The threat of abandoned mines on the stability of urban areas

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Abstract: The consequences of centuries of mining and mineral extraction range from ground movement to gas emission and polluted water flows. Shaft sinking and pumping commenced in the 14th Century to allow deeper exploration, down to a depth of around 1000m. The extraction of an estimated 4,800 million tonnes of coal has left an estimated 1,000 million cubic metres of voids, which, in turn, has resulted in significant changes at the ground surface, including long term subsidence over large areas and catastrophic failure at localised points above shallow workings. There are numerous examples of subsidence due to abandoned mines, which have impacted on the urban area including the rerouting of the east coast line at Dolphinstone at the cost of £56m.

Rules of thumb which have been developed to predict the field of influence of the abandoned mines include voids are unlikely to migrate more than ten times the seam thickness; no remedial measures are required if there is 18.3m of rock cover above the workings; the presence of a competent bed, 1.75 times the appropriate span, between the workings and the surface is sufficient to arrest the collapse process; room-and-pillar workings do not give rise to subsidence other than through pillar failure; and workings greater than 150m deep rarely produce surface subsidence and damage to structures.

Historical evidence however shows that old workings within 300m of the surface can be a threat to the stability of potential or existing development sites and that threat can exist for up to 200 years after a mine has been abandoned. This paper presents case studies to show that commonly accepted rules of thumb are invalid and the consequences of the legacy of old mine workings can have significant financial impact on urban communities in coal mining areas.

Résumé: Les problèmes associés à l'exploitation minière et à l'extraction des minéraux, au cours des derniers siècles, sont multiples: movement des terrains, émission de gaz et pollution des flux d'eau. Le pompage et l'enfoncement des puits ont commencé au 14th siècle afin de permettre une exploitation allant jusqu'à 1000 mètres de profondeur. L'extraction d'environ 4800 million de tonnes de charbon a laissé un espace vide d'environ 1000 million de mètres cubes qui a provoqué un changement considérable sur les terrains, y compris l'effondrement à long terme de vastes étendus ainsi que la rupture catastrophique aux points situés au dessus des mines superficielles. Il existe de nombreux exemples d'effondrement du à des mines abondonnées. Ceci à un impact manifeste dans les zones urbaines, par exemple le déroutement de la ligne cotière à Dolophinstone qui a coûte £ 56 Million.

Des méthodes empiriques ont été développées pour prédir the champ d'influence des mines abondonnés. Par exemple, il est improbable que les vides souterrains se propagent plus de dix fois l'épaisseur; il n'est pas nécessaire de prendre des mesures de redressement quand il y a une couche de 18.3 m de roche au dessus de la mine ; bord et pilier des mines ne provoquent des subsidences qu' à travers la rupture de pilier ; et les mines à 150 mètres de pronfondeur rarement produisent des subsidences à la surface et endommagent les structures.

Par contre, les evidences historiques montrent que des anciennes mines situées à 300 mètres de la surface peuvent poser un risque de stabilité pour les sites de développement. Ce risque peut durer jusqu' à 200 années après que la mine à été abondonnée. Cet article présente des cas d'études afin de montrer que les méthodes empiriques, généralement acceptées, sont invalides et que les mines fermées peuvent avoir des conséquences financières importantes dans les zone urbaines.

Keywords: Mining, subsidence, urban areas, pillar and room, longwall.

INTRODUCTION

Mining and mineral extraction carried out in the UK has given rise to ground movements, gas emissions and polluted water flows (Jackson, 2000). With the ability to sink shafts and pump mine water from depth from the 14^{th} century came the extraction of coal down to a depth of around 1000m (Wilcock, 1975). The extraction of an estimated 4,800 million tonnes of coal has left approximately 1,000 million cubic metres of voids (Norton, 1996), which, in turn, has resulted in significant changes at the ground surface, including long term subsidence over large areas and catastrophic failure at localised points above shallow workings (Culshaw et al, 2000). There are numerous examples of subsidence due to abandoned mines, which have impacted on the urban area including the rerouting of the east coast rail line at Dolphinstone, near Prestonpans, just east of Edinburgh in Scotland at the cost of £56m, between 1988 and 2001. These phenomena are not restricted to the UK. For example, the Ohio Mine Subsidence Insurance Underwriting Association estimates the cost of mining subsidence damage to be $1,189,000 since 1987.

