HIGH RESOLUTION MICROGRAVITY INVESTIGATIONS FOR THE DETECTION AND CHARACTERISATION OF SUBSIDENCE ASSOCIATED WITH ABANDONED, COAL, CHALK AND SALT MINES

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ABSTRACT: The closure and decay of industrial activity involving mining has scarred the landscape of urban areas and geohazards posed by subsurface cavities are ubiquitous throughout Europe. Features of concern consist of natural solution cavities (e.g. swallow holes and sinkholes in limestone gypsum and chalk) and man-made cavities (mine workings, shafts) in a great variety of post mining environments, including coal, salt, gypsum, anhydrite, tin and chalk. These problems restrict land utilisation, hinder regeneration, pose a threat to life, seriously damage property and services and blight property values. This paper outlines the application of microgravity techniques to characterise abandoned mining hazard in case studies from Coal, Chalk and Salt Mining environments in the UK.

KEYWORDS: Microgravity, Subsidence, Chalk, Salt, Coal.

RESUME : La fermeture et l'affaiblissement de l'activité industrielle liée à l'exploitation minière a marqué le paysage de secteurs urbains et les dangers posés par les cavités proches de la surface sont omniprésents en Europe. Cela concerne des cavités de dissolution (par exemple des dolines et des fontis apparaissant dans le gypse et la craie) et des cavités creusées par l'homme (exploitation minière, puits) dans une grande variété d'environnements, comme le charbon, le sel, le gypse, l'anhydrite, l'étain et la craie. Ces problèmes limitent l'aménagement des terrains de surface, freinent la régénération, expose la population à un risque qui peut être mortel, endommagent sérieusement les propriétés individuelles et les services. Cet article décrit l'application des techniques de microgravité pour caractériser la présence d'exploitation minière abandonnée dans des secteurs d'exploitation de charbon, de craie et de sel au Royaume -Uni.

MOTS-CLEFS : Microgravité, Affaissement, Craie, Sel, Charbon..

1. Introduction

The microgravity technique consists of measuring minute changes in the gravitational pull of the Earth and interpreting the presence of subsurface density variations, such as those produced by voids and cavities, from an analysis of these readings. These gravity anomalies are superimposed onto much larger variations produced by elevation, topography, latitude and regional geological variations and are, usually, almost undetectable by conventional gravity investigations. microgravity surveying has developed considerably over the last ten years with the development of modern, high resolution instruments, prudent field acquisition procedures, sophisticated data reduction methods and advanced analysis techniques. Qianshen et al. (1996) presents a thorough review of the microgravity technique. It is now possible to detect and interpret anomalies as small as 10 microgal with a repeatability of a few microgals under favourable site conditions (the microgal is the commonly used unit for microgravity surveying; 1 microgal = 10^{-6} cm s^{-2}). Not only can the isolated anomalies reveal the location of mines, caverns and voids, either natural or man-made, but they also provide information on their depths, shapes and morphology. Through the use of Gauss's theorem, the 'missing mass' associated with the void can be calculated in order to provide vital information for the development of remediation strategies and, ultimately, the costs associated with cavity filling. Through the targeted use of post-remediation surveys, assessments can be made on the success, or not, of the remediation process and help verify the location and distribution of materials used to 'grout up' the void space. These attributes have led to the method becoming widely used in hydrogeological, engineering and geotechnical investigations with the significant advantage of leaving the ground completely undisturbed.

2. Microgravity as a tool for the detection and characterisation of subsurface cavites

The presence of karstic features or mining-related cavities in the rock mass often leads to severe restrictions in land utilization and a variety of subsidence-related problems for both current and future users of that land. Cavities constitute a hazard to both development and redevelopment as their migration to the surface, as sinkholes or fractured and disturbed ground, may seriously damage property, services and, in some cases, cause significant groundwater contamination problems. Features of interest usually consist of natural and/or man-made cavities and are generally termed 'targets'. The most common natural targets in karst environments are solution related features such as voids, extended cavern systems and the collapse/drainage features associated with swallow holes (or sinkholes). Man-made cavities, which include mine workings, shafts and tunnels, are just as important and, in fact, can be even more prevalent than natural features, particularly in industrialized environments. Prior to the development (or redevelopment) of a site, the most common method of site investigation has been to drill an extensive pattern of boreholes over the target area in an attempt to locate and then define the spatial extent of any cavities. Indirect techniques such as geophysics can give a cost effective, non-invasive method of cavity delineation with targeted drilling used as a verification tool rather than a primary search technique. A cavity usually has a lower density than the surrounding material and may also be filled with air (i.e. a void), water, sediment, collapse material, or a mixture of all of these. The existence of the cavity alters the physical state of the strata and results in a contrast between the cavity and the host stratum that can be detected using suitable geophysical methods if the contrasts are large enough and the features are of a sufficient size (McDowell et al. 2002).

