Subsidence Due to Abandoned Mines: Risk, Evaluation and Mitigation

F.G. BELL
B.Sc., Ph.D., C.Eng., C.Geol., F.I.M.M., F.I.Min.E., F.G.S.
Professor of Engineering Geology, University of Natal, Durban, South Africa
B. MORTIMER
B.Sc., F.G.S.
Lecturer in Engineering Geology, University of Natal, Durban, South Africa

SUMMARY. Abandoned mine workings, especially those at shallow depth, because of their potential to cause ground subsidence, often represent significant problems in urban areas where development or redevelopment is to take place. In the United Kingdom information needed to locate potential hazards due to mine-workings is available but occurs in numerous scattered locations and considerable time and effort may be involved in its collection. In recent years thematic geological maps have been produced for certain coalfield areas where workings have long since closed. These can be used as an initial aid to hazard avoidance when such areas undergo redevelopment.

Nonetheless old workings should be located prior to the development of a site, and their layout and condition determined, wherever possible. This can be accomplished by a combination of indirect and direct methods of exploration. The site then can be zoned according to the degree of risk that the workings present. This may result in buildings not being permitted in those areas of maximum risk unless the ground is stabilized beforehand. Stabilization measures may involve occupying the workings with hydraulic fill or cheap bulk grouts. In areas of less risk special foundation structures may be used.

1. INTRODUCTION

In Britain coal mining began to be carried out on a significant scale in the thirteenth century. Drifts and adits into shallow workings were usually situated at the base of quarries and open pits or along the coal outcrops in hilly country. The workings extended as far as natural drainage and ventilation permitted.

By the fourteenth century outcrop workings had largely given way to bell pits. The shafts of bell pits rarely exceeded 12.2 m in depth and their diameter was usually around 1.3 m. Extraction was carried on around the shaft until such times as roof support became impossible, another shaft was then sunk nearby.

The pillar and stall method of extraction developed in the sixteenth century. Underground workings were shallow and not extensive. In very early mining the remnant pillars were rather haphazard in size and arrangement, but with time mining became more systematic and pillars of more or less uniform shape were formed by driving intersecting roadways in the seam. Also there was a general tendency for the size of stalls to increase.

Although mining has gone on in many coalfields in Britain for several centuries, the first statutory obligation to keep mine records only dates from 1850 and it was not until 1872 that the production and retention of mine plans became compulsory.

2. PILLAR AND STALL WORKINGS AND THEIR POTENTIAL FAILURE

In pillar and stall workings pillars sustain the redistributed weight of the overburden which means that they and the rocks immediately above and below are subjected to added compression. Stress concentrations tend to be located at the edges of pillars and the intervening roof beds tend to sag. Although the intrinsic strength of coal varies, the important factors in the case of pillars are that their ultimate behaviour is a function of seam thickness to pillar width, the depth below ground and the size of the extraction area since these control the load on pillars. If a pillar fails, then the mode of failure also involves the character of the roof and floor rocks. Pillars in the centre of the mined out area are subjected to greater stress than those at the periphery. Individual pillars in dipping seams tend to be less stable than those in horizontal seams since the overburden produces a shear force on the pillar. When a structure is to be built over an area of old pillared workings the additional load on the pillars can be estimated simply by adding the weight of the appropriate part of the structure to the weight of the column of strata supported by a given pillar. This method is very conservative except when used for large concentrated loads where old workings are located at shallow depth.

Collapse in one pillar can bring about collapse in others in a sort of chain reaction because increasing loads are placed on those remaining. Slow deterioration and failure of pillars may take place after mining operations have long since ceased, although observations at shallow depth and the resistance of coal to weathering suggests that this is relatively uncommon at depths less than 30 m. Attempts, based upon statistical analysis, have been made to try and predict the maximum time required for a pillar to fail after a mine has been abandoned (Van Besien and Rockaway, 1988). They have been unsuccessful. Old pillars at shallow depth have occasionally failed near faults and they may fail if they are subjected to the effects of subsequent longwall mining. If yielding occurs in a large number of pillars, then this can bring about a shallow broad subsidence over a large surface area. The ground surface tends to displace radially inwards towards the area of maximum subsidence, thereby generating tangential compressive strain, and circumferential tension fractures frequently are developed. Such movements often develop rather suddenly, the major initial movements lasting, in some instances, for about a week. The shape of the profile can vary appreciably with mine layout and geological conditions. Maximum profile slopes and curvatures frequently increase with increasing subsidence.

