Approaches to inform redevelopment of brownfield sites: an example from the Leeds area of the West Yorkshire coalfield, UK

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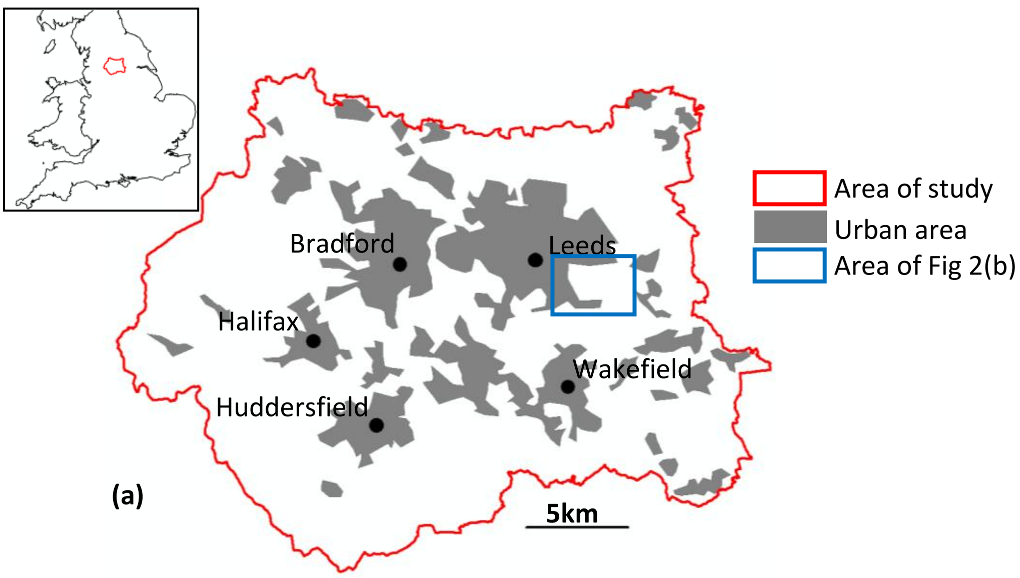
Abstract

Government-led regeneration schemes and policies encouraging the use of brownfield land present a challenge, particularly in coalfield areas. Coalfields have typically experienced multiple phases of development and can be susceptible to a suite of problematic ground conditions that may be rooted in the near-surface geology or result from anthropogenic activity. Such problems, related to the nature of void backfill, undermined and unstable ground and the presence of contaminated land in the near-surface, may deter investment in the very areas earmarked for redevelopment. An understanding of previous developments within coalfields is required to identify potential geological hazards, so that regeneration proposals include measures that address these issues. Public records of landfill sites, site investigations and minerals exploration, including opencast mine plans, can reveal the distribution, thickness and high-level descriptions of fill materials, although the coverage of data typically precludes a comprehensive analysis of entire cities. The best way to show the spatial distribution of fill materials is currently as a two dimensional national/regional scale dataset. Depending on the distribution of data points, however, 3D modelling can be possible, which is much more detailed and accurate. Focusing on the heavily urbanised county of West Yorkshire in northern England, the assessment of opencast coal mining on the landscape and benefits of quantifying the impact are discussed. We demonstrate how certain types of publicly available data allow a greater understanding of the interaction between human activity and natural superficial and bedrock geology. If successful, this approach can help lessen the impact of delays and increased financial costs caused by unforeseen ground conditions.

1 Introduction

This study underlines the need for planners and developers to have access to accurate information describing the shallow subsurface, and investigates the use of publically available information to better characterise previously developed areas and mined ground. This applies to the UK as a whole, but is particularly relevant to brownfield sites in coalfield areas, where problems associated with fill materials can adversely affect developments. The sources of data discussed in this paper are intended to complement, rather than substitute site investigations, and highlight potential issues that can be investigated further with site investigation. Figure 1 (a) shows the extent urban development within the West Pennine coalfield, where the landscape has been extensively modified through coal mining. Figure 1 (b) shows the extent of former opencast coal workings in the Aire Valley area, south-east of Leeds.



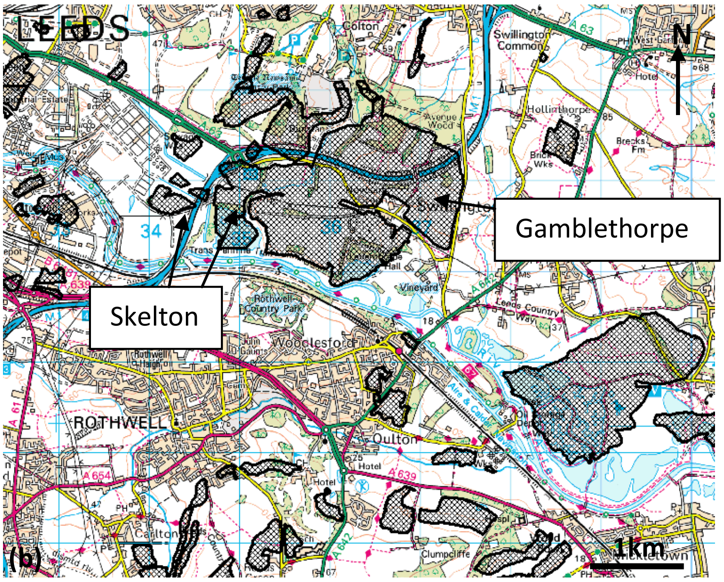


Figure 1(a) Area of study in the West Yorkshire coalfield (outlined in red), comprising the district authority areas of Leeds, Bradford, Wakefield, Calderdale and Kirklees. The extent of urban development, digitised from Ordnance Survey maps, is shown in grey; (b) detailed view of the Aire Valley area of south-east Leeds. Backfilled opencast sites, including Skelton and Gamblethorpe, are recorded in BGS's DiGMap-GB50 artificial ground dataset and shown as cross-hatched

Over the past few decades, UK planning policy has prioritised the redevelopment of brownfield areas in an effort to bring vacant land back into use, as well as encourage urban regeneration and preserve greenbelt land (Department for Communities and Local Government, 2012). In 1998, the UK government introduced a national target of 60% of new housing to be built on brownfield land (DCLG, 2011). In 1997, 53% of new residential properties were built on brownfield land in Leeds, rising to 97% in 2006 (Brannen, 2012). Since 2006 the number of new residences built on brownfield land in Leeds has steadily fallen in response to adverse economic conditions, totalling 86% in 2011 (Brannen, 2012). The National Planning Policy Framework (DCLG, 2012) introduced in England and Wales 2012 removed the national target and enabled local authorities to set their own. The National Planning Policy Framework encourages the development of brownfield sites in preference to greenbelt land, provided that the land in question is of little historical or environmental significance. In this context, brownfield land is regarded as any previously developed site (DCLG, 2012). This presents a challenge, particularly in coalfield areas, where many planning concerns are related to underlying geology and the exploitation of mineral resources. Coalfield areas include some of the most densely populated areas of the UK, including parts of Strathclyde, the West Midlands, and South Yorkshire, parts of which have experienced multiple and strategically uncoordinated episodes of redevelopment since the onset of a modern coal mining industry during the 1700s.

