THE ENGINEERING GEOLOGY OF THE NOTTINGHAM AREA, UK

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Abstract

Nottingham was built near a crossing point on the River Trent in the East Midlands of England. Initially, the City developed on a low sandstone hill close to the north bank of the river, which provided a secure, well-drained location above the marshes that bordered the river. Geologically, Nottingham stands at the boundary between Palaeozoic rocks to the north and west, and Mesozoic and Cainozoic strata to the south and east. The area is underlain by coal-bearing Carboniferous Coal Measures, Permian dolomitic limestones, Permo-Triassic mudstones and weak sandstones, Jurassic clays and Quaternary glacial and alluvial deposits. Artificial deposits, resulting from the social, industrial and mineral extraction activities of the past cover the natural deposits over much of the area.

This geological environment has underpinned the economic development of the area through the mining of coal (now largely ceased), oil extraction that was important during the Second World War, brickmaking from clays, alluvial sand and gravel extraction from the Trent Valley and gypsum extraction from the Permo-Triassic mudstones. The Permo-Triassic sandstone is a nationally important aquifer and has also been exploited at the surface and from shallow mines for sand.

However, this history of the use and exploitation of mineral deposits has created a number of environmental problems including rising groundwater levels, abandoned mine shafts and mining subsidence, and, within the City itself, the occasional collapse of artificial cavities in the sandstone and contaminated land left by industrial activities. Natural constraints on development include gypsum dissolution, landslides, rockfalls, swell-shrink problems in Jurassic clays and flooding. Occasional minor earthquakes are attributed to movements due to

coal mining or natural, deep geological structures. Thus, Nottingham's geological context remains an important consideration when planning its future regeneration and development

Introduction

Legget (1987) stated that "land is the surface expression of geology" and advised that "land-use planning can only be carried out with satisfaction if there is a proper understanding of the geology concerned." Therefore, geology must be considered at an early stage in the land-use planning process. In the case of Nottingham, its history is intimately bound up within its geological setting.

The City of Nottingham and its suburbs straddle the River Trent, the City itself being located on sandstone hills close to a suitable bridging position on this major navigable river (Figure 1). The broad relatively flat valley floor contrasts with dissected high ground to the north and south of the river. Although the earliest settlement may date back to Roman times (or before), the earliest record of Nottingham's existence dates back to the invasion of the Danes in the middle of the 9th Century and their conquering of the settlement in 867 AD. The settlement was built on a prominent sandstone hill, above the River Trent, which could be excavated to create cave dwellings. Construction of the first castle, by the Normans, began in 1068 on a second, adjacent hill. The City gained a Royal charter in 1155. In the Middle Ages, the main industry was woollen manufacture. The population rose from about 1 500 at the time of the Norman invasion to 5 000 at the end of the 17th century, and over 28 000 at the time of the first census in 1801. Industry expanded in the 19th and 20th centuries, with the main ones being textiles, cigarette manufacture, bicycles and pharmaceuticals. The population expanded rapidly in the 19th century but the City's response was poorly planned, resulting in the creation of appalling slums. The latter part of the 20th century has seen a gradual move from an economy based on heavy industry to one based on light manufacturing and services. The population now stands at about 260 000.

The bedrock of the Nottingham area includes rocks of late Carboniferous to Jurassic in age. These are overlain by extensive superficial deposits of glacial and post-glacial material such as till, alluvium, sand and gravel. Faults trend from north-west to south-east across the area displacing the outcrops of Coal Measures and Triassic rocks at the surface. The Nottingham area is well endowed with mineral deposits including coal and gypsum that have been both mined and worked at the surface. Gravel, sand, brick clays and building stone also are present

in workable amounts. Furthermore, the Sherwood Sandstone (Trias) is the second most important aquifer in England, supplying water to Nottingham and other areas that it underlies.

Adverse ground conditions represent the principal environmental restraint on planning and development in the Nottingham area. The suitability of the natural ground to a particular engineering requirement depends mainly on the geotechnical properties of the soils or rocks that are present. In addition, the ground conditions may have been affected by human activity. In particular, coal mining has a long history in the area and has left a legacy of disturbed strata, abandoned shafts and deteriorating workings. Old gypsum mines are also present, as are artificial cavities in the sandstones beneath the City formally used for storage, shelter or minor industrial activities. Other factors that may complicate the ground conditions include disused quarries and pits, which may have been used for the disposal of a variety of waste materials.

Bedrock geology

The oldest rocks of the Nottingham area are Carboniferous in age and occur to the west of the City centre (Figure 2). The oldest of these, that are found at the surface, belong to the Lower Coal Measures, are 290 to 440 m in thickness and occur in the far west of the Nottingham area. Borehole evidence indicates that below them there are more than 600 m of rocks of Namurian age, principally gritstones, and that these, in turn, are underlain by some 150 m of limestones, sandstones and mudstones of Dinantian age. These Namurian and Dinantian strata outcrop to the west of the area in the southern Pennine Hills.

The Middle Coal Measures also sub-crop to the west of the centre of Nottingham where the complete sequence ranges in thickness from 215 to 325 m. The Upper Coal Measures do not occur on the surface in the area and are only present, at depth, in the extreme south and west of the district where their maximum recorded thickness is around 170 m. Mudstone and siltstone and, to a lesser extent sandstone, comprise most of the Coal Measures. Their economic significance derives primarily from the presence of coal and, to a lesser extent, gannister, fireclay, ironstone, pottery clay and brick clay. Coal Measures sandstone has been used for buildings purposes. Regional uplift of the Pennine area by the Variscan Orogeny in the late Carboniferous resulted in a long period of denudation that extended into early Permian times and resulted in the removal of massive amounts of Carboniferous strata.

