Ground deformation caused by fault reactivation: some examples

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Abstract: Faults, when located within an area undergoing mining subsidence, are susceptible to reactivation. Residual movements along faults may also occur long after mining has ceased, although this can be difficult to prove. Fault reactivation can result in the disruption of the ground surface due to the formation of fault scarps. These features are often referred to by subsidence engineers as 'steps' in the subsidence profile or 'break- lines' along the ground surface. Reactivated faults vary from subtle disturbances along the ground surface to major topographic scarps up to 4 m high and 4 km long. These may, or may not, be accompanied by fissuring, compression, lateral spreading, graben formation, groundwater discharge, mine gas emissions, acid mine drainage and shear displacements. In spite of reactivated faults being widespread throughout Great Britain, in existing and former mining regions, these types of ground movements are not always widely appreciated by engineering geologists, geotechnical engineers, civil engineers and planners. The movement along faults can have a detrimental impact on existing or planned structures and on land. Fault reactivation has caused damage to civil engineered structures, residential property, industrial premises, transportation networks (roads, railways and canals), and underground utilities (gas and water mains, sewers, drains, pylons, and communication cables). The objectives of this paper are to provide a review of the main types of ground movements and geological hazards in the vicinity of fault outcrops, and to document their affects primarily in urban areas. It is hoped that by drawing attention to these types of ground movements that the mechanisms of their formation may be better appreciated so that their associated geotechnical risks may be investigated and properly assessed during the planning process for future development.

Résumé: Les failles, lorsqu'elles se situent dans une zone soumise à un affaissement minier, sont susceptibles d'être réactivées. Des mouvements résiduels le long de ces failles peuvent se produire longtemps après que l'activité minière a cessé, bien que cela puisse être difficile à prouver. La réactivation d'une faille peut engendrer des changements brusques de la surface du sol dus à la formation d'escarpements de faille. Les ingénieurs spécialistes de la subsidence parlent souvent de 'marche' dans le profil de subsidence ou de 'lignes de rupture' à la surface du sol. Les failles réactivées sont d'un aspect variable qui peut aller de subtiles perturbations de la surface du sol jusqu'à des escarpements topographiques majeurs de 4 m de haut et 4 km de long. Ceux-ci peuvent ou non être accompagnés par des phénomènes de fissuration, compression, écartement, formation de graben, épanchement d'eau souterraine, émission de gaz miniers, drainage minier acide et cisaillements. Malgré la fréquence des failles réactivées en Grande-Bretagne, dans des régions présentement ou anciennement minières, ces types de mouvements de terrain ne sont pas toujours pris en compte de manière générale par les ingénieurs géologues, les ingénieurs géotechniciens, les ingénieurs en génie civil et les planificateurs. Les mouvements le long des failles peuvent avoir un impact indésirable sur des structures existantes ou en projet et sur le terrain lui-même. La réactivation de failles a endommagé des structures de génie civil, des résidences, des implantations industrielles, des infrastructures de transport (routes, chemin de fer, canaux) et des réseaux souterrains (gaz, eau, eaux usées, drains, câbles). Ce papier a pour buts de passer en revue les principaux types de mouvements de terrain et hasards géologiques à proximité des manifestations des failles à la surface du sol, et de documenter leurs effets en milieu urbain plus particulièrement. En attirant l'attention sur ces types de mouvements de terrain, il est espéré que les mécanismes de leur formation seront mieux appréciés, ceci afin que les risques géotechniques qui leur sont associés soient étudiés et évalués de manière satisfaisante durant le processus de planification des développements futurs.

Keywords: geological hazards, environmental geology, deformation, discontinuities, subsidence, urban geoscience

INTRODUCTION

Faults located in areas prone to mining subsidence are susceptible to reactivation. They occur in the urban and industrialised parts of Britain on both exposed and concealed coalfields. Reactivated faults were historically suspected when linear lines of structural damage (known as 'break lines') were observed on brittle ground (e.g. roads), through densely populated or built up areas, often without any trace on granular or cohesive soils that form grass verges or parks and gardens. The aim of this paper is to draw attention to examples of fault reactivation in Great Britain and to demonstrate how fault reactivation and faulted ground may have detrimental impacts, particularly on infrastructure. This includes surface structures (buildings, houses, industrial premises and bridges), services and utilities (sewers, water conveyances, gas mains, pipelines, pylons communications cables) and transport networks (tracks, roads, railways, rivers and canals). Such movements may have implications for site investigations and the subsequent siting and design of foundations, structures and utilities. Further information of mining-induced fault reactivation is given by Bell et al. (1988, 2002, 2004), Donnelly & Reddish (1994), Donnelly & Melton (1995), Donnelly *et al.* (1993, 1998a, 1998b, 2004), Donnelly (1996, 1998a, 1998b, 2000a 2000b, 2005 and 2006), McCann *et al.* (1999), Culshaw *et al.* (2000).