The legacy of coalfield developments can lead to unpredictable and deleterious ground conditions related to both well documented and unrecorded surface and shallow mine workings that can have an adverse impact on regeneration schemes. Such adverse effects include extensive deposits of variable composition and thickness, resulting from a variety of materials tipped onto the ground surface, such as colliery spoil, rubble, industrial and domestic refuse (Waters et al, 1996). The margins of open pits and subsurface excavations may become unstable where not properly engineered or restored, leading to ground movements initiated by deep and shallow coal mining (Bell and Donnelly, 2006; Price et al, 2011). Coalfields can also be prone to landslides, caused by the alternation between more permeable sandstones and less permeable mudstones, allied with the development of topography over-steepened during glaciations (Cooper and Gibson, 2003). Human activity associated with the extraction of minerals for fuel and construction have induced further geological hazards, such as the deposition of spoil or the removal of natural materials from steep slopes. Different styles of mining are characterised by contrasting types of subsidence affecting the land surface, allowing predictions to be made regarding subsidence if the mining technique is known (Bell & Genske, 2001). For example, lowering the water table by pumping water from underground mine workings can cause subsidence of relatively large areas (Bell and Donnelly, 2006).

Contaminants derived from fill deposited in coalfield settings can migrate from fill materials into the surrounding bedrock. Methane gas emanating from domestic landfill material used to back fill opencast workings at Loscoe in Derbyshire was found to be the cause of a gas explosion at a residential property located 70m away, with ground heating observed 100m away from the site (Williams and Aitkenhead, 1991).Contaminants derived from the bedrock itself can also lead to possible groundwater contamination. Pyrite-rich lignite, for example, can cause acidification of the water in flooded surface workings (Younger et al, 2002), which can migrate and corrode cement foundations that are not resistant to sulphate attack.

Another issue that can affect brownfield site development is the increasing demand for underground space, from shallow infrastructure, such as sewerage networks, to underground storage for materials, such as waste and gas (Evans et al, 2009). New technologies can enable previously sterilised areas to be re-used. For example, water held in flooded underground mine workings may be contaminated, but could be utilised in ground-source heating schemes (Evans et al, 2009). In the deeper subsurface, regulations designed for a particular activity may preclude the possibility of other operations occurring in the ground either below or above. The use of underground space requires careful planning to ensure that conflicts on underground space are kept to a minimum and any potentially useful resources are maximised. Areas that are suitable for coal mining are not generally considered suitable for carbon dioxide sequestration because of conflicts in land use related to potential interactions between the host for CO_2 and deeper coal-bearing strata. Areas where coal seams are classed as unminable (over 1,200m deep and over 500m away from mine workings) are considered most appropriate for carbon dioxide sequestration (Jones, et al. 2004) and can be identified using modern 3D modelling and GIS (Geographical Information Systems).

A study of 5000 industrial construction projects revealed that half were delayed by more than a month, and all developments on redevelopment land had encountered unforeseen ground conditions although, only 2-3% of the total cost of a typical construction project is spent on site investigation to assess the geology and soil conditions (www.bexley.gov.uk). With the aim of reducing construction costs by 33% and build times by 50%, the UK Government, in partnership with industry, introduced the Construction 2025 strategy in 2013 (anon, 2013). Industry standards, such as BS5930 (anon, 1999), set out a detailed code of practice for site investigation, beginning with a desk study, but this is not a statutory requirement.

Preliminary assessments of ground conditions should take place at the planning stage, in order to keep the resource effort to a minimum and to avoid the delays associated with unforeseen ground conditions (Marker, 1998). In Britain, the statutory obligation to record the location of mine workings was established in 1850, and the compulsory documenting of mine plans dates from 1782 (Bell & Genske, 2001). Many pre-1850 coal workings are unrecorded and can adversely affect properties built above them. In Glasgow, for example, some developments are located in areas of shallow mining and the collapse of these old workings and the settlement of fill materials in these areas have resulted in damage to buildings (Browne et al, 1986).

Parcels of undeveloped brownfield land may serve to deter regional redevelopment and investment. It is therefore beneficial to regions with the potential for redevelopment that any barriers to improvements are identified and mitigated. Additionally, some areas previously considered unsuitable for mineral extraction or development due to environmental hazards are now being included in development plans as new technologies and incentives allow. The Environment Agency (England) are investigating new ways of treating water from mine workings to prevent contaminants reaching natural water courses. One scheme is the five hectare area Lamesley Wetlands in County Durham, north east England, where biological processes used in the treatment of sewage improve the effectiveness of mine water treatment. Lamesley Wetlands serves as a nature reserve and benefits the local community, and is included in a local regeneration scheme (Johnston et al, 2007). The economy is now exploiting innovative ventures for industrial activities or infrastructure in the shallow subsurface. This increases the need to better understand human impacts on surface and subsurface space (Evans et al, 2009).

Developers of brownfield sites in coalfield areas need reassuring that the relevant local authority has adequately assessed any land instability issues arising from former coal mining activity. For example, the heterogeneous nature of opencast fill materials, such as variation in sorting and grain size, can lead to differential compaction (Younger et al, 2002), although where properly engineered, opencast fill can have excellent engineering properties (Waters et al., 1996). Differential settlement can also occur at the margins of backfilled opencast sites, due to the different load bearing strengths of in situ bedrock and fill material (Waters et al, 1992). Extraction needs to occur prior to development to avoid unnecessary sterilisation of resources, such as coal, sandstone, fireclay and brick clay. The Coal Authority is responsible for licensing and permitting coal extraction and public safety arising from the legacy of coal mining. Local authorities are responsible for site remediation prior to development through Part IIa of the Environmental Protection Act, 1990, which requires contaminated land is surveyed for, identified and compulsorily remediated, and that the local authority and environmental regulators maintain a register of sites. Additionally, there is a requirement through the National Planning Policy Framework (DCLG, 2012) that unstable ground is identified as part of the planning process. The developer is subsequently responsible for ensuring that the site is safe and suitable for the proposed use. Therefore, the responsibility for a brownfield site changes over time, with the local planning authority maintaining an input at key stages.

2 Previous studies and related work

This study investigates ways of improving the characterisation of artificial ground using publicly available data sources (geological maps, opencast mine plans, borehole logs and landfill site records), with a view to better informing planners and developers of the ground conditions at potential brownfield development sites in coalfield areas. This is particularly relevant in areas where brownfield land has been prioritised for development. Proposed major infrastructure developments, including the north-eastern spur of the High Speed II rail link, drive the need for continually improved accuracy and quality of information describing artificial ground. The ground conditions in this area need to be well understood in order for any problematic ground conditions to be identified and accommodated for within proposed redevelopment plans.

Seven planning and development reports for cities in coalfield areas, including Leeds (Lake et al, 1992), Bradford Metropolitan District (Waters et al, 1996), Castleford and Pontefract (Barclay et al, 1990), and Morley-Rothwell-Castleford (Giles, 1988) were commissioned by the UK Government Department of the Environment (now part of the Department for Communities and Local Government) under their Geological and Minerals Planning Research Programme between 1983 and 1996. These land use, planning and development reports include a series of themed maps that consider geological hazards, and aim to better inform planners and developers of the expected ground conditions. The geological hazards identified include the distribution and thickness of superficial deposits, surface bedrock geology, and their engineering properties. The distribution of artificial ground is also included, comprising material placed on the ground surface, such as colliery spoil, and areas where the ground surface has been artificially lowered through shallow mining activities. An investigation into the benefits of these themed geological maps for planners and developers recommended that such studies are kept up-to-date in order to remain relevant and accurately describe the current ground conditions (Smith and Ellison 1999), especially in areas that have experienced extensive or multiple phases of development. Waters et al (1996) provide guidance to planners and developers, and quote contemporary mineral planning policy, which states that planning permission applications should take into account mineral resources, either by protecting them, or extracting them before development takes place. Waters et al (1996) also identify potential opportunities for disused mineral workings, such as turning them into local nature reserves or repositories for waste.

