. Proceedings of the Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst Springfield/Missouri/6-9 April 1997. A.A.Balkema, Rotterdam.

Thomson, A., Hine, P.D., Greig, J.R. and Peach, D.W. 1996. Assessment of subsidence arising from gypsum dissolution: Technical Report for the Department of the Environment. Symonds Group Ltd, East Grinstead. 288pp.

Lu Yaoru and Cooper, A.H. 1997. Gypsum karst geohazards in China. 117-126 in Beck, F.B. and Stephenson, J.B (Editors) The Engineering Geology and Hydrogeology of Karst Terranes. Proceedings of the Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst Springfield/Missouri/6-9 April 1997. A.A.Balkema, Rotterdam.

Economics and cost-benefit analysis

Beck B.F.1991. On Calculating the Risk of Sinkhole Collapse. 231-236 in Kastning, E.H. and Kastning, K.M. (eds) Appalachian Karst. Proceedings of the Appalachian Karst Symposium, Radford, Virginia, March 23-26, 1991. National Speleological Society, Inc.

Department of Transport. 1996. Highways Economics Note No.1: 1995 Valuation of Road Accidents and Casualties, DoT, London.

ISGS. 1991. Benefits and Costs of Geologic Mapping Programs in Illinois: Case Study of Boone and Winnebago Counties and its Statewide Applicability, by Bhagwat S B and Berg R C. Department of Energy and Natural Resources, Illinois State Geological Survey.

NAO. 1992. Coastal Defences in England. Report by the Controller and Auditor General, National Audit Office. London, HMSO.

ODA. 1988. Appraisal of Projects in Developing Countries: A Guide for Economists. Overseas Development Administration, HMSO, London.

USGS. 1993. Societal Value of Geologic Maps. United States Geological Survey Circular No. 1111, by Bernknopf R L, Brookshire D S, Soller D R, McKee M J, Sutter J F, Matti J C and Campbell R H. United States Government Printing Office.