SURFACE STRUCTURES

Detached house

Damage to detached houses by fault reactivation may vary from the subtle (cracking of plaster and bricks) to the severe (evacuation of occupants and subsequently demolition). Examples occur throughout Britain. For instance, a large detached house was situated on the outcrop of the Hopton Fault, Oulton, Staffordshire (Figure 1). This suffered repeated damage each time the fault was undermined by longwall workings. By January 1993, the scarp was distinct, high-angled, 1.0 to 1.5 m high and could be traced for 2 km. The house was eventually demolished due to severe structural damage. The scarps were subsequently ploughed flat on adjacent land, road ‘steps’ were eventually repaired and a new house built on the same sites, a few metres from the original fault scarp and house position.

Figure 1. Damage to houses caused by the mining-induced reactivation of the Hopton Fault, Oulton, Staffordshire, UK.

Terraced house

Fault-induced movements may result in structural damage to terraced houses some distance from the actual fault scarp position. This may be attributed to the strength of the terraced block. Damage occurring at the weakest part of the elongate structural block, which may not necessarily coincide with the fault scarps position. A distinct scarp occurred across Springswood Street, Bonds Main, Temple Normanton, Chesterfield in 1966. This caused severe damage to rows of terraced houses. The scarp was generated during the working of the ‘23 Soft Deep’ coal seam, below the village, from workings at the former Williamthorpe Colliery (now closed and demolished). In addition to structural damage, a gas-main fractured and four single houses were reported to have been demolished. The scarp coincided with the outcrop position of the High Hazels Seam and may have been generated by translational bedding plane shear, which is not uncommon, and is consistent with similar observations from other coalfields (Donnelly & Reddish 1994, Donnelly 1994, 1998a, Lee 1965).

New housing estates

If site investigations are properly undertaken, potentially active faults and recently faulted ground may be avoided, or treated prior to construction, although this may be difficult in practise. A new housing development, in the Silverdale District of North Staffordshire, was planned in the early 1990s in such a configuration as to avoid the outcrop of the Hollywood Fault (also known as the Millbank Fault). It was anticipated by planners and subsidence engineers that the fault would be reactivated during longwall mining. This fault crops out in the north-western parts of the North Staffordshire Coalfield, to the north of Newcastle-under-Lyme. In underground workings at the former

Hollywood Colliery, in the 'Ten Foot Seam', the fault displayed an indeterminable amount of lateral shear and vertical displacements of approximately 200 m. To reduce the likelihood of damage to the new houses in the event of expected renewed activity along the fault, Ashbourne Road was constructed along the anticipated outcrop of the fault. This is because during fault reactivation the deformation of the ground surface is usually limited to about 10 m either side of the fault scarp's outcrop position and therefore damage was expected to be limited to the road only. This could be repaired easier than damage to houses. The reactivation of the fault actually occurred 50 m to the north of the anticipated outcrop position and this resulted in damage to several houses and other road surfaces. Vertical displacements were not observed but instead reactivation was dominated by approximately 0.3 to 0.5 m of lateral shear. This was great enough that cars could not be driven into garages located adjacent to houses. The causative mechanism was attributed to the relative position of the longwall panel, being located not directly beneath the fault. Lateral shear was also facilitated by the contrasting rock types on either side of the fault; to the north, the weak, relatively plastic mudrocks of the Upper Carboniferous Etruria Formation and to the south, the stronger, more brittle sandstones of the Upper Carboniferous Newcastle and Keele Beds (Donnelly & Reddish 1994).

In 2002, four ground fissures were observed in the vicinity of a partially constructed new housing development, at Eakring Road, Mansfield. The fissures were 1-2 m wide, up to 10 m long, and oriented east-west, consistent with the dominant fault trend in the area. The fissures were observed within the thin sandy topsoil. The bedrock consisted of the Triassic Sherwood Sandstone Group, which dips gently to the east and unconformably overlies the Carboniferous Coal Measures. One of the fissures, located adjacent to a public footpath, was partially bridged by thin soil and contained loose blocks of friable sandstone, which had fallen from the fissure walls. Some of the fissures had been filled with garden and industrial waste (possibly an unsuccessful attempt to stabilise them). Several seams of coal had been extracted from the nearby Mansfield and Rufford Collieries (now closed). It is possible that the fissures were generated at the time of mining, or shortly afterwards, but were not visible at the ground surface due to bridging soil and vegetation. These became apparent years later after periods of prolonged heavy rainfall, or as a result of ground disturbances associated with construction and the development of the site. The fissures represented the dilation of fault planes and joints, and others were suspected to occur in this region (Donnelly 2002).