Rules of thumb which have been developed to predict the field of influence of abandoned mines include voids are unlikely to migrate more than ten times the seam thickness (Healy & Head, 1984); no remedial measures are required if there is 18.3m of rock cover above the workings (Taylor et al, 2000); the presence of a competent bed, 1.75 times the appropriate span, between the workings and the surface is sufficient to arrest the collapse process (Piggot et al,

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1977); room and pillar workings do not give rise to subsidence other than through pillar failure; and workings greater than 150m depth rarely produce surface subsidence and damage to structures (Healy & Head, 1984).

Unfortunately however many of these rules of thumb are still used as evidence at public inquiries where development above abandoned mine workings is proposed (Taylor et al, 2000). They are used as general rules under a variety of geological conditions and do not take into account that there will be changes in the condition of the mine workings and of the overlying rock mass over time. Historical evidence shows that old workings within 300m of the surface can be a threat to the stability of potential or existing development sites for as long as 200 years after the mine has been abandoned. This paper presents case studies from Scotland and the Durham coalfield in north east England to demonstrate that commonly accepted rules of thumb are invalid and that the legacy of old mineworkings often has a significant financial impact on urban communities in coal mining areas.

THE COALFIELD GEOLOGY

The coalfields of north east England, (Figure 1), are formed from Upper Carboniferous rocks known as the Lower and Middle Coal Measures or the Westphalian. In County Durham the Westphalian coal measures show that the sedimentary sequence was laid down on a broad deltaic flat. Sandstones, siltstones and shales predominate, with coal being underlain by seatearth (Johnson, 1995). Many of the beds within the sequence do not show lateral continuity; in particular, individual coal seams cannot be traced more than 20km without changing in character by splitting or becoming impoverished (Johnson 1995). The seams are of bituminous rank and vary in thickness from 3m to traces only tens of millimetres thick.

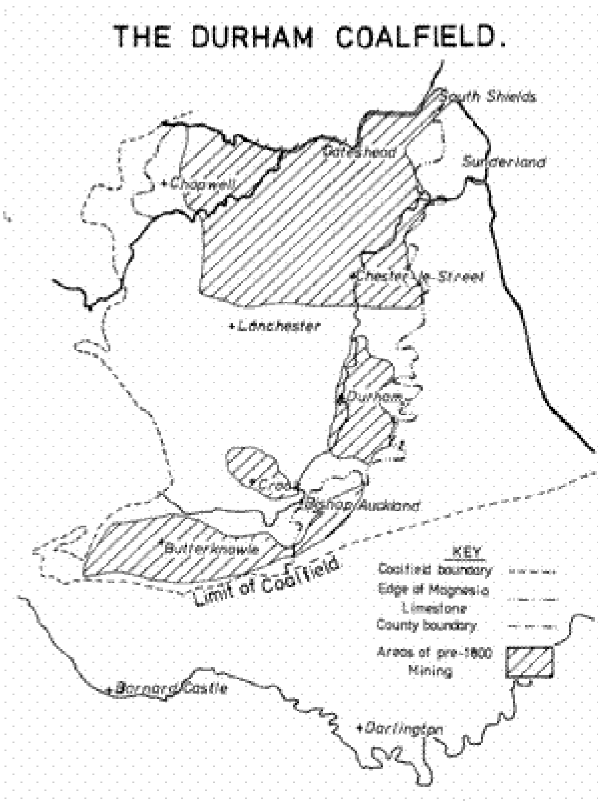

Figure 1. The Durham Coalfield showing areas worked pre 1800 (after Wilcock 1979)

THE METHODS OF WORKING

From the thirteenth century onwards coal was mined from shallow seams (Healy & Head 1984) which outcropped on hillsides, cliffs and river banks. In such places the winning of coal was a relatively easy operation by digging a drift or adit into the hillside (Bell & Genske 2001) and following the seam a short distance. Alternatively a shallow shaft, up to 12m deep was dug down to the seam to form a bell pit (Figure 2). These pits continued to the seventeenth century creating a pock-marked surface following subsidence.