One area where these datasets could be useful is Leeds, located in northern England. Leeds City Council has taken steps to encourage the redevelopment of brownfield land, including adopting development plans, such as the Local Development Framework, introduced in 2004 under the Planning and Compulsory Purchase Act (www.leeds.gov.uk/council/Pages/Introduction to Local-Development-Framework). Leeds City Council also supplies developers with planning briefs and planning statements to advise on potential uses for the sites and suggests ideas for building design (Brannen, 2012). Leeds City Council is currently drafting the 'Aire Valley Leeds Area Action Plan', to encourage regeneration in the Lower Aire Valley between Leeds City Centre and the M1 motorway, an area identified for development, which covers over 400 hectares of development land (www.leeds.gov.uk/council/Pages/Aire-Valley-Leeds-Area-Action-Plan). Located approximately 5km to the east of Leeds the 142 hectare Aire Valley Leeds Enterprise Zone (airevalleyleeds.com) is one of four Enterprise Zones in West Yorkshire (**Figure 2**), and 35 UK-wide, established in 2012 to stimulate the local economy and create employment opportunities through incentivising business development. Businesses can benefit from Government grants and tax incentives, together with simplified planning rules through the introduction of a 'Local Development Order' to encourage new development and investment (DCLG, 2012). Aire Valley Leeds Enterprise Zone lies within an area of previously exploited near-surface coal resources.

This late 2000s property 'boom' was buoyed by several factors: UK Government policy favoured the development of brownfield land; population growth resulted in a demand for housing, and the economic conditions at the time favoured home buyers and developers. From 2005, £28 million worth of brownfield site property was sold in the district authority are of Leeds City Council, with an estimated 1,500 housing units developed on 38 hectares of brownfield land (Brannen, 2012). Since economic conditions became less favourable in 2007-2008, the rate of property development in Leeds city centre has slowed and many brownfield sites that were purchased for redevelopment have remained vacant. The commercial value of this development land has decreased since it was purchased, and the residential complexes that were planned will not give the financial returns that were predicted at the time of purchase (Brannen, 2012).

3 Methods

The collation of geological data in coalfield environments may be aided by the development of a semi-prescriptive methodology, where relevant information is identified, databased, and incorporated into revised maps and models that acknowledge the local geological framework. Information describing the effects of opencast and shallow coal mining up to 30m below ground level on the landscape can be captured and communicated through modified digital geological data in the form of digital geological maps and 3D models. However, the inclusion of artificial ground on geological maps in the UK only became routine nationally during the early 1980s and is therefore poorly represented in data derived from older geological maps. Even modern geological maps tend to under represent human impacts on the landscape, as the focus for artificial ground mapping is primarily on mineral workings, industrial areas and transport routes. For many areas this has resulted in a poor understanding of the coverage of artificial ground, a situation that is typically worse in urbanised coalfield districts than non-coalfield, or lesser urbanised areas due to the complexities of multiple phases of development. Changes to the land surface can be incorporated within these datasets, and information concerning the subsurface can be extracted from borehole and mine plan records. These data may be better visualised when incorporated into 3D models, allowing the relationship between natural and man-made geological units to be clearly represented.

The coalfield in West Yorkshire, northern England, comprising the district authority areas of Leeds, Bradford, Wakefield, Calderdale and Kirklees, has historically been the focus of heavy industrial activity. The underlying coal-bearing Carboniferous bedrock (**Figure 2**) has been extensively exploited for its natural resources, mainly within the Pennine Coal Measures Group, with coal extraction in the area dating back to Roman times (Goodchild, 2000). UK coal production figures published in a fact sheet on the National Coal Mining Museum for England web site (www.ncm.org.uk) dating from 1900 to 2004 show that UK coal output exceeded 200 million tonnes a year between 1900 and 1955. Since then UK coal output has been in steady decline, with annual opencast coal production from West Yorkshire falling to 89,000 tonnes by 2010, and no opencasting recorded in 2011 (Bide et al, 2012).

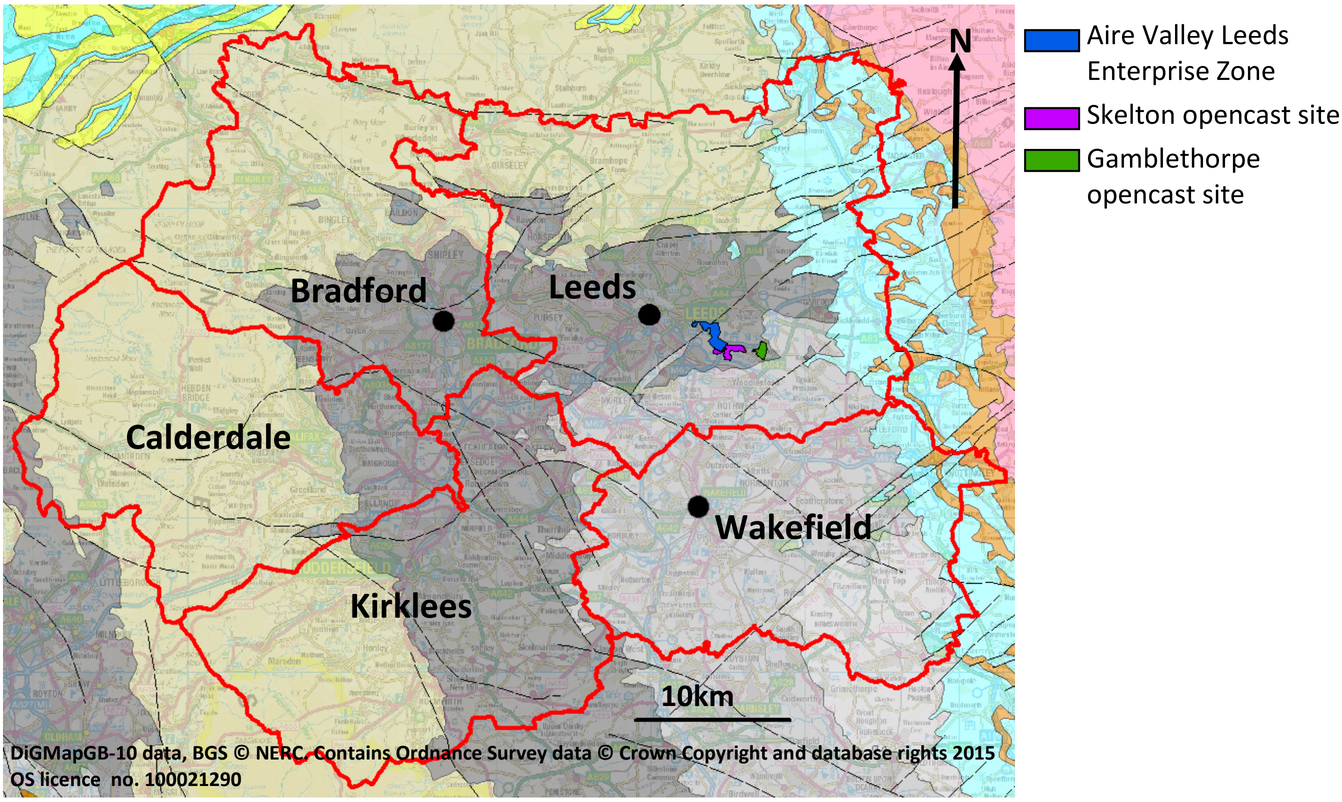


Figure 2 1:625,000 scale bedrock geology map of the West Yorkshire coalfield, comprising the district authorities of Leeds, Bradford, Wakefield, Calderdale and Kirklees (outlined in red). Almost all of the area is underlain by Carboniferous Coal Measures, which have been extensively exploited through underground and opencast mining methods.