The microgravity survey technique is a powerful cavity location method. Because a void represents a mass deficiency in the subsurface, a small reduction in the pull of the Earths gravity is observed over the cavity, which is called a negative gravity anomaly. Although the method is simple in principle, measurement of the minute variations in the gravity field of the Earth requires the use of highly sensitive instruments, strict data acquisition procedures, stringent quality controls, careful data reduction and sophisticated digital data analysis techniques in order to evaluate and interpret the data. Conventional site investigation techniques are then employed, as directed by the microgravity results, to verify the areas deficient in mass. In order to detect a target using microgravity there must be a difference in density between the target and its surroundings, resulting in a significant deficiency in mass, otherwise the target will be undetectable using microgravity and other geophysical methods may be more suitable. However, cavities usually do provide significant density contrasts with their surroundings with air filled cavities offering the largest anomaly condition because of the complete absence of material. The simplified picture of a solitary cavity described above is not usually the case for natural or man-made cavities. This is primarily because the rock surrounding the cavity is often disturbed and extensively fractured, particularly in the case of natural cavities and unsupported mines. The fractured zone may extend for two or more diameters away from the cavity (Daniels 1988) and a similar effect is often observed with karst cavern systems due to the development of sinkholes, collapse features, passages, dissolution and the enlargement of faults/joint systems, etc. consequently , the 'effective' size of the target is dependent not only on the strict volume of the cavity, but also its connectivity with the surrounding rocks. This secondary effect (or cavity enhancement) is often termed a 'halo' and serves to increase the effective target size, meaning the cavity may be indirectly sensed (Chamon & Dobereiner 1988; Bishop et al. 1997; Patterson et al. 1995).

The detectability of cavities in salt beds using gravity is well documented by (Speed, 1970). The detectability was assessed by comparing maximum anomaly amplitudes as a function of cavity depth, diameter thickness and ellipticity with values of precision of measurement and uncertainty of gravity background. The literature records some early examples of the application of microgravity techniques to detect cavities (Colley 1963; Arzi 1975). Neumann (1967) performed a microgravity survey to locate a buried concrete water tank reservoir, and also succeeded in tracing the existence of a subsurface gallery during the survey of an old quarry. Fajklewicz (1976) describes the application of vertical gravity gradient measurements for the detection of tunnels and rock caverns beneath Polish towns, whilst Butler (1984) applied microgravity and gradient techniques to the detection and delineation of shallow subsurface cavities and tunnels. Chamon and Dobereiner (1988) evaluated gravity, resistivity, magnetic and very low frequency (VLF) electromagnetic techniques over a mapped sandstone cavern system in the Amazon sedimentary basin. They concluded that: 'From all the methods used, the gravity survey was the only one which detected the presence of the cavern. It was observed that small caverns in sandstones, in the range of two to five meters in diameter, 40 to 50 metres below the surface can be detected by the microgravity method. It is important to mention that the gravity attraction of such small cavities would escape the sensitivity of the gravity meter. However, due to features associated with the cavern (dolines, collapsed structures, caves, porosity, etc.) it could be indirectly sensed…'. The cavity was subsequently investigated by topographic surveying and theoretical gravity profiles calculated from the known volume of the caverns. The observed microgravity anomalies were twice as large as those predicted from theory, again demonstrating the enhanced anomaly which is caused by secondary effects surrounding the cavity.

Al Rifaiy (1990) describes the use of microgravity to detect the presence of cavities associated with sink-holes in the Eocene Dammam Limestone in the Al-Dahr area 27 km south of Kuwait City. Negative gravity anomalies between -20 to -80 microgals were associated with the presence of sink-holes and their upward propagation through the overlying Kuwait group which consists of poorly cemented sands and gravels. Ghatge (1993) reports on the use of a small microgravity trial to detect shallow (only 2 to 3m below the surface) abandoned mine workings in New Jersey. Lyness (1985) discusses how gravity measurements can be used to detect mining subsidence. Most of these surveys relied upon data gathered along discrete profiles which can often fail to adequately sample the anomaly caused by a mass deficiency at depth. Emsley et al. (1992) and Bishop et al. (1997) describe the utilisation of the microgravity technique using gridded maps of data in the detection of both Karstic and man-made cavities. The papers also describe how the resulting data can be enhanced by image processing to better define the anomalies associated with the targets. In particular they describe how the microgravity data which we collected in Kuwait and which was described by Al-Rifaiy (1990) can be enhanced by subsequent data processing.