Very often pillars were robbed on retreat. Extraction of pillars during the retreat phase simulates the longwall surface condition, although it can never be assumed that all pillars have been removed. At moderate depths pillars, particularly pillar remnants, are probably crushed and the goaf (i.e., the worked out area) compacted, but at shallow depths lower crushing pressures may mean the closure is variable. Furthermore artificial supports may have been used for the extraction of thicker seams. Some of the pillars shown on mine plans may have been removed and replaced with packs and timber stacks. The stability of such temporary structures defies analysis.

Prediction of subsidence as a result of pillar failure requires accurate data regarding the layout of the mine. Such information frequently does not exist in the case of abandoned mines. On the other hand when accurate mine plans are available, the tributary method outlined by Goodman et al (1980) may be used to evaluate collapse potential. The approach adopted by Goodman et al (1980) allows zones of minimum stability in abandoned pillar and stall workings to be located. The procedure may be summarized as follows:

(1) Plot pillar locations and dimensions.

(2) Determine pillar strength (S_p) for each pillar, having regard to the unconfined compressive strength (UCS) of the rock materials and the shape and size of the pillars. This is expressed by:

$$S_p = \frac{(UCS \times N\text{-}shape \times N\text{-}size)}{FS} \quad (1)$$

where FS is a factor of safety. The N-shape factor is influenced by the width (W) and the height (H) of the pillar:

N-shape = (0.875 + 0.250 W/H)

(3) The stress (σ) on each pillar then is calculated from:

$$\sigma = \frac{(P \times A_t)}{(A_p - A_w)} \quad (2)$$

where P is the initial vertical stress at the level of the roof of the opening, A_t is the area tributary to each pillar, A_p is the cross sectional area of the total pillar, and A_w is the area of pillar lost from load carrying by virtue of weathering, loosening or overbreak.

The ratio S_p/σ gives a factor of safety for each pillar and these values are plotted on the pillar plan. Pillars which have factors of safety of less than one are considered potentially unstable and are therefore removed from the plan. Their tributary areas are reassigned to adjacent pillars and the calculation repeated. In the second calculation more pillars may be found to have failed and they may be removed for further reiteration of the calculation, if so required. Although the method requires the exact shape of individual pillars to be known, as well as the mechanical properties of the coal and overlying rocks, it nonetheless offers an approach to recognizing where the most potentially unstable areas exist so that support works can be located optimally. Previously a review of the various methods of determining pillar strength and failure was provided by Bell (1978). In addition, a survey of underground excavation failure mechanisms was given by Hoek and Brown (1980).

Even if pillars are relatively stable the surface may be affected by void migration. This can take place within a few months of or a very long period of years after mining. Void migration develops when roof rock falls into the worked out areas. When this occurs the material involved in the fall bulks, which means that migration is eventually arrested, although the bulked material never completely fills the voids. Nevertheless, the process can, at shallow depth, continue upwards to the ground surface leading to the sudden appearance of a crown hole. The factors which influence whether or not void migration will take place include the width of the unsupported span; the height of the workings; the nature of the cover rocks, particularly their shear strength and the incidence and geometry of discontinuities; the thickness and dip of the seam; the depth of overburden; and the groundwater regime.

It is frequently maintained that the maximum height of void migration is directly proportional to the thickness of seam mined and inversely proportional to the change in volume of the collapsed material. It would appear that the height of collapse is independent of the width of the excavation although it is a limiting factor. In other words the larger the span, the more likely is collapse to occur. The maximum height of migration in exceptional cases might extend to 10 times the height of the original roadway, however, it generally is 3 to 5 times the roadway height. If a competent bed occurs in the roof rocks, which is thicker than 1.75 times the span width, it will arrest the collapse. Even so voids which occur just below the surface represent just as awkward a problem.