Key to Figure 2 geological map: bedrock geology listed in stratigraphic order. Geological descriptions are taken from the BGS LEXICON of Named Rock Units (www.bgs.ac.uk/lexicon)

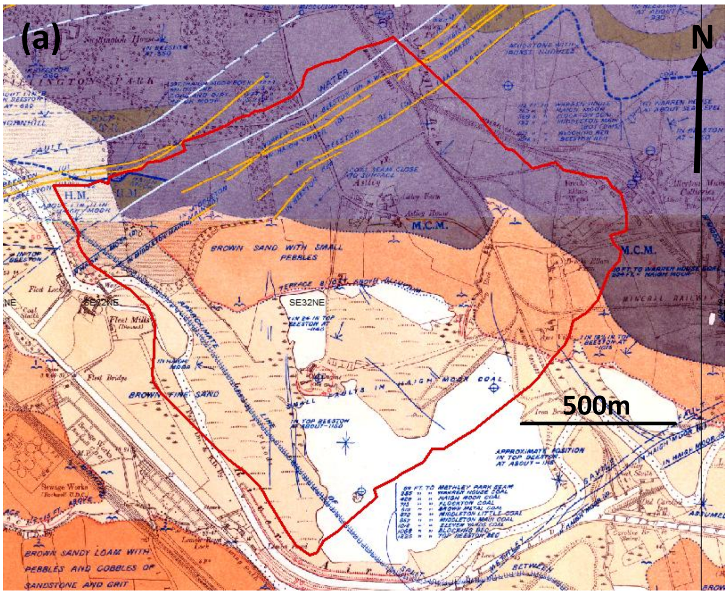
Geological Period	Geological stage	Geological group	Geological formation	Typical composition	**Legend**
	Geological fault				– – – – –
Triassic		Sherwood Sandstone Group	Undifferentiated	Sandstone; red, yellow and brown in colour, part pebbly, with subordinate red mudstone and siltstone	
Permian	Late Permian	Zechstein Group	Undifferentiated	Mudstone, siltstone and sandstone	
			Undifferentiated	Dolomitised limestone and dolomite	
Carboniferous	Bolsovian (Westphalian C)	Pennine Coal Measures Group	Pennine Upper Coal Measures Formation	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	
	Duckmantian (Westphalian B)		Pennine Middle Coal Measures Formation	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	
	Langsettian (Westphalian A)		Pennine Lower Coal Measures Formation	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	
	Namurian	Millstone Grit Group	Undifferentiated	Mudstone, siltstone and sandstone	

Surface coal extraction and mining in the shallow subsurface has impacted on the land surface in this area (Waters et al, 1996). Perhaps the most obvious effect of human exploitation of geology is where minerals are extracted from large surface pits. In the case of Pennine Coal Measures Group, opencast methods have been employed to extract coal and fireclay (Lake et al, 1992). Opencast coal mining is considered possible to a depth of approximately 50m below the surface, taking into account the economic viability of removing overburden and the amount of recoverable coal (Jones et al, 2004), at which depths would include the exposed and shallow parts of the concealed coalfield.

3.1 Revising bedrock, superficial and artificial ground themes on BGS geological maps using opencast coal mine plans

There are many sources of information that describe the shallow subsurface and the impact of human activity on the Earth's surface. One source of information is the British Geological Survey's holdings of digital geological map data (British Geological Survey, 2008; 2012) that are available at a variety of scales (Smith, 2009), with 1:10 000 (DiGMapGB-10) suitable for local studies and 1:625 000 (DiGMapGB-625) for countrywide studies. This type of spatial data represents the position of geological units and boundaries at the ground surface at particular snapshots in time. In Britain, large-scale opencast coal mining was uncommon prior to 1942 and many geological maps completed before this date therefore record the position of coal seam outcrops, which were often inferred using borehole and mine shaft data, and the extent of any overlying superficial deposits. Following World War II, the coalfield landscape changed considerably with some districts subject to extensive opencast coal mining operations, and the position of naturally occurring beds of coal and adjacent geological units altering radically in response to mineral extraction. The introduction of digital geological map data enables revisions to linework to be carried out relatively quickly and easily with the use of Geographical Information Systems (GIS). Scanning and spatially referencing opencast mine plans also makes it relatively simple to compare them to existing geological linework.

Reliable and accurate information describing the impact of opencast coal mining on local geology, such as the modification of coal seam outcrops and the removal of overlying superficial deposits, can be obtained from opencast coal completion plans. These are detailed plans of opencast coal sites, which are submitted to the UK Government's Coal Authority on behalf of the Health and Safety Executive as a statutory requirement (HSE, 2015), and show the position of coal seams and geological faults following opencast activity. With knowledge of the relationship between the position of a particular coal seam and beds of sandstone or mudstone, these plans may be used to revise the geological linework in and around areas of opencast coal activity. **Figure 3 (a)** shows an extract from the 1931 edition of a geological map that pre-dates St Aidans opencast site, located close to Great Preston, approximately 3km north-west of Castleford (**Figure 2**). When compared with the 1985 geological map of the same area (**Figure 3 (b)**), the extent of superficial cover has reduced, and the position of coal seam outcrops has changed as a result of opencasting.



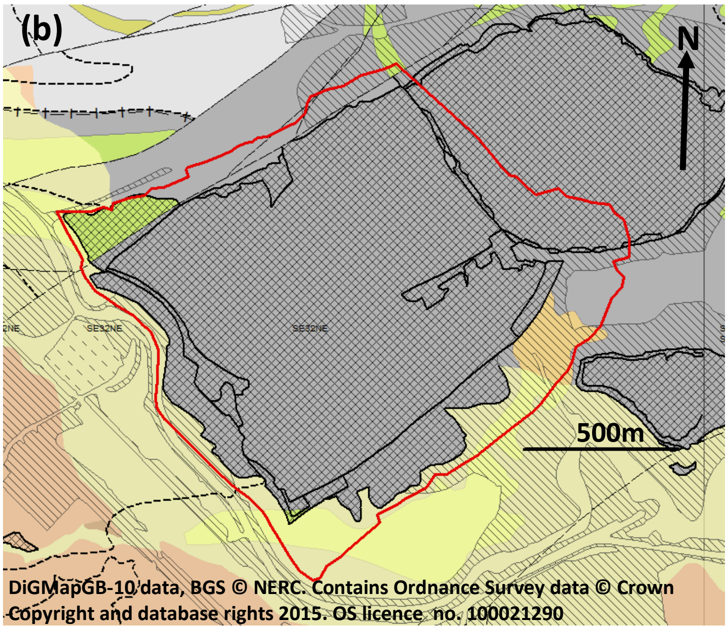


Figure 3 (a) 1931 edition of County Series 1:10,560 scale geological maps Yorkshire 234NW and Yorkshire 219SW, St Aidans opencast site outlined in red. The 1931 geological maps record the original position of overlying superficial deposits, with River Aire alluvium (pale yellow) and associated river terrace deposits (orange). Grey areas represent Pennine Middle Coal Measures bedrock at surface. (b) St Aidans opencast site outlined in red, with current 1:10,000 scale digital geological map data for sheet SE32NE (published in 1985). Note the complete removal of river terrace deposits and the modified extent of alluvium, with bedrock now at surface throughout the opencast site. Modified coal seam outcrops are shown as black lines. The cross-hatching indicates that this opencast site has been worked and backfilled; hatched areas indicate made ground.