Yule et al (1998) describe the use of microgravity for the detection of cavities in a switchyard with the results confirmed by investigatory drilling. Patterson et al (1995) describe the use of the microgravity technique for the detection of dissolution subsidence in gypsiferous Permo-Triassic strata in Yorkshire. They assess the realistically achievable accuracy of their measurements to be c 4 microgals and on this basis postulate that voids as small as 4 metres diameter might be detected in the right circumstances down to 12 metres. Recently the technique has been used with great success in the detection of old partially filled abandoned stope workings in Kalgoorlie Consolidated Gold Mines Open Pit even in the presence of very large terrain corrections caused by the topographic effect of the 250m deep excavations associated with the open-cut workings (Closed-File Report to KCGM 1997). A very valuable piece of information about an area which is underlain by cavities, is the amount of material which has been removed or lost from this area, in other words the mass deficiency. It is particularly useful in estimating the total mass deficiencies due to the presence of subsurface voids and is used to calculate the amount of grout required to fill the voids. This mass deficiency, which is the cause of the negative gravity anomaly, can be estimated by a mathematical theorem known as Gauss' theorem directly from the anomaly map without any prior knowledge of the exact location or nature of the targets.

The identification of the cause of the subsidence (i.e. a cavity or solution feature) is only the first objective of a site characterisation program. The stability and potential hazard posed by the migration to the surface and possible collapse of such a feature is an integral part of the remediation process. Time-lapse microgravity is a technique in which repeated microgravity surveys can be used to identify sub-surface density contrasts and monitor their development over time. The use of time-lapse microgravity to track the development of sub-surface density contrasts can provide a fast, real-time, cost-effective, monitoring technique, which has little or no impact on the residents or environment. Although microgravity surveys have become accepted practice in site investigations over the last ten years, time-lapse microgravity remains a relatively new discipline although examples of its use exist in the literature. Repeated microgravity surveys were used by Poeter (1990) to locate textural heterogeneities within the cone of depression caused by pumping in an unconfined aquifer. Pool and Eychaner (1995) also used time-lapse microgravity to monitor the movement of groundwater. In this case temporal-gravity surveys were used to directly measure aquifer-storage change and estimate values of specific yield. A forward inversion was performed by Hare et al. (1999) to investigate the potential of time-lapse microgravity to monitor the success of a proposed water injection in the Prudhoe Bay reservoir, Alaska. However, until recently (Rybakov et al, 2001), time lapse microgravity has not been used to detect and then monitor areas of low density in unstable environments. Rybakov et al. used repeated microgravity surveys to monitor the evolution of sinkholes at the western edge of the Dead Sea. Recent refinements have been made to this technique, including its application in a 4-D (temporal) mode, by the Applied and Environmental Geophysics Group at Keele University and these are reported in a number of papers, for example: (Styles 2003, 2004, Styles et al 2005) and in this paper.

3. Case Studies

3.1 The use of microgravity for the detection of abandoned Coal workings.

Extensive areas of the UK Coalfields were worked with shallow mining in the 19th C with few or no records kept of their abandonment. We have carried out many successful surveys to detect the presence, and state of stability of coal workings all over the UK.

3.2 Case Study: Shallow Coal Mining, Bristol

A major redevelopment scheme was proposed for the Longwell Green area of Bristol. The site was known to be underlain by abandoned shallow pillar and stall coal mine workings in the form of seams, tunnels and drifts and voids had been proved at depths of between 12 and 18m below ground level by rotary drilling. Typical void sizes ranged from 0.5 to 3.5m and clearly posed a significant hazard to the proposed development a retail Park with steel portal frame structures.