The Permian strata form an area of gently undulating upland with a west facing escarpment (Figure 3). The rocks rest unconformably on the Coal Measures and dip gently to the east. The earliest Permian deposits consist of breccias deposited under continental conditions. These deposits are diachronous and range in age across the area from early to late Permian and in thickness from 0 to 8 m. The Basal Breccia is succeeded by the Cadeby Formation, which consists of a lower mudstone facies followed by an overlying carbonate facies. The mudstone facies is a few metres thick and thins out to the south but thickens eastward. Most of the rocks of the carbonate facies are dolomites that were originally deposited as limestones. They thicken to the north and reach a maximum of 65 m. The uppermost formation in the Permian is the Edlington Formation. This consists of silty mudstone with thin beds of dolomitic sandstone. It is no more than 9 m thick where it outcrops and dies out to the south. However, in the north-east nearly 30 m of these deposits have been found in boreholes.

The strata of Triassic age in the Nottingham area fall into two groups, namely, the Sherwood Sandstone Group and the overlying Mercia Mudstone Group (Figure 2). The Sherwood Sandstone Group is subdivided into the Lenton Sandstone Formation below and the Nottingham Castle Sandstone Formation above (Bell & Culshaw 1993). The Lenton Sandstone Formation is a poorly-cemented, fine to medium-grained friable sandstone with lenses of mudstone and siltstone, and occasional gravelly horizons. The sandstones are commonly reddish in colour with yellow mottling and range up to 30 m in thickness. The Nottingham Castle Sandstone forms a notable outcrop northwards from the City and consists of buff to pale red-brown sandstone. Subordinate horizons of siltstone, mudstone and conglomerate occur within this sandstone and it tends to vary both vertically and laterally over short distances. The Nottingham Castle Sandstone thickens to the north from some 65 m in the south to around 150 m in the north. The sandstones of both formations consist predominantly of quartz particles, the quartz content commonly comprising over 90% of the rock.

The Mercia Mudstone Group may be regarded as a fining upward sequence of strata of mostly hypersaline lacustrine sediments in which occurs coarser material and gypsum (Firman & Lovell 1988). The Sneinton Formation occurs at the base of the Mercia Mudstone Group. According to Bell & Culshaw (1998), the basal 6 to 9 m of the Sneinton Formation consists of pale grey mudstones that are, in part, finely micaceous with some silty and sandy beds. Overlying these basal beds are over 60 m of interbedded sandstones, siltstones and mudstones

that pass up into the Radcliffe Formation without marked change in lithology. Medium to thick beds of sandstone, which are generally reddish-brown in colour, are present at some localities. The principal constituent in these sandstones is quartz, averaging almost 75%. Feldspar is a secondary constituent and clay size material, which forms the matrix of the sandstones, constitutes between 4 and 18%. Commonly, the Sneinton Formation gives rise to undulating, incised topography in which the more resistant beds of sandstone locally give rise to more marked features. However, most of the formation is overlain by alluvial deposits of the River Trent and its tributaries. The succeeding Radcliffe Formation consists of reddish-brown and grey-green, laminated mudstones and siltstones with subordinate fine-grained sandstone. Then follows the Gunthorpe Formation, a sequence of interlayered mudstone, siltstone and fine-grained sandstone. Again the rocks tend to be reddish-brown or grey-green in colour. Numerous dolomitic siltstone and fine-grained sandstone beds frequently form upstanding topographic features (Charsley *et al*. 1990). Some intricate patterns of gypsum veins are found, notably in the upper part of the sequence. The formation varies in thickness from about 50 to 80 m. The Cotgrave Sandstone forms the base of the following Edwalton Formation and is some 1.5 to 4 m thick. Most of the rest of the formation comprises reddish-brown and grey-green, silty mudstone or siltstone except for the uppermost 7 m of alternating sandstones and mudstones that are referred to as the Holygate Sandstone. The whole of the Edwalton Formation ranges from about 35 to 54 m in thickness. The latter formation is succeeded by the Cropwell Bishop Formation, another sequence of reddish brown mudstones and siltstones with fine-grained sandstones. Thick units of stratiform gypsum (the Tutbury and the Newark Gypsum beds) occur locally in this formation but, generally, the formation is poorly exposed. It varies in thickness between about 35 and 55 m. Lastly, the Blue Anchor Formation represents the uppermost strata in the Mercia Mudstone Group. This consists of approximately 6 to 8 m of greenish, dolomitic mudstone and siltstone. It occurs in the south of the area but is poorly exposed except in pits or quarries (Figure 4).

The Penarth Group represents a transition stage between the Triassic and Jurassic systems. It consists of two formations, namely, the lower Westbury Formation and the upper Lilstock Formation. The former consists of grey to black mudstone with thin lenses of sandstone towards the top. It is some 5 to 7 m thick and outcrops in the south of the area where it often forms an escarpment (Figure 3). A thin bed, referred to as the Rhaetic Bone Bed, occurs sporadically at the base of the formation and contains fossil remains of fish and reptiles. The Cotham Member is the only representative of the Lilstock Formation in the Nottingham

district and is around 3 to 5 m thick, and similarly outcrops in the south of the area. It consists of grey silty mudstone with discontinuous bands of limestone nodules and is capped by a thin bed of limestone.