Anthropogenic modifications to the land surface through the emplacement or removal of material are classed as artificial ground, and can be held as appropriately attributed polygons in digital map systems. Artificial ground is commonplace in coalfield areas, and includes the extent of workings at St Aidans opencast site, shown in **Figure 3 (b)** as a cross-hatched area of infilled ground because backfilling has occurred. The current artificial ground classification scheme used in Britain divides artificial ground into five classes (Ford et al, 2010), which are listed in **Table 1**.

Table 1 Classification scheme for artificial ground used on BGS geological maps

Class	Description
Made ground	Areas where the land surface has been raised by the emplacement of artificial deposits upon it. This includes flood, road and railway embankments, spoil heaps and flood defence embankments
Worked ground	Areas where the land surface has been lowered as a result of man-made excavations. This includes pits, quarries and road and railway cuttings
Infilled ground	Man made excavations that have been backfilled, such as backfilled quarries, restored opencast workings and infilled railway cuttings
Landscaped ground	An area where the land surface has been extensively remodelled, but where it is impossible to distinguish between zones of made ground, worked ground or disturbed ground. This classification is often used to for large industrial developments
Disturbed ground	Areas of poorly defined surface disruption associated with surface or near-surface development or collapse. Examples include collapsed shallow workings, such as 'bell pits' for near-surface coal extraction

Although this classification scheme can help inform users of geological map data why artificial ground is present at a particular location, such as distinguishing between a canal or road embankment, a limitation is that the scheme does not describe its composition or thickness (Ford et al, 2014).

3.2 Using archive material to quantify the composition and thickness of artificial ground

Landfill sites are areas that are used for the transfer and disposal of waste, authorised by the Environment Agency in England (www.environment-agency.gov.uk/wiyby37823). Information describing the composition of artificial ground can be obtained from landfill site records. BGS holds an archive of approximately 3000 pre-1974 waste disposal sites obtained from local authorities across England and Wales. A database of these waste sites is linked to an online GIS, available through the BGS web site (www.bgs.ac.uk/geoindex), where they are displayed as points. 190 of these waste disposal sites fall within the district authority areas of Leeds, Bradford, Wakefield, Kirklees and Calderdale. In addition, an assessment of 437 landfill sites across the area of Bradford Metropolitan District Council produced a database in parallel with a planning and development report (Waters et al, 1996). This database lists the location of each site location, type of waste disposed of and details of the landowner but has not been incorporated into the national BGS dataset. Modern landfill records can be obtained from the Environment Agency, and were not used in this study.

In order to enhance the existing database and associated GIS feature layer of these landfill site records, the paper archives for this subset of 190 sites were examined. Many of the paper records relating to these sites contain more detail than is stored in the associated GIS layer and database, including the composition and tonnage of waste material disposed of. Among the diverse range of waste materials recorded at some sites are contaminants, including 'asbestos', 'toxic sludge', 'railway sewage' and 'waste oil'. This extra level of detail enables the general composition and approximate amount of material held in these waste disposal sites to be quantified. Many records of waste disposal sites also include site plans, allowing for improved accuracy of the spatial representation of historic landfill sites.

Site investigation borehole records provide information on the composition and thickness of artificial ground, often in areas where none is held in digital databases or shown on topographic or geological maps and plans. Artificial ground mapping tends to focus on well defined topographic features, such as road and rail cuttings and embankments, or mineral workings, and does not typically capture artificial ground with little or no surface signature, such as that associated with housing developments. By its very nature, artificial ground is transient, particularly in urban areas, where parcels of land have often been developed multiple times (Price et al, 2010).

Borehole data tends to be concentrated in urban areas, coalfields, and associated with major infrastructure developments, such as transport and pipeline routes, due to the relatively high amount of development activity typically associated with these areas. With the exception of drilling new site investigation boreholes, they represent one of the most accessible ways of finding out the composition and thickness of fill material. For example, BGS holds 1491 site investigation borehole records associated with Skelton opencast coal mine, located on the eastern edge of Leeds (**Figure 2**), which occupies an area of approximately 3km^2. The vast majority of these boreholes were drilled prior to opencasting, and record the depth from contemporary ground surface and the thickness of coal seams intercepted.

However, a number of boreholes were drilled to assess the ground conditions ahead of the construction of the M1-A1 link road, which post dates the restoration of Skelton and Gamblethorpe opencast sites along the route. These boreholes vary considerably in the amount of detail provided in the lithological descriptions, making some more useful than others for assessing the composition of opencast backfill material. This is illustrated in two site investigation boreholes drilled three years apart for the A1-M1 link road. Borehole SE33SE 3073, located at Gamblethorpe opencast site (National Grid Reference: 437422 431269) records 20m of 'opencast fill'. In contrast, borehole

SE33SW 3287, located at Skelton opencast site (National Grid Reference: 434956 431158) records 18.5m of fill material, with full lithological descriptions provided (**Table 2**). This illustrates the value of site investigation boreholes that are logged according to British Standard BS5930 (anon, 1999).

Table 2 Thickness and detailed description of opencast backfill material recorded in borehole SE33SW 3287, drilled to assess the ground conditions along part of the A1-M1 link road that passes through the restored Skelton opencast site

Depth below ground level (m)	Description
0-18.5	MADE GROUND: Very stiff friable grey and yellow brown slightly sandy silty clay with much angular fine to coarse gravel and occasional cobble and boulder sized fragments of siltstone, sandstone, coal and ironstone nodules (Opencast Backfill) 0-2m stiff to very stiff dark grey 4-6m stiff to very stiff At 5m occasional medium gravel sized fragments of brick 7.7-8.15m angular coarse gravel sized fragments of concrete At 9.5m occasional gravel sized fragments of brick 14.5-17m firm to stiff
18.5-19	Grey thinly laminated moderately weathered silty MUDSTONE, weak

3.3 Modelling opencast sites in three dimensions

Opencast coal workings can be represented in 3D modelling software, which enables the volume of backfill material emplaced after coal extraction has ceased to be quantified. In total, 25 opencast sites located around Leeds, Wakefield and Pontefract were modelled using opencast coal completion plans, which display contour lines, measured spot heights recording the elevation of coal seam bases, and an outline of the coal workings. This coal seam elevation data was captured as points in a GIS and converted into to a Triangular Irregular Network (TIN) in 3D modelling software. Where a sequence of coal seams had been worked at the same locality, only values relating to the deepest coal seam were recorded. This gives a terrace-like appearance to the sides of the modelled opencast sites as progressively deeper seams tend to be worked towards the site centre. Spot heights measured around the edges of excavations were also included to provide information on the height of the original ground surface.

This method is particularly useful for representing backfilled opencast sites, where the natural ground level has been considerably modified. A separate TIN surface was generated for each of the 25 sites to represent the maximum depth of the opencast workings prior to any backfilling. To ensure a consistent approach, and to honour the coal seam elevation data exactly, it was assumed that the modelled opencast sites were excavated no deeper than the base of the deepest coal seam. Other opencast sites could not be modelled, however, due to spatial inaccuracies inherent in the data, such as hand drawn topographic maps, lack of grid references, use of an unspecified local elevation datum, and depth conversion issues.

The modelled opencast sites include Skelton, a cluster of five surface pits, worked between 1989 and 1994, and Gamblethorpe, a single opencast pit roughly 500m east of Skelton. These restored opencast sites are located at Swillington, approximately 5km southeast of Leeds city centre (**Figure 2**). Gamblethorpe covers an area of approximately 0.67km^2, with a maximum excavation depth of -11.7m OD and the modern land surface ranges from +10m OD to +80m OD. Excavations at Skelton are much deeper, reaching to -44m OD. Surfaces representing the base of workings at Skelton and Gamblethorpe are shown in **Figure 4** as colour ramped 1m interval contours, overlain with a triangular mesh Digital Terrain Surface depicting the modern land surface. A geological fault, trending roughly east-west, with a displacement of up to 23m, is recorded on the opencast coal completion plan for the largest pit at Skelton, with elevation data on the deepest coal seam recorded either side of the fault trace **(Figure 5)**. Honouring this sharp elevation change over a relatively small distance enables the sub-vertical fault plane to be represented as a steep ramp in the floor of the modelled opencast site.

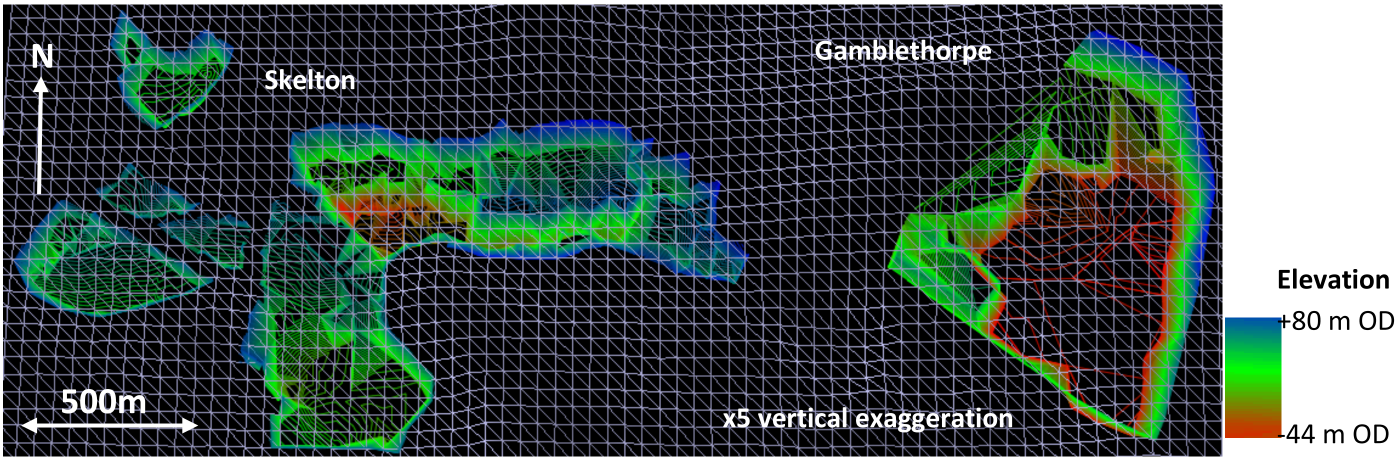


Figure 4 3D view of Skelton and Gamblethorpe restored opencast sites, located at Swillington, approximately 5km southeast of Leeds. Elevations of coal seam contours and spot heights recorded on opencast coal completion plans were captured in a GIS and converted into TIN surfaces in 3D modelling software. These surfaces are displayed as 1m interval contours, with a blue to red colour ramp (high elevation in blue and low elevation in red). The modern ground surface is represented as a transparent triangle mesh, showing that the site has been backfilled. The contoured surfaces represent the depth of opencast workings at the site, prior to being backfilled, and visualise the thickness, bulk distribution and volume of backfill material.

The modelled surfaces of opencast sites are accurate scaled representations of the true extents and depths of the opencast workings at the time when coal extraction had ceased, and before any fill material was emplaced. The thickness of the fill material at restored opencast sites can be calculated using the digital terrain surface as the top and the depth of workings as the base. This calculation gives a maximum thickness value of fill material of 82m for Gamblethorpe and 68.7m at Skelton opencast site. At the same time, the 3D modelling software calculates the volume of fill material, giving a value of approximately 36.76 million cubic metres at Gamblethorpe opencast site. The calculated top and base surfaces of fill material at the Skelton and Gamblethorpe opencast sites were exported from the 3D modelling software as grids, together with a thickness grid representing the distribution of fill material, into a GIS to enable variations in the thickness of artificial ground to be represented (**Figure 5**).

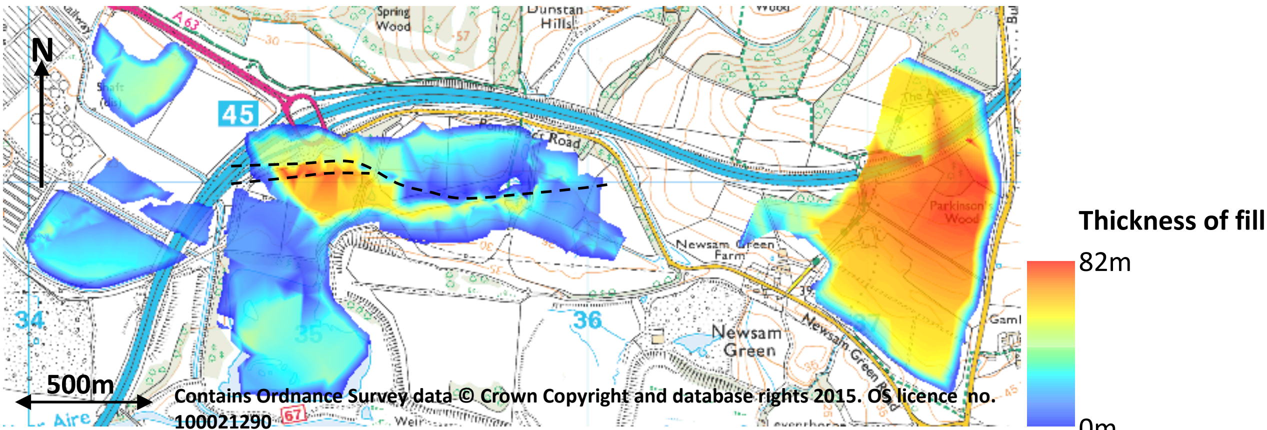


Figure 5 Grid showing the distribution and thickness of fill material at Skelton and Gamblethorpe opencast sites, displayed with a blue to red colour ramp. Red areas indicate where the fill material is thickest, the maximum thickness being 82m. The thickness of fill material was calculated in 3D modelling software, using the modelled base of workings derived from opencast coal completion plans as the base of the fill, and the modern digital land surface as the top. The thickness of artificial ground increases across geological faults (dashed black lines) in the main pit at Skelton, indicated by the red area, where the excavation deepens on the downthrown side of the fault.

Base of coal seam contour lines and spot heights displayed on mine plans relating to Gamblethorpe opencast site reveal that a sequence of seven stacked coal seams have been worked to a maximum depth of -11.7m OD. These coal seams are offset by three closely spaced sub-parallel geological faults, each with a maximum vertical displacement of approximately 6m. The worked coal seams at Gamblethorpe are illustrated schematically in Figure 6, with the backfilled former workings shown in grey, together with the original land surface and coal seams.