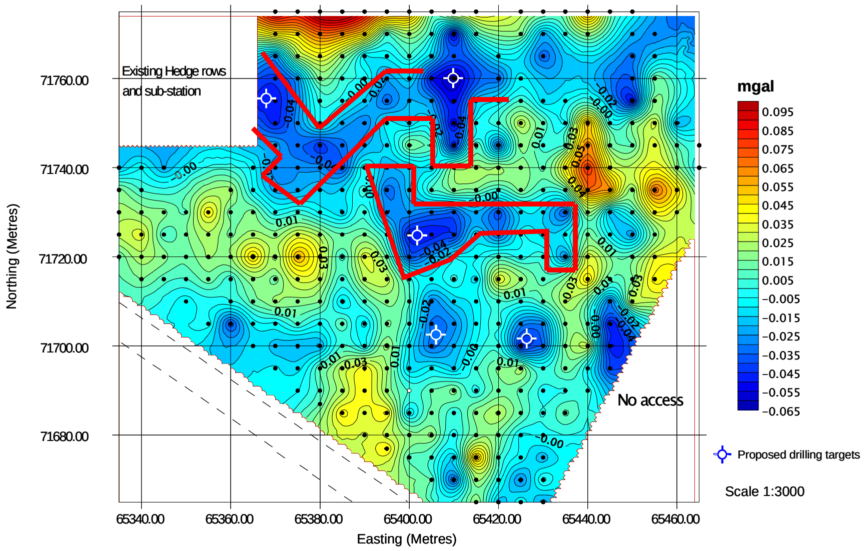

Figure 1 Microgravity map and drilling results showing an area of abandoned coal workings in Bristol, UK

A microgravity map at a 5-metre grid produced the above map after data reduction and clearly shows the presence of significant negative gravity anomalies. Drilling targets were selected on the basis of this map and the mine workings outlined in red were confirmed with voids identified at 12m to 14m below surface and the analysis of the gravity map predicts that the total mass missing from beneath the site was 995 tonnes which is a useful guide to the amount of remedial grouting required to stabilise the site.

4 Case Study The legacy of Chalk mining in the UK

Chalk has been extracted extensively in the United Kingdom for more than 4,000 years with excavations for flints at Grimes Graves, near Thetford in Norfolk probably being the earliest. From as early as Roman and Saxon times the flint was initially mined for building purposes while in later years the chalk bedrock itself was extracted and burnt to make lime for producing mortar and agricultural dressings and to aid the disposal of bodies from the epidemics which ravaged Britain in the period 1348 to 1666. Many parts of Kent and Sussex are pock-marked by ancient workings called dene-holes which are underground structures consisting of many small chalk mines entered by a vertical shaft. Several major towns have extensive areas which are underlain by historic Chalk workings, most notably Reading, Norwich and the Blackheath and Lewisham districts of south east London.

4.1 Case Study : A2 Collapse Greenwich London

In April 2002 a major collapse occurred within the A2 (London to Dover road) where it climbs Blackheath Hill in southeast London. The collapse occurred after subsoil washed away triggering subsidence of chalk pits dating from the mid-Fifteenth Century (and possibly Roman times) through to the mid-Nineteenth Century. The collapse caused traffic chaos with extensive diversions for many months, a number of people were evacuated from their homes, and investigation and remedial works spanning ten months was carried out at a cost of several million pounds. An extensive microgravity survey was carried out along the spine of the road and in adjacent areas of land. After correction for the terrain effects of a number of low-rise residential blocks, the data revealed the presence of areas where chalk had been historically excavated primarily from beneath the edges of the road. It also indicated areas of the road underlain by undisturbed ground. Approximately 150 boreholes were sunk to prove the results of the gravity survey which showed excellent correlation with the identified areas of mass deficiency.