Towards the end of the fourteenth century there appears to have been a change from small bell pits to mines with shafts and galleries in the Durham coalfield (Wilcock 1979). Pillars of coal (Figure 3) (also known as stoops, bords and posts) were left unworked to support the overburden and this allowed a greater quantity of coal to be removed at depth, via a single or pair of shafts (Healy & Head, 1984). These mines rarely extended below 60m in depth or ventured more than 200m from a shaft (Healy & Head 1984).

The longwall method of mining was developed in the seventeenth century (Healy & Head 1984). This is a method of total extraction, which results in collapse of the mine often followed by immediate surface subsidence (Waltham 1994). The coal was originally hand worked but in modern mines is machine worked from 'longwall' faces with roadways running at right angles to the face to remove coal and allow for ventilation. These roadways were made through goaf (backfilled area of total extraction) and supported on both sides by stone packs (resembling dry-stone walls) and timber, steel or masonry supports.

Figure 2. Bell pit workings uncovered during opencast operations at a site near Wakefield. (Photo courtesy of Carl Drury, The Banks Group).

Figure 3. Room and pillar workings uncovered during opencast operations at Buckhead Site, Co Durham

Cessation of mining and closure of mines results for a number of reasons not least because of total extraction methods but also because of changes in the geology and/or changes in the market (Smith & Underwood 2000). As the abandoned mines age they tend to become associated with marked changes in the topography and hydrogeological regime, which can lead to a range of stability and contamination issues (Smith & Underwood 2000). It is the stability issues, which are predominantly the subject of this paper.

MECHANISM OF SUBSIDENCE

Subsidence is an inevitable consequence of mining activities and this has been recognised at least since 1447 when the lease for pits at Tursdale and Spennymoor stated explicitly that pillars of coal had to be left in the mine in an attempt to avoid surface damage. Nevertheless since this time subsidence has still occurred and is often attributed to the failure of the pillars, or the collapse of the roof or the heave of the floor between them.

Pillar Failure

The room and pillar method of mining results in between, 15% and 90% of the coal being extracted. This causes an increase of around 60% to 90% of the load on the pillars giving rise to stress concentrations on the edge of the pillars. This can lead to spalling and a reduction in cross sectional area of individual pillars (Figure 4). The ultimate behaviour of a pillar is a function of the geometry of the mine including the seam thickness to pillar width, the depth below ground and the size of the extracted area, the properties of the coal including its strength and the presence of any fractures, joint and faults. Pillar failures have been known to occur over 100 years after the initial abandonment.

Roof Failure

The roof of a room will deform due to the lack of support (see Figure 5). Deformation will occur during extraction and continue with time. Any natural fractures in the rock will open and cracking may develop in intact rock because of the stress changes. These cracks can progress leading to collapse of the overlying beds into the room and the possible formation of a crown hole (Figure 6). The extent of the crown hole depends on the bulking factor of the collapsed material and the presence of any stronger overlying beds. Crown holes are considered to extend to a maximum distance of ten times the seam thickness above the room which when looked at in the context of the north east coalfield is up to 30m because of the maximum thickness of the coal seams. There is however evidence that this can be exceeded (Goodman 1989). Multiple pillar collapse can lead to a surface depression known as an 'areal' subsidence (Sizer and Gill, 2000). Bruhn et al. (1981) have shown that areal troughs are as much as 480m in diameter, with a maximum trough depth of 0.90m and a depth to workings of around 137m.