The strata of the Lias Group of the Jurassic system occur in the south of the Nottingham district to the east and south of the Penarth Group (Figure 2). Only the lowest unit of the Lias Group, the Scunthorpe Mudstone Formation, is represented in the area. The Barnstone Member occurs at the base of this formation and comprises alternating beds of calcareous mudstone and limestone. It is about 6 m thick in this area and is succeeded by mudstone of the Barnby Member.

The bedrock geology is described in more detail by Howard *et al.* (in press).

Structural geology

The Carboniferous rocks of the region were subjected to uplift during the Variscan Orogeny and underwent a period of erosion prior to the deposition of Permian strata. Appreciable faulting also took place as a result of the Variscan Orogeny and the major faults may reflect deeper basement structures. Periodic tectonic activity occurred during the Mesozoic era, which led to new faults being formed and some older faults being reactivated. The regional dip of the Carboniferous strata in the Nottingham area is generally towards the north-east at low angles (Charsley *et al.* 1990). The post-Carboniferous strata have not been affected by the Variscan Orogeny but by the younger Alpine Orogeny. The regional dip of these rocks is broadly towards the south east, at low angles, rarely greater than 2° (Figure 3). Angles of dip may increase locally due to fold structures or to drag adjacent to faults (Figure 4). A broad regional syncline, with gently dipping limbs and a shallow plunge to the east-south-east, occurs to the immediate south of Nottingham, which is complemented by anticlines to the north and south (Edwards 1951). The predominant trend of the faults varies between west to east and north-west to south-east. Another set of faults of lesser importance trend in a north-west to south-east or north to south direction.

Superficial deposits

The distribution of superficial deposits in the Nottingham district is shown in Figure 5. These deposits consist of till, gravel and sand, silt, clay and organic material, which were formed under glacial, fluvio-glacial, periglacial, lacustrine and fluviatile conditions. The glacial tills

are found chiefly in the south-east of the area where they occupy the higher ground, or as isolated patches in valleys. The thickest deposits occur on the Wolds, to the east of Nottingham, where as much as 35 m have been recorded. Generally, the till consists of silty or sandy clays with pebbles and cobbles. Where sand is the main component, the material is referred to as sandy till.

Deposits of glacial sand and gravel, with or without flint gravel, are found in the extreme south of the Nottingham area, where they may be up to 4 m thick. Further north small patches of flint-free sand and gravel are present on higher ground.

Fluvial and possibly fluvio-glacial deposits of sand and gravel were formed during later Pleistocene times. Firman & Lovell (1988) referred to a series of terraces being present in the Nottingham area and Charsley *et al.* (1990) indicated that the Bassingfield, Beeston and Holme Pierrepont Sands and Gravels are terrace deposits of the River Trent (Figure 5). The first consists of sand and sandy gravel that is clayey in places and contains discontinuous beds of clay; the second may be up to 4 m in thickness at Beeston and the third is composed of sand and gravel with impersistent beds of silt or silty clay. They have been eroded periodically and redeposited by the present day, much smaller, River Trent.

Head is a deposit that has moved downslope and accumulated on lower slopes and in valley bottoms. Head is an unstratified or poorly stratified accumulation of particles and fragments of local origin that may mantle higher ground, or occur on slopes and in the bottoms of valleys. It is usually formed under periglacial conditions by solifluction, that is, the bodily creep of soil downhill. A veneer of Head is present in many areas and may be up to 4 m thick in places. It varies in character from relatively pure sand or clay to a chaotic mixture of clay, silt, sand and gravel.

Lacustrine deposits, locally up to 4 m in thickness, occur south of the River Trent near Edwalton and Ruddington, and on Ruddington Moor (south west of Ruddington) (Figure 5). The lowermost beds show signs of cryoturbation and contain reworked debris from underlying units. Higher beds consist of silt or clay, which may be laminated or massive. Fossils are present in this material and, locally, the shell debris may be sufficiently concentrated to be mapped as 'Shell Marl'. Organic clay and peat occur in the upper layers of these lacustrine deposits.

Alluvial deposits occupy the floor of the River Trent and many of its tributaries. The alluvium consists of silts and clays overlying sands and gravels. Thicker deposits of sand and gravel occur within the Trent Valley and probably represent infills that have been redeposited during times of flood. Lenses of peat, that accumulated in cut-offs, occur within the alluvium and can be an unexpected cause of poor ground conditions.

The superficial deposits are described in more detail by Howard *et al.* (2008).

Artificial deposits

Human influence on the heavily urbanized Nottingham area has been substantial (Charsley *et al*. 1990). This is illustrated in Figure 6, which shows significant areas of made, infilled and disturbed ground in the area. Made ground consists of material that has been deposited on top of the original land surface. Therefore, it includes areas of construction such as embankments for roads, railways and canals. Made ground in some areas may be thicker than the alluvial deposits beneath. For example, in the Dunkirk–Lenton Lane industrial area made ground is over 10 m in thickness in some areas. Many areas of made ground have been reclaimed and landscaped or built over. Infilled ground occurs where excavations or depressions have been infilled artificially.

Landscaped ground refers to those areas where the original land surface has been extensively remodelled. It consists mainly of topsoil, subsoil that has been reworked within a location such as a housing estate or golf course. However, additional material such as soil, colliery spoil or building waste may have been brought to a site from elsewhere. Landscaping is ubiquitous within most urban areas. Built-over ground comprises those parts of the area, given over primarily to urban development, where appreciable modification and disturbance of the land surface has taken place at the construction stage. Usually, it excludes extensive areas of landscaped ground but both may exist together in places.