Apartments

Crompton Hall residential apartments building, built in the early part of the 1900s, was located in the densely populated, industrialised part of the East Lancashire Coalfield (known as the Bradford Coalfield) to the east of Manchester. The Bradford Fault, one of the principal faults that cross the coalfield, outcrops approximately 5 km to the east of Manchester city centre. The Bradford Fault was observed in underground workings at the former Bradford Colliery, not as a single dislocation, but as a shatter zone up to 90 m wide, consisting of numerous broken and interlocking discontinuities. At least six seams had been extracted from the beneath the fault. The reactivation of this fault was detected on two survey lines, one at an acute angle to the fault, the other perpendicular. Reactivation resulted in the generation of a scarp along the ground surface with compressive strains of 4.91 mm/m (Figure 2). The flats suffered moderate to severe damage, and they were subsequently demolished (Marr 1961, Lee 1965, Donnelly 1994).

Industrial premises and sewerage works

Moderate damage was caused to an industrial estate and sewerage treatment works at Newstead, Stoke-on-Trent, during the reactivation of the Hollybush Fault in the early 1990s. Damage was consistent with the mining of the Yard and Great Row seams from the former Trentham Colliery. Dextral shear displacements of up to 0.2 m occurred along the fault, which outcropped through the industrial estate and a conspicuous scarp, with vertical displacements of up to 1.0 m, were observed (Figure 3).

Farm buildings

Fault reactivation has caused extensive deformation that has damaged numerous farm buildings located on the periphery of industrial centres in the West Midlands, South Wales and North East England. Historically, the citing of farm buildings was largely determined by availability of water, so many were situated adjacent to springs that issued from faults. A farm building situated a short distance from the Hollybush Fault in Stoke-on-Trent was periodically flooded, by up to 0.5 m of groundwater discharge from the fault. Widespread damage also occurred to several farm buildings in the Moddershall and Oulton area of Staffordshire from at least 1985 to 1992.

Historical and national heritage buildings

Barlaston Church is situated adjacent to Wedgwood Hall, in Staffordshire south of Stoke-on-Trent. Both are heritage sites of historical value. Wedgwood Hall was built between 1756 and 1758, and the church was rebuilt in 1760. As a consequence of extensive coal mining, subsidence and reactivation of the Hollybush Fault, in the late 1980s and early 1990s, both of these buildings were severely damaged (Figure 4). The two buildings became unsafe, but could not be demolished since they are listed as sites of national heritage. They have had to undergo extensive stabilisation works. The church has been partially rebuilt, with its tilted and detached tower being straightened, and the hall was underpinned. Bedding plane translational shear at a faulted contact was the likely mechanism responsible for the generation of the distinct fault scarp. This occurred at the contact of a sandstone and mudstone in the Carboniferous Halesowen Formation.

Schools

Inkersall School is located in the centre of Inkersall village, approximately 6 km east of Chesterfield, Derbyshire. In the early 1990s it consisted of two separate buildings. These suffered from repeated subsidence and fault reactivation, causing structural damage from at least 1985 to 1993. One of the schools was partially demolished and rebuilt using the CLASP (Consortium of Local Authorities Special Programme) method to reduce the anticipated damage from further phases of movement along the fault. The was a common method of mitigating subsidence damage by the introduction of flexibility into a structure that is flexible enough to accommodate differential subsidence by being able to deflect sufficiently to ride the approaching subsidence wave without cantilevering over it. The Inkersall Fault crops out in the Middle Coal Measures, beneath one of the main school buildings. The fault zone consists of two parallel splays separated by a distance of a few hundred metres, before rejoining to the west. The fault is a high-angled normal fault with an apparent sinistral component of slip, dipping at 74° towards the northeast, with a throw of 50 m. At least six coal seams have been extracted in the vicinity of the fault in both the hangingwall and footwall regions. The earliest records of fault reactivation were during the working of the Deep Hard Seam in the 1950s. Further phases of reactivation occurred in 1985, during the working of the Piper Seam from the former Markham Colliery. This resulted in the formation of a distinct scarp across the school grounds (Donnelly 1994, 2000b, Phillips 1991, Phillips & Hellewell 1994).