In a recent investigation Garrard and Taylor (1988) found that the majority of void collapse height interrelationships were explained by variations in either or both the width of the working and the type of roof rock. Old workings with roofs of interbedded strata were found generally to be wider and to have collapsed to higher levels than workings in which the roofs were formed of sandstones, siltstones or mudrocks. In addition the collapse structures in polylithological sequences had significantly greater collapse height to width ratios and steeper failure surface angles than monolithological sequences. It would appear that once voids start to migrate in interbedded rocks they reach higher levels because of the rapid change between competent and incompetent beds. This perhaps destroys the coherence of the rock unit and facilitates delamination, bed separation and fracture.

Most voids are bridged when the span decreases through corbelling to an acceptable width. Walton and Cobb (1984) mentioned that three times the width of the stall appeared to be an upper limit to the extent of most void migrations in abandoned coal mines whilst Garrard and Taylor (1988) suggested that the collapse height can be obtained by multiplying the width of the workings by 2.68. However, because of the difficulty of obtaining stall dimensions in abandoned workings, the height of void migration normally is determined from the thickness of mineral extracted and the difference in densities between the roof material in situ and when collapsed.

Exceptions, of course, do occur and void migration in excess of 20 times the seam thickness concerned has been recorded. The self-choking process may not be fulfilled in dipping seams, particularly if they are affected by copious quantities of water which can redistribute the fallen material. This can lead to the formation of supervoids and their migration to rock head, then produces large scale subsidence at ground level (Carter, 1985).

3. INVESTIGATIONS IN SUBSIDENCE AREAS

A site investigation for an important structure(s) requires the exploration and sampling of all strata likely to be significantly affected by the structural loading (Bell, 1975). The location of subsurface voids due to mineral extraction is of prime importance in this context. In other words an attempt should be made to determine the number and depth of mined horizons, the extraction ratio, the pattern of the layout, and the condition of the old workings. The sequence and type of roof rocks may provide some clue as to whether void migration has taken place and if so, its possible extent. Of particular importance is the state of the old workings, careful note should be taken of whether they are open, partially collapsed or collapsed, and the degree of fracturing and bed separation in the roof rocks should be recorded, if possible. This helps to provide an assessment of past and future collapse which is obviously very important.

The desk study includes a survey of appropriate maps, documents, records and literature. The presence on geological maps of mineral deposits which could have been mined suggests the possibility of past mining unless there is evidence to the contrary, and geological and topographic maps may show evidence of past workings such as old shafts, adits and spoil heaps. All the geological and topographic maps of the area in question, going back to the first editions, should be examined. All the same, instability problems associated with abandoned mine workings cannot necessarily rely on old mine plans. Sometimes these are early working plans which do not reflect the state of the mine at abandonment. Added to which, old mine plans are often incomplete and inaccurate. Nevertheless, such records can provide useful information relating to the extent and method of mining.

The use of remote sensing imagery and aerial photography for the detection of surface features caused by subsidence is more or less restricted to rural areas. Colour photographs may be more useful than black and white ones in the detection of past workings since they can reveal subtle changes in vegetation related to subsidence and, if there are differences in thermal emission, then infra-red (false colour) photographs should show these differences.

The reconnaissance survey involves a walk-over visit of the site to allow familiarization. Subtle variations in the topography may be observed together with evidence of past land use. If sufficient information is gathered at this stage, it may be possible to pass straight into a field investigation involving direct exploration of the ground by drilling. If this is not the case, then indirect subsurface exploration using geophysical techniques, may be undertaken.

Considerable care should be exercised at the planning stage of a geophysical survey for the location of subsurface voids because of the variable nature of the target (Cripps et al 1988). The selection of the most appropriate technique necessitates consideration of four parameters, namely, penetration, resolution, signal to noise ratio and contrast in physical properties. The size and depth of the workings, and the character of any infill control the likelihood of the workings being detected as an anomaly. With the information obtained from the desk study and the reconnaissance survey, many of the available geophysical methods can be assessed at the selection stage, using a model study, and accepted or rejected, without any requirement for field trials. Generally it is possible to detect a cavity whose depth of burial is less than twice its effective diameter. Otherwise more sophisticated surface methods or drillhole methods have to be employed. However, since the presence of a void is likely to affect the physical properties and drainage pattern of the surrounding rock mass, this can give rise to a larger anomalous zone than that produced by the void alone.