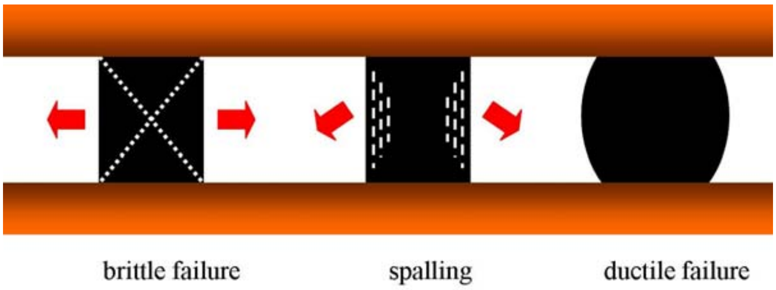

Figure 4. Mechanisms of pillar failure

Opencast excavations have revealed that there is another failure mechanism possible, that is, the deformation of the roofs of rooms over time (creep deformation), which also results in 'areal' subsidence (see Figure 7).

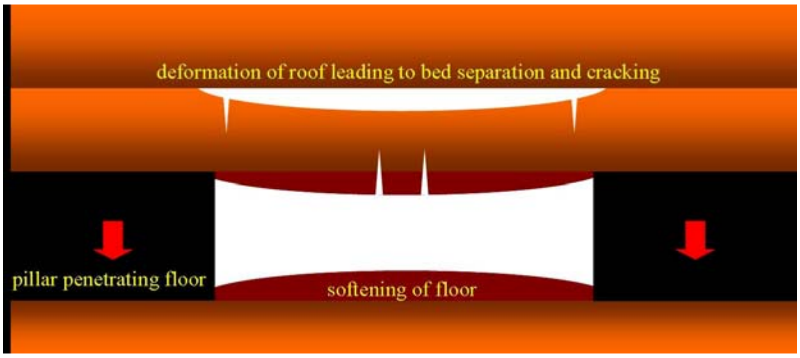

Figure 5. Mechanisms of floor and roof failure

Figure 6. Crown hole collapse uncovered during opencast excavations (Photo courtesy Prof Paul Younger)

Floor Failure

Floor heave occurs where a seatearth (or underclay) is exposed below the mined out coal seam. Free water is absorbed by the seatearth, which results in swelling of the clay and consequently heave of the floor (Figure 5). Where the seatearth lies below the pillars the softening of it allows the pillars to 'punch' into it through shear failure (Goodman 1989).

PREDICTING GROUND MOVEMENTS

There are several 'rules of thumb' methods used to predict the extent of ground movements above room and pillar workings. Piggot et al. (1978) proposed that the extent of a crown hole collapse was dependent on the seam thickness and bulking factor as shown in Figure 8. Observed evidence is that the collapse rarely exceeds ten times the seam thickness and it is normally within three to five times the seam thickness.

Figure 7. Creep deformation over pillars uncovered during opencast excavations at Langley site, Co Durham