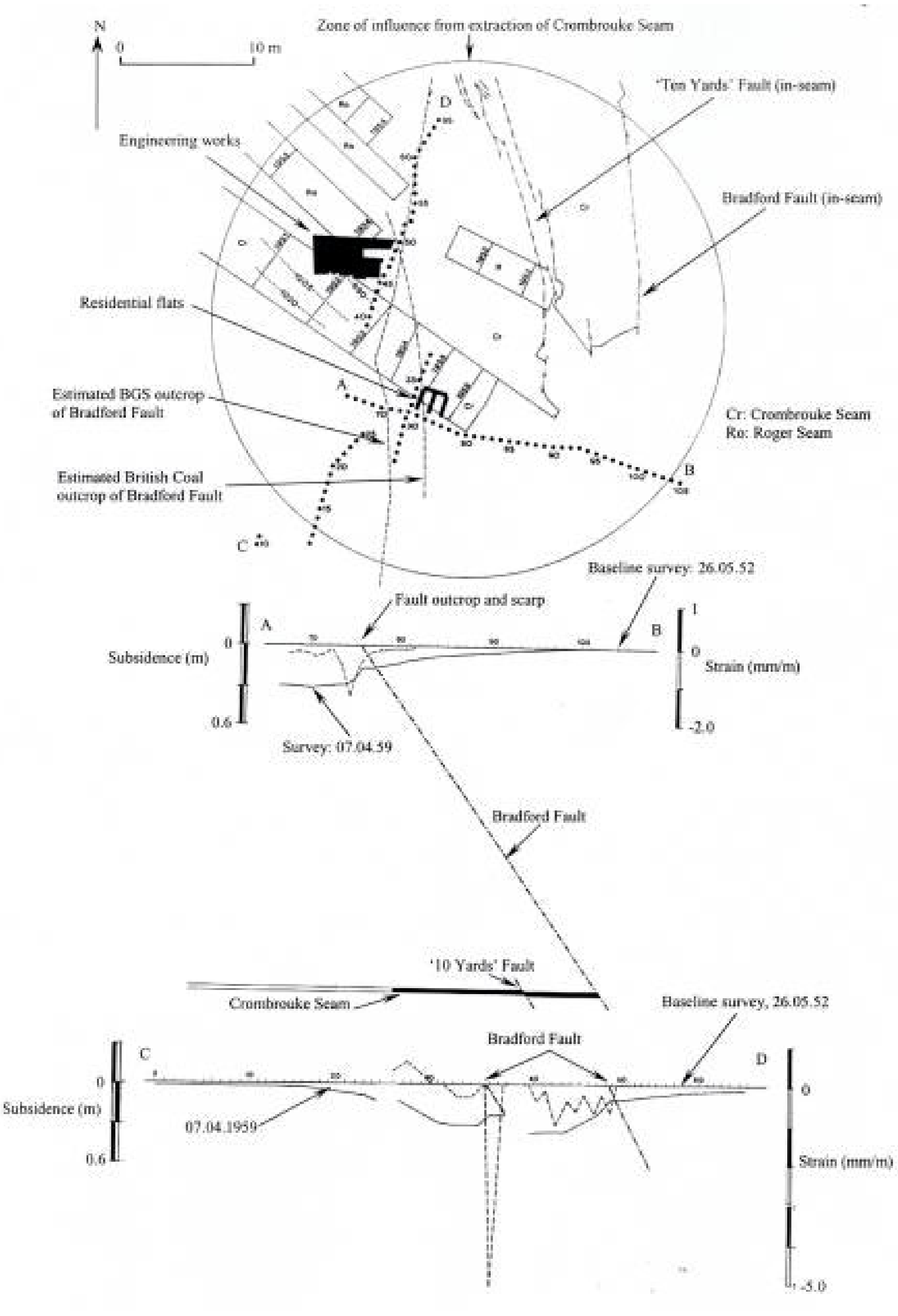

Figure 2. Schematic illustration documenting the reactivation of the Bradford Fault, Lancashire, UK, showing the suspected outcrop and in-crop positions of faults and survey lines (upper), subsidence data recording the development of the subsidence trough and fault reactivation along the cross sectional (middle) and transverse (lower) subsidence monitoring lines.

Figure 3. Lateral shear along the outcrop position of the Hollybush Fault, Staffordshire, UK. Note the 0.1 to 0.3 m of shear displacements to the kerbstones, paving slabs and the building's wall.