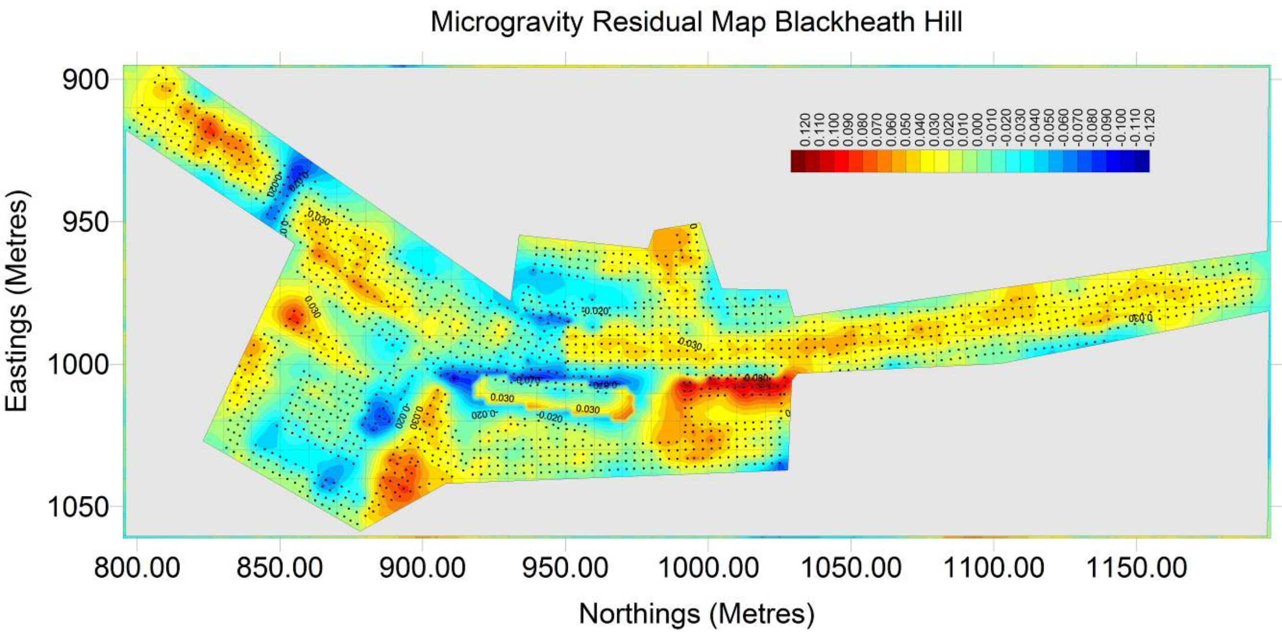

Figure 2 Residual microgravity map of a region of the Roman Road (A2) into London showing areas where chalk was excavated after the Black Death in the C15th and which recently collapsed

Similar microgravity surveys have been carried out in Norwich, Norfolk and Hatfield, Hertfordshire (Figure 3) where extensive areas of old chalk mines and quarries are present and chalk related subsidence has occurred since the last Century.

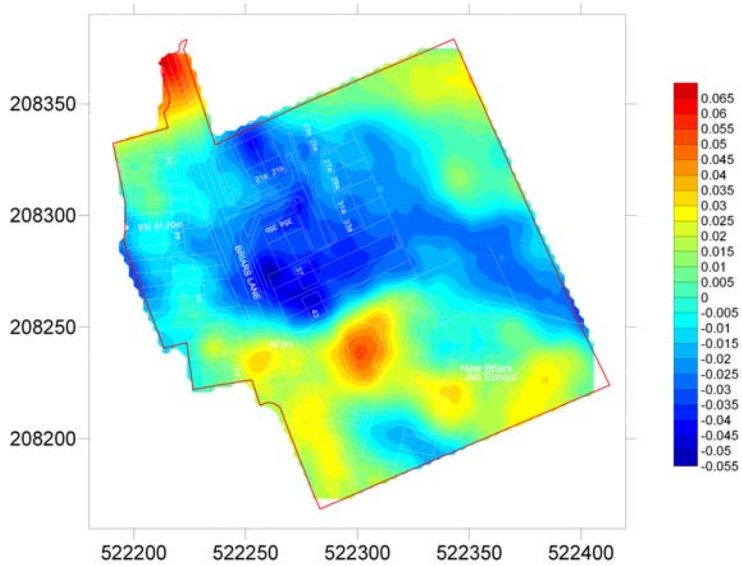

Figure 3. Microgravity Map showing an extensive area of chalk workings beneath Hatfield, Hertfordshire

5 Case Study Salt Mine Characterisation

5.1 Salt Mine stability evaluation using microgravity in Northwich Cheshire

Rock salt was first discovered in Great Britain in 1670 near Northwich UK. However, it is difficult to determine the exact number of mines that were sunk in the area as no official records were kept until 1873. Mining in Northwich was continuous and important from 1791 to 1928. Although the salt industry brought work and wealth to Northwich, the exploitation of the rock salt deposits has been accompanied by the serious problem of subsidence. Initially mining was concentrated in the upper salt bed, about 30m below the surface in a seam 30m thick. Later a second seam, also 30m thick, was found at a depth of 60m. Most of the upper level mines flooded and subsequently collapsed leaving large crater like holes. The likelihood of collapse was increased, as once the water running into the mineshafts became saturated, the "Bastard Brine" was pumped out in order to satisfy the continuing demand. The consequence of this action was the repeated drawing of fresh water into the mine dissolving the supporting pillars resulting in catastrophic collapse. The pumping of Bastard Brine became popular and many brine pumping shafts were established in the Northwich area. Again this accelerated the dissolution of salt at "Wet Rock Head" i.e. the area where the termination of the salt bed is in contact with groundwater. (If the salt bed terminates below the level of the local groundwater this surface is termed "Dry Rock Head"). More importantly however, the dissolution was uncontrolled and often occurred some distance away from the Pumping station. Subsidence was common throughout the town in the late 19th and early 20th Centuries and many of the houses built in that era were mounted on jacks so that they could be raised to the level of the road after a subsidence event. The town centre of modern Northwich is underlain by abandoned salt workings, which has led to significant planning blight and the threat of continued subsidence. We have used microgravity successfully in Northwich Cheshire to monitor upwards-propagating subsidence in Permian marls associated with salt dissolution occurring at the interface between marls and salt (wet rock-head). In this case the cause is continuing brine pumping which has led to the dissolution of salt at wet rock head and the associated collapse of the overlying Keuper Marls. In order to discriminate anomalies of this small magnitude careful field procedures, data reduction (including correction for the terrain effects of buildings) and interpretation procedures must be followed. However, with these procedures it is then possible to distinguish both the presence and the state of stability of most shallow and hazardous abandoned mine workings .

Figure 4 Location of Northwich, Cheshire, UK and specifically Peter Street where three repeat microgravity surveys have been acquired from 1998 through to 2002

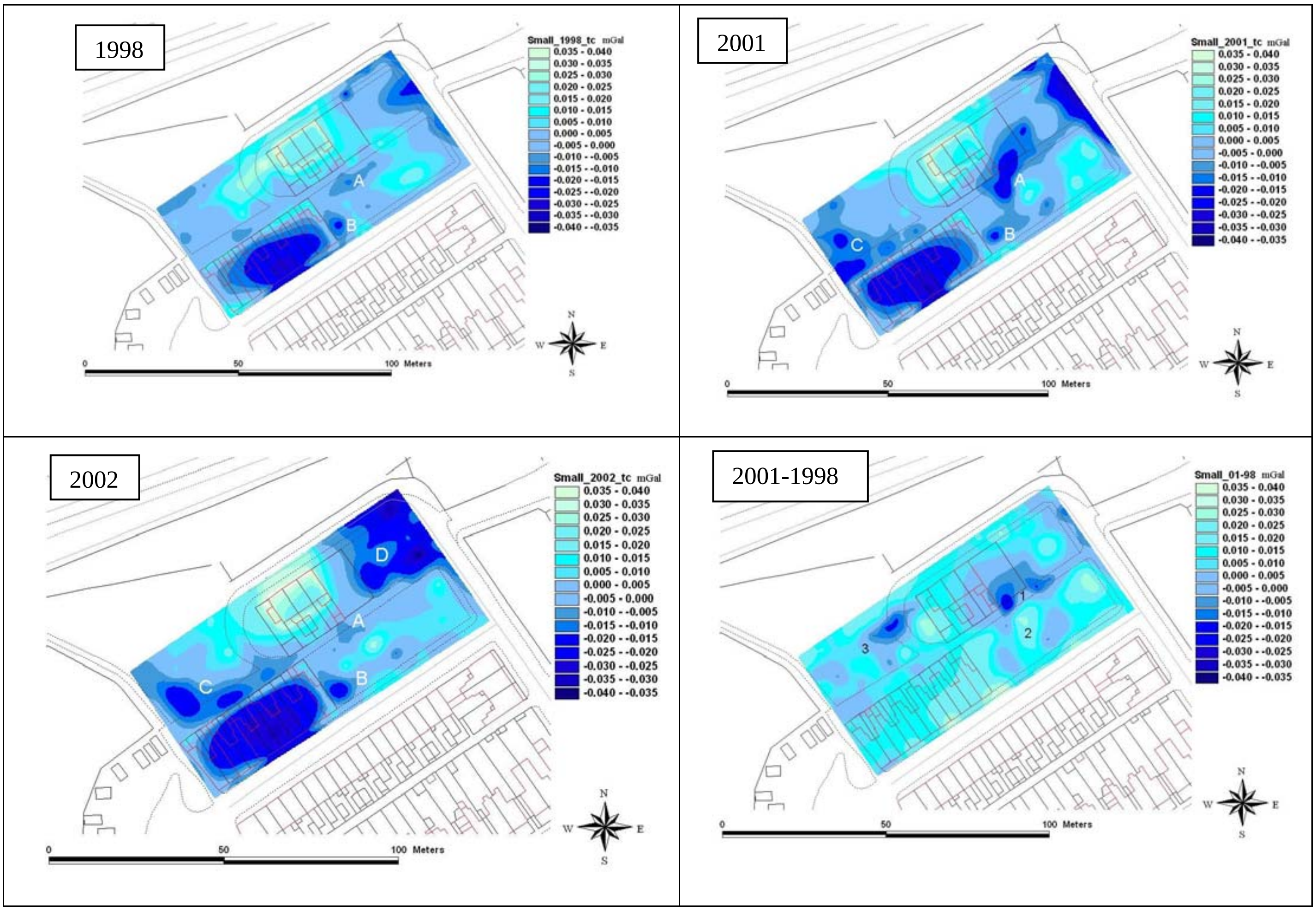

Figure 5 Contour map of the gravity data acquired in 1998, 2001 and 2002. The later surveys covered a larger area but extractsa which coincide with the original more limited survey have been selected. A first order polynomial has been removed from each set of data after the gravitational effect of the buildings has been corrected for. Negative gravity values are denoted by dark shades of blue. The final figure shows a contour map of the gravity change between 1998 and 2001.

A new variation called time-varying differential microgravity has considerable potential for detecting changes in mass distribution beneath an area and has the advantage that only a limited sub-set of the original survey need to be re-sampled to detect the time-varying part of the signal. This is particularly appropriate when known cavities or voids are being monitored to detect the onset or development of instability. Branston and Styles (2003) describe the use of time lapse microgravity in Northwich, Cheshire, UK (Figure 4). Peter Street is an area of terraced housing suffering from subsidence that was thought to be mine related. Microgravity and resistivity profiling were used on Peter Street to as non-invasive techniques to investigate the cause of subsidence. The first microgravity survey was carried out in the Peter Street area in 1998 (Simon Emsley and Sarah Corrie of Golder Associates) and in 2001 and again in 2002 by Keele University. The 1998 survey was carried out using a Scintrex CG-3M Microgravity Meter with three readings taken at each point in quick succession to ensure repeatability. The 2001 and 2002 surveys were carried out a Lacoste and Romberg D Meter (D-141), on a 5m by 5m grid with repeat readings at each point for repeatability and topographic heights of survey points measured to within 2mm for Free Air Corrections. In both surveys base readings were taken at the start and end of each day, and at hourly intervals between. Both surveys were processed to produce a residual Bouguer gravity map where the effect of drift, elevation and topography are removed. These are shown in Figure 5.

The 1998 survey detected an negative gravity anomaly (A) coincident with the reported area of subsidence,. Its amplitude is approximately -15µGal and the anomaly extends in a NE-SW direction. The results of the 2001 survey shows the main feature is a negative anomaly (B to C) of amplitude -60µGal trending from the NW to the SE which has grown in amplitude and steepened in gradient. A second anomaly (A) branches off this and trends towards the NE, the principal area of recorded subsidence. Through the use of various modelling techniques it has been shown how this change in the anomalies characteristics corresponds to a shallowing of the causative body. The results of the 2002 survey again show the main feature identified in the 2001 survey, a large negative anomaly trending NW-SE. Again a second linear anomaly can be seen to branch off this main anomaly towards the NE. However, the amplitude of this anomaly (A) has become less negative over the monitoring period, i.e the anomaly has reduced in amplitude and volume. This has been attributed to further shallowing and a reduction in volume of the body due to progressive collapse and infilling. A second, more localised anomaly (B), was recorded south of anomaly A. Anomaly B has an amplitude of -20µGal and is circular in extent. When we consider the 2002 survey some interesting aspects emerge. Although the monitoring period is shorter, it is evident that the area has also been active during this period. Interestingly, anomaly A has decreased in amplitude to -12µGal.. Anomaly B remains consistent with the 1998 and 2001 surveys. Its amplitude and extent has remained relatively constant. Alarmingly, anomaly C has continued its growth and now has an amplitude of -30µGal. The NE of the grid is the second area where the value of gravity has continued to decrease. Anomaly D appears to be the development of the NE extension of anomaly (A) seen in the 2001 survey. It has a large extent, some 20m^2, with maximum amplitude of -35µGal. Concentrating on the area of the 2001 microgravity survey that is coincident with the 1998 survey (it becomes evident that the area has been mobile between 1998 and 2001. Anomaly A has grown in amplitude and extent. Its amplitude is now -25µGal, and it has broadened towards the NE, extending onto the waste ground left by the demolition of the houses in 1985. Anomaly B is still evident although it appears to remain relatively constant in amplitude and extent. However, the area to the west has become increasingly negative resulting in anomaly C. The maximum amplitude in this area is -20µGal. Figure 5.d shows that there is a high degree of negative change in the area around the principal subsidence (1). The area of negative change also extends southwards towards Peter Street. At its maximum a change of -35µGal has been recorded This is well above the expected error of a time-lapse microgravity survey (~15µGal), and so we must conclude that the causative body, or zone has been active during this time period. Interestingly, there has also been a positive change in the area (2). This is also present in the difference plot between 2002 and 1998. The cause of this will be investigated during the interpretative modelling. The other area of interest is in the west of the survey area (3). This area also shows a negative change with a maximum of -25µGal.