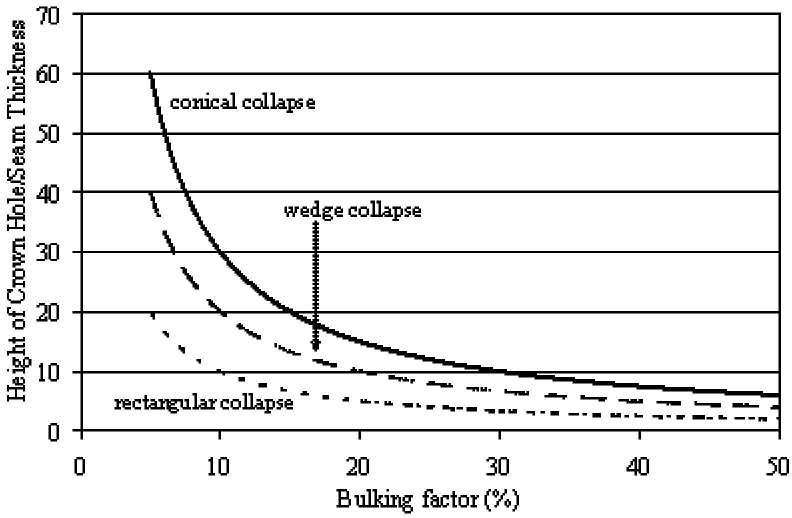

Figure 8. Extent of crown hole collapse depending on bulking factor and seam thickness (after Piggot et al. 1978)

Local experience in Bathgate, Scotland (Carter et al. 1984) suggested that room and pillar mine workings rarely affected the ground surface if the depth of overburden exceeded 18.3m (the '60ft rule'). It is also believed that "ancient workings" (defined as those worked before records began), will not cause any further ground movement (Carter et al. 1984).

The above rules are known to be invalid where steeply dipping workings are present as the collapsed material can slide down the workings or where there is significant groundwater flow, which can wash away collapsed material. It is also a widely held belief that it is the roof that fails and not the pillars because of the width to height ratio; that is the pillars are believed to be much wider than they are high. It is also noted that abandonment mine plans may not necessarily be correct, especially where pillar robbing may have taken place on abandonment, meaning that pillar widths may be significantly less than recorded.

CASE STUDIES

A review of several hundred cases of documented subsidence in Pittsburgh, USA (Bruhn et al. 1981) has led to the conclusion that unless total extraction has taken place, there is no definitive height above an abandoned mine which ensures safety from subsidence, or a reduction in the severity of the damage. The movements due to modern longwall mining, which is a total extraction method, take place soon after excavation occurs and they are generally parallel and perpendicular to the advancing face. Movements due to earlier forms of longwall mining and room and pillar mining however, can occur some time after the mine is abandoned.

Records of mine workings and shafts are incomplete. Coal mine abandonment plans were not a statutory obligation in the UK until an Act in 1859, which required plans to be kept showing the workings and the system of ventilation. This Act was updated in 1872, to include any ironstone workings connected with a colliery (Hughes 1981). The 1872 Act also required more detail to be kept, such as the boundary of the workings, to enable future and neighbouring mine owners to safely work the coal (Hughes 1981). Despite this legislation there is still a significant risk from the presence of unchartered shallow old workings. Even where old mine plans do exist they are often inaccurate (Bell and Genske, 2001). This may have been due to poor surveying technique and equipment, or simply due to pillar robbing which was largely ignored to avoid paying royalty.

The following case studies document the unpredictability of mining subsidence and give testimony that well known “rules of thumb” are often shown to be questionable.

Bathgate, Scotland

Three events took place in Bathgate, Scotland between 1975 and 1977, which led to the development of 200m diameter subsidence troughs with a maximum settlement of 300mm. These were caused by the collapse of shallow, abandoned, multi-seam pillar and stall workings (Carter et al. 1981). Within the general area there was a history of shallow-mining instability associated with the outcrops of coal seams. Beneath the town centre however, there are drift deposits comprising stiff glacial till between 7 and 10m thick, below which lies the limestone coal group. This coal group is over 100m thick and comprises six named coal seams, some banded ironstone and a significant thickness of sandstone. Two coal seams, 15m apart, had been worked, namely the Jewel (1.5m thick) and the Wilsontown Main Coal (2m thick) lying at depths of 20 and 42m below the town centre.

The seams had been worked since the early eighteenth century with most of the coal being extracted by the 1930s. Site investigation work revealed that there were generally 0.5m high voids overlying mine waste material at each seam and that the majority of pillars encountered showed oxidised coal. It was considered likely that an area of pillars, which had weakened with time, had subsequently collapsed during the Christmas of 1975. This would have placed additional loads on to the neighbouring pillars, thus instigating the other two subsidence events. The 300mm of subsidence measured was only a small proportion of the worked thickness. This was considered to be due to a number of factors including, the percentage of coal left in the pillars, the bulking of mine waste with the collapsed roof material, and the possible arching and separation of bedding planes at shallower depths. There was also a possibility of the creation of super voids due to the flow of ground water through the steeply dipping seams washing out the fill from the upper seam to the lower seam. A few such migrated voids from the Main coal were encountered immediately below the Jewel during grouting operations.