Figure 4. Barlaston church, Staffordshire, UK, was severely damaged by mining induced fault reactivation. The church was partially rebuilt, the tilted and damaged tower and the historical Wedgwood family graves stones repaired.

Retaining walls and perimeter walls

Walls are particularly vulnerable to damage by mining subsidence fault reactivation. They may become tilted, distorted, skewed or fractured. Frequently, it is the damage to perimeter walls and retaining wall, which provides the first evidence that fault reactivation may have occurred. A typical example was the reactivation of a fault at Eastwood Hall, Nottinghamshire, in the 1980s. This caused a high degree of localised buckling to a 5.0 m high brick wall accompanied by the appearance of fault scarp 0.3 m high (Figure 5). Surface buildings were also severely damaged and required rebuilding (Donnelly 2000b, Whittaker & Reddish 1989).

Figure 5. Compression to a 5.0 m high retaining wall, caused by fault reactivation and subsidence, Eastwood Hall, Nottinghamshire, UK.

TRANSPORT NETWORKS

Roads and motorways

Damage to roads by fault reactivation causes traffic delays and increases road maintenance costs. Relatively brittle road surfaces are particularly susceptible to deformation. Broad, open scarps or 'fault ramps' may be generated along road surfaces, often reaching in excess of 1.0 m high, with no, or little, evidence of fault reactivation on the adjacent road-side grassed verges. This may be explained by the relatively ductile, plastic properties of soil, such as glacial till, alluvium or peat, along road-sides. For example, roads in Barnsley suffered widespread damage in the 1960s (Lee 1965). Around Barlaston, Staffordshire, over 50 km of fault scarps have been generated, resulting in a continual road repair programme from the 1960s to 2000.

Fault reactivation and road damage was caused by workings at Hem Heath (previously Trentham) and Florence collieries (Donnelly & Rees 2001). These scarps across roads may reach 2.0 m in height and may be traced across the ground surface for distances of several hundreds of metres. The Crowcrofts Fault outcrops on Wedgwood Drive, near Barlaston, south of Stoke-on-Trent in Staffordshire and from the 1960s to the 1990s underwent several phases of reactivation separated by periods of relatively stability. This was caused by the longwall working of multiple coal seams. A fault step, varying from a subtle flexure to a distinct steep-sided fault scarp over 1 m high, could be traced for a distance of over 3.5 km. Road repairs were necessary on a regular basis causing local traffic delays (Figure 6). The road was repeatedly surveyed over a period of several years and, more recently; these results have been compared with those obtained from satellite radar interferometry (Culshaw *et al.* 2006).

Figure 6. Repairs to Wedgwood Drive, Barlaston, Staffordshire, UK, caused by the reactivation of the Crowcrofts Fault. This generated a scarp at least 1.0 m high and 1.5 km long, during multiple phases of reactivation from the 1960s to 1990s.

In the 1980s the Twenty Acre Fault was being undermined at the disused USAF Burtonwood Airfield from workings at the former Sutton Manor Colliery in the Lancashire Coalfield. Multi-seam longwall workings up to 900 m deep caused the reactivation of this fault, resulting in a broad fault scarp 2 m high, with compressive ground strains of 8 mm/m. This also caused a broad open ramp and fissuring to affect the M62 motorway, which crosses the former airfield (Donnelly 1994, 2000a, Crook & McNichols 1977, Wilde & Crook 1984, McNamara *et al.* 1985).

Adjacent to the Keele Service Station on the M6 motorway in Staffordshire, a fault scarp, at least 0.1 to 0.2 m high, damaged both the north and southbound carriageways on at least two occasions in the 1990s. This caused traffic delays since road repairs were necessary to the surface of the motorway. Two similar scarps developed across the northbound section of this part of the M6 motorway, again adjacent to Keele Service Station, in March 2005, several years after mining had ceased. The causes of the ground movement are not fully understood but the type, scale and magnitude of ground deformation are consistent with fault reactivation.