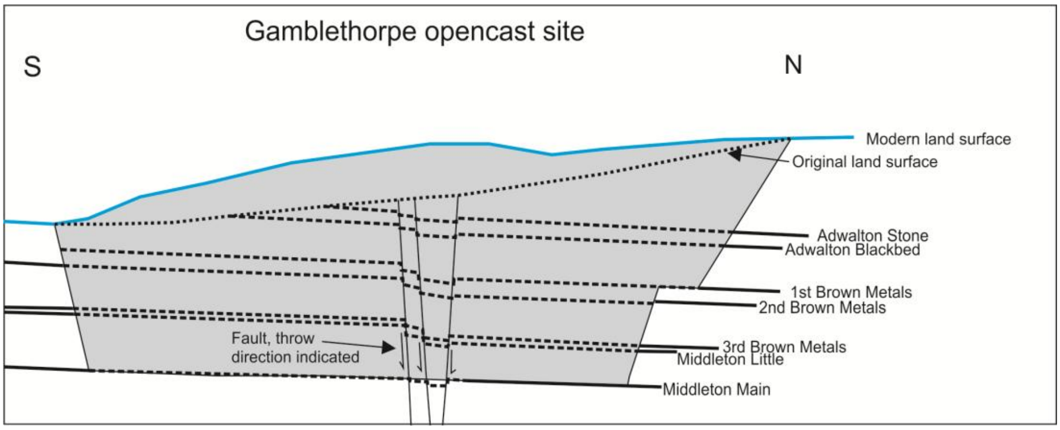


Figure 6 Schematic representation of Gamblethorpe restored opencast site, showing the area occupied by fill material (grey) and the sequence of 7 worked coal seams. The coal seams and original land surface are dashed through the area occupied by fill material.

4 Results

In this study, several datasets that provide information on the shallow subsurface were examined in order to ascertain whether artificial ground in coalfield areas could be characterised and understood.

Digital geological map data

Artificial ground data could help developers identify potential problems that may affect a particular site. Geological maps are a useful indicator of the presence of artificial ground in coalfield areas. Many operational or unfilled opencast sites are delineated as areas of worked ground, and restored sites are represented as infilled ground.

Site investigation borehole logs

Site investigation boreholes provide information for identifying potentially problematic ground conditions at brownfield sites. On modern borehole logs that comply with BS5930 (Anon, 1999), the British Standard code of practice for ground investigation, the composition and thickness of artificial ground are recorded. BS5930 compliant borehole logs can also provide information on the engineering and hydrogeological behaviour of artificial ground, which can be influenced by the nature of the fill material itself, such as grain size, compaction and water content (Lake et al, 1992). BGS holds records for 44946 publically available site investigation boreholes within the district authority areas of Leeds, Bradford, Wakefield, Calderdale and Kirklees. Index level data, such as location, name and BGS reference numbers are available for all boreholes online, with scans of the logs available via the BGS web site (http://www.bgs.ac.uk/geoindex).

Landfill site records

Information concerning the composition of fill material is held in the BGS archive of pre-1974 waste disposal sites (www.bgs.ac.uk/geoindex). The dataset does not have national coverage, but does contain records of 3120 known waste disposal sites in England and Wales dating up to 1974. Of the 190 pre-1974 waste disposal sites located in South Yorkshire, 184 contain information describing the composition and approximate weight of material, as well as distinguishing between commercial waste and domestic refuse. Additional information on the type of waste permitted to be disposed of can be obtained from waste disposal site licences held at local authorities. This study also highlights the presence of contaminants, including asbestos and oil. This information, and the extent of the landfill sites, could be of great value to developers of brownfield sites in identifying potential contaminated land, which could support development strategies and mitigation (Rosenbaum et al, 2003). However, one important omission in these site records is the lack of information on whether the sites had been lined with an impermeable barrier prior to the emplacement of waste material. This level of information would be useful in understanding pollution potential and the development of pathways from sources to receptors.

3D models derived from opencast coal completion plans

Modelling opencast coal sites in three dimensions allows the bulk 3D distribution of fill materials to be visualised and accurately quantified. The process of gathering coal seam elevation data from coal mine plans can be labour intensive, and subject to spatial errors that may be present in the source materials. For example, some older completion plans are difficult to use if they are hand drawn or do not include grid references. Coal seam elevation depths only tend to be recorded on modern opencast coal plans, making the modelling of historic sites problematic. Because of this, the fill depicted on completion plans for only 25 out of 109 known opencast sites in the Leeds, Wakefield and Pontefract area can be confidently modelled in three dimensions. However, this technique proved particularly useful when modelling restored opencast sites, where the workings have been backfilled, leaving little evidence of their original extent.

Site investigation boreholes that post date the restoration of opencast coal mines can be used to validate the 3D representation of fill material, and can improve the accuracy of any models generated. For example, the thickness of fill material recorded in borehole SE33SW 3287 at Skelton opencast site is 18.5m, whereas the thickness anticipated by the geological model at that locality is 21.4m. This 2.9m difference occurs because coal seam depths recorded on opencast coal completion plans were the only data source used to constrain the 3D model, and the nearest coal seam elevation control point to this borehole is located 18m to the south. Additionally, the borehole log for SE33SW 3287 states a start height of 27.34m, whereas the land surface represented in the model at this location has an elevation of 24.6m, a difference of 2.77m.

In 25 out of 109 opencast sites it has been possible to generate robust models of the shallow subsurface, enabling data from opencast coal mine plans to be visualised in ways that enable consideration of the interaction of fill materials and local geology, as well as quantifying the gross distribution, thickness and volume of fill materials. Some of the more modern opencast coal completion plans used in this study also show areas of coal workings. This level of detail was not recorded in this study, but could be a used as an indicator of where fractures in the surrounding bedrock may have occurred, making those areas more permeable and susceptible to coal gas migration from intact coal and/or the leaching of pollutants from the backfill material.

The thickness of fill materials and compositional variation can be successfully processed using 3D modelling software. Using numerous closely spaced borehole records in the Rotherhithe docks area of London, south east England, a 3D model was created using stochastic modelling methods, where the space occupied by the fill material is divided into cells, each of which is attributed with composition information provided by the borehole records (Price et al, 2012). This method could be applied to backfilled opencast sites where the number and density of borehole data is sufficient for the end use of the model. If sufficient detail is recorded in the borehole logs, this approach could give information of the anthropogenic history and sequential emplacement of fill at a site.

3D geological models that incorporate bedrock and superficial geology and accurately recorded artificially modified ground information are often easier to interpret than 2D geological maps

(Kessler and Mathers, 2004). 3D models could be particularly useful to local authorities and planners and developers of brownfield sites, who may benefit from a clearer visualisation of the spatial interaction between geological units, including their inherent properties (such as permeability), and other aspects of infrastructure, such as pipelines, cables and transport tunnels that a 3D model can clearly illustrate (Aldiss, et al, 2012).

5 Discussion

Planners and developers need access to accurate up to date information in order to inform decision making at an early stage of brownfield site development. Many datasets, including geological and cartographic agency map and spatial data, typically under represent the distribution of artificial ground and currently offer scant detail describing the composition of fill material, although there are schemes and protocols that could be adopted to improve this situation (Rosenbaum et al, 2003). These include detailed descriptions conforming to recognised standards such as British Standards (anon, 1999) in site investigation boreholes; through to more anecdotal descriptions of bulk character of landfill material, such as country-wide assessments of pre-1974 waste disposal sites carried out by the Department for the Environment in 1973 (www.bgs.ac.uk/geoindex). More localised reviews of urban areas include planning and development reports commissioned by the Department for the Environment for UK coalfield areas, including Leeds (Lake et al, 1992) and Bradford (Waters et al, 1996). Together with spatial data, including geological records, these enable a better understanding of the nature of artificial ground, and can be used to inform planners and developers of the expected ground conditions.