Bedlington, Northumberland

Sizer & Gill (2000) have documented a case of areal subsidence in Bedlington, Northumberland. Cloverdale Terrace was demolished in 1994 due to subsidence damage. The Terrace was constructed around 1970 but no damage was recorded until March of 1990. A settlement trough had developed beneath the terrace such that the centre of the trough was roughly in the centre of the terrace. The depression was ellipsoidal in shape, approximately 46m long and 35m wide orientated north west – south east. A maximum of 260mm of settlement occurred at the centre of the depression.

Mining, at a depth in excess of 40m, had taken place beneath the terrace site in the Top Main seam in 1953. The Yard seam had also been worked at 75m depth, however, the details of working method and seam condition were not documented. The Top Main seam is 2.2m thick at a depth of 44m below the surface and was worked into pillars 16m long by 16m wide. The roadways in the Top Main were generally 5m wide, which resulted in roughly 45% extraction. Some pillars had been split by driving a new roadway through the middle leaving two narrow pillars 4m wide by 16m long, giving an increased extraction rate of 65%. Mining records indicated that this was the case beneath the terrace.

Borehole investigations were carried out on behalf of the National Coal Board, in 1994, and the Coal Authority, in 1997. The open holes were drilled to a depth corresponding to the Top Main. In total, fifteen holes were drilled. Of these ten would have been expected to encounter coal, but only four did so the conclusion was that either the pillars had been removed by mining or had deteriorated badly with time. The boreholes provided much evidence of roof collapse within the workings suggesting that the pillars had been reworked on retreat.

The roof rock between the pillars comprised 1m of mudstone overlain by 2-3m of siltstone. It was considered that the relatively weak overlying mudstone settled around the remaining pillars, allowing the strata above to relax. Beneath the coal there is a 1m thick layer of seatearth, which may have allowed some pillars to punch or settle. Either or both of these subsidence mechanisms, in addition to pillar deterioration, would have allowed the strata above to sag and collapse.

Dipton Colliery Council School

Damage to a school in Dipton four miles north east of Consett (County Durham) (grid reference NZ153 536) started in 1892 and continued for over twenty years. Within the area coal had been extracted by both pillar and stall and total extraction methods from eight different seams, over a depth of 213m, for more than 60 years. Pillars were left in the seams beneath the school, which was built in 1878. Sandstones and shales lie between the seams, whilst sandstone of considerable strength lies above the top seam, which is some 14m below ground level. Damage to the school seems to have resulted from collapse of the upper shallow pillar and stall workings caused by subsidence in the more recent totally extracted seams below, suggesting that progressive collapse can occur due to deeper more recent mines triggering subsidence features in the overlying older worked seams.

Flint Hill School

Flint Hill School, near Dipton (grid reference, NZ165 545) was opened in January 1875 and built on ground that was subsiding due to the total extraction of 4.8m of coal from three seams between 70 and 140m depth. These workings were described as ancient workings because the dates of extraction were unknown. Further mining by total extraction took place at greater depths up to 1959. Support to the school was maintained by pillars within an angle of draw of 12^{o} or goaf. The School was pulled down in 1976 and in 1987 a house was constructed on the site.

Tanfield Lea Schools

Damage occurred to Tanfield Lea School, 7 miles south west of Gateshead (grid reference NZ189 536) as it was being built in 1910. Beneath the school lay seven coal seams that had been worked down to a depth of about 220m. Further room and pillar mining took place after the School was built but coal was not extracted in an area up to 100m from the footprint of the School. Mining continued in the area until about 1976. Pillars were left beneath the zone of influence of the excavated seams but the geological maps indicate that the area was faulted. Subsidence damage continued for another ten years due to mining activities that had taken place up to thirty years earlier.