The nature of the environment around a site affects the success of geophysical surveys. For instance, traffic vibrations adversely affect the results obtained from seismic surveys, as do power lines and electricity cables in the case of electromagnetic and magnetic techniques. Of particular importance is that there should be sufficient physical property contrast between the void and the surrounding rock mass so that an anomaly can be detected.

Seismic refraction has not been used particularly often in searching for voids created by previous mining at shallow depth since such voids are often too small to be detected by this method. This is because of attenuation of seismic waves in the rock mass (Anon, 1988).

Also except for workings with a depth of cover less than 5 m, it is unlikely that resistivity profiling would detect the presence of dry pillar and stall workings. On the other hand electrical resistivity depth sounding can be applied to the location of voids where the width to depth ratio is large. Mine workings which produce an air-filled layer can often be identified on the sounding curve as an increase in apparent resistivity.

Down to a depth of 30 m terrain conductivity surveys are more effective than resistivity traversing. Conductivity values can be contoured to indicate the presence of any anomalies. Penetration into the ground achieved by electromagnetic radiation can be limited by excessive attenuation in ground of high conductivity.

Generally speaking, voids in shallow abandoned mine workings are too small and located at depths too great to be detected by normal magnetic or gravity surveys. However, the fluxgate magnetic field gradiometer permits surveys of shallow depths to be carried out since it provides a continuous recording of lateral variations in the vertical gradient of the Earth's magnetic field rather than giving the total field strength. It tends to give better definition of shallow anomalies than the proton-magnetometer. On the other hand, a proton-magnetometer can more easily detect larger and deeper features, and yields results which are more suitable for contouring. Micro-gravity meters may be successful when the voids have a significant lateral extent.

Ground probing radar appears to be capable of detecting small subsurface cavities directly and may prove one of the most promising methods for the future. The high frequency of the system provides high resolution and characteristic traces are produced by air filled voids. Depths to voids can be determined from the two way travel times of reflected events if velocity values can be assigned to the strata above the void. The conductivity of the ground imposes the greatest limitation on the use of radar probing in site investigation as depth to which radar energy can penetrate depends upon the effective conductivity of the strata being probed. This, in turn, is governed chiefly by the water content and its salinity, and is also a function of temperature and density as well as the frequency of the electromagnetic waves being propogated.

Drilling to prove the existence of old mine workings is frequently done by open holes, which allows relatively quick probe drilling (Bell, 1986). The drillhole should be taken to a depth where any voids present are not likely to influence the performance of the structures to be erected. If a grid pattern of drillholes is used some irregularity should be introduced to avoid holes coinciding with pillar positions. The sequence should be established by taking cores in at least three drillholes. The presence of old voids is indicated by the free-fall of the drill string and the loss of flush.

One of the principal objectives of investigations of abandoned mine workings is to determine their extent and condition. Accordingly core material needs to be obtained. Double barrel sampling tubes with inner plastic liners can be used to obtain core which then can be photographed and logged, and the rock quality designation (RQD) or fracture spacing index recorded. Drilling penetration rates, water flush returns and in situ permeability tests may be used to assess the degree of fracturing. The degree of fracturing is important in that it tends to increase as old workings are approached.

Detailed mapping of galleries is best made by driving a heading from the outcrop if this is close at hand or by sinking a shaft to the level of the coal seam to obtain access to the workings. Sometimes access has been gained via old shafts. Radial holes may be drilled from the shaft to establish the dimensions of the pillars and stalls.

Below surface workings may be examined by using drillhole cameras or closed circuit television, information being recorded photographically, or on videotape, and used to assess the geometry of voids and, possibly, the percentage extraction. However, their use in flooded old workings has not proved very satisfactory. Occasionally smoke tests or dyes have been used to aid the exploration of subsurface cavities.

Most of the geophysical methods have a down-the-hole counterpart which can be used to log a hole. Crosshole techniques can be used when the depth of burial of the void is more than two or three times the diameter of the void. In interdrillhole acoustic scanning an electric sparker, designed for use in a liquid filled drillhole, produces a highly repetitive pulse. This signal is received by a hydrophone array in an adjacent drillhole, similarly occupied by liquid (McCann et al, 1975). Drillholes must be spaced closely enough to achieve the required resolution of detail. The method can be used to detect subsurface cavities, if the cavity is directly in line between two drillholes and has at least one tenth of the drillhole separation as its smallest dimension. Air filled cavities are more readily detectable than those filled with water.

Crosshole seismic testing has also been used, employing two or more drillholes, to detect near-vertical subsurface anomalies. Acoustic tomography techniques are now being developed to map voids between adjacent drillholes.

4. OLD MINE WORKINGS AND HAZARD ZONING

Assessments of mining hazards has usually been on a site basis regional assessments being much less common. Nonetheless regional assessments offer planners an overview of the problems involved. This should lead to the avoidance of planners imposing unnecessarily rigorous conditions in areas where they really are not warranted.

In recent years thematic maps have been produced in Britain of both urban and rural areas with a view to benefiting planners and civil engineers concerned with land use and ground stability. Early thematic maps produced by the British Geological Survey depicted areas of undermining assumed to be within 30 m of the surface on the one hand and at depths exceeding 30 m below the surface on the other (McMillan and Browne, 1988). This 30 m depth is the subject of interpretation and is based on limited information. It assumes that bulking factors of 10 to 20 per cent will affect the strata involved in void migration. However, "safe" depth rules are often broken. Known and suspected mining areas were not differentiated. Modifications were introduced for the map of the Glasgow district so that only areas of mining shown on mine plans were represented and no areas of suspected mining were shown. No attempt was made to infer the extent of working beyond the limits defined by mine plans other than to plot relevant drillhole data. The introduction of single and multiple seam working led to the requirement that areas of shallow working (less than 30 m below rockhead) should be identified in terms of seams worked. Separate maps were prepared illustrating areas of total known mining; current mining; known mining within 30 m of rockhead, together with the locations of shafts and drillholes encountering old shallow workings; and mining for minerals other than coal and ironstone. In Fife, known and inferred old shallow mining were differentiated on the same map. Each modification has reflected an attempt to clarify the presentation of known and inferred mining. An indication of the area in which mining might be expected can be obtained by plotting all drillholes which encounter colliery spoil outside areas of workings known from abandonment plans. In areas where coal outcrops are reasonably well known, areas of suspected workings can be mapped as a separate category, although it is then necessary to assume that all workable seams have been exploited, at least in the near surface area.

In an assessment of the degree of risk due to subsidence incidents associated with abandoned mine workings in South Wales carried out by Statham et al (1987), they found that of the 388 events 64 per cent occurred in open land and so posed no threat to person or property. Twenty one per cent had occurred when people were nearby or threatened property. The remainder caused damage to highways, buildings or other property and only one of these resulted in minor injuries. In the context of the South Wales coalfield this represents a low level of hazard. Assuming that a typical incident affects an area of 5 m^2, then the probability of collapse occurring on any 25 m^2 plot is of the order of 10^{-7} per year. Even if the number of subsidence incidents which have remained undiscovered increased the above total figure by a factor of 3, then the overall risk would still be low. Statham et al

(1987) found that over 90% of the incidents occurred within 100 m of the outcrop of the coal seam concerned. They produced a development advice map for South Wales which showed two zones inside the outcrops of worked seams corresponding to migration ratio (thickness of rock cover ÷ extracted thickness) values of 6 and 10, which were expected to contain 90 per cent and 100 per cent respectively of relevant subsidence incidents. The map makes a contribution towards regional planning by taking account of a possible development constraint at an early stage and offers an early warning on the likely scale of ground investigation required at specific sites. Attempts also have been made to zone ground underlain by old mine workings in terms of its suitability for different types of foundation (Gostelow and Browne, 1986).

However, it must be borne in mind that thematic maps which attempt to portray the degree of hazard represent generalized interpretations of the data available at the time of compilation. Therefore, they cannot be interpreted too literally and areas outlined as "undermined" should not automatically be subject to planning blight. Obviously there is a tendency to assume that the limits of old mine workings represented on a map indicate the full extent of the workings but it must be borne in mind that interpretation of their location is based on scanty information and includes assumptions, some of which may be unfounded. It should be recognized that engineering problems in areas of past mining only occur if buildings are not properly planned, designed and constructed with reference to the state of undermining. Also zoning based entirely upon depth of cover above workings cannot be relied on completely, since occasionally subsidences have occurred in zones labelled "safe".

5. MEASURES TO MITIGATE SUBSIDENCE EFFECTS

Where a site which is proposed for development is underlain by shallow old mine workings there are a number of ways in which the problem can be dealt with. The first and most obvious method is to locate the proposed structure on sound ground away from the old workings or over workings proved to be stable. It is not generally sufficient to locate immediately outside the area undermined as the area of influence should be considered. In such cases the angle of influence or draw is usually taken as 25°, in other words the area of influence is defined by projecting to the surface an angle of 25° to the vertical from the periphery and depth of the workings. Such location is, of course, not always possible.

If old mine workings are at very shallow depth, then it might be feasible, by means of bulk excavation, to found on the strata beneath. This is often an economic solution, particularly at depths of up to 7 m or on sloping sites.

Where the allowable bearing capacity of the foundation materials has been reduced by mining, it may be possible to use a raft. A raft can span weaker and more deformable zones in the foundation, thus spreading the weight of the structure well outside the limits of the building. However, rafts are expensive and therefore tend to be used where no alternative exists. For low-rise buildings, up to four storeys in height, it is occasionally possible to use an external reinforced ring beam with a central lightly reinforced raft as a practical and more economic foundation.

Reinforced bored pile foundations also have been resorted to. In such instances the piles bear on a competent stratum beneath the workings. They also should be sleeved so that concrete is not lost into voids, and to avoid the development of negative skin friction if overlying strata collapse. There may be a problem with lateral stability of piles passing through collapsed zones above mine workings or through large remnant voids.

Where old mine workings are believed to pose an unacceptable hazard to development and it is impracticable to use adequate measures in design or found below their level, then the ground itself can be treated. Such treatment involves filling the voids in order to prevent void migration and pillar collapse. In exceptional cases where, for example, the mine workings are readily accessible, barriers can be constructed underground and the workings filled hydraulically with sand or pneumatically with some suitable material. Hydraulic stowing also may take place from the surface via drillholes of sufficient diameter. Pneumatic or gravity stowing often is considered where large subsurface voids have to be filled.

Grouting is generally achieved by drilling holes from the surface into the mine workings, on a systematic basis, generally on a grid pattern, and filling the remnant voids with an appropriate grout. If it has been impossible to obtain accurate details of the layout and extent of the workings, then the zone beneath the intended structure can be subjected to consolidation grouting. The grouts used in these operations commonly consist of cement, fly ash and sand mixes, economy and bulk being their important features. If the workings are still more or less continuous, then there is a risk that grout will penetrate the bounds of the zone requiring treatment. In such instances dams can be built by placing pea gravel down large diameter drillholes around the periphery of the site. When the gravel mound has been formed it is grouted. The area within this barrier is then grouted. If the old workings contain water, then a gap should be left in the dam through which the water can drain as the grout is emplaced. Pea gravel also may be used as a bulk filler where a large amount of grout is required for treatment. Alternatively foam grouts can be used.

6. CONCLUSIONS

The pillar and stall method of mining was developed in the United Kingdom in the sixteenth century to work coal, the pillars being left in place to support the roof rocks. However, because there was no legal obligation to produce and deposit mine plans prior to 1872, the presence of many old mines and their layout remains unknown. This can present a problem when structures are to be erected above old abandoned mine workings since the ground may not be capable of carrying the load safely.

A number of subsidence problems can be associated with old pillared workings. These result from either failure and collapse of the pillars or from roof collapse above the stalls with gradual migration upward of voids.

Because of these problems an extensive investigation is called for when an area above suspected shallow old mine workings is to be developed. Such investigations involve searches through old records, where available. Geophysical methods frequently have been used in an attempt to determine the nature of old workings. Unfortunately, however, they have not always been successful. Direct investigation of old workings involves drilling into them. They can then be explored by borehole camera or closed circuit television if conditions permit. Gaining access to old workings by sinking a shaft has occasionally been resorted to.