The pre-1974 waste disposal sites dataset (www.bgs.ac.uk/geoindex) gives information concerning the composition and quantity of waste material disposed of, and in some instances, periods of emplacement. Waste disposal site records are particularly useful in two ways: for alerting planners to the presence of potential pollutants, and as a screening tool to the presence of compressible ground that may suffer differential compaction if built over. Waste disposal archives also include a site plan, showing the full extent of the licensed disposal site. However, even with this additional information, no depth information describing the thickness of fill in a particular landfill is associated with the site in this particular dataset. From these records alone, it is not possible to accurately quantify the volume of refuse within an individual landfill site.

Opencast coal mine plans are a useful source of information when representing human impacts on coalfield areas. However, the integration of geological information from the opencast site plan with the geological map depends on the content of the opencast mine plan, with modern plans typically providing more information (e.g. depths of workings, details of worked coals) than plans compiled in the 1940s and 50s. For example, a plan that shows the outline of only the worked area can be used to represent the extent of workings, but does not confirm the position of coal seams post-extraction, which may be subject to interpretation. The main limitation of opencast coal mine plans in the understanding and prediction of problematic ground conditions in coalfield areas is that they convey no details on the nature of any backfill material placed in them. This information can be available in site investigation boreholes, many of which are logged to BS5930 standard (Anon, 1999), with detailed lithological descriptions of the artificial and natural deposits encountered. These boreholes convey accurate information on the thickness and composition of artificial ground, often where none is indicated on the geological map. However, older borehole logs in particular often convey scant information on artificial ground, or ignore it altogether, depending on the purpose of the borehole. Borehole logs, whilst very useful, can quickly become outdated if a site is re-developed, with each log representing the ground conditions at the time of drilling. Furthermore, the distribution of borehole data is a function of prior development activities and is typically clustered in urban areas.

Coal seam elevation depths recorded on opencast mine plans enable accurate volume quantification and the representation of the thickness and distribution of fill material. Despite different ages of plans conveying varying levels of detail, it is possible to model the artificial ground at 25 opencast coal mines in West Yorkshire. Opencast coal mine plans are useful for accurately representing the depth and location of former workings, the position of modified geological outcrops, and in some cases the distribution, volume and thickness of fill material, which can be represented in 3D models. This method could be used to identify potential problematic ground conditions and feed into early stage site investigation, mitigation and development plans.

A number of site investigation boreholes drilled for the M1 motorway that crosses several backfilled opencast sites give detailed lithological descriptions and thicknesses of the opencast fill material. However, the spatial distribution of these boreholes makes them relevant to the area where they are located, but prevents them being applicable to the opencast coal sites as a whole.

Borehole records are a particularly useful resource in coalfield areas, where thousands of site investigation boreholes may be required at a single opencast site to assess the ground conditions and coal reserves prior to mining. Site investigation boreholes are available for many parts of the UK, and require minimum processing to extract relevant information describing the subsurface. However, they should be used in conjunction with other data when assessing the site conditions as they normally pre-date major developments and the artificial ground information recorded in them can quickly become outdated. To gain the maximum value from borehole records, it is recommended that the relevant information recorded in them is databased, taking into account the date and method of drilling, and the composition and thickness of artificial ground recorded in them. Other information, including the date of drilling, may have relevance to other information recorded, such as the level of first water strike encountered at a particular investigation borehole.

The datasets described in this paper are held by different organisations, in separate databases and paper archives, and can be difficult to locate. Opencast coal mine completion plans are held by the British Geological Survey and The Coal Authority, with copies of some plans held by both organisations, and others at one organisation only. To make the disparate datasets held by the BGS more accessible to end users, the BGS Enquiries service provides 'GeoReports' to inform developers of the expected ground conditions at site specific detail (https://shop.bgs.ac.uk/GeoReports). These structured reports are compiled by experienced geologists, who assess various datasets, including 1:10 000 scale geological maps, boreholes, memoirs and historic Ordnance Survey maps. Included with each report is a list of archive data within a set search radius around the site, which the user can obtain copies of. The mining plans portal, http://www.bgs.ac.uk/nocomico/, has been developed to host non-coal mine plans held by several public sector bodies. Other commercial organisations collate geo-environmental information held by multiple agencies.

Conclusions

There is an apparent challenge with planning policy concerning the redevelopment of brownfield sites located in disused coalfield areas. The intense and long-developed urbanisation that characterises many coalfield districts, allied with typically high population densities and localised centres of industry, results in high turnover of land for re-development. Natural hazards associated with coalfield geology include landslides and flooding. Mineral workings can also alter the natural groundwater regime, which can impact on slope stability and lead to flooding if the workings are located in a floodplain and the water table has been lowered to enable mining. Pressure on land has resulted in a desire by government to redevelop sites that are prone to difficult ground conditions that may serve as a deterrent to redevelopment and investment.

Planners and developers need access to timely, up-to-date and quality information to underpin policy and inform redevelopment initiatives. Geological information describing the subsurface can be used to identify problematic ground conditions in coalfield areas. Some information is freely available from Government and Non Government Organisations, however, some of these datasets are out of date and lack the detail needed to quantify the subsurface. In many instances, publicly available data can be used to better characterise the near-surface in coalfields and enable some problematic ground conditions to be identified prior to site development. Data can be successfully processed using 3D techniques to quantify man-made ground associated with coal mining or landfill. This makes these datasets a useful resource to planners and developers of brownfield sites in coalfield areas. However, to be of greatest potential benefit, these datasets should be consulted early in the planning process to identify potential problematic ground conditions and avoid the possibility of delays and costs associated with rectifying them. The presence of brownfield sites in an area can have the effect of delaying regional redevelopment, and a holistic approach, from investment through to ultimate redevelopment, is recommended.

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airevalleyleeds.com Web site run by Leeds City Council to provide information on Aire Valley Leeds Enterprise Zone

www.bgs.ac.uk/geoindex Searchable map-based index of BGS datasets, including boreholes, landfill site records and digital geological map data

www.bgs.ac.uk/lexicon BGS Lexicon of Named Rock Units. Database listing definitions of terms used in BGS maps and publications

http://www.bgs.ac.uk/nocomico/ BGS Mining Plans Portal web site

www.bexley.gov.uk London borough of Bexley web site building control pages

www.environment-agency.gov.uk/wiyby37823 Environment Agency web page on landfill sites

http://www.leeds.gov.uk/council/Pages/Introduction to Local-Development-Framework Leeds City Council web pages on the Local Development Framework

http://www.leeds.gov.uk/council/Pages/Aire-Valley-Leeds-Area-Action-Plan Leeds City Council web pages on the Aire Valley Leeds Area Action Plan, providing information on planning policy

www.ncm.org.uk Web site of the National Coal Mining Museum of England. Statistics in Mining fact sheet on UK coal production statistics from 1900 to 2004 available at: www.ncm.org.uk/collections/research/factsheets

https://shop.bgs.ac.uk/GeoReports/ BGS 'GeoReports' service, where clients can purchase bespoke site specific reports on the expected ground conditions and potential hazards associated with geology