Pelton School

The village school at Pelton (grid reference NZ257 532) was built in about 1908 on ground underlain by four seams, which had been worked since 1834. A further two seams were worked when damage was reported in 1914. Mining ceased in the area in 1987. The ancient workings were either room and pillar or longwall. A pillar, 40m in diameter, was left in one seam at 200m below ground level. This was subsequently removed. The claim, which followed, suggested that the deeper excavation triggered movements in the seams above.

DISCUSSION

Evidence from the above case studies is that subsidence damage often occurs some years after the abandonment of mining, and in areas where room and pillar workings have taken place, subsidence damage has resulted from mine workings at depths in excess of 200m. There is evidence that the movement in room and pillar and longwall workings can be triggered by mining in deeper seams, and by creep of the overburden. Thus, the commonly accepted "rules of thumb" discussed earlier should be treated with caution, since there is a risk that subsidence due to ancient workings can occur at some considerable time after the mines have been abandoned and the zone of influence can extend to depths well in excess of current guidelines.

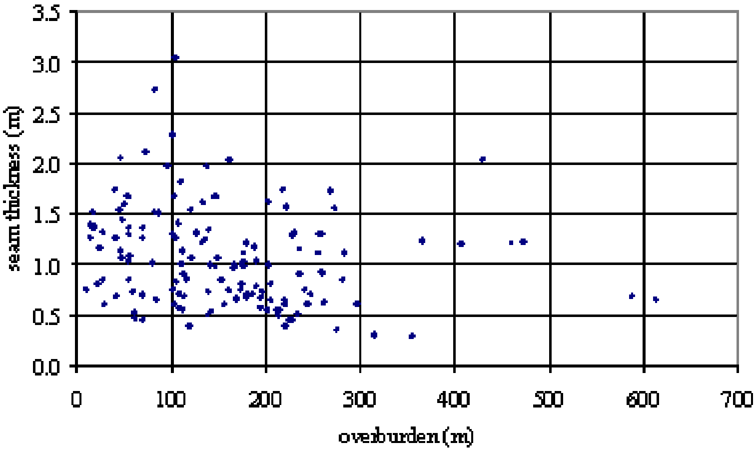

Figure 9. Seam thicknesses and overburden ratio for seams worked in the Durham coalfield

Subsidence in the Durham coalfield has continued long after the mines were abandoned. Figure 9 shows the range of seam thickness and depth of overburden at locations where subsidence has been recorded. Not all the seams will have caused subsidence but there are seams within the depth range that have caused subsidence. Longwall mines were introduced to increase extraction. Goaf was used to reduce settlement of the roof of the mine and hence the surface subsidence.

The 'seam thickness rule', Piggot et al. (1977), is based on experience and suggests that roof material spanning the extracted seam will collapse with time resulting in the gradual choking of the upward migrating void. Stability is reached when the void is completely choked with broken roof material and in exceptional cases can reach ten times the original formed void, though 3 to 5 times is more typical.

Ove Arup Ltd introduced the concept of the "migration ratio" as the ratio of the overburden to the seam thickness. Figure 10 shows that the ratio for sites in the Durham coalfield, where subsidence occurred, can vary from ten to over a thousand with the majority of ratios between 25 and 400. There is evidence however, that mining activity can trigger movement in other seams previously worked. In that case the migration ratio is the ratio of the distance to the next seam above the seam of interest, divided by the seam thickness. The corrected migration ratio varies between ten and nine hundred with the majority of ratios being between 5 and 100.

Modern longwall mining is designed to limit settlement. Therefore, a further correction can be applied by considering the room and pillar workings only. The distribution of the migration ratio for the room and pillar seams (discounting the longwall seams because of the backfill) is similar to that of all of the seams.