In 2001, fissuring of the A690 trunk road at Houghton-le-Hole, County Durham, Northeast England, caused damage to both the carriageway and the cutting through which the road passes. The road is cut through an escarpment of the Raisby Formation (part of the Magnesian Limestone), a dolomitic limestone of Permian age, which overlies a sand formation that, in turn, sits on Carboniferous Coal Measures. Multiple coal seams were exploited, with several metres of coal being extracted. However, mining finished in the 1970s so subsidence related directly to mining had long-since ceased. Since the cessation of mining, groundwater levels have risen in the Durham Coalfield, though the pattern of minewater rise is complex because parts of the coalfield are still being pumped to control the rate and location of groundwater level rise. Some of the fissures extended for a distance of about 1 km and were observed as 'crown holes' (caused by the collapse of bridging soil cover and vegetation). Numerous other fissures were observed in the cutting walls but these were not visible on the ground adjacent to the cutting due to dense vegetation and soil cover. On the west side of the cutting at least 12 individual parallel fissures strike mainly between 070^0 and 085^0; others form distinct tension gashes. Most of the fissures are aligned west-southwest (but this is variable) and their spacing is typically between around 1.0 and 10 m. They are persistent, open, clean, fresh and unstained by weathering, with void spaces up to 0.5 m (suggesting they were recently active). Some fissures were bridged or partially filled with limestone blocks fallen from the walls. Others narrowed upwards and appeared to terminate, or are refracted against bedding planes. The collapse of some fissures gave rise to gullies, which reached 3 m wide. There was no evidence of either dissolution or the depositing of carbonate flowstone; tilting or vertical displacements were nowhere observed (Goulty & Kragh 1989, Goulty 1998, Donnelly 1998b, Mitchinson 2000, Wigham 2000, Young & Culshaw 2001). When compared with the geological maps of the area and with information contained in mine plans, it was found that the line of fissuring coincided with the line of the Seaham Fault. Similar lines of open fissures were mapped elsewhere in the immediate area and, again, the lines of fissuring appeared to coincide with the surface projections of faults encountered during mining (Young & Culshaw 2001). The active fissuring caused concern about the integrity of the Houghton Quarry Landfill Site which lies a little to the northwest of the damaged road. It was feared that fault reactivation might have damaged the lining of the waste containment system, hence allowing leakage into the dolomitic limestone of the Raisby Formation. However, examination of the quarry walls appeared to indicate that the quarry had not intersected the Seaham Fault.

Railways and bridges

There are few examples of mining-induced fault reactivation damage to railways lines. In South Wales, the reactivation of the Kilkenny Fault in the 1990s and 1990s generated a fault scarp 1.5 m high, which caused severe buckling of the Cardiff to Merthyr Railway, nearby roads, a railway bridge and associated infrastructure (Figure 7). The longwall working of the Seven Feet Seam caused the most widespread and extensive damage to the railway line at Quakers Yard. The fault trends northwest-southeast, consistent with the main regional trend for major faults across the coalfield.

Figure 7. Reactivation of the Kilkenny Fault, South Wales, UK causing severe damage (compression) and buckling to the Cardiff to Taff Merthyr railway tracks.

Canals and rivers

The Trent-Mersey Canal, built between 1766 and 1777, runs approximately north to south through the industrialised part of Stoke-on-Trent and Newcastle-under-Lyme, Staffordshire. The western tow path of the canal suffered extensive fissuring in the early 1990s caused by the reactivation of the Newcastle Fault in the Trentham area. The canal was situated to the east of the fault scarp, but was within the zone of deformation. The scarp itself was observed as a linear line of damage, 0.1 to 0.5 m high, and it could be traced for a distance of over 2 km through a housing estate, farmland and across a major road. Some houses had to be demolished and others required underpinning and structural repairs. The scarp was distinct on brittle pavements, the canal tow path and road surfaces, and shows extensive compression and en-echelon fracturing, though on grass verges and across gardens the trace of the fault was marked only by a gentle downwarp and subtle flexuring.

SERVICES AND UTILITIES

Gas mains

Underground utilities are prone to damage where they cross faults being undermined. A high-pressure gas main was exposed in a trench, to the south of Wedgwood Drive, Staffordshire, where it crossed the Crowcrofts Fault. It was monitored for subsidence and strain accumulations to prevent disruption and damage. The surveys recorded the reactivation of the fault and the formation of a distinct fault scarp up to 1m high.

In South Wales, the northwest-southeast trending Rhos Fault forms the south-western edge of the Dowlais Trough and has a throw of 119 m in the Brithdir Seam and 91 m in the Seven Feet Seam. The fault was observed in underground workings from the Taff Merthyr Colliery and consisted of highly slickensided rock with prominent ductile drag folding of the strata adjacent to the fault. The Rhos Fault crossed the 1.2 m diameter, very high pressure (VHP) Dowlais to Nelson Gas Main, on Gelligaer Common. This is an elevated area of ground in an urban part of the coalfield. The fault was scheduled to be undermined by an advancing longwall panel in the Brithdir Seam, which occurs at a depth of approximately 660 m. A ground monitoring programme was implemented to ensure that the gas main did not buckle and rupture during the anticipated reactivation of the Rhos Fault, accompanying the subsidence. The survey consisted of precise levelling observations, total station and electronic distance measurements. The gas main was exhumed and exposed in a deep observation trench to monitor strain accumulations (Figure 8). Approximately 0.6 m of vertical displacement was measured along the fault, accompanied by fissuring on the moorland and road. As a result, the extraction of the seam was terminated to prevent further damage to the gas main (Donnelly 1994, 2000a).