Once the nature and extent of old mine workings has been determined the ground above can be zoned in terms of the hazard they represent. Depth below ground surface has frequently been used as the basis of hazard zoning, 30 m below surface or rockhead often being taken as the boundary between safe and questionable ground. However, exceptions to this rule of thumb have occurred.

Special foundation structures such as rafts and piles have been used in areas of shallow abandoned workings. The use of the latter, however, has been questioned. Alternatively the ground can be treated, by filling the voids, usually by grouting with bulk or foam grouts.

REFERENCES

Anon. (1988). Engineering Geophysics: Report by the Geological Society Engineering Group Working Party. Quarterly Journal Engineering Geology, Vol. 21, pp 207-271.

Bell, F.G. (1975). Site investigations in Areas of Mining Subsidence. Newnes-Butterworths, London.

Bell, F.G. (1978). Subsidence due to mining operations. In: Foundation Engineering in Difficult Ground, Bell, F.G. (Ed.), Butterworths, London, pp 322-362.

Bell, F.G. (1986). Location of abandoned workings in coal seams. Bulletin of the International Association of Engineering Geology, No 30, pp 123-132.

Carter, P.G. (1985). Case histories which break the rules. In: Mineworkings '84, Proceedings of International Conference on Construction in Areas of Abandoned Mineworkings, Edinburgh, Forde, M.C., Topping, B.H.V. and Whittington, H.W. (Eds.), Engineering Technics Press, Edinburgh, pp 20-29.

Cripps, J.C., McCann, D.M., Culshaw, M.G. and Bell, F.G. (1988). The use of geophysical methods as an aid to the detection of abandoned shallow mine workings. In: Minescape '88, Proceedings of Symposium on Mineral Extraction, Utilisation and Surface Environment, Harrogate, Institution of Mining Engineers, Doncaster, pp 281-289.

Garrard, G.E.G. and Taylor, R.K. (1988). Collapse mechanisms of shallow coal mine workings from field measurements. In: Engineering Geology of Underground Movements, Engineering Geology Special Publication No 5, Bell, F.G., Culshaw, M.G., Cripps, J.C. and Lovell, M.A. (Eds.). The Geological Society, London, pp 181-192.

Goodman, R.E., Korbay, S. and Buchignani, A. (1980). Evaluation of collapse potential over abandoned room and pillar mines. Bulletin of the Association of Engineering Geologists, Vol 17, pp 27-37.

Gostelow, T.P. and Browne, M.A.E. (1988). Engineering Geology of the Upper Forth Estuary. Report of British Geological Survey, 16, 8p.

Hoek, E.L. and Brown, E.T. (1980). Underground Excavations in Rock. Institution of Mining and Metallurgy, London.

McCann, D.M., Grainger, P. and McCann, C. (1975). Interborehole acoustic measurements and their use in engineering geology. Geophysical Prospecting, Vol 23, pp 50-59.

McMillan, A.A. and Browne, M.A.E. (1987). The use and abuse of thematic information maps. In: Planning and Engineering Geology, Engineering Geology Special Publication No 4, Culshaw, M.G., Bell, F.G. and Cripps, J.C. (Eds.), The Geological Society, London, pp 237-246.

Statham, I., Golightly, C. and Treharne, G. (1987). The thematic mapping of the abandoned mining hazard - a pilot study for the South Wales Coalfield. In: Planning and Engineering Geology, Engineering Geology Special Publication No 4, Culshaw, M.G., Bell, F.G. and Cripps, J.C. (Eds.), The Geological Society, London, pp 255-268.

Van Besien, A.C. and Rockaway, J.D. (1988). Influence of overburden on subsidence development over room and pillar coal mines. In: Engineering Geology of Underground Movements, Engineering Geology Special Publication No. 5, Bell, F.G., Culshaw, M.G., Cripps, J.C. and Lovell, M.A. (Eds.), The Geological Society, London, pp 215-220.

Walton, G. and Cobb, A.E. (1984). Mining subsidence. In: Ground Movements and Their Effects on Structures, Attewell, P.B. and Taylor, R.K. (Eds.), Surrey University Press, London, pp 216-242.