Figure 8 shows that this corrected migration ratio is consistent with Pigggot et al. (1978) theory provided the bulking factor is less than 10%. However, should pillar failure occur then the effective size of the room will increase which can result in a potential areal collapse. The hybrid mechanism, that of creep can occur whether, or not, pillars fail. That also can lead to an areal collapse.

The angle of draw (that is the angle to the vertical of the area influenced by the collapsing zone) can lead to a limited collapse as in the case of crown hole collapse or to an areal collapse as in the case of pillar failures or creep of the overburden.

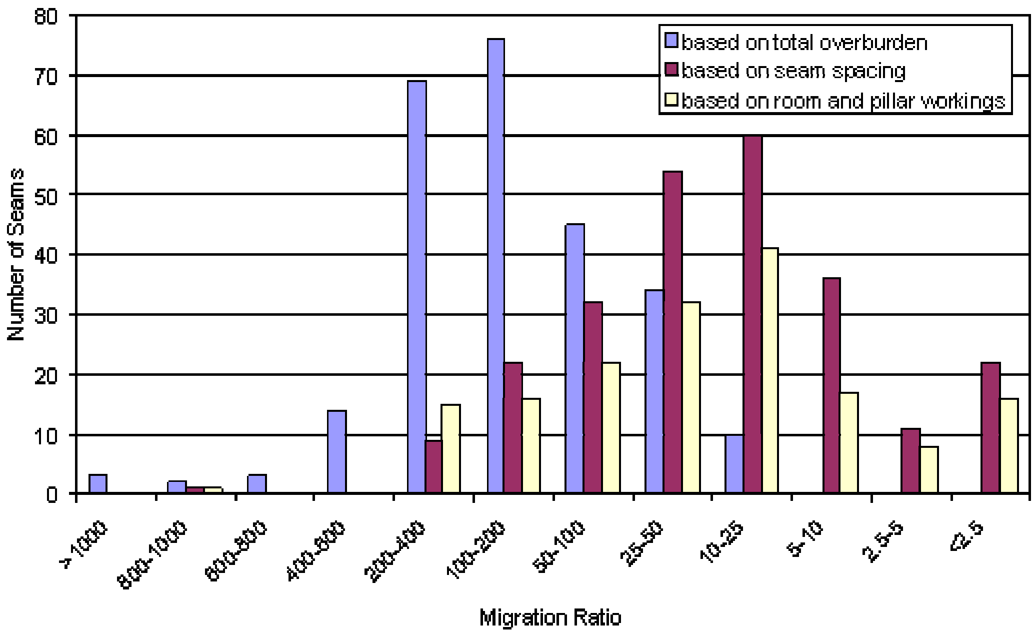

Figure 10. The Migration Ratio (for seams down to 600m below ground level and based on total overburden, seam spacing and room and pillar workings)

CONCLUSIONS

A review of published and unpublished data has shown that surface subsidence can occur some time after a mine has been abandoned. This delayed movement is caused by a number of factors including pillar deterioration, creep of the overburden, failure of the floor due to seatearth softening and collapse/failure of the roof. The failure mechanism can be limited by the size of the rooms, the seam thickness and the strength of the overlying strata. However, it can extend to the surface if the seam is within the top twenty metres or if the failure leads to an areal subsidence. The former is due to crown hole collapse; the latter is due to pillar collapse or creep of overburden.

Deep mining activity can trigger movements in older, shallower, often unrecorded overlying mines and, thus, the critical ratio becomes the distance to the next seam as opposed to the thickness of the overburden. In this case, the zone of influence is governed by the seam thickness, the bulking factor and the distance to the next seam.

Thus, ground movements due to old mine workings are a hazard in urban areas and can remain so for some considerable time after the workings have been abandoned. The risk of these ground movements occurring is difficult to predict and is probably very low given the amount of development in former coalfields but, nevertheless, the risk is there.

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