The Gelligaer Fault, located a few kilometres to the south of the Rhos Fault, also crosses beneath the Dowlais to Nelson Gas Main. Ground deformation monitoring was carried out in the late 1980s and early 1990s. It was considered necessary to monitor the movement of the fault as it was affected by subsidence during longwall working of the Seven Feet Seam. The reactivation of the fault caused the generation of a scarp and compression along the Gelligaer Road. Ground movements in the vicinity of the fault's outcrop were observed up to ten years after mining finished. The mechanism of these ground movements is not fully understood but may be related to residual subsidence, minewater rebound or fluctuations in groundwater levels

Figure 8. Influence of fault reactivation on gas mains. The Nelson to Dowlais gas main, exposed for strain accumulations and subsidence monitoring where it crossed the Rhos Fault, South Wales, UK.

Sewers and storm water drains

At Easington, County Durham, the generation of a fault scarp over 300 m long, caused severe damage to rows of terraced houses and roads. The damage was occasionally accompanied by tremors felt by local residents (Donnelly 1998b). Distinct narrow grabens were observed across the road surfaces and these were consistent with ground deformation observed in other small towns where fault reactivation had occurred, such as Barlaston in Staffordshire, Pontypool in South Wales, Halton in Lancashire and Inkersall in Derbyshire. The characteristic style of deformation was caused by the collapse of sewers and gullies. In some cases, ground compression, which accompanied fault reactivation, caused the failure of cast iron and concrete sewer and covers.

Mine drainage tunnels

The Irwell Valley Fault is one of the major geological structures to cross the Lancashire Coalfield. There is no documented evidence for the reactivation of this fault at the ground surface. However, approximately 1.5 to 2.0 m of lateral shear displacements were observed underground on the walls of an 18th Century drainage channel, located on the southern bank of the River Irwell, at the site of the former Wet Earth Colliery. The fault plane consisted of a zone of complex plastic deformation and movements within the zone that had resulted in the failure of the brick and masonry lining of the tunnel.

Communication cables

Buried communication cables, located about 0.5 m below ground level, were damaged by the generation of ground fissures in the Triassic rocks of Downes Bank, Staffordshire. The area rises to almost 50 m in height above the Carboniferous Coal Measures rocks of the area and is generally free of Quaternary cover, but is covered by a thin sandy soil. Several faults were subjected to subsidence in the 1990s. This caused the dilation of the fault plane with, or without, a component of vertical slip and resulted in the generation of the ground fissures. Some fault-fissures strike for a distance of over 1 km; their depths are unknown but have been estimated to be at least several metres. These represent the dilation of faults and joint sets during mining subsidence. Where observed in cross-section, in 10 m deep trenches, the faults consist of distinct, parallel and sub-parallel dislocations with a loose sandy gouge. Fissures in the ground surface caused by fault reactivation have been observed in other parts of Britain where the Productive Coal Measures underlie strong, brittle and well-jointed rock. These include the Triassic Sherwood Sandstone Group in the English Midlands, the Permian Magnesian Limestone in the Eastern Pennine Coalfield and Carbonifeorus Coal Measures sandstone, such as the Pennant Sandstone, in South Wales and the Wickersley Sandstone in the East Midlands (Figure 9).

Figure 9. Fissuring associated with the reactivation of a fault, Downes Bank, Staffordshire. This caused disruption to underground communications cables. The fault is exposed in a trench and the ground stabilised using a geotextile mesh and granular fill.

Pylons and overhead power lines

During the reactivation of the Inkersall Fault, Chesterfield, a broad, open fault scarp was generated, approximately 1 m high and over 1 km long. A pylon located in the vicinity of the fault scarp was tilted, resulting in a loss in tension on the overhead high voltage cables. Similarly, the reactivation of the Hopton Fault in Staffordshire caused the development of a distinct scarp about 1.5 m high and 2 km long. This caused tilting and loss in tension to overhead power lines. It is not know if either of these caused interruption of power supplies.

Lamp posts and telegraph poles

Lamp posts and telegraph poles located in areas prone to subsidence and fault reactivation may undergo an appreciable amount of tilt. A notable example occurred in Knutton, Staffordshire, during the reactivation of the Apedale Fault in 1963 (Figure 10).

Figure 10. Reactivation of the Apedale Fault, in 1963, causing tilt to a lamp post, (note the vertical string hanging from the lamp post), Knutton, Staffordshire, UK

SLOPES & EXCAVATIONS

Fault reactivation can influence the stability of natural and engineered slopes. This can result in slope failure and the generation of landslides, which, in turn, may potentially damage land and infrastructure. Fault reactivation has contributed to deep-seated rotational landslides in South Wales as well as causing first time failures of slopes, long after normal ground movement caused by mining had ceased (Donnelly 2005, 2006) (Figure 11).

In 1991, fissuring of the ground surface was observed along the crest of an escarpment at Bolsover, Derbyshire. Over the following two years, this developed into a large compound landslide, causing severe damage to 18 properties located at the toe of the slope and to nine buildings on the crest of the escarpment. Ten buildings subsequently were demolished. The crest of the slope is underlain by approximately 10 m of Permian Magnesian Limestone, comprising thinly bedded, moderately strong, dolomitic limestone that rests on about 20 m of weak calcareous mudstone forming the Lower Permian Marl. This overlies a basal Permian breccia approximately 0.2 m thick. These beds dip gently to the east and unconformably overlie Middle Coal Measures (Upper Carboniferous). The solid strata are covered by up to 4 m of colluvium. At least six coal seams were extracted beneath the escarpment from 1902 to 1984. The seams were extracted by narrow longwall panels oriented sub-parallel to the faulting in the area. Subsidence monitoring and a comparison of Ordnance Survey benchmarks established in the latter part of the 19th Century indicated that there had been up to 0.45 m of subsidence in Bolsover town. These investigations showed that mining had a significant effect on the strata. This had caused the development of the initial failure and its subsequent extension in 1991. However, these movements occurred several years after the expected cessation of normal surface subsidence due to longwall mining (Cobb *et al.*, 2000).

Figure 11. The 3-4m high and 4km long Tableland Fault scarp, which has influenced the Darren Goch landslide and displaced stream valleys, South Wales.

The St. Aidans Extension opencast coal mine is located approximately 10 km southeast of Leeds, on the flood plain of the River Aire. A massive failure occurred in the wall of the opencast workings in March 1985. This caused the displacement of approximately 600,000m^3 of Coal Measures strata into the pit. The failure was about 350 m long, 120 m wide and 50 m high. This consequently caused a breach of the riverbank and flood control levees and, for at least 3 days, flooding of the opencast pit occurred. Around 17 million m^3 of water flowed into the open pit and a lake was subsequently created that was up to 70 m deep and covering an area of about 100 ha. Coal mining operations were suspended for ten years, sterilising approximately 2 million tonnes of coal reserves. The whole of the site was located between two major faults, the Water Haigh Fault to the north and the Methley-Savile Fault to the south. Both faults trend west-southwest and downthrow to the south-southeast with throws of 135 m and 25 m respectively. Mining records indicated that at least three sets of secondary faults occur within the cell defined by the major faults. A maximum subsidence of 3.6 m and tensile strains up to 10 mm/m were generated in the vicinity of the faults, which was likely to have caused their reactivation. The pumping of the floodwaters from the mine workings, re-routing of the river and the canal and the reestablishment of new mining operations have been estimated to have cost approximately £36 million (54 million) (Hughes & Clarke 2001).

CONCLUSIONS & RECOMMENDATIONS

This paper describes case examples of the damage to the ground and infrastructure caused by mining-induced fault reactivation. The majority of the examples occur in the more densely populated urban and industrial parts of the British coalfields. Reactivated faults in these areas were more likely to have been observed and reported to have caused damage to structures and therefore subsequently investigated. The greater numbers of cases of fault reactivation seem to reflect the increased population and greater density of commercial and industrialised land use. However, the recorded cases are likely to be an under-estimation of the actual number of fault reactivation cases. Recent unpublished research in North-east England has shown that local authorities often have evidence of damaging ground movements without necessarily knowing the cause of it.

The examples show that fault reactivation can take place decades after mining operations have ceased. It is suggested that this may be the result of minewater levels rising (to re-establish their pre-mining levels). If so, further cases of fault reactivation may be expected until water levels reach equilibrium.

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