Bull Eng Geol Environ (2010) 69:159–183
DOI 10.1007/s10064-010-0277-z

ORIGINAL PAPER

# Review of approaches to mapping of hazards arising from subsidence into cavities

**Brian R. Marker**

Received: 5 July 2009 / Accepted: 22 January 2010 / Published online: 26 March 2010


**Abstract** This is one of a series of papers presenting results of work by IAEG Commission No. 1 Engineering Geological Maps, on hazard mapping. Subsidence into cavities is a major constraint to development in many areas leading to damage and, sometimes, loss of life. Many events relate to former mining but subsidence associated with karst is also widespread. Proper assessment of hazard and risk is needed to safeguard property and investment and has an important part to play in planning the location and design of new development and site investigations. Documentation maps and inventories of information are an important starting point but interpretative maps are needed to assess the full extent of the potential hazard. Many decisions have to be made by planners and developers who may not be trained in geoscience thus simplified maps are needed to alert them to potential problems and to the need to seek expert advice as well as providing a basis for prioritizing rehabilitation initiatives. To date, few published studies address the issue of risk mapping.

**Keywords** Subsidence · Hazard · Risk · Mining · Karst

**Résumé** Cet article fait partie d'un ensemble d'articles issus du travail de la commission AIGI N° 1 : Cartes de Géologie de l'Ingénieur relatives à la cartographie d'aléas. Les effondrements au-dessus de cavités souterraines constituent une contrainte majeure pour le développement dans beaucoup de régions, à l'origine de dommages et de pertes en vies humaines. De nombreux événements font référence à des activités minières anciennes mais les effondrements liés aux phénomènes karstiques sont aussi très répandus. Une évaluation correcte des aléas et des risques est nécessaire afin de garantir les biens et les investissements, pour contribuer à la planification et la conception de nouveaux développements, ainsi que pour les reconnaissances de sites. Des cartes documentaires et des inventaires constituent un point de départ important, mais des cartes prévisionnelles sont nécessaires pour évaluer complètement la répartition des aléas potentiels. De nombreuses décisions doivent être prises par les planificateurs qui peuvent ne pas être compétents en géosciences, de sorte que des cartes simplifiées sont nécessaires afin de les avertir de problèmes potentiels et les orienter vers des experts, tout en leur fournissant les bases pour les prises de décisions de réhabilitation de sites. A ce jour, peu d'études publiées concernent le sujet de la cartographie des risques.

**Mots clés** Effondrement · Aléa · Risque · Excavation souterraine · Karst

## Introduction

Subsidence is a major constraint to development in many areas. It causes increased costs, and delays, to new development; damage to existing development and infrastructure; and, in the worst cases, injury or loss of life. It may give rise to derelict land, loss of industrial production, and loss of homes. Numerous damaging subsidence events occur each year often because past development has taken place in subsidence prone areas. Many cities are associated with underground mines and have commonly grown across, originally peripheral, mining areas (see, for instance, Price 1971). There is a need to be aware of the

B. R. Marker (✉)
40 Kingsdown Avenue, London W13 9PT, United Kingdom
e-mail: brian@amarker.freeserve.co.uk

potential for subsidence and, where appropriate, to monitor and treat the ground to safeguard property and the public.

Defining and dealing with problems helps to safeguard property prices and encourages investment that is essential for reclamation and regeneration. Thorough site investigation usually allows clear definition of any problems and provides the basis for assessing problems and designing solutions. Sound precautionary measures will normally allow development to proceed safely although, in some cases, the cost of the work that is needed may make certain small developments economically unviable. Even so, subsidence problems affecting recent and new development are generally due to failure to recognise, or to fully evaluate, subsidence potential where:

- the problem is not expected in the area concerned;
- the site investigation is not appropriate for the circumstances or is of inadequate scope or funding; or
- precautionary or remedial measures that are adopted are not appropriate for dealing with the hazard fully.

Problems can be minimised by ensuring that:

- land allocated for building and construction in development plans is suitable;
- ground subsidence is taken into account when determining planning applications;
- site investigations are properly designed, and provide all of the information needed for planning decisions, and design and construction of structures and foundations; and
- adequate planning conditions and building control measures are imposed to ensure proper ground preparation and development.

Therefore, there is an important role for generalised information in alerting those who are considering development of land, or who are preparing site investigations to possible problems. Information pitched at this broader level can also assist land use planners in making decisions on allocations of land for specific purposes and in deciding what information is needed to make sound decisions on specific planning applications. It is in these contexts that hazard maps are most useful.

This paper presents selected examples to illustrate the range of types of hazard maps that have been prepared to address subsidence associated with the collapse of man made cavities such as mines, tunnels and cellars and of entrances such as shafts, adits and wells and of natural cavities, such as caves and fissures, and associated openings. It examines sources and assembly of evidence and then reviews the presentation of information as: documentation maps; maps integrating and interpreting information to differentiate susceptible zones and relative levels of hazard; maps simplified for land use planning; and maps dealing with risk. The term map is used here for both paper and electronic presentation of spatial information.

## Sources of information

Sources of information for preparation of subsidence hazard maps are varied. There are often considerable amounts of available documentary evidence on the extent of mined ground and on specific subsidence incidents. However, while natural cavities and past subsidence may be recorded to some extent, documentation of these is often less complete. However, in most, if not all, areas additional investigation is normally needed.

### Well-documented areas

Recent mining (i.e. within the past 25 years) is usually well documented in properly surveyed mine plans and abandonment plans. Maximum use should be made of these, supported, as necessary, by other sources of data. It is important that abandonment plans, at least, should be retained for use after the mining operation has closed. However, these need to be readily accessible, preferably at a central depository (DTLR 2002; Freeman Fox Ltd 1988). The need to collate information may be obvious in areas in and around populated areas but can seem less relevant elsewhere. Even for non-developed areas, it is prudent to keep information since long-term future land uses, occupation patterns, and transport networks are difficult to foresee. In addition to the relevance of this material to planning, development and reclamation of land, it is of value to emergency services if people are lost in mines or caves, or a life-threatening subsidence event occurs. It may also be useful when mining prospects are reassessed, new uses are found for abandoned mines such as secure storage, or where conservation interests are to be safeguarded.

Recent mines are often well recorded in a wide range of documents including:

- mine plans, cross-sections and drawings;
- cadastral and topographical maps;
- geological maps and field slips;
- aerial and other photographs;
- geophysical records;
- written accounts and other documents such as legal agreements, sales ledgers, and transport records;
- newspaper accounts of subsidence events; and
- site investigation reports.

Useful supplementary information is contained in accounts by travelers and historians, and from personal knowledge of researchers and of local residents.

Some information may have been published but much is likely to consist of manuscripts in archives and files in both public and private collections, sometimes distant from the areas to which it relates. Practical problems in securing these data include locating them, absence of indexes, staff effort involved in retrieving documents, and the commercial confidentiality and value of some types of information. Whilst major collections have access arrangements for enquirers, many smaller sources do not. Therefore, the search for information for a desk study prior to ground investigations may be time consuming, expensive, and incomplete. Searches are often, wastefully, repeated each time that development is proposed. However, some local authorities or other organisations have set up collections of mine information for specific areas to make this process more effective. A good example is the Atlas des Carrières Souterraines de Paris published in 1922 and revised in 1936 and 1964. This contains maps at 1:1,000 scale compiled from detailed plans of gypsum mines that exist in two series at 1:1,000 and 1:5,000 scales, respectively (Arnoud et al. 1979). In many, if not most, mined areas, however, there is, as yet, no centralised archive or index.

There are additional benefits in securing and recording information on treatments carried out on disused workings and mine openings. Although data from site investigation reports and development records are relatively rarely collated for strategic assessments of hazards, as opposed to responses to specific events, it is wise to record this to better inform proposed changes to the use of land and to reduce the costs of subsequent ground investigations.

However, in many places mining has a history of hundreds, or sometimes thousands, of years. Old mines have been forgotten. Also documentation of natural cavities is often much more limited than information for mined ground. Many caves have been well surveyed by researchers and recreational cavers, but some records can be misleading. Some have been published in the caving literature or are held by speleological societies but many are in private hands and can be difficult to locate. Many caves are yet to be discovered. Some are inaccessible and many are likely to remain undiscovered.

### Poorly documented areas

Significant numbers of unrecorded mine workings are discovered in the course of site investigations and construction works. In many developed countries, it was not until to mid- to late 19th century, and sometimes later, that any requirement to lodge mine plans with an appropriate authority came into force (Freeman Fox Ltd 1988). Even then collections may not be complete due to loss, destruction, failure to deposit the plans or because of illicit unrecorded mining. Where voids are suspected but records do not exist, new information is required. This is often so for poorly documented mined areas and is almost always the case in respect of natural underground cavities. Such information is secured from:

- walk-over inspection and field surveying;
- examination of air and satellite imagery, including results of multi-spectral and infra-red surveys;
- geophysical sounding and profiling;
- direct or indirect monitoring of ground movements; and
- borehole and trial pit investigations.

However, there can difficulties in combining and weighting the significance of material and data from mixed sources. Interpretation always remains a matter for experts and even then contains uncertainty.

### Inventories of information

Basic principles underlying collection and collation of mining data were reviewed in a study undertaken by Freeman Fox Ltd (1988). This examined retrieval of data from dispersed sources and compilation into a database. Key factors were:

- location of material: while there are usually a limited number of obvious major sources of data such as the geological survey, mineral operators, major landowners, and public authorities, there may be a great deal of important information held in other locations, including private collections. Seeking additional information is often a matter of diminishing returns. There is a practical limit on what can be achieved;
- condition and confidentiality: the physical condition of original documents is highly variable. Early plans may be fragile, unwieldy, and difficult to read. Some documents contain commercially sensitive information. Some owners may not allow access;
- accuracy: this varies greatly. Whilst many plans and other documents were prepared by engineers, surveyors, geologists or other trained personnel, much information was recorded by less expert observers. It can be difficult to decide which, amongst conflicting records, are most reliable;
- scales, projections and coordinates: are vary variable so it may be difficult registering exact positions of features depicted on early maps on modern ones, and many are in arbitrary so-called ‘plant’ coordinate systems;
- organisation: useful material may be scattered amongst other documents or stored inaccessibly. Lack of indexing can make retrieval prohibitively time consuming and expensive;
- retention: even well-organised collections are sometimes discarded when organisational changes occur, for

instance when public authorities are abolished or amalgamated. Problems of integration of different sets of material may also occur when there is no common standard or procedure between authorities; and
- interpretation: seeking and interpreting mining information requires considerable expertise and can require experienced specialists such as mining surveyors or engineers and mining historians. In an investigation of chalk mines in the City of Norwich, UK, for instance, it was necessary to have an archivist experienced in reading mediaeval documents held in Cathedral archives (Howard Humphreys and Partners 1993).

A wide variety of information may be stored but key categories include:

- mine openings that, with the exception of linear open-vein workings, are mainly point data;
- mine roadways and drainage galleries, which are essentially linear and networks of rectilinear features;
- laterally extensive workings which, with the exception of some linear workings in veins, are areas of worked ground; and
- topographical and geological features within which unrecorded mine workings or openings may be suspected on the basis of known local patterns of mining activity.

In addition, systems may record subsidence incidents or other relevant features such as conservation interests, uses of mines and mine openings, and treatment works. It is also important to record sources of data to assist in assessment of reliability and tracing of original records (Freeman Fox Ltd 1988).

The full value of investment in a data system is realized if new data are added as they become available and existing data similarly are updated. Further searches at intervals are relatively inefficient. It is desirable for planners, engineers, developers, and others to lodge data in appropriate databases as a matter of course for the common benefit of all users of mining information. Therefore, clear guidelines about how to provide information are needed to ensure that all site investigation reports are referred to the data managers. Hazard maps need to be revised as new information comes to hand. This is much easier nowadays since well-maintained databases linked to GIS can update maps quickly.

Therefore recorded data should be factually as precise, complete, and carefully transcribed as possible but it is prudent to leave interpretation to the expert user. Guides to users should emphasise that no databases of mining information are likely to be complete and that users should attempt to collect additional, unrecorded features that may be present in any site, and to seek appropriate expert opinions where necessary. Failure to provide an appropriate disclaimer might give rise to legal liability on the part of the owner of the data system. Similarly, great care is needed in transcribing information from original records to avoid any charge of negligence. It is wise to charge the user with checking original records. Since information from different sources varies in accuracy and reliability, it is generally unwise to make judgements without further investigation since an apparently poor record may report a real and dangerous void, while an apparently well-presented report may contain crucial errors. It is better to report the information in a neutral manner but to accompany it, as necessary, with a separate commentary on limitations. Examples are:

- the failure of geophysical techniques to indicate the presence of a void or shaft does not mean that these are absent but, rather, that they have not been detected; and
- two separate records of a mineshaft at a single location do not necessarily relate to a single shaft since one, or both, may not have been plotted precisely; similarly two clearly separated records of shafts from different sources may refer to a single shaft.

It is also sensible to separate data delivered from the database from interpretative steps such as hazard or risk assessment and mapping undertaken by the database holder.

Many of these considerations apply also to natural cavities if documentary records exist. However, it is usually necessary to extrapolate from additional information on factors such as the physical, structural and chemical properties of the bedrock and superficial deposits, geomorphological setting and hydrological and hydrogeological conditions, rather than to rely on documented occurrences, as well as taking account of environmental changes since cavity formation may have taken place in past conditions, be relatively inactive at present, but resume in the future.

## Documentation maps

If existing documentation is extensive, even though not usually complete or wholly accurate, it is a reasonable starting point for:

- outlining areas which may contain mined ground or mine openings and, thus, for defining areas within which past mining may have taken place; and
- providing essential background information for the planning of site investigations.

Documentation maps simply showing areas where subsidence has taken place can be shown by the plotting of locations of known underground cavities and of past subsidence incidents.

A national review of mining instability in Great Britain (Arup Geotechnics 1992) involved the collection and collation of existing information on mined ground for the whole country with the main purpose of alerting local authorities of the need to take account of mined ground when planning for development and regeneration. All 1 km squares within which some mining had been recorded were coloured in on maps at 1:250,000 scale for five categories of minerals, together with a general indication of how conclusive the documentary evidence was. Coalfields were outlined as a whole, even though records were comprehensive only for parts of these, because mining was known to have been widespread. Users could consult a database using codes shown on the map. Data sheets provided a summary of mining by county and district, mining area schedules, lists of mines and mined areas, and references.

A similar national review of natural underground cavities (Applied Geology Ltd 1993a) could not adopt this approach because existing information was too sparse and was biased towards, for example, popular areas for karst research, and areas of recent subsidence problems. Cavities were classified into four categories: cavities produced by dissolution, marine erosion, cambering and other processes. Since dissolution cavities are strongly related to geology, point locations of these were plotted on an overlay to a geological map to enable users to relate records to the geological strata and, thus, to obtain a general impression of subsidence potential. However, it was recognized that this could be misleading since lithology is only one of several factors that influence their distribution.

Broad scale documentation maps often show point locations for subsidence phenomena and events. For example, a map of part of Calvados, France where subsidence is associated with both mines and karst phenomena, observed features were distinguished, were left undifferentiated where the cause was uncertain. At the scale of representation the symbols used were of standard size rather than reflecting the scale of the individual events (Durville and Hameroux 1995).

In an area of gypsum dissolution at Ripon, UK, surface hollows were mapped (Fig. 1, taken from Cooper 1989). It was difficult to distinguish choked subsidence structures, which became waterlogged and infilled with peat, from

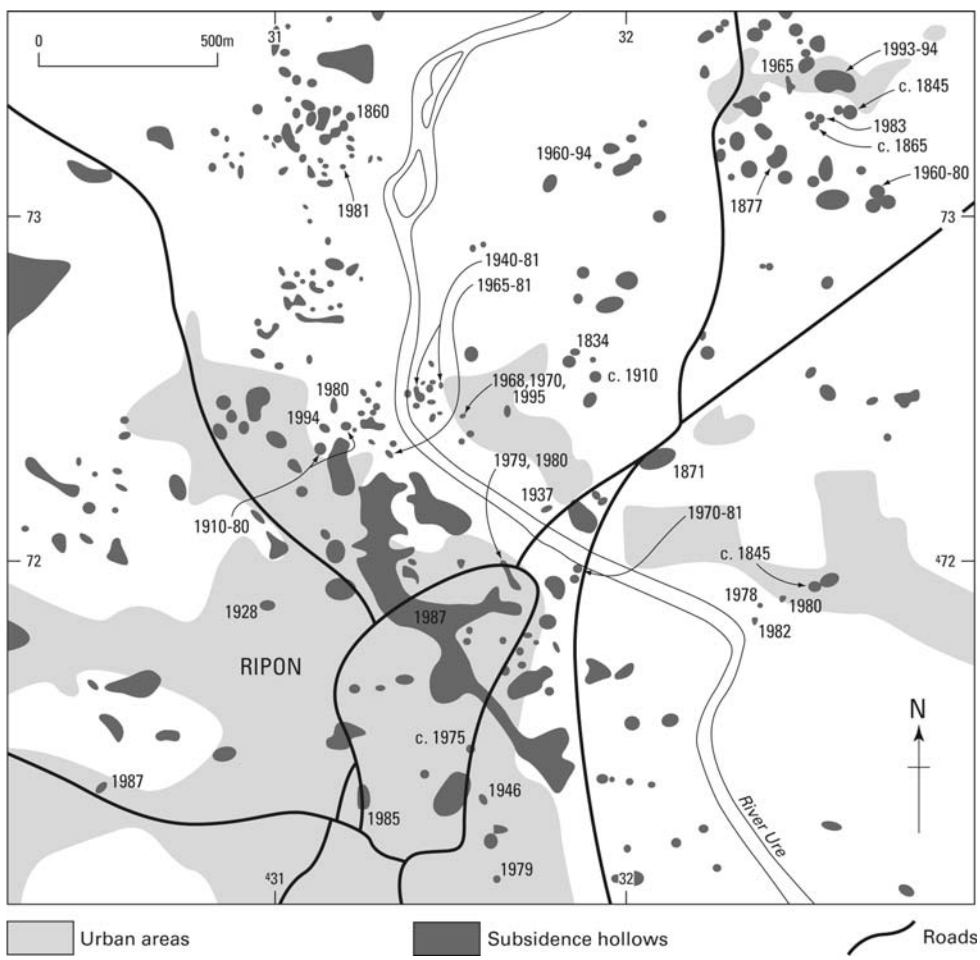



**Fig. 1** Distribution of subsidence hollows in the Ripon area, UK, showing dates of subsidence events where known (from Cooper 1989)

hollows formed by melting of ice during late Pleistocene de-glaciation. Therefore, all hollows were regarded as suspicious until proved otherwise. Large hollows were shown at true scale but smaller structures were point representations. The dates of subsidence events were shown, where known, to give some indication of frequency.

Documentation maps may present information from mine plans. In the example from Paris mentioned earlier (Arnoud et al. 1979, op cit) detailed information on the extent and internal characteristics of mine voids was plotted. An alternative approach is to indicate the maximum extent of mined ground rather than details of workings. For instance, the City of Bristol, UK, is underlain by Carboniferous Coal Measures, which are partly concealed by Mesozoic strata and superficial deposits. The Carboniferous strata area extensively folded, with dips of up to 60°, and faulted and are, in places, overfolded or thrusted. Therefore, patterns of coal mining were complicated. The earliest record is a document of 1223 AD. Early mining was at outcrop but, by the 14th century, bell pits were worked close to the outcrops of coal seams. Pillar-and-stall mining was introduced in the 15th century and, by 1670, there were about 70 pits working to depths of about 30 m in the Kingsmead area of the city. With the advent of steam pumps the industry expanded rapidly so that, by 1750, there were about 150 operational collieries in the Bristol area. The later stages of mining were by topple and longwall methods. Machine cutting was not introduced widely because of the folded and faulted nature of the strata. The coalfield went into rapid decline in the late 19th century and the last colliery closed in 1956. Thus, the area was left with both recorded and undocumented mine voids of a variety of types, sizes, depths, and ages.

A study of about 100 $km^2$ of the central and south parts of the City and the urban fringe to the east was based mainly on published and manuscript documents. The largest source was sets of mine abandonment plans held by the then National Coal Board but some older mine plans were held by the Bristol City Records Office. Other sources held site investigation reports prepared by civil engineering contractors in connection with construction and which provided information on many otherwise undocumented areas. The compiled information was sufficient to outline key areas of mining but records were fairly complete only for the period since 1872 when it became mandatory to produce mine abandonment plans. Earlier mining was sparsely recorded for instance there were records of shafts but none of associated workings in four parts of the area. The resulting maps showed the recorded extent of mined ground in a number of individual coal seams at various levels within the ground (Fig. 2, Howard Humphreys and Partners 1987).

In the City of Nottingham, UK, more than 400 "caves" occur in Permo-Triassic sandstones. Most are within the urban area of the City of Nottingham and, especially, in its mediaeval core. Although a few sandstone mines are known, most of the "caves" were cut in the weak to moderately weak, easily excavated sandstone for storerooms, basements, factories, cellars, dwellings and air raid shelters over a period of about 750 years. Some of the caves are of historical interest, merit conservation, or are used for tourist visits while others present potential problems for redevelopment of land. Many have been filled, destroyed, or lost and forgotten. Even so, a large number are either still accessible or have been recorded in the course of site investigations (Waltham 1992, 1993). In the 1980s the British Geological Survey was commissioned to compile a register of the caves (Owen and Walsby 1989) based on site investigation and other documentary data. The resulting database is available for consultation by planners and developers. This provided plans at scales of 1:2,500 scale and commentaries on the characteristics of each cave, including historical and archaeological interest, and sources of data. Subsidence incidents were described and available details of treatment works were included.

Documentation mapping provides valuable information to those preparing site investigations and alerts users to historic subsidence. However, integration and interpretation of data is needed to define subsidence potential.

## Integration and interpretation of data

Integration and interpretation of data is required to establish the likely maximum extent of zones that may be susceptible to subsidence and the relative levels of hazard in different parts of these. Essentially two approaches can be taken to integration and interpretation of data. Probabilistic approaches rely on the occurrence in time and space of hazard events and therefore require extensive high quality data on these. However, for many subsidence hazards there are insufficient available data. Deterministic methods consider factors that bring the hazard about and do not quantify the hazard but, rather, indicate the potential for events. This approach has the advantage that factors can be re-assessed as knowledge improves, or additional factors can be added to reflect, for example, environmental (including climate) change (Harrison and Forster 2003). The majority of published subsidence hazard evaluations are deterministic in nature.

Maps are classified, in general, in this paper into those showing the extent of zones that are susceptible to subsidence, and maps depicting relative levels of hazard within such zones.

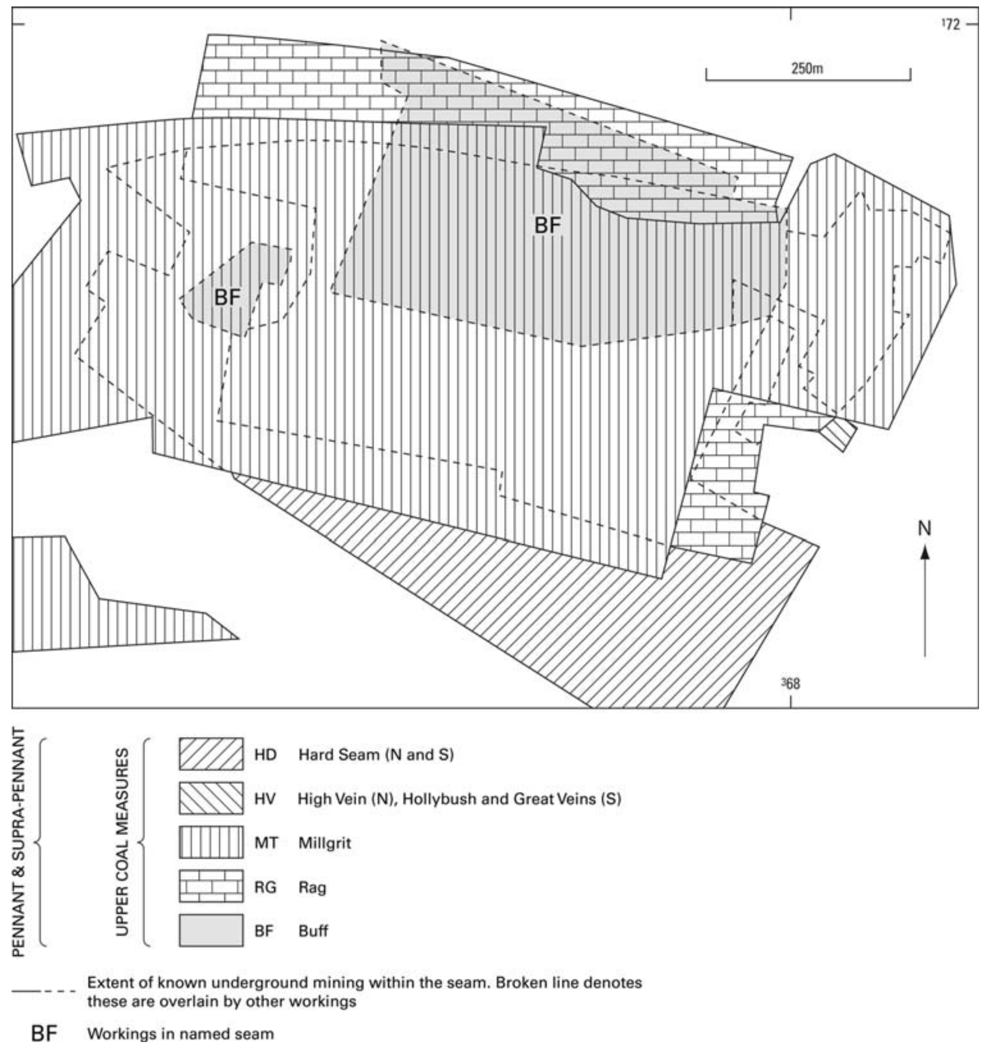



**Fig. 2** Areas of underground mining for coal recorded on abandonment plans, Bristol, UK. Original is at 1:100,00 scale (from Howard Humphreys and Partners 1987)

## Susceptible zones

Three examples are presented here of approaches to outlining areas that may be susceptible to subsidence. These deal with areas mined, respectively, for salt, gypsum, and coal with fireclay.

Northwich, UK, had a long history of salt mining, from 1777 to 1933 that still gives rise to collapses of ground from time to time. Initially shallow pits and brine springs were used. In the mid 19th century it became necessary to sink boreholes and to pump the brine to the surface. The salt was found to occur in a narrow linear belt extending northeast to southwest through the town. Ground subsidence was reported at a number of locations in the 1920s. By 1979, the local authority was able to observe a number of sinkholes and water filled hollows within the linear zone, together with general broader scale subsidence. Local consultancies had records extending back for many years. Analysis of these suggested that after cessation of brine pumping in 1972, natural dissolution of salt became the main factor, as the groundwater, disturbed by earlier pumping, regained its equilibrium. However, that equilibrium differed from the original situation because of the development of more extensive dissolution cavities during the exploitation of the resource. Geomorphological mapping and records of past mining, building damage and ground movements were used to define areas: undermined but showing no surface expression of subsidence; with surface evidence of actual or potential subsidence; or surface evidence of complete collapse. This allowed classification into areas of significant to severe surface subsidence, significant surface subsidence, stream and valley slopes, and areas in which severe to significant surface subsidence had occurred in combination with significant slopes (Lee and Sakalas 2001). It was possible to develop a four-fold classification of the area linked to subsidence behaviour (Fig. 3, Applied Geology Ltd 1993b):

- active brine run (“A” in Fig. 3): areas known or anticipated to be experiencing differential ground settlement, most of which is concentrated at the margins of the zone. Maximum annual settlement in the axis was recorded as up to 17 mm per year, and the maximum differential settlement discerned was up to 1 mm (vertically) in 4,000 mm (horizontally) per year;

- passive brine run ("B"): areas known or anticipated to be experiencing minor ground movements not exceeding 5 mm per year with little or no differential factor. This zone may possibly become active in the future;
- historical brine run ("C"): areas that, on the basis of hydrogeology and geological structure, may possibly experience ground movements in the future. Presently the zone is stable, but it is possible that movements may develop in future; and
- suspected brine run ("D"): areas that, on the basis of geological structure, are suspected to be experiencing ground movements in the manner of zones A and/or B.

There were insufficient data available to be more certain.

In some mapping exercises, more emphasis is placed upon ground investigations. For instance, a succession of Eocene limestones, marls and sands outcropping in the north of Paris includes gypsiferous horizons, of very variable thickness, beneath a sandstone cap. The gypsum has been mined and a good set of mine plans existed. However, the distribution of dissolution cavities and other suspect zones is less well known (Arnoud et al. 1979, op cit). Engineering geological mapping, supported by a borehole survey, was undertaken in order to identify the extent and thickness of deposits of gypsum, whether they had been quarried, and the depths at which the gypsum occurs. The geotechnical characteristics of the deposits were identified and the ground water conditions were examined. The results were used to predict the necessary depths of site

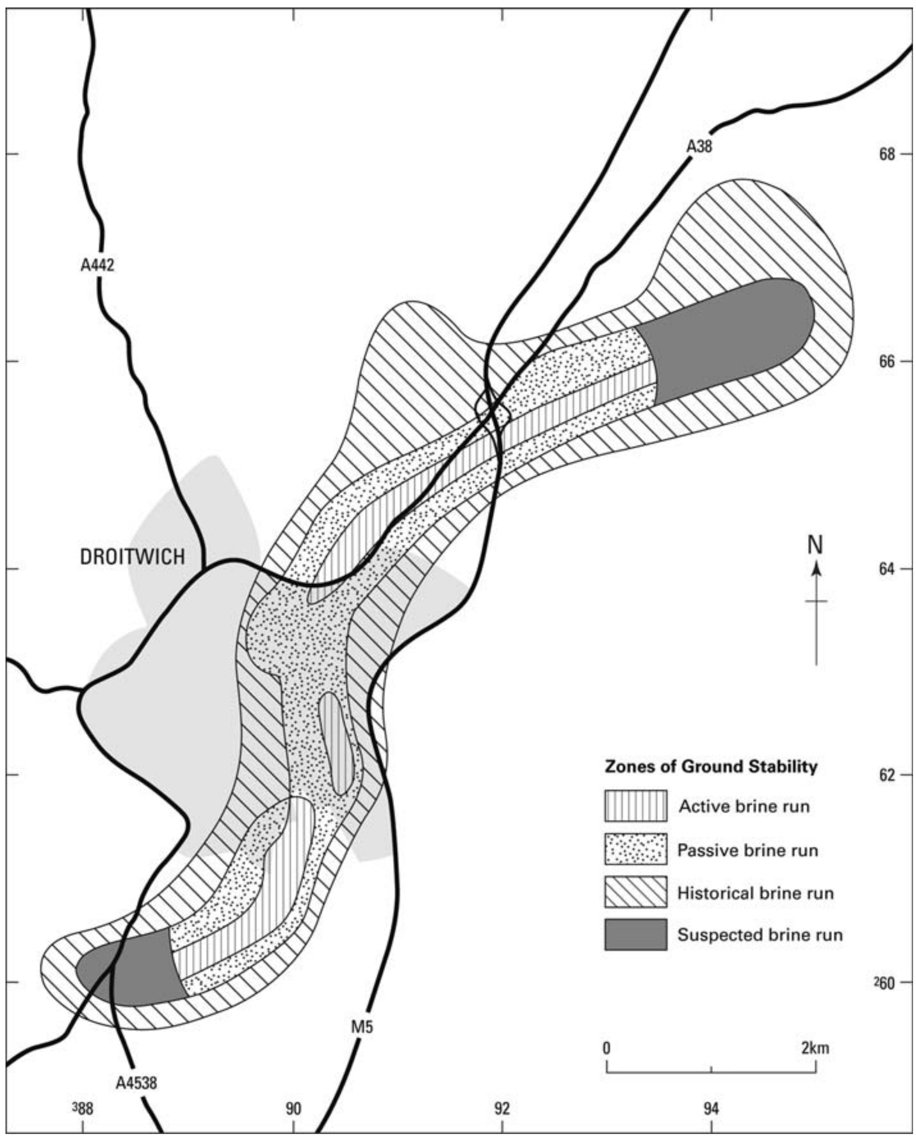
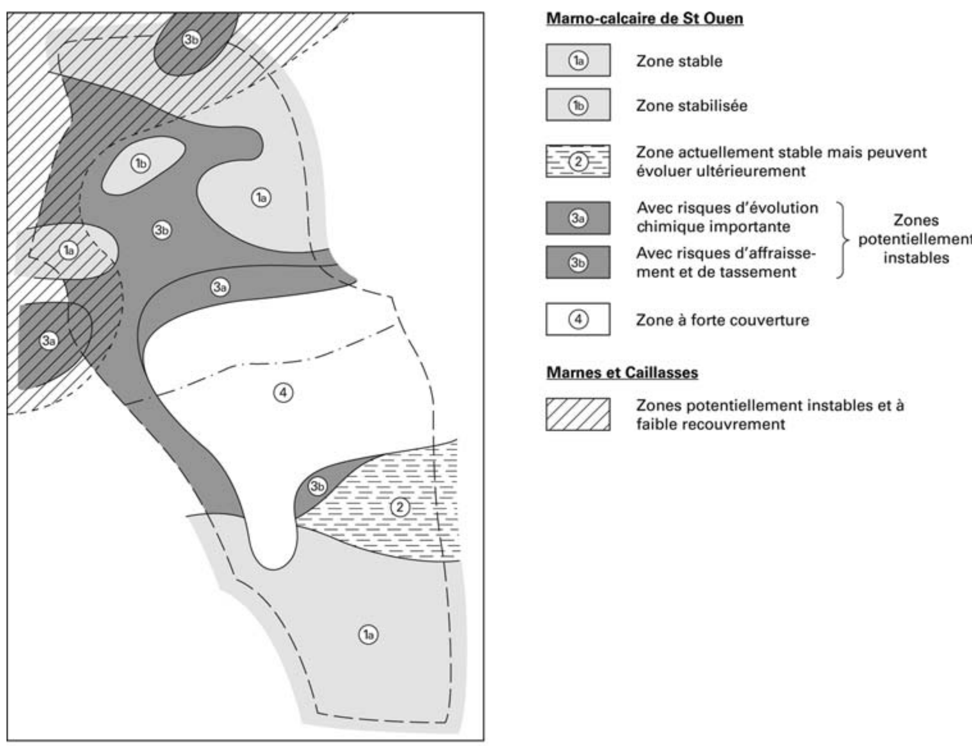



**Fig. 3** Stability zones within the Droitwich salt field, UK. Original scale 1:500,00 (from Applied Geology Ltd. 1993a)

investigation boreholes. A map showing solution hazard zones was prepared (Deveughèle and Usseglio Polatera 1979) based on the extent of the gypsum, the dissolution characteristics, and the depth of the gypsum below ground level. These factors were used to define 4 zones, and a number of subzones related to potential for dissolution (Fig. 4).

Alternatively, interpretation may be based on deduced subsidence behaviour. A study of ground mined for coal and fireclay at Bradford, UK drew on knowledge of subsidence characteristics in the area. The area consists of about 400 $km^2$ of land underlain by Carboniferous strata. These consist of alternating sandstones and shales (Millstone Grit) passing up into rhythmic shales, sandstones, and coals (Coal Measures). The Carboniferous rocks are covered extensively by superficial deposits consisting of till on the higher ground and outwash sands and gravels infilling the valleys. The Coal Measures provided fuel for an important manufacturing industry in the 19th century. This left a legacy of mined ground and contaminated land. Sandstone was also mined for building stone. The geology of the area was remapped by the British Geological Survey (BGS) resulting in significant amendments to the existing maps because of revised correlations between coal seams and improved information on made ground. All available published and manuscript information was collected and collated. This included nearly 11,000 borehole and trial pit records, air photographs, mine abandonment plans,




**Type 1: Zones stables ou stabilisées sans possibilité d`évolution ultérieure**

**1a:** Zones stables. Ce sont celles où le Marno-calcaire de Saint-Ouen est présent sous le faciès calcaro-marneux, non gypseux, et avec de bonnes caractéristiques géotechniques.

**1b:** Zones stabilisées. Ce sont celles où le Marno-calcaire de Saint-Ouen est essentiellement marneux et dont le gypse a en principe été totalement lessivé. L`évolution de ces zones est ancienne et les terrains sont reconsolidés. La stabilité d`ensemble est bonne, la stabilité locale peut présenter quelques aléas.

**Type 2: Zones actuellement stables mais pouvant évoluer ultérieurement**

Ce sont les zones où le Marneux-calcaire de Saint-Ouen présente une phase gypseuse saine et où les risques de dissolutions sont actuellement inexistants.

**Type 3: Zones potentiellement instables**

**3a:** Zones où un risque d`évolution chimique est à craindre. Ce sont des zones où la phase gypseuse est actuellement practiquement intacte ou encore importante, mais où le processus de dissolution semble engagé suite au modifications récentes de l`hydrodynamisme de la nappe. L`évolution peut être rapide et à l`échelle de la durée de vie des ouvrages. Il convient dans ces zones d`accorder une attention toute particulière aux données hydrogéologiques.

**3b:** Zones présentant des risques d`affraissement ou de tassement. Ce sont des zones où la phase gypseuse du Marno-calcaire de Saint-Ouen a été en grande partie lessivée à une période récente et où la formation présente géneralement à la fois des traces de gypse résiduel, des vides éventuellement remplis par un bourrage argilo-sableux, des zones décomprimées. Ces zones présentent des risques certains d`instabilité qu`il convient donc d`identifier pour pouvoir y faire face.

**Type 4: Zones où le toit du Marno-calcaire de Saint-Ouen est à plus de 30 mètres de la surface du sol**

Une figure en surcharge indique les zones où les Marnes et Caillasses sont à une profondeur relativement faible dans lesquelles un risque d`instabilité, lié à la phase gypseuse de cette formation, est à craindre.

**Fig. 4** Dissolution hazard associated with gypsum deposits, Saint-Ouen, France (from Deveughle and Usseglio Polatera 1979) hydrological, and hydrogeological records. Computer databases of borehole and trial pit data, site investigation reports and other data were prepared. Maps were presented, at 1:25,000 and 1:50,000 scale. Past subsidence events demonstrate that the ground surface is normally only disrupted by subsidence associated with coal mine voids at depths of 30 m or less. Therefore, the map of mined ground showed the outcrop area of the Coal Measures where workings for coal potentially exist, known underground colliery based mining at depths less than 30 m below ground surface, areas of known colliery based mining deeper than 30 m, and areas known to contain bell pits and crown holes. This, therefore, indicated areas where subsidence associated with these mines was most likely to occur (Waters et al. 1996; Fig. 5). An unusual feature of the investigation was that local authority planners contributed to the design of the project and were involved in the work throughout. In addition, a seminar was held at the start of the work for representatives from the local authority, businesses, financial interests and regulatory agencies giving the work a degree of local “ownership” from the outset. A high level of interest was maintained throughout and attendance at a final seminar to present the results was good. The Borough Council then took account of the material in the preparation of a development plan for the area and made use of the databases prepared during the research, although a subsequent showed that results are not now being used in the planning process as fully at they could be, probably due to staff changes since the original research was undertaken (Smith and Ellison 1999).

Simón-Gómez and Soriano (2002) considered the density of occurrence of dolines in the vicinity of Zaragoza, Spain. Fluvial terraces of the Rio Ebro overlying gypsiferous deposits are affected by subsidence structures of the order of 10–100 m wide and 1–12 m deep as well as larger shallow depressions up to 1,100 by 600 m in extent. The

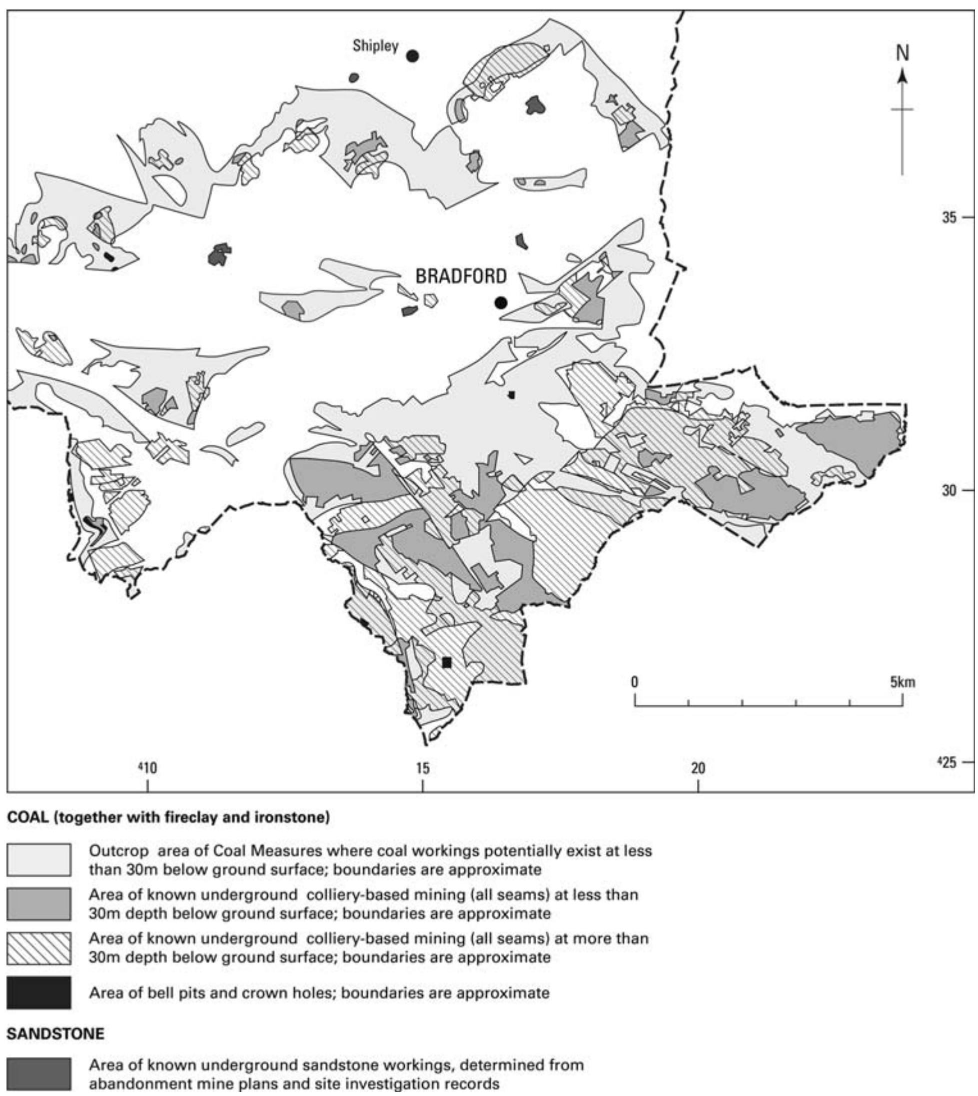



**Fig. 5** Map showing the extent of underground mining, Bradford Metropolitan District, UK (simplified version from Waters et al. 1996)

subsidence structures were mapped using four sets of air photographs spanning a 40 year period and field survey. In urban areas features such as fractures in, and tilting of, built structures as well as subsidence of the ground level were used to map features. The results were then expressed as numbers of unit dolines per km$^2$ where the unit dolines measured between 10 and 100 m across. The larger scale subsidence features were taken into account by weighting these with a coefficient proportional to the relative area. The resulting 1:50,000 scale map (Fig. 6a) provided an overview of the past occurrence of subsidence within the study area.

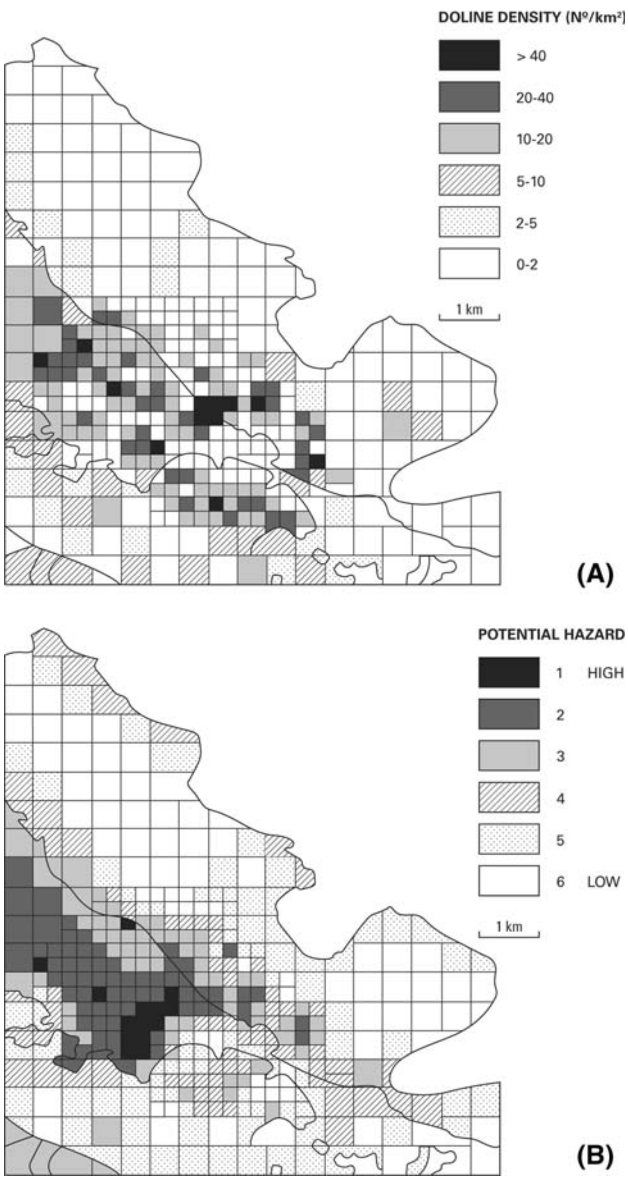



**Fig. 6** **a** Density of occurrence of dolines near Zaragoza, Spain (from Simon-Gomez and Soriano 2002). **b** Subsidence potential near Zaragoza, Spain (from Simon-Gomez and Soriano 2002)

## Relative hazard

While it is useful to know which areas are potentially susceptible to subsidence, it is better to be aware of relative levels of hazard within these areas. The main approaches involve estimating the frequency of subsidence phenomena, or methods of weighting according to factors that influence subsidence potential.

In the work on the Nottingham caves, mentioned earlier, the compiled data permitted quantitative plotting of the distribution (Charsley et al. 1990). Three classes were defined with, respectively, 1, 2–9, and more than ten occurrences per 0.0625 km$^2$ (1/16 km$^2$) and were contoured. A somewhat similar approach was used to identify localities especially prone to subsidence from limestone dissolution in Lawrence County, Indiana USA (Adams and Lovell 1984).

Research undertaken on the St Helens area of Merseyside, UK included plotting the distribution of disused mineshafts (Doornkamp and Lee 1992) on a 1 km square basis. Six classes were defined with the limits (0–5) (6–10) (11–15) (16–20) (21–25) and more than 25 per km$^2$. In the Lawrence County study, envelopes were drawn around areas of similar values while in the St Helens work a pixel-based presentation was adopted.

However, the relative frequency of occurrence of structures related to subsidence potential and subsidence events provides only a very general guide to the hazard. Also, past circumstances may not be a good guide to the future because of climate and other environmental changes. More advanced approaches attempt to give relative weights to influencing factors. Five examples are reviewed here.

Dougherty Plain, southwest Georgia, USA, is underlain by Eocene Ocala Limestone generally covered by up to 50 m of Oligocene to Recent residual deposits. The area has numerous karst features including dolines, uvalas, semi-blind and blind valleys, sinking streams and springs. Closed depressions had formed as a result of subsidence and suffusion of the limestone. In recent years, subsidence events have become more frequent. Increasing exploitation of ground water resources led to concern that sinkhole formation might further accelerate. A study (Brook and Allison 1986) was undertaken to assess the susceptibility of land within the area to subsidence based on the principles that:

- formation of one doline tends to promote subsurface conditions conducive to the formation of others (Ford 1964);
- areas of West Virginia underlain by the most cavernous rock displayed the most dolines and that the percentage of the limestone area consisting of dolines and the

doline density were useful indicators (Ogden and Reger 1977); and
- preferential formation of solution voids along zones of high secondary permeability that concentrate groundwater flow had been observed.

United States Geological Survey maps showed only about 40% of the known sinkholes in the area because the remainder were too shallow to be plotted using a 10 foot (3.05 m) contour interval. Therefore, sinkholes were mapped using infrared satellite images from presence of surface water, vegetation and soil moisture patterns, and topography. Mapped boundaries were corrected for distortion and were transferred to 1:24,000 scale topographical maps. A total of 1,011 sinkholes were plotted giving an average density in Dougherty County of 1.1 per $km^2$.

The County was divided into 1 $km^2$ cells and, for each of these:

- the number of sinkholes was recorded: the maximum number in any cell was 15; and
- the total area of sinkholes: only five cells had more than 30% of their area covered by sinkholes.

The results were broadly indicative of the numbers of cavities in the limestone and, thus, of the likelihood of further subsidence or suffusion of residual deposits. It was postulated that the numbers of sinkholes within a cell increased until about 15 had formed, after which these coalesced to form uvalas and fewer new sinkholes formed. It was also noted that many of the sinkholes were elongated and that groups of sinkholes appeared to lie on linear trends. A statistical analysis of linear elements of sinkholes in randomly selected cells were measured and grouped in 10 degree classes. It was found that six classes were non-random at the 0.95 level of confidence. When adjacent significant classes were merged, three preferred compass orientations were revealed 005, 030, and 315 degrees. A full analysis of linear trends was then undertaken and infrared images were checked for supplementary evidence. In all, 1,298 possible fracture trends were mapped. End points of factures were then digitised and lengths and orientations were counted. Fractures were then grouped in 10 degree classes and the numbers and total lengths of fractures in each class were deduced. Six classes were non-random at the 0.95 level of confidence. When adjacent classes were grouped three major preferred orientations emerged: 005, 040, and 325 degrees, close to the earlier results. The "fracture density", "fracture intersection density" and total lengths of fractures in the area were then calculated. These agreed well with field observations of trends of joints in the Ocala Limestone, as well as other strata in nearby areas of Georgia and Florida, supporting the view that sinkholes developed above, and are elongated parallel to, fractures in the underlying limestone.

GIS technology was used for analysis. The sinkhole and fracture data files were used to model susceptibility of cells to subsidence. Susceptibility was assumed to increase with all variables except sinkhole area such that it reached a maximum when 15–24% of the cell was occupied by sinkholes after which lateral coalescence became dominant. Intersection modelling involved identification of cells with specific values of identified variables taking broader ranges of values for the variables in successive intersections. The initial identified cells (thought to be most susceptible), thus, had cells thought to be less susceptible added successively to them (Table 1). Of the total 855 cells, 577 had not been identified in the fourth intersection and thus had the lowest susceptibility assigned to them. Linear combination modelling was then undertaken. Each variable was weighted in respect of its judged influence on susceptibility of the area to future ground subsidence. Each cell was assigned a map value using the equation:

$$\text{Map value} = W_{k1}r_{k1} + W_{k2}r_{k2} + W_{k3}r_{k3}\ldots W_{kn}r_{kn}$$

where $W$ = variable weight.

$r$ Value weight.
$k_{1-n}$ Index of the variable.

The model was used to generate variable and value weights (Table 2). The numbers of sinkholes and numbers of fractures in a cell were considered to be the most important measure of susceptibility to future development and were assigned the highest weight (20) The number of fracture intersections was thought to be the next most

**Table 1** Values of variables specified for intersections 1–4, Doughty Plain, south west Georgia, USA (after Brook and Allison 1986)

| Variable | Specified values of variable | | | |
|---|---|---|---|---|
| | Intersection 1 | Intersection 2 | Intersection 3 | Intersection 4 |
| Number of sinkholes | 12–15 | 10–15 | 4–15 | 12–15 |
| % area of cell covered by sinkholes | 15–24 | 10–29 | 5–35 | 5–35 |
| Number of fractures | 7–9 | 5–9 | 3–9 | 1–9 |
| Number of fracture intersections | 12–19 | 8–19 | 4–19 | 2–19 |
| Length of fracture (kms) | 3.7–7.2 | 2.8–7.2 | 1.9–7.2 | 1.0–7.2 |

**Table 2** Variable and value weights used in linear combination modelling, Doughty Plain, south west Georgia, USA (after Brook and Allison 1986)

| Variable | Variable weight | Values (V) and value weights (VW) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of sinkholes | 20 | V | 0–1 | 2–3 | 4–5 | 6–7 | 8–9 | 10–11 | 12–13 | 14–15 | | |
| | | VW | 1 | 4 | 4 | 6 | 6 | 9 | 9 | 9 | | |
| % area covered by sinkholes | 6 | V | 0–4 | 5–9 | 10–14 | 15–19 | 20–24 | 25–29 | 30–34 | >35 | | |
| | | VW | 1 | 4 | 6 | 9 | 9 | 4 | 4 | 1 | | |
| Number of fractures | 20 | V | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | | VW | 1 | 4 | 4 | 6 | 6 | 6 | 9 | 9 | 9 | 9 |
| Numbers of fracture intersections | 15 | V | 0–1 | 2–3 | 4–5 | 6–7 | 8–9 | 10–11 | 12–13 | 14–15 | 16–17 | 18–19 |
| | | VW | 1 | 4 | 4 | 6 | 6 | 6 | 9 | 9 | 9 | 9 |
| Length of fractures (kms) | 12 | V | 0–0.9 | 1–1.8 | 1.9–2.7 | 2.8–3.6 | 3.7–4.5 | 4.8–5.4 | 5.5–6.3 | 6.4–7.2 | | |
| | | VW | 1 | 4 | 4 | 6 | 6 | 9 | 9 | 9 | | |

significant, followed by total length of fractures in cell (15 and 12). The area of a cell occupied by sinkholes was thought to be least important and was given the lowest weight (6). Calculated map values were classified into five groups each covering an equal portion of the total range of map values assigned and these were regarded as relatively, high, moderately high, moderate, moderately low and low susceptibility. Comments were then made on the relevance of the findings to exploitation of water resources and disposal of waste.

Assessment of dissolution hazard was undertaken for the Moscow-Nizhny Novgorod Railway in Russia (Tolmachev et al. 1999). Depths to "dissolution anomalies" were mapped along the line and were classified into three classes (0–15), (10–60), and (25–75) metres. The frequency and probability of collapse ($P_r$) were then assessed and the following empirical equation was constructed:

$$P_r = (A_n/A + d.\, A_o/d_{max}.A)(1 - P)$$

where $P = \exp\,(-LA_t)$ and $A = (A_o + A_n)$.

$L$ Frequency of collapse in kms/year.
$A_n$ Area of railway track bed.
$A_o$ Area of site along railway at distance $d_{max}/2$ from the toe of the embankment or edge of the cutting.

Although this technique was used for a nearly linear assessment, the method could be adapted for use over a broader area.

Subsidence, which occurs in, and near the outcrop of chalk in South East England relates to either solution features or to the collapse of old mines. Extraction commenced with Neolithic flint mines. Later, workings were undertaken for carbonate or for lime for agricultural or other purposes. Most mines were abandoned unrecorded before the late 19th century. Both mines and solution features are known to occur beneath thin Eocene and Pleistocene cover. Some types appear to be preferentially located where chalk is covered by thin superficial deposits (Edmonds et al. 1987) because of geomorphological processes influencing dissolution and mines for agricultural carbonate and lime were sunk through thin sands and gravels where the excavated material was needed for application to the soil. Research was undertaken in order to develop a subsidence prediction model taking account of both the natural and man-made voids. Factors governing the spatial distribution, stability, and subsidence triggers associated with artificial cavities were identified. These were a regional factor (R), locational factor (L) and a stability factor (S), to be combined as:

$$SHR_A = (R + L)S$$

where $SHR_A$ is the subsidence hazard (SH) rating for artificial cavities. The regional factor took account of the varying numbers of cavities in regions and thus per unit area on a weighted scale of 0–10. The locational factor took account of the variation of type and purpose of cavities between locations on a scale of 0–5. The stability factor related to the soundness of the cavities, which depended on factors such as type, size, the skill of the original excavators, geological situation and rock mass properties. The incidence of subsidence of the cavity types was established from a collected database and was used to rank the cavity types on a scale of 0–10.

Six key factors were identified as governing the distribution of natural solution features:

- the lithostratigraphy of the chalk ($G_1$) reflecting the relative proportions of metastable solution features associated with the main stratigraphical divisions of the chalk on a scale of 0–20;
- the nature of post Cretaceous deposits ($G_2$) taking into account the importance of the presence of such deposits (0–20), characteristics of the Tertiary (0–20) and Quaternary deposits (0–5) and summed to give a single value;

- water table ($H_1$) to allow for the influence that this has on the subsidence process (0–10);
- topographical relief and drainage ($H_2$) which is especially important in reflecting relative proportions of metastable features associated with particular settings (0–10);
- former drainage paths ($GM_1$) rated (0–10) for similar reasons; and
- glacial deposits ($GM_2$) since the presence of this may be conducive to subsidence (0–5).

These were combined into the formula:

$$SHR_N = (G_1 + G_2 + H_1 + GM_1 + GM_2)H_2$$

where $SHR_N$ is the subsidence rating for natural solution features.

The model was applied by subdividing trial areas into small units on the basis of topographical relief and drainage using air and satellite imagery in conjunction with topographical maps. The model for artificial cavities was tested in a trial on an area around Dartford (Fig. 7) and, on natural solution features, near Henley (Fig. 8), both UK, because good information on the distributions of cavities was already available. The maps showed good correspondence with the known distributions. The method was later consolidated and extended (Edmonds 2001a, 2001b).

Work on the coast of the Western Algarve, Portugal (Forth et al. 1999) illustrates a different approach to weighting. The succession consists of Miocene limestones, beneath Pleistocene sands. The limestones are subject to the formation of caves, sinkholes and gullies; the research examined the factors influencing their formation. Geomorphological, geological and vegetation cover mapping was undertaken at scales of 1:2,000 and 1:5,000. Factors that were examined were sinkhole and sea-cliff formation, cave formation, gulleying, slope angle, tension cracks, fissures, rockfalls, mechanical strength and vegetation cover. These were classified in terms of the degree of influence on hazard. The weighting system is summarised in Table 3. In practice, the summed weightings for selected parts of the area gave maximum scores of 40 for very highly influential, 30 for highly influential, 20 for moderately influential and 10 for slightly influential factors. This approach was applied to each 100 $m^2$ and plotted onto a 1:5,000 scale base map.

Simón-Gómez and Soriano 2002 (op.cit.) examined subsidence potential in the Zaragoza area by comparing five influencing factors with doline distribution data. They found that karst depressions form preferentially where sulphate content in the groundwater is low, the mean grain size of detrital cover is coarse, buried palaeovalleys exist at the contact between soluble and clastic materials, the maximum annual variation of the water table is large, and


**Fig. 7** Subsidence hazard assessment for deneholes, Dartford, UK. Original scale 1:25000 (from Edmonds et al. 1987)

detrital cover is thin. Examination in detail of each of these allowed the researchers to develop weightings for each which could then be combined into a hazard model. The empirical equation used was:

$$H_t = 850/\left(0.5S + 70I_b + 5L + 20T_q - 125V_w\right)$$

where $H_t$ was the theoretical hazard index, S the sulfate content of water in ppm, $I_b$ the height index of the Tertiary-Quaternary surface in arbitrary values from 1 to 5, $L$ the percentage of lutites in Quaternary sediments, $T_q$ the thickness of Quaternary cover in metres, and $V_w$ the maximum annual variation of the water table in metres. The results (Fig. 6b) were plotted on the same grid as Fig. 6a. A good correspondence between the doline density map and the potential hazard map was found except in the east of the area where actual occurrences exceeded predicted occurrences. The authors cautioned that the results are

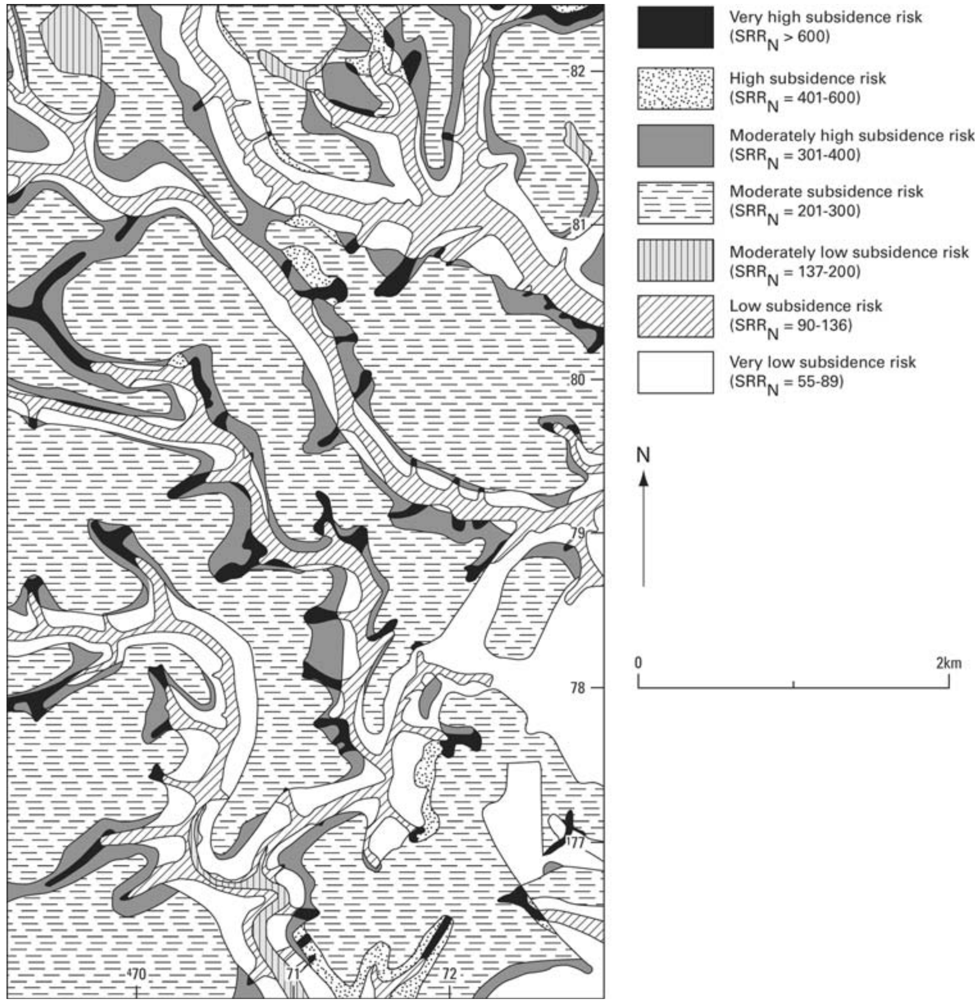



**Fig. 8** Subsidence hazard assessment for natural solution features, Henley, UK. Original scale 1:25000 (from Edmonds et al. 1987)

valid only at the scale used and that other variables also need to be taken into account, including fractures in the soluble substratum, irrigation networks, and groundwater abstraction.

All of these approaches, while valuable in their own right, are not easily used by non-specialists for whom simplification is required.

## Simplified maps for planning and development

Many land use planners are not trained in the geosciences or related disciplines and need clear guidance on where subsidence hazards need to be taken into account. Simplified maps based on sound data, and linked directly into land use planning procedures, are needed.

In Bristol, UK, described earlier, a means was needed to alert planners and developers to the possibility of mining on a wider basis than that actually recorded in documents (Howard Humphreys and Partners 1987). Any shallow productive seam in the Bristol area may have been mined, at least locally, before systematic records were kept so it is good practice to check if this at all likely. The requirement was, therefore, for a map of priorities for site investigation. It was considered that:

- any seam over 300 mm in thickness may have been worked;
- most crown holes in the area were initiated at a depth of less than 25 m; and
- almost all crown holes in the area were initiated at a depth of less than 50 m.

It was necessary, therefore, to determine the extent of ground in the area underlain by shallow coal seams of 300 mm thickness or more, and the angles of dip to establish where the seams passed below 25 and 50 m of cover materials. Existing geological maps of parts of the study area showed only "disturbed strata". A further complication was that old plans and records used more than one name for a single coal seam and, in some cases, used the same name for different seams. It was necessary, therefore, to revise seam correlations throughout.

**Table 3** Classification and weighting of features associated with limestone dissolution on part of the coast of the Algarve, Portugal (after Forth et al. 1999)

| Feature | Factor | Weighting |
|---|---|---|
| Sink hole | Infilled with sand | 10 |
| | Open to beach level | 20 |
| | Diameter (m) | |
| | 0–2 | 5 |
| | 2–5 | 10 |
| | 5–10 | 15 |
| | >10 | 20 |
| Cave | Entrance area ($m^2$) | |
| | <50 | 4 |
| | 50–199 | 8 |
| | 200–499 | 12 |
| | 500–1000 | 16 |
| | >1000 | 20 |
| | Underground extent (m) | |
| | <20 | 4 |
| | 20–40 | 8 |
| | 41–60 | 12 |
| | 61–80 | 16 |
| | >80 | 20 |
| Gulleying | % of cell occupied by gully | |
| | 0–25 | 4 |
| | 26–50 | 8 |
| | 51–75 | 12 |
| | 76–100 | 15 |
| Average slope angle (degrees) | <10 | 2 |
| | 10–25 | 4 |
| | 26–50 | 6 |
| | >50 | 10 |
| Tension cracks | Horizontal persistence(m) | |
| | 0–5 | 1 |
| | 6–10 | 2 |
| | 11–15 | 3 |
| | 16–20 | 4 |
| | 20> | 5 |
| | Aperture (mm) | |
| | <6 | 1 |
| | 6–20 | 2 |
| | 20–60 | 3 |
| | 60–200 | 4 |
| | >200 | 5 |
| Fissuring | Fracture permeability (Veni 1987) | |
| | High | 8 |
| | Low | 12 |
| | Moderate | 20 |
| Rockfall | Above inter-tidal zone | 5 |
| | Intertidal zone | 20 |
| | Length of rockfall parallel to cliff edge (m) | |
| | <20 | 3 |
| | 21–50 | 7 |
| Estimated mechanical strength (Mpa) | Very weak <1.25 | 10 |
| | Weak 1.25–5 | 8 |
| | Moderately weak 5–12.5 | 6 |
| | Moderately strong 12.5–50 | 4 |
| | Strong-extremely strong >50 | 2 |
| Vegetation cover | Trees and bushes >2 m | 10 |
| | Bushes 1–2 m | 6 |
| | Small bushes <1 m | 2 |
| | Grasses | 10 |

The areas of known underground mining were presented on two sets of maps. One covered mine plans before 1872 and was taken from the work of Anstie (1873). The other related to statutory mines post-dating 1872. These were presented separately because the latter were likely to be more accurate since some of the original plans compiled by Anstie (1873) had been lost and could not be verified. The map showing depths to coal seams allowed a margin for error in plotting the 25 and 50 m zones (100 m). Areas with over 25 or 50 m of Mesozoic cover were also plotted.

The plans classified coal seam gradients into four categories:

A Dip greater than 45°
B Dip range 18–45°
C Dip range 8–18°
D Dip less than 8°

Where a value fell on the boundary between categories it was conservatively placed in the less steep category. The majority of seams were within category B. The results were plotted as separate maps at 1:10,000 scale showing:

- locations of wells, shafts, and adits;
- areas of known underground mining (taken from mine plans);
- depth to coal seams;
- coal seam gradients; and
- priority areas for site investigation.

The resulting map of priority areas for site investigation therefore showed envelopes around all areas known or suspected to be mined as well as areas subject to other natural and man-made hazards (Howard Humphreys and Partners 1993, op cit). Because there were numerous workable seams at different levels many of the defined envelopes overlapped.

Intermittent formation of gypsum dissolution sinkholes in the Ripon area, UK, described earlier, has been known for many years. Most incidents were small and took place in open country. Subsidence occurred occasionally within the urban area (Cooper 1998). The then, Department of the Environment commissioned the development of a method for responding to this hazard within the planning and building control systems. The area is underlain by Permian dolomitic limestones and marls dipping eastwards beneath Triassic sandstones. Gypsiferous horizons occur at the bases of two marl units. The existing geological maps were revised following study of site investigation and borehole records. It was found that the geographical extent of gypsum bearing strata was slightly greater than had been thought. A deep glacial channel infilled with alluvial deposits exists beneath the present course of the River Ure. Funds were not available to undertake extensive primary investigations but a limited number of boreholes were sunk and logged, and geophysical profiles were made, to establish subsurface structure and the depth of the buried channel. Piezometric measurements were undertaken in the boreholes and were supplemented by water company records. A behaviour model was developed to explain the groundwater flow patterns and, thus, the control on gypsum dissolution. It was concluded that effects of the dissolution processes were likely to be particularly concentrated on the western edge of the buried valley. Potential rates of gypsum dissolution were then assessed. A procedure for taking account of the findings in the planning system was then developed. It was based on a simple classification of the area into zones where: (a) no gypsum is present; (b) some gypsum is present at depth; and (c) gypsum is present and susceptible to dissolution. Subsidence hollows were shown also on this map since it was felt that further ground movements might occur close to these (Thompson et al. 1996, 1998). This simple classification was linked to a development advice procedure (Table 4) and a declaration form to be completed by those preparing site reports (Department of the Environment 1990; Table 5).

Research was undertaken to develop a method for preparing coalmine subsidence advice maps in South Wales (Statham and Treharne 1991; Ove Arup and Partners 1995a, b; Scott and Statham 1998). Part of Ebbw Vale, was selected as an initial trial area and the resulting method was later tested on the Islwyn area. The researchers drew upon mine plans, other historical documents, site investigation reports and aerial photographs. The geological map was updated and coal seam outcrops were projected so that areas where the seam was likely to be at 50 m or less below rockhead could be defined and plotted at 1:10,000 scale. Mine entrances were recorded but the variable accuracy of the original records made it necessary to plot positions as a 30 m circle. Information was collected on 396 mining subsidence events for the whole coalfield since there was insufficient data in the trial area. These were related to geology and mining history. About 50% of the incidents concerned the collapse of mine entrances and another 25% were linked to collapse of workings very close to the outcrop. Most subsidence events of mines took place where the workings were below cover less than six times the original height of the workings, establishing that subsidence hazard diminishes rapidly in the down-dip direction from the outcrop. This allowed general assessment of the subsidence reputation of shallow workings in individual seams and in various parts of the trial area. The approach used is outlined in Table 6.

The resulting map (Fig. 9) defined "consideration zones" where mining instability may be relevant to planning policies and decisions. A novel feature was a considerable amount of information given in the legend to assist the non-specialist user. The maps were incorporated

Table 4 Summary of development guidance categories and suggested procedures, Ripon, UK (after Thompson et al. 1996, 1998)

| Development control area | Gypsum-related subsidence hazard | Forward planning applications | Suggested development control procedures |
|---|---|---|---|
| A | No gypsum present according to current geological maps | Areas suitable for development in accordance with the Local Plan. Gypsum problems impose no constraints on Local Plan development proposals | No requirements with respect to gypsum at planning stage. Building control measures may be needed if isolated outliers of gypsum are discovered during site investigation work |
| B | Slight subsidence hazard associated with very localized, existing, near-surface cavities formed originally by slow localized dissolution of deep-seated gypsum deposits | Areas which are generally suitable for development in accordance with the Local Plan. Gypsum related subsidence hazard may impose minor localized constraints which should be identified and taken account of in Local Development proposals | A ground stability report prepared by a Competent Person* will normally** be required before planning applications for new building development in this area can be determined. In most cases it is likely that the report would need to be based only upon a geotechnical desk study and site appraisal, although site investigations to identify existing cavities may be required if problems are identified by the initial desk study. In recognition of the very limited degree of risk involved in this area, these requirements may often be imposed in the form of conditional planning consent |
| C | Areas which may be potentially subject to localized subsidence hazard, associated with both existing cavities and with the on-going dissolution of gypsum deposits in areas affected by groundwater moving towards the Ure Valley | Areas which are potentially subject to significant constraints on development. Local Plan development proposals should identify and take account of these constraints, making use of the detailed hazard assessment contained within the technical report | A ground stability report, prepared by a Competent Person*, will normally** be required before planning applications for new buildings, or those relating to the change of use involving increased exposure of the public to a known risk of subsidence, can be determined. In most cases the report would need to be based on a geotechnical desk study and site appraisal followed up by a programme of ground investigation designed to provide information needed for detailed foundation design, unless adequate information from previous boreholes on the same site is available. Where planning consent is given, this may be conditional upon the implementation of approved foundation or other mitigation measures, designed to minimize the impact of any future subsidence activity |

* A "Competent Person" is defined as a Geotechnical Specialist, as defined by the Site Investigation Steering Group of the Institution of Civil Engineers. Ideally, this process would also have appropriate experience in the investigation and remediation of gypsum-related subsidence problems within the Ripon area. Further guidance can be obtained from the current edition of the British Geotechnical Society's Directory of Geotechnical Specialists

** Permitted development under the Town and Country Planning (General Development) Order 1995 and other minor developments including most householder applications such as modest extensions, will not normally be subject to the development control requirements set out above. In the case of householder applications, the Council will issue an advice note, drawing the applicant's attention to the potential risk of subsidence, but reserves the right to request ground stability reports in situations where there are particular reasons for greater concern, for example in locations which are close to sites of recent subsidence activity

formally into the development of planning policies and consideration of planning applications, and the use of the system by planners was monitored for 1 year. Procedures were outlined for dealing with planning applications, preparing planning conditions, and for ensuring that appropriate preventive or remedial measures were undertaken after a planning consent was given.

An important issue is how information on hazards can be easily delivered to non-specialists. To that end, the British Geological Survey set up a system called GeoSure

**Table 5** Ground stability declaration form, Ripon, UK (after Thompson et al. 1996, 1998 and Department of the Environment 1990)

| Ground stability declaration form | | |
|---|---|---|
| Site name: | Site address and proposed development: | |
| Category | Question | Answer yes or no |
| Competent person | Has the report been prepared by a Geotechnical Specialist as defined by the ICE Site Investigation Steering Group? | |
| A. Site history | Has the site been affected by known historical subsidence? | |
| | Is the site underlain by strata which may contain natural cavities or be liable to subsidence due to adverse foundation conditions? | |
| | Has there been previous development on the site such as mining or industrial development that could result in underground cavities or made ground? | |
| | Is mining or underground excavation proposed beneath the site? | |
| | Have any previous ground investigation reports and/or borehole records from this or nearby sites been consulted? | |
| | Have any cavities, broken ground, made ground or other adverse foundation conditions been identified beneath or near the site? | |
| B. Site inspection | Has a detailed site inspection been carried out? | |
| | Does the land within or adjacent to the site bear any geomorphological evidence of former, on-going or incipient subsidence? | |
| | Does the site or neighboring property bear any evidence of structural damage or repairs that might be associated with subsidence or evidence of mine entries? | |
| C. Ground investigation | Has a ground investigation been carried out? | |
| | Have any cavities, broken ground, made ground or other adverse foundation conditions been identified beneath or near the site? | |
| | If so, have their locations and dimensions been properly identified? | |
| Assessment of subsidence | Is the information under A, B and C above adequate to assess the likely effects of subsidence on the site? | |
| | Can subsidence be reasonably foreseen within or adjacent to the site within the design life of the proposed development? | |
| | Have the potential effects of subsidence on existing or proposed development been assessed? | |
| Mitigation measures | Have mitigation measures been proposed with respect to subsidence? | |
| | Are these designed to reduce the effects of any actual or potential subsidence to an acceptable level? | |
| | Are they likely to have any adverse effects on other adjacent sites e.g. by affecting the groundwater regime? | |
| Name, qualifications and signature of the person responsible for the report | Full name: | |
| | Qualifications: | |
| | Geotechnical specialist? | |
| | Signature: | |
| | Company represented: | |

for internet delivery. National coverage of Great Britain became possible when complete digital coverage of Great Britain at 1:50,000 Scale (DiGMap GB-50) became available in 2001. The initiative adopted a deterministic approach to hazard mapping. The intention is to cover all significant geological hazards. Results on soluble rocks are already available (http://www.bgs.ac.uk/products/geosure) and mined ground will be included in due course. Work on soluble rocks required separate consideration each of the lithologies shown in the digital base map. These were considered in terms of the nature of the materials and the three-dimensional structure of the ground, taking account of sub-crops beneath superficial deposits. Constraints were considered relative to the potential degree of hazard. Multi-Criterior Analysis was undertaken for each lithology using GIS. Vector maps were generalised to a 25 m cell grid because of the large data sets and the imprecise nature of geological assessment. The results were subjected to expert

**Table 6** Method of preparing development advice maps, Islwyn, South Wales (after Ove Arup and Partners 1995a, b; Scott and Statham 1998)

| Step | Activities | Source of data |
|---|---|---|
| 1 | Prepare best available geological map, check against coalfield system for seam correlation, and estimate draft thickness | British Geological Survey maps, and file information, Opencast Executive prospecting records and development maps, and readily available site investigation reports from local authorities |
| 2 | Establish positions of workable seams and positions of recorded mine entries | Local mining history archival material and local historians; Coal Authority abandoned mine plan catalogue for geological information and seam elevations, dates, methods of working and seams worked, and locations of mine entrances; review of information on mine entrances against other records to assess reliability; examine aerial photographs |
| 3 | Establish "seam reputations" | Previous South Wales subsidence desk study report; Opencast Executive experience in nearby working pits; shallow workings exposed in existing mines; aerial photographs to identify areas of previous instability |
| 4 | Draw development advice map and set out procedure for choosing zones | South Wales Mining subsidence desk study report |

validation in order to assure quality. A careful audit trail as to how judgments and weightings were arrived at was kept because of potential for legal challenge of results.

The system was essentially aimed at financial institutions, civil engineers, land managers and householders. Therefore, results were presented in terms of six perceived level of hazard.

1. no problems identified;
2. problems unlikely to be present;
3. problems may be present or anticipated;
4. problems probably present or have occurred in the past;
5. problems almost certainly present; and
6. problems present or active.

These were linked, for example, to development advice for planners, site investigation design recommendations for engineers, and advice to alert householders and property interests. The system is now successfully in use (Harrison and Forster 2003).

## Assessment of risk

Even though social and economic impacts of subsidence are locally important in planning, as yet few published exercises take the additional step of risk mapping. Two exceptions are outlined below. The first concentrated on potential economic losses while the second focused primarily on risk to people.

A study of the Black Country limestone mines in the West Midlands of England. Silurian limestones were worked extensively in the 18th and 19th centuries in pillar and stall mines. The limestones are fairly tightly folded and come to the surface locally in anticlinal ridges. In the intervening areas they are fairly deeply buried beneath Carboniferous Coal Measures containing coal seams, fireclay and ironstone. The close proximity of these and the limestone was a spur towards early industrialisation and extensive mining. The legacy was a large number of mines for both limestone and for coal, a number of which were poorly known. Following a major subsidence event at an industrial estate in the late 1980s research was commissioned in order to determine the scale of the problem and to define a strategy for dealing with it (Ove Arup and Partners 1983). The initial step was to collect and collate existing information from mine plans and site investigation records. This allowed a number of mined areas or "consideration zones" to be mapped. These were defined as the zones in which consideration should be given to the need to investigate the ground in relation to the movements that could be caused by deterioration of old limestone workings. The boundaries of the zones were defined by a predicted 0.2% horizontal tensile strain contour using a method developed by the National Coal Board (Anon 1975). This was improved by varying the angle of draw through specific beds in the lower Wenlock Limestone on the basis of local experience of "crown hole" subsidence. Boundaries were refined by entering and surveying dry mines, and investigating those below the groundwater table by drilling boreholes and inserting closed circuit television and various probing tools. The priorities for doing this were determined by means of a risk assessment for each consideration zone. The risk was defined as a combination of:

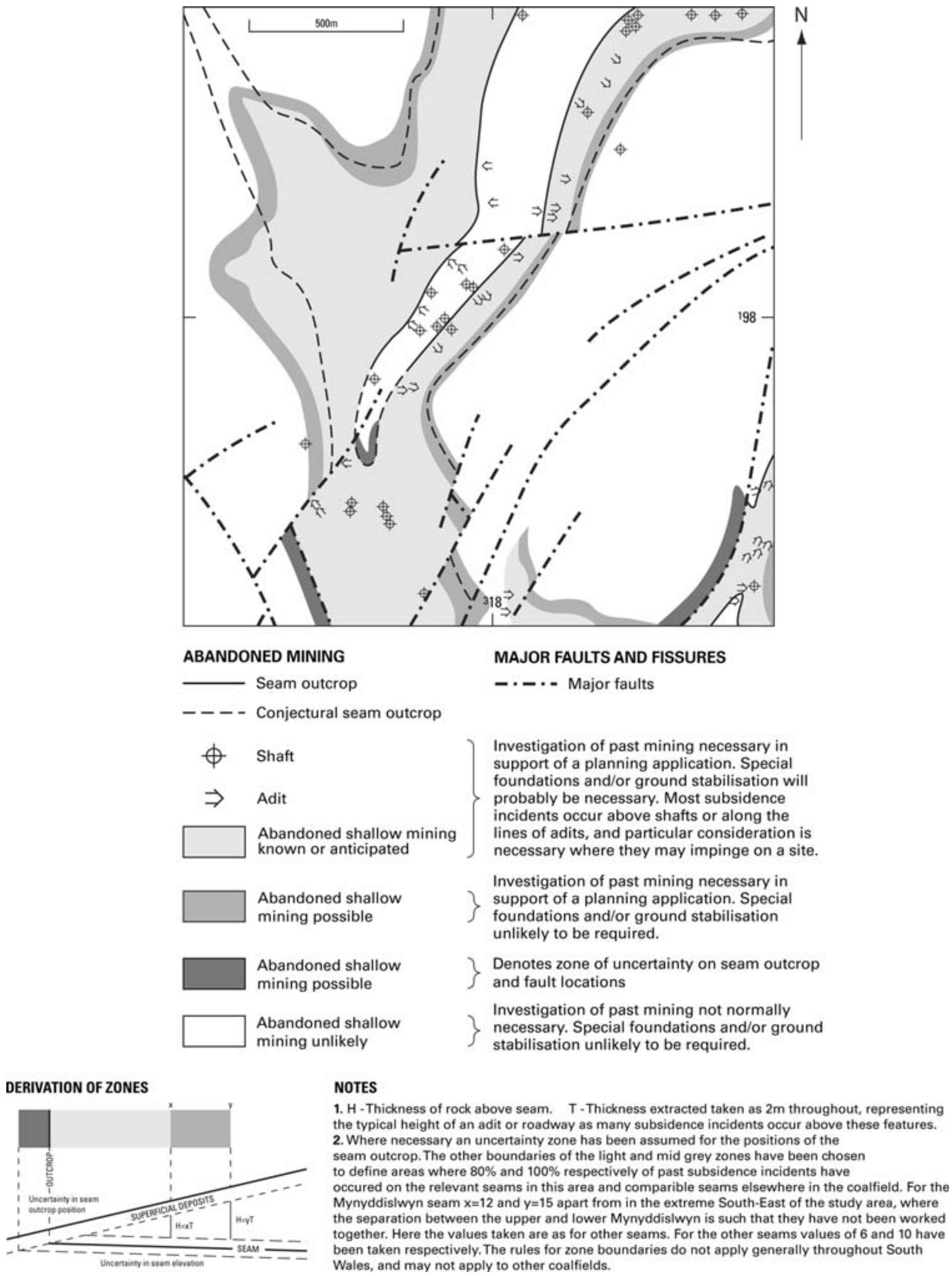



**Fig. 9** Subsidence hazard map for an area of coal mining adapted for land use planning, Islwyn, South Wales, UK (from Ove Arup and Partners 1995b)

- potential for collapse (P) related to the likelihood of occurrence within a specific period of time of a collapse which affects a given area based on the stratigraphy, annual rate of collapses, and age and depth factors; and
- the importance of land within the zone (I) determined by the magnitude of the effect of any collapse on the community from the point of view of maintaining essential services, and not with regard to the importance to life since no instances of loss of life due to surface collapse of limestone mines had been recorded.

The relative risk of collapse within each consideration zone was assessed as the product of the potential for collapse and the average importance to land use $R = P \times I$

The average importance ($I$) was the sum of the products of the importance of structures ($S$) and their area ($A$) divided by the area of the consideration zone (CZ):

$$I = E^{\ln} I_{sn} \times A_n / \text{area CZ}.$$

The risk ($R$) to an individual structure associated with a collapse above, or near, a particular mine was taken as the combination of potential for collapse and importance with the vulnerability of the structure $R = P \times I_s \times V$.

The vulnerability ($V$) was related to the type of structure ($V_s$) and the material from which it is constructed ($V_m$):

$$V = V_s \times V_m$$

A land use survey was undertaken for each consideration zone in order to evaluate these equations (Roger Tym and Partners 1985). The resulting map was updated as more information became available thus providing a dynamic framework for a reclamation strategy that is now nearly complete (Brook 1991).

Ragozin and Yolkin (2003) undertook qualitative hazard and risk assessment at a regional scale (1:100,000–1:500,000) for part of the Tartar Republic. Two areas were selected where Upper Permian carbonate and carbonate-sulfate rocks are overlain by Pliocene-Quaternary silty-clayey sediments at depths mostly in the range of 20–50 m. Data were compiled on karst phenomena, regional geology, climatic zones, and land use and the areas were zoned on the basis of the main features that influence karst subsidence. Hazard was estimated for each zone using the formulae:

$$H(C) = R_f(C) = \sum_{i=1}^{n} P \times (C_i) \cdot S_i \approx S_c/t$$

$$H_s(C) = R_{fs}(C) = R_f(C)/S \approx S_c/S.t$$

where $H$ ($C$) and $H_s(C)$ are the total karst hazard and that normalized over the area which are, respectively, equal to the total ($R_f$) and specific ($R_{fs}$) risks of karst damage ($m^2$ per annum and $m^2/km^2$ per annum). $P \times (C_i)$ is the frequency of generation of the *i*th type of karst features (events per annum). $S_i$ is the average area damaged by this deformation ($m^2$). $S_c$ is the total area of karst deformations within the given area ($m^2$) t is the time interval of these events (years) and $S$ is the total area under consideration ($km^2$).

The second formula was first used to calculate the area intensity of collapses (specific physical hazard) for the most severely affected areas within fields of kettle holes in the superficial deposits. The features dated using isotope geochemistry ranged between 0.05–0.1 and 2–10 thousand years. Second order areas, up to 2 kms from the most severely damaged areas, were then considered. As a result of this procedure six categories of karst hazard were defined as follows:

1. insignificant <0.1 $m^2/km^2$/year;
2. slightly hazardous 0.1–1.0 $m^2/km^2$/year;
3. moderately hazardous 1–10 $m^2/km^2$/year;
4. hazardous 10–100 $m^2/km^2$/year,
5. very hazardous 100–1,000 $m^2/km^2$/year; and
6. extremely hazardous >1,000 $m^2/km^2$/year.

Attention was then turned to social and individual risk based on area intensity of subsidence and on physical and economic vulnerability. The individual risk was calculated for a typical representative of a certain population group in the zone of possible subsidence in terms of death, injury or other negative effects. The following formulae were used:

$$R_{fj}(C) = R_{fs}(C).S_j$$

$$R_s(C) = R_{fj}(C).d_s.V_t(C).V_s(C)$$

$$R_{si} = R_s(C)/D_p$$

where $R_{fj}$ ($C$) and $R_{fs}$ ($C$) are, respectively, the risk of physical total ($m^2$/year) and specific ($m^2/km^2$.year) losses of land for the jth risk area. $S_j$ is this area ($km^2$). $R_s$ ($C$) is the total social risk for the population in the considered area (persons/year); $d_s$ is the population density (persons/$km^2$); $V_t$ (C) is the vulnerability of the population to karst collapses within the group of people with similar risk (decimal fractions); $R_{si}$ ($C$) is the individual risk of similar population harm amongst people with similar risk (persons/persons.year) and $D_p$ is the number of people in the area.

Vulnerability depends on where people are at the time of a subsidence event. Therefore, the authors set vulnerability in open country at 0.5 and in a moving vehicle at 0.75. Vulnerability also depends on how long people stay in specific locations. Therefore, an occupancy factor was derived using:

$$V_t(C) = t_d.t_y/24 \text{ h}.365 \text{ days}$$

where $t_d$ and $t_y$ are represent the duration of stay of an individual at a particular point during a day and a year.

The method was then applied to three examples involving: a significant number of people who permanently occupy a particular settlement; an agricultural land area; and a length of road with a specially constructed pavement.

## Discussion

### Data systems

Data systems have been utilized for many areas of previous underground mining. These systems usually consist of one or more index maps linked to data sheets, cross-referenced by a system of numbers. Some of these relate to formal requirements to lodge and compile mine plans while many were established for specific projects aimed either at giving a national overview or as a basis for research on a particular area. The approaches taken, and design of data sheets, vary from area to area. Only in a few places has national guidance been given on the setting up of such data systems. Diversity of approaches may, however, lead to difficulties where there is a need to combine data systems, for instance when public authority boundaries are changed or amalgamated. There is a need to consider to what extent standard approaches, central depositories, and metadata indices are necessary or practical.

Data systems are an important resource for both basic and applied research as well as giving an immediate overall appreciation of the nature and scale of problems. Data may be invaluable to emergency services if subsidence incidents occur or if people become lost underground. Whilst initial investment in data collection and hardware may be expensive, data retrieval and maintenance costs, thereafter, are usually modest. Major economies arise through increasing the efficiency of data searches and avoiding duplication of effort in successive projects. In addition, information may help more effective design of site investigations; reduce delays to development and redesign of structures at a late stage and financial losses when development is affected by subsidence. Many data systems are set up for a single research project and are not augmented after work is completed. This does not make the best use of the initial investment since modest updating may maintain these as a valuable long-term resource. There is, therefore, a sound economic case for maintaining readily accessible sources of information. A long-term centralised data depository, however, requires some administrative mechanism to ensure that information is lodged in it.

Data systems usually focus on the characteristics of voids and on associated geological, ground and water conditions. Only rarely, however, do they incorporate details of preventive and remedial works even though this information may be of great importance in future site investigation and development of land. There is a strong case for incorporating these aspects into any data system.

The compilation of a database carries responsibilities. It is incumbent on those setting up a system to transfer information as accurately as possible. It is prudent to separate interpretation from information and to comprehensively state what has been recorded. Direct cartography, whether printed or on screen, may give a false sense of accuracy and precision that non-specialists may not appreciate. It is important, therefore, for guidance to be given by specialists on the meaning and limitations of results.

## Documentation maps

These collate basic information from documentary sources, supplemented to a varying extent by field investigations, is the commonest form of subsidence hazard mapping. These maps are useful as an index to more detailed documentary records and also help to give some overall picture of the nature and extent of the problem. They may, however, be misleading. They are only as good as the information that is used in plotting them and, in particular, are constrained by the quality and accuracy of basic geological mapping. For reasons of time or money, field verification is often very limited. Some existing information may be misleading and omissions may understate problems. Therefore, caution is required in using the resulting maps. For many purposes, such as use in desk studies in preparation for site investigation, the selection of sites for development, and the consideration of cost implications of land reclamation strategies, the more information which is included, the better. However, that can make conventional maps difficult to read, a difficulty that is overcome by using GIS technologies.

## Maps depicting susceptible zones

Many hazard maps show only the broad extent of areas that may be susceptible to subsidence. These provide a good means of alerting geoscientists, planners and developers to potential problems but do not discriminate the relative levels of hazard. They are, therefore, of limited value in, for instance, setting out relative priorities for action to deal with ground problems.

### *Maps showing relative degrees of hazard*

These include, at the simplest level, those which express the occurrence of hazards in terms of number per unit area and, thus, give some relative idea of concentrations of past events. Whilst this may give a basis for ranking precautions and priorities it is a fairly crude approach, particularly if there is no statistical test of validity or forecast for future events. Maps that incorporate information on the frequency of events or which attempt to project what is known may give a more representative view of the many areas in which documentation is incomplete. However, caution is needed in the expression of relative potential for subsidence. Commonly work on specific areas leads to a classification of the potential for subsidence into “high”, “moderate”, “low”, and “absent” categories. These categories may have rational and statistically based definitions but may mean very different things in different places. For instance, a particular location that experiences only very sporadic subsidence may have a “high” incidence in relative terms compared with adjacent areas. In national or international terms, however, that same area may have a very low incidence. The expression “high”, in this context, is often misinterpreted by residents, insurers and financial interests and should be avoided. A suitable approach might be to set up standard categories based on a larger area such as a region and to make comparisons with these. Little has been found in the reviewed literature on ways in which environmental, including climate, change might affect the situation. This is in marked contrast to work on other hazards such as landslides where there is a growing body of literature on impacts of climate change.

Maps for land use planning

Maps for land use planning normally require simplification for use by non-specialists. This may be done, for example, by extrapolation of the known extent of underground mining or geological information and records of subsistence events. Another approach is to attempt to model ground behaviour by combining various weighted variables. It is important to recognise that modelling may give a spurious sense of precision. It is only as reliable as the understanding of materials and processes that influencing the factors to be identified and given appropriate weights. Examples such as those cited have been successful because much detailed information is available. All of these types of maps give some indicative measure of the subsidence hazard although none can be considered a complete statement.

Maps indicating levels of risk

Relatively few published examples of maps that consider risk by, for example, taking into account property valuation were found in the preparation of this review. The study of the Black Country, referred to earlier, was stimulated by the need to phase expenditure on reclamation making it imperative that the largest potential losses were safeguarded first. The work of Ragozin and Yolkin 2003 (op cit) focused more on risks to people. There appears to be considerable scope for publication of more work on this difficult aspect of subsidence mapping.

## Conclusions

The approach adopted in preparing subsidence hazard maps should reflect the aim of the exercise. Any inventory should ideally include all of the available information. Any detailed technical appraisal, whether for research or for planning of development of land, requires as much information as possible. Planning of land use can be undertaken, however, with outline information since the objective is essentially to alert planners and developers to the possibility of a hazard and to encourage them to seek professional advice or more detailed information. In such circumstances, a generalised statement that the whole of an outcrop could be affected by dissolution or an area by mining or a broad zonation (e.g. Ripon) is enough to trigger a response. The fact remains, however, that whilst relatively cheap first approximations can be readily drafted for most areas, the basis for action becomes progressively better as more information and understanding of the problem is obtained. Therefore, monitoring and updating is important, and a phased approach may be appropriate. However, there are relatively few published studies where the practical use of maps has been traced over an appreciable period. It would, in particular, be interesting to see the extent to which results of monitoring of modelling exercises are borne out by subsequent events and ground investigations. It follows, that the key of a map aimed at planners should be simplified and, perhaps, expressed in terms of actions, which should be carried out rather than the characteristics of the defined areas. In particular, it is essential that maps aimed at planners are integrated into the administrative process to ensure that they are used. There also appears to be considerable scope for publication of more work on this difficult aspect of subsidence risk mapping. Finally, there appears to be a need for more consideration of the implications of environmental, including climate, change on future subsidence potential.

**Acknowledgments** Thanks are due to Niek Rengers (ITC) and Alan Forster (BGS) for useful comments on an earlier draft of this paper and Martin Culshaw (University of Nottingham and past Chairman of Commission No. 1) for encouragement of the work; to authors and publishers that gave permission for reproduction of the figures; and to Dr David Brook who inspired the UK research initiative and planning guidance on unstable land. BGS kindly prepared the figures.

## References

Adams FT, Lovell CW (1984) Mapping of limestone bedrock problems. Transp Res Rec 978:1–5

Anon (1975) Subsidence engineers' handbook. National Coal Board, London

Anstie J (1873) The coalfields of Gloucestershire and Somersetshire. Kingsmead Reprints (Bath)

Applied Geology Ltd (1993a) Review of instability due to natural cavities in Great Britain—summary report. Appl Geol Ltd (Royal Leamington Spa)

Applied Geology Ltd (1993b) Review of instability due to natural cavities in Great Britain, vol 2.3, Review of ground treatment and structural design techniques. Applied Geology Ltd (Royal Leamington Spa) Appendix D

Arnoud M, Broquet JF, Deveughèle M, Usseglio Polatera JM (1979) Cartographie geotechnique de la ville de Paris—première realisations (13ème, 19ème et 20ème arrondissements) Bull Internat Assoc engineer geol 19:109–115

Arup Geotechnics (1992) Mining instability in Great Britain—Summary Report Department of the Environment (London) 22 pp

Brook D (1991) Abandoned limestone mines in the West Midlands: a strategy for action. In: Johnson AI (ed) Land subsidence. IAHS Publication No. 200, pp 215–223

Brook GA, Allison TL (1986) Fracture mapping and ground susceptibility modelling in covered karst terrain: the example of Dougherty County, Georgia. In: Johnson AI (ed) Proc of IAH Conference, Venice, 1984 IAHS Publication No. 151, Institute of Hydrology (Wallingford), pp 595–606

Charsley TJ, Rathbone PA, Lowe DJ (1990) Nottingham—a geological background for planning and development. British Geological Survey Technical report WA/90/1, 82 pp
Cooper AH (1989) Airborne multispectral scanning of subsidence caused by Permian gypsum dissolution at Ripon, North Yorkshire. Q J eng geol 22:219–229
Cooper AH (1998) Subsidence hazards caused by the dissolution of Permian gypsum in England: geology, investigation and remediation. In: Maund JG, Eddleston M (eds) Geohazards in engineering geology. Geol Soc Lond Engineer Geol Spec Pubn 15, Geological Society (London) pp 265–275
Department for Transport, Local Government and the Regions (DTLR) (2002) Planning Policy Guidance Note 14 Development on Unstable Land, Annex 2 Subsidence and Planning. DTLR (London) 56 pp
Department of the Environment (1990) Development on unstable land. Planning Policy Guidance Note 14. HMSO (London) 25 pp
Deveughèle M, Usseglio Polatera JM (1979) Cartographie des zones exposées aux risques lies aux dissolutions de la fraction gypseuse du marno-calcaire de Saint-Ouen dans les 19ème et 20ème arrondissements de la ville de Paris. Bull IAEG No 19, pp 121–125
Doornkamp JC, Lee EM (1992) Geology and land use planning: St Helens, Merseyside-summary report. Rendel Geotechnics (Birmingham) v+ 64 pp
Durville JL, Hameroux M (1995) Les risques dus aux carrières souterraines abandonées et leur prevention—strategies et methodes de prevention. Bull IAEG No 51, pp 113–128
Edmonds, CN (2001a) Predicting natural cavities in the chalk In: Griffiths JS (ed) Land surface evaluation for engineering practice. Geol Soc London Engineer Geol Spec Pubn 18 Geological Society (London) pp 29–38
Edmonds, CN (2001b) Subsidence hazard in Berkshire in areas underlain by chalk karst. In: Griffiths JS (ed) Land surface evaluation for engineering practice. Geol Soc Lond Engineer Geol Spec Pubn 18, Geological Society (London) pp 97–106
Edmonds CN, Green CP, Higginbottom IE (1987) Subsidence hazard prediction for limestone terrains, as applied to the English Cretaceous chalk. In: Culshaw MG, Bell FG, Cripps JC, O'Hara M (eds) Planning and engineering geology. Geol Soc Engineer Geol Spec Pubn 4, Geological Society (London) pp 290–291
Ford DC (1964) Origin of closed depressions in the central Mendip Hills: abstracts of papers, 20th International Geographic Congress, London, pp 105–106
Forth RA, Butcher D, Senior R (1999) Hazard mapping of karst along the coast of the Algarve, Portugal. Eng Geol 52:67–74
Freeman Fox Ltd (1988) Methods of compilation, storage and retrieval of data on disused mine openings and workings. HMSO (London) 18 + 58 + 32 pp
Harrison M, Forster A (2003) The application of GIS modeling to the assessment of geological hazard potential a National scale. In: Proc Ann Conf Inter Assoc Mathem Geol, September 7–13, 2003 (Portsmouth) 6 pp
Howard Humphreys and Partners (1987) Environmental geology study in the Bristol area. Howard Humphreys and Partners (Leatherhead) 99 pp and two volumes of maps
Howard Humphreys and Partners (1993) Subsidence in Norwich HMSO (London) 112 pp
Lee EM, Sakalas CF (2001) Subsidence map development in an area of abandoned salt mines. In: Griffiths JS (ed) Land surface evaluation for engineering practice. Spec Pub 18 Geol Soc (London) 29–38
Ogden AE, Reger JP (1977) Morphometric analysis of dolines for predicting ground subsidence, Monroe County, West Virginia In: Dilamarter RR Csallany SC (eds) Hydrogeologic problems in Karst Regions Western Kentucky University Press 130–139
Ove Arup, Partners (1983) Limestone mines in the West Midlands—a legacy of mines long abandoned. Department of the Environment (London) 24 pp
Ove Arup, Partners (1995a) Islwyn shallow mining—development advice maps. Ove Arup and Partners (Cardiff)
Ove Arup, Partners (1995b) Islwyn shallow mining—final report. Planning procedures and guidelines for the use of development advice maps. Ove Arup and Partners (Cardiff) 35 + 11 pp
Owen JF, Walsby JC (1989) A register of Nottingham's caves. Brit Geol Survey Technical report WA/89/27, vol 3
Price DG (1971) Engineering geology in the urban environment. Q J Eng Geol 4:191–208
Ragozin AI, Yolkin VA (2003) Individual karst risk qualitative assessment at a regional level (an example of Tartar Republic) In: Proc Ann Conf Inter Assoc Mathem Geol September 7–12, 2003 (Portsmouth) 6 pp
Roger Tym, Partners (1985) Land use affected by limestone mining in the Black Country. Final report Vol 1 R Tym and Partners (London) 35 pp + plans
Scott MJ, Statham I (1998) Development advice maps: mining subsidence. In: Maund JG, Eddleston M (eds) Geohazards in engineering geology. Geol Soc Lond Engineer Geol Spec Pubn 15, Geological Society (London) pp 391–400
Simón-Gómez JL, Soriano MA (2002) Actual and potential doline subsidence hazard mapping: case study in the Ebro Basin, Spain In: Bobrowsky PT (ed) Geoenvironmental mapping: methods, theory and practice AA Balkema (Lisse), pp 649–666
Smith A, Ellison RA (1999) Applied geology maps for planning and development—a review of examples for England and Wales 1983 to 1996 Quart J Eng Geol 32 (supplement) S1–S44
Statham I, Treharne G (1991) Subsidence due to abandoned mining in the South Wales Coalfield, UK: causes, mechanisms and environmental risk assessment. In: Land subsidence IAHS Publication No 200 143–152
Thompson A, Hine PD, Greig JR, Peach DW (1996) Assessment of gypsum subsidence arising from dissolution (with special reference to Ripon, North Yorkshire). Symonds Travers Morgan (East Grinstead) 95 pp
Thompson A, Hine P, Peach D, Frost L, Brook D (1998) Subsidence hazard assessment as a basis for planning guidance in Ripon. In: Maund JG, Eddleston M (eds) Geohazards in engineering geology. Geol Soc Lond Engineer Geol Spec Pubn 15, Geological Society (London) pp 415–426
Tolmachev VV, Pidyashenko SE, Balashova TA (1999) The system of antikarst protection on railways of Russia. In: Beck BB, Pettit AJ, Herring JG (eds) Hydrogeology and engineering geology of sinkholes and karst. Balkema (Rotterdam) pp 423–429
Veni G (1987) Fracture permeability: implications for sinkhole development and their environmental assessment In: Beck BF (ed) Proc 2nd multidisciplinary conference on sinkholes and the environmental impacts of karst (Orlando, Florida) pp 101–108
Waltham AC (1992) Sandstone caves of Nottingham. Mercian Geol 13(1):1–32
Waltham AC (1993) Crown hole development in the sandstone caves of Nottingham. Q J geol Soc Lond 26(4):243–252
Waters CN, Northmore K, Prince G, Marker BR (1996) Geological background to planning and development in the City of Bradford Metropolitan District. BGS Technical Report WA/96/1 vol 2, A technical guide to ground conditions. Brit Geol Survey (Keyworth) 126 pp