Branston and Styles 2003 found that Peter Street had subsided by up to 23cm between July 1998 and July 2001. The microgravity surveys showed that this subsidence is coincident with a low density gravity anomaly, and time-lapse microgravity shows that this low density anomaly has grown in size over the 3 year period. Modelling shows that the propagating edge of the low density body has risen by approximately 4m in the 3 years between surveys. Resistivity profiling supported the conclusions drawn from gravity data, suggesting an anomalous area coincident with the gravity and topographic lows.

6 Future planned work

The Institut National de l'Environnement Industriel et des Risques (INERIS), France, have identified an experimental site for the geophysical survey of salt cavities as part of the BCRD research program “Underground reconnaissance using geophysical methods applied to sounding and the detection of underground cavities” (Program BCRD-DRS-04/01). The site ‘Pistes de la Rape’ near Art-sure-Meurthe, Loraine, France is made up of 29 wells split into three main tracks that were mined by dissolution between 1971 and 1993. The resulting salt cavities are at depths of 110 to 180m in various shapes and sizes. Argillites overlie the salt roof and, as a result of a successive argillite disintegration mechanism, the cavities have migrated until a more resistant layer was reached. The cavities have been classified into 3 groups according to their location in relation to the geological formations:

1. The roof of the cavity is located along the base of the dolomite bed.
2. The cavity is entirely within the argillites.
3. The cavity has reached the salt roof.

An extensive programme of geophysical techniques in planned for Summer 2005 to determine their efficacy in characterising the stability parameters of salt mines. As part of the BCRD research program (BCRD-DRS-04/01) described above, the Applied and Environmental Geophysics Research Group of Keele University will carry out a microgravity surveys (normal and time lapse) at ‘Pistes de la Rape’, near Lenoncourt, Art-sure-Meurthe , Lorraine In July/August 2005. There are several different type of cavities exhibiting differing behaviours and they will be surveyed in order to differentiate the characteristic of these stability environments

1 **Zone 51. Piste 3** This is a zone of active collapse where a large cavity has breached the surface. The lateral extent of this cavity is uncertain and a set of profiles at 3 metres spacing will be collected to attempt to identify the spatial configuration of the subsurface void.

2 **Zone 31 Piste 1** This is not thought to be particularly active but a considerable number of other geophysical techniques will be trialled here and it is useful to have a complementary microgravity survey for integration into the synthesis of the interpretation. This area will be chosen for a 3-d grid of gravity data at 5 meters spacing over a zone of c 100 metres by 100 metres.

3 **Zone 41 Piste 2** This is a zone where activity is though to be high and which is likely to have significant on-going dissolution with associated instability. This area will be chosen for a 3-d grid of microgravity gravity data at 5 meters spacing over a zone of c 100 metres by 100 metres.

A second survey will be carried out over the same area Zone 41 in July/August 2006 using the same equipment and techniques in order to determine the changes in microgravity which have taken place and the associated changes in sub-surface void configuration.

7 Conclusions

A wide range of microgravity investigations have now been carried out in the UK over many types of abandoned shallow mines including coal, chalk, tin and salt. In all of these environments the microgravity method has proved to be a useful tool for the detection, delineation and characterisation of subsurface cavities and this has been validated by extensive progammes of drilling (150 boreholes for the A2 collapse in London). The agreement between predicted and proven cavities has been extremely good, leading to the technique becoming widely used in site investigations where abandoned mine-workings are suspected to exist.

In selected areas, it has been possible to carry out repeated surveys in order to investigate the temporally varying componet of the microgravity field. Over intervals as short as a year significant changes in gravity have been deteced and have been shown to be assoiated with areas of enhanced subsidence. This technique has the advantage of removing the need for terrain and geological corrections as they are identical between surveys. Areas of maximum subsidence and potential collapse can be identified and treated by grouting to stabilise the area.

The technique has equivalent application for karst cavities as shown by Styles et al (2005) and also for the detection of piezometreic changes in aquifers and mine-water rebound.

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