Geological resources

The Nottingham area is well endowed with mineral resources, especially coal and groundwater. Other resources include sand, gravel, brick clay, dimension stone, gypsum, and small deposits of oil, discovered in the 20th century and possibly with the potential for some renewed production in the 21st.

Coal

Coal has been mined in the Nottingham area for hundreds of years. Moller (1925) reported evidence of commercial scale coal mining in 1610. The first workings were from outcrops and then from bell pits, the scars of which may still be seen in Strelley (Ager *et al.* 2004). The pillar and stall method of working was developed around the sixteenth century and longwall mining began to evolve in tandem with the Industrial Revolution (Bell 1988). The extent of colliery-based underground coal mining is shown in Figure 7. However, as a result of the contraction that has taken place in the deep coal mining industry since the late 1980s, coal mines are no longer operational in the area. Nonetheless, the coal resources beneath the area remain substantial (Charsley *et al.* 1990). Opencast mining developed in the Nottingham district from the 1940s onward. These surface workings may extend to a depth of 100 m and, thus, the potential for opencast mining extends beyond the exposed coalfield into that part of the concealed coalfield where Coal Measures occur at shallow depth beneath Permian strata. However, urban development and local community opposition means that the potential for opencast development is constrained.

Sand and gravel

Gravel and sand deposits, which were laid down by the present and former River Trent are extracted for use in the construction industry. Worked deposits include gravel from beneath the present flood plain and from the river terraces alongside it, that is, the Holme Pierrepont, Bassingfield and Beeston Terraces. The silt and clay overburden is usually less than 1 m thick. Generally, the gravels and sands are thickest in the centre of the floodplain, the thickness varying from zero to over 4.5 m. Many of the gravel and sand resources have been sterilized by urban development. Both the Lenton Sandstone and Nottingham Castle Sandstone have been worked for sand, both being weakly cemented and relatively easy to work. Sand obtained from both these formations possesses finer and more rounded grains than that obtained from the Trent Valley deposits making them more suitable for use as mortar or in asphalt than sand from the latter.

Brick clay

The principal sources of brick clay in the Nottingham area are from the Edlington Formation and the Mercia Mudstone Group. Mudrocks from the Edlington Formation were extracted for brick making in the north west of the area but no brickworks are currently active. The

mudrocks of the Mercia Mudstone Group's Gunthorpe Formation were extracted for brick making at Dorket Head and, elsewhere, have been worked to the east and south of the City. Mainly the lower and upper parts of the formation were worked. Mudrocks from the Middle Coal Measures were worked formerly and, because of their mineralogical composition, the shales and mudstones from the Coal Measures often produced a high quality brick, frequently of engineering grade.

Gypsum

Gypsum has been extracted for many years to make plaster related products for use in the building and construction industry and, in the distant past, locally extracted alabaster was used in local churches for plaques commemorating benefactors, altars, tombs and statues. The works of Nottingham's kervers (alabaster carvers) were to be found throughout England and were particularly popular in France.

Gypsum was extracted by both surface pits and underground by pillar and stall methods. According to Firman (1964), gypsum was worked around East Bridgford from the seventeenth or eighteenth century until the 1940s from mines and shallow pits. The gypsum occurs primarily as crosscutting veins but also may run parallel to the bedding. Gypsum occurs in the lower part of the Edwalton Formation and the underlying Gunthorpe Formation but the principal formation from which gypsum has been worked is the Cropwell Bishop Formation (Figure 4), the main gypsum horizons being the Tutbury Gypsum and the Newark Gypsum. Firman described the Tutbury Gypsum as consisting of a composite unit of gypsum with subordinate mudstone, which averages 2.4 m in thickness but can be as much as 6 m thick. Gypsum occurs as coarsely crystalline beds, nodules or lenticular masses. The Tutbury Gypsum was extensively mined around Gotham Hill and is still mined using pillar and stall methods near East Leake. The Newark Gypsum is made up of multiple beds that vary in form. Sherlock & Hollingworth (1938) maintained that the Newark Gypsum was approximately 15 to 25 m in thickness and may consist of up to 16 beds of gypsum separated by mudstone in which reticulate veins of gypsum may be present. The mudstone layers may be up to a metre thick. The dimensions of the layers of gypsum vary. They may be lens-shaped or nodular. The nodules have been referred to as 'cakes' and tend to consist of massive gypsum often fringed by fibrous gypsum. These nodules are either flat or convex on top. Layers of gypsum occasionally expand and unite into large masses, and have been given individual names such as the Top White Rock, Riders, Middle White Rock and Blue Rock. The thicker Top White

Rock is white in colour with a saccharoidal texture and is one of the purer forms of gypsum, with only about 4% of impurities (Bell 1994). The gypsum of the Riders usually has a slightly bluish or pink shade indicative of the presence of mudstone. This material usually consists of less than 90% gypsum and at times may contain up to 25% of impurities. The gypsum in the Middle White Rock is white in colour and is medium to coarsely crystalline. It contains very fine veins of gypsiferous mudstone and a few mudstone inclusions that tend to stain the surrounding gypsum. It contains between 5 and 10% of impurities. The Newark Gypsum, according to Firman (1964), has been obtained by quarrying and underground mining around Cropwell Bishop since the nineteenth century

Building stone

Building stone has been quarried in the Nottingham area since medieval times when sandstone from the Sneinton Formation was used by the Normans in the construction of the first Nottingham Castle. However, the principal dimension stone in the area is obtained from the dolomite of the Cadeby Formation currently referred to locally as 'Bulwell Stone', which probably also has been worked since medieval times. The dolomite outcrops over a large area in the north-west of the area where its thickness ranges from 6 to 12 m. The dolomite has a granular texture resembling that of a sandstone but in places it has undergone recrystallization to produce a fine grained, well cemented dolomite. When first extracted, the rock is easy to work but with time it dries out and the outer crust becomes hardened.

Groundwater

A copious, high quality water supply is obtained from the Sherwood Sandstone Group which outcrops beneath much of the City of Nottingham and underlies more than two thirds of the Nottingham area from surface outcrop to depths of less than 280 m. This is the second most important aquifer in England next to the Chalk and yields water of such good quality that it only needs basic chlorination for use as a public supply. However, high nitrate levels have been encountered, especially in some rural areas where the Sherwood Sandstone is exposed and the use of nitrogen-based fertilizers has been high. The whole area of the outcrop has been designated a nitrate vulnerable area (Allen *et al.* 1997). The Sherwood Sandstone in the Nottingham area has been extensively developed for public and industrial water supply but groundwater abstraction was uncontrolled before 1963 and the groundwater level was significantly depressed. Those streams that were dependent on baseflow discharge from the aquifer were also adversely affected. Groundwater management policies introduced after

1963, together with the decline in demand from industries, such as brewing, that depend on water, have meant that groundwater levels have risen significantly giving problems in areas like Basford.

Groundwater yield from the carbonate facies of the Cadeby Formation is erratic except where there are well-developed systems of fissures. Usually, the yields of wells are only sufficient to supply the needs of small farms and groundwater is not abstracted for public supply from this limestone. The hardness of groundwater in the limestone is very high, in the range 400 to 600 mg l^{-1}. Other formations in the area yield limited supplies of variable quality that are unsuitable for use as a public supply.

Oil

The importance of the location of UK oil resources had been recognised during the 1914-18 war and a search was made focusing on the folds flanking the Pennines, a range of hills and mountains running down the centre of northern England. Some exploitable reserves were found at Hardstoft, in Derbyshire, to the west of Nottingham, but not of sufficient importance to continue production after the war ended. However, the D'Arcy Oil Company continued exploration in the interwar years with some slight success elsewhere in the UK but their most significant find was at Eakring in Nottinghamshire, to the north east of Nottingham. Their first well in 1939 (Eakring No 1) found oil in the sands of basal Coal Measures and in three other sand levels. The first deep well through the Carboniferous Limestone was Well 146 at Dukes Wood where commercially important quantities of oil were found in very dark, fine grained, phyllitic sandstones, dark grey quartzite and hard, black shale at a depth of between 2274.7 and 2276.2 m below the ground surface (www.dukeswoodoilmuseum.co.uk). This well and others at Caunton and Kelham Hills, in Nottinghamshire, were the start of the UK's first commercial onshore oilfield. During the start of the 1939-45 war this field was rapidly developed at a time when oil was a vital war resource. However, in 1942 it was recognised that the speed of development was limited by the drilling equipment that had been designed for exploration not production. Therefore, arrangements were made to bring in modern, American oil field production rigs and technology manned by 44 Oklahoma roughnecks. Thus, a dramatic increase in productivity was achieved and a useful addition of 1.4 million barrels of high quality oil to the UK's wartime oil supply was made by the Dukes Wood oilfield alone. Production continued until 1971 by which time it had produced a total of 4.7 million barrels of oil. The site is now a nature reserve, which includes a trail that visits relics

of its oil field past including a statue erected in 1991 commemorating and naming the 44 'Oil Patch Warriors' from Oklahoma (Figures 8 and 9).

Ground conditions: bedrock

The bedrock strata usually provide satisfactory foundation conditions but still have the potential for geological hazards that may require avoidance, prevention or mitigation (Table 1). A report (Forster 1989) on the engineering behaviour of the geological materials of the Nottingham area, which included a summary of their geotechnical properties, was part of an applied geological study by the British Geological Survey for the (then) Department of the Environment (Charsley *et al.* 1990). Much of the geotechnical data quoted below are derived from that report.

The Lower and Upper Coal Measures are not exposed in the Nottingham area. The Middle Coal Measures comprise mainly mudrocks with subordinate sandstones. The clays of the Middle Coal Measures normally are stiff to very stiff and range from intermediate to high plasticity. They tend to be of medium compressibility with undrained shear strengths varying from 50 to 300 kPa. Standard Penetration Test (SPT) 'N' values suggest allowable bearing capacities ranging from 100 to 600 kPa. In some instances the pyrite content may be high enough to warrant precautions against sulphate attack on buried concrete and can result in acidic mine drainage from old workings. The sandstones, mudstones and coals have median values of unconfined compressive strength of 23 MPa, 8 MPa and 4 MPa respectively.

The mudstone facies of the Cadeby Formation consists of clays that tend to be firm to very stiff and more sandy components that are medium dense to dense. The moisture content of these materials tends to decrease with depth that is reflected in a rise in undrained cohesion values. Values of plasticity vary from intermediate to high and allowable bearing capacities tend to be in the range 200 to 400 kPa. Normally, these materials are not likely to cause sulphate attack on buried concrete. The carbonate facies of this formation consists of granular dolomitic limestone with silty micaceous bands. However, according to Forster (1992), this facies shows a wide range of lithological variation, with further variation being attributable to the effects of weathering. On weathering, the dolomitic limestone tends to produce a sandy or sandy, silty, clayey material. The moisture content tends to increase with depth from about 17% within 3 m of the surface to 5% or less at depths of over 6 m, which reflects the degree of weathering. The weathered fine-grained material has low plasticity whilst the dolomitic

limestone has an unconfined compressive strength usually ranging between 22 and 42 MPa. The results of Standard Penetration Tests and those of undrained triaxial tests suggest that the cohesive weathered material has an allowable bearing capacity that may vary between 150 and 400 kPa. The dolomitic limestone is well jointed and the joints may be enlarged by weathering. Cambering on valley sides has tended to dilate joints to form gulls, which may remain open or be filled with superficial material. Karstic dissolution features occur within the dolomitic limestone that can act as rapid pathways for pollutants to reach groundwater.

The mudrocks of the Edlington Formation also show a decrease in moisture content with depth, with values between 12 and 46% within the upper 3 m whilst below that depth they range from 12 to 22%, again reflecting a decrease in the degree of weathering with depth. This may suggest that the lower limit of significant weathering occurs around 3 m below the ground surface. Samples of mudrock exhibit a wide spread of plasticity values but most fall within the medium to high category. Undrained triaxial test results suggest allowable bearing capacity values between 100 and 300 kPa. Generally, the clayey material is firm to stiff and has a medium degree of compressibility.

The Lenton Sandstone Formation consists of sandstones that generally are poorly cemented and contain lenses of mudstone and siltstone with occasional gravelly horizons. The sandstones consist dominantly of quartz particles and are fine to medium grained with a mean grain size of around 0.19 mm (Bell & Culshaw 1993). These sandstones generally are uniformly sorted and tend to have a low dry density, averaging around 1.83 Mg m^{-3} (Anon. 1979). They have a correspondingly high effective porosity with a mean value of 24%. The sandstones of the Lenton Formation exhibit a higher permeability in the horizontal than the vertical direction but in both cases their primary (intergranular) permeability is only slightly permeable to very slightly permeable. Groundwater yield is mainly by fissure flow. In terms of strength, these sandstones fall just within the moderately strong category (Anon. 1970), their mean unconfined compressive strength being around 15 MPa. On saturation, the strength values decrease by about 35%.

The sandstones of the Nottingham Castle Sandstone Formation also consist predominantly of uniformly sorted quartz grains. However, these sandstones generally are medium-grained, with a mean grain size of 0.27 mm. These poorly-cemented sandstones contain occasional pebble layers and small lenses of siltstone and mudstone. Again, most of the sandstones of

this formation have a low dry density but some may be very low (mean value around 1.83 Mg m^{-3}). This is reflected in their high values of effective porosity, which may range from 22 to 29% (Bell & Culshaw 1993). The mean coefficient of permeability of the sandstones of the Nottingham Castle Sandstone Formation is higher than that of the Lenton Sandstone Formation, being 2.53 x 10^{-7} m s^{-1} compared with 1.28 x 10^{-7} m s^{-1}. These values are for vertical primary permeability, which is about two thirds that of horizontal permeability. In fact, the majority of the sandstones of the Nottingham Castle Sandstone Formation are just slightly permeable. Most of these sandstones according to their unconfined compressive strength could be described as either moderately weak or moderately strong, with values ranging from less than 6 to 22 MPa. The unconfined compressive strength tends to decline with increasing particle size and porosity. Furthermore, the strength of these sandstones is reduced to a greater extent on saturation than those of the Lenton Sandstone Formation, this time by around 40% on average but this may be as high as 60% or as low as 23%. The largest reductions of strength on saturation tend to be in the weaker sandstones with higher porosities. The Nottingham Castle Sandstone Formation is deeply weathered, Standard Penetration Test results indicating that loose sand may be present to a depth of up to 4 m, with medium dense sand as deep as 8 m and dense sand extending to 10 m but the weak nature of the sandstone may make it difficult to determine the depth to rockhead by percussion drilling with SPT 'N' value measurements (Forster 1992).

The Sneinton Formation occurs at the base of the Mercia Mudstone Group and consists of mudstones overlain by interbedded sandstone siltstones and mudstones. These rocks tend to weather to give firm silty clays and dense sands respectively. The silty clays have a low plasticity and the results of Standard Penetration Tests suggest that allowable bearing capacity ranges between 200 and 400 kPa. Consolidation data indicate that these clays are of medium compressibility. Thick sandstones are present at some localities. These usually are either medium or fine-grained with a mean grain size of 0.198 mm and are poorly sorted. The dry density of these sandstones has a relatively small range, it being from 2.22 to 2.31 Mg m^{-3}, which is reflected in the small range of porosity, namely, 8.9 to 14.1%. The sandstones are moderately strong (Anon. 1970) with a range of unconfined compressive strength from 17.4 to 39.8 MPa (Bell & Culshaw 1998). The loss of strength on saturation varies from about 19 to 45%. However, those sandstones with the highest saturation moisture contents do not necessarily undergo the greatest loss in strength. Dobereiner & de Freitas (1986) suggested that the strength of sandstones should be defined in terms of their saturated unconfined

compressive strength and that weak sandstones, in particular, should be regarded as those with a saturated unconfined compressive strength in the range 0.5 to 20.0 MPa. The saturated unconfined compressive strength of the sandstones from the Sneinton Formation lie within the range 14.1 to 25.6 MPa. Consequently, most of these sandstones would be classified as weak according to the Dobereiner and de Freitas criterion.

The mudstones of the Radcliffe, Gunthorpe, Edwalton and Cropwell Bishop Formations of the Mercia Mudstone Group consist of stiff to hard silty clayey material. Particle size analyses carried out on fresh or less weathered mudstones from the Mercia Mudstone Group tend to have a large proportion of silt sized particles whereas the clay fraction tends to predominate in the more weathered material. Such an increase in the clay fraction of the weathered material suggests that some silt-sized particles in the unweathered/slightly weathered mudrocks may be aggregates of clay sized particles (Davis 1968). The silt particles presumably are held together by cement that breaks down on weathering. Chandler (1969) recognized five zones of weathering from unweathered to fully weathered material. Weathering begins along the fissures in the mudrock. Such a generalized weathering profile may be modified considerably and lateral variations are not uncommon. The unweathered or slightly weathered mudrock generally has a low to intermediate plasticity. The plasticity index increases with the degree of weathering and when fully weathered the material can have a high plasticity. Similarly, the natural moisture content increases with the degree of weathering whereas the bulk density decreases. Values of undrained cohesion range up to 860 kPa, with weak zones of low strength occurring at depths down to 15 m. The compressibility of the mudrocks tends to increase with increasing degree of weathering, from 0.1 to 1.5 m^2 MN. Usually, the sulphate content of these mudrocks is less than 0.2% so that in most cases ordinary concrete mixes can be used for buried structures. Because of the presence of veins of gypsum in these mudrocks it might be expected that this would provide sulphate on breakdown that would adversely affect the cement fraction of concrete. However, the gypsum frequently is leached from the mudrock in the near-surface zone. A much fuller account of the engineering geology of the mudstones of the Mercia Mudstone Group has been provided by Hobbs *et al.* (2002) and of engineering in these mudstones by Chandler & Forster (2000).

Gypsum occurs at several horizons within the Mercia Mudstone Group but it is found primarily in the Cropwell Bishop Formation. The Tutbury Gypsum and Newark Gypsum occur in this Formation. Bell (1994) found that the dry density of gypsum in the Nottingham

area showed little variation, ranging from 2.21 to 2.26 Mg m^{-3} and that the effective porosity varied from 1.5 to 6.6%. He found that the unconfined compressive strength tended to vary with the amount of impurity present in the gypsum, that is, that gypsum with the lower impurity content possessed lower values of strength. This was in accord with the suggestion made by Skinner (1959) that impurities in calcium sulphate rocks tend to reduce the crystal size and that the strength increases with decreasing crystal size. For example, the ranges of unconfined compressive strength for the three categories of gypsum related to impurity content mentioned above, least impurity first, were 12.2 to 28.0 MPa, 14.9 to 24.3 MPa and 14.0 to 34.9 MPa respectively. The respective average values of strength were 18.2 MPa, 21.6 MPa and 24.1 MPa. These values of strength indicate that the gypsum can be regarded as moderately strong rock (Anon. 1970).

The mudstones of the Scunthorpe Mudstone Formation are fissured and very stiff but are often soliflucted and cryoturbated in the upper few metres, particularly on sloping ground. The median moisture content decreases with depth from about 25% at the surface to around 16% at a depth of 4 m. The median bulk density also increases with depth from approximately 1.97 Mg m^{-3} at the surface to 2.11 Mg m^{-3} below 4 m. The plasticity of the material increases with the degree of weathering, tending to vary between intermediate and high plasticity. Strength also tends to vary with depth as the influence of weathering declines, the undrained cohesion increasing from 40 kPa to 180 kPa in the depth range 0 to 5 m. The weathered material may be subject to swelling and shrinkage with changes in moisture content. Sulphate attack on buried structures is unlikely.

Ground conditions: superficial deposits

Till is not widespread in the Nottingham area but is usually a sandy clay, of variable pebble content, with a low to intermediate plasticity. The moisture content and bulk density vary within the area, the former ranging from 15 to 30%, whilst the latter ranges from 1.8 to 2.3 Mg m^{-3}. The tills possess a low to medium compressibility with a coefficient of consolidation that varies from 0.1 to 10 m^2 yr^{-1}. Values of cohesion tend to vary between 100 and 350 kPa and allowable bearing capacity between 200 and 600 kPa. Generally speaking, the tills do not give rise to problems of sulphate attack on concrete below the ground surface.

Extensive deposits of gravel and sand occur in the valley of the River Trent. The lowest, the Holme Pierrepont Sand and Gravel, is found beneath a capping of alluvial silty clay. They

normally comprise clean uniform gravels with some lenses of sand but silt and clay are only rarely present. The sand content varies from 30 to 50%. The results of Standard Penetration Tests suggest that three zones of relative density are present. The material at the surface may be relatively loosely packed with SPT 'N' values of around 10. A medium dense unit occurs beneath the loosely packed unit and has an average SPT 'N' value of 25. This overlies a very dense unit in which the SPT 'N' values exceed 50. These gravels afford good foundation conditions with allowable bearing capacities ranging up to 600 kPa. They are free draining, having medium to high permeability (6.2×10^{-4} to 6.2×10^{-2} m s^{-1}). In most instances, sulphate attack on buried concrete structures is not likely to occur.

The higher river terrace deposits consist of gravel, sand and sandy gravelly clay. Standard Penetration Test 'N' values indicate that these deposits vary from medium dense to dense and occasionally may be very dense. The allowable bearing capacities of the gravel/sand material range from 100 to 400 kPa (Forster 1992). These deposits are unlikely to give rise to sulphate attack on buried concrete structures.

Head in the Nottingham area usually is thin and of variable composition depending on the nature of the parent material ranging from a cohesive soft to stiff material to a non-cohesive loose to dense material. Head may be crudely stratified but normally is massive in appearance. However, this could be deceptive in that relict sub-horizontal shear planes may be present and these may be reactivated if disturbed. If Head is composed of cohesive material, then this generally is of low to intermediate plasticity but may be of high to very high plasticity where the parent material had such a plasticity (for example, the Scunthorpe Mudstone). The cohesive material tends to have a low strength and in many instances may be close to the residual strength of the parent material. Consolidation data indicate that the cohesive material is of medium to high compressibility.

The largest area of alluvium occurs in the valley of the River Trent where it generally lies on top of extensive deposits of river gravel. It is composed primarily of normally consolidated clay, silty clay and sandy clay. Occasionally, organic rich layers and channels are present. The moisture content of these alluvial soils tends to fall between 10 and 50% but in the organic more peaty soils it can be as high as 420%. The clays range from low to high plasticity depending on the proportion of clay, silt or sand they contain. Normally, the consistency varies from soft to firm but on occasions very soft or stiff clays may be present in the

alluvium. The clays, silts and organic deposits range in compressibility from medium to very high, possessing coefficients of consolidation between 0.1 and 100 $m^2 yr^{-1}$. Values of undrained cohesion range up to 200 kPa but mostly they are below 100 kPa. Sulphate attack on buried concrete is not a common problem.

Deposits of peat are present in the alluvium of the Trent valley and in post-glacial lacustrine deposits. In the alluvium they tend to occur as relatively isolated pockets and channel infills. The thickness of the peat varies but in one abandoned channel of the River Trent at Beeston up to 3.5 m of peat has been recorded (Charsley *et al.* 1990). Low strength, very high compressibility and acidic character coupled with a potential to generate methane are properties associated with peat. This can mean foundation failure and substantial settlement of buildings placed on peat if precautions are not taken. Furthermore, because the peat occurs in pockets or channel infillings, the possibility exists of a building being founded partly on peat and partly on much less compressible material, which will give rise to differential settlement. Depending on its thickness and depth of occurrence, peat may be removed and replaced with fill. Alternatively, raft or piled foundation structures may be used. Gas proof membranes, with passive venting, may be needed to mitigate ground gas risks.

Ground conditions: artificial deposits

A wide variety of material has been used as fill or for made ground including many types of waste (Bell & Culshaw 2003). Thus the engineering behaviour of such areas depends upon the material's composition, the method by which it was placed and any subsequent geotechnical treatment. Non-engineered fills can be regarded as those that are placed without any control whereas engineered fills have been compacted to some extent or to achieve a specified engineering performance, and consequently provide sufficient support for the engineering requirement. Waste fills may include inorganic mine waste, coarse colliery discard subject to spontaneous combustion, municipal and industrial wastes or combinations of some or all of them. Certain industrial wastes, in particular, may be contaminated. In the Nottingham area archival data frequently proves inadequate to define the total distribution and limits of former waste disposal sites. In addition, the character of the material at such sites often has not been recorded or has been recorded unreliably. The relevant local authority inspection strategy produced as a requirement of Part 2A of the Environmental Protection Act (Department of the Environment 1990) provides an overview of both the industrial history and likely made ground deposits in the area.

There are a large number of types of industrial wastes, which include chemical wastes, off specification products, decommissioned plant, boiler and bottom ash. Industrial wastes commonly are associated with derelict sites. Unfortunately, many industrial wastes are contaminated to a greater or lesser extent and have the potential to cause harm to human health or the environment, including surface and ground water. Pulverized Fuel Ash (PFA) is waste that is produced by coal-fired power stations, which were once common along the banks of the Trent. The particles of PFA are primarily of silt size and are more or less spherical in shape. Their specific gravity ranges from around 1.90 to 2.72, depending on their source and they are non-plastic. Ashes may exhibit cohesive properties. Most PFA is used for land reclamation projects or for general and structural fills (for example, embankments, foundation fills, fills behind retaining walls). In the Nottingham area, the most extensive spread of made ground in which there is industrial waste occurs between Beeston and the City Centre. This includes the Dunkirk-Lenton Lane industrial area where some of the thickest deposits of made ground occur, in places being over 10 m thick. The made ground south of Wilford Lane and at the former Wilford Power Station includes some PFA. At the former site up to 6.5 m of PFA occurs locally. Pulverised Fuel Ash can contain total heavy metal concentrations in excess of generic screening values; however, the bioavailability of these to humans or ecological receptors is low.

In developed countries the nature and composition of waste has evolved over the decades, reflecting industrial and domestic practices. For example, in Britain domestic waste has changed significantly since the 1950s, from largely ashes and little putrescible content of relatively high density to low density, highly putrescible waste as domestic heating switched from burning coal (and domestic waste) to burning natural gas or oil. Hence, waste disposal or sanitary landfills now usually are very mixed in composition and suffer from continuing organic decomposition and physico-chemical breakdown. They can consist of a heterogenous collection of almost anything including waste food, garden rubbish, paper, plastic, glass, rubber, cloth, ashes, building waste, tins and minor metallic items. Matter exists in the gaseous, liquid and solid states in landfills, and all landfills comprise a delicate and shifting balance between the three states. Any assessment of the state of a landfill and its environment must take into consideration the substances present in a landfill, and their mobility now and in the future. Much of the material of which a modern landfill is composed is capable of reacting with water to give a liquid rich in organic matter, mineral salts and bacteria, namely,

leachate. Methane and hydrogen sulphide often are produced in the process and accumulations of these gases in pockets in fills followed by their lateral migration have led to explosions in dwellings (Williams & Aitkenhead 1991). The leaching of soluble compounds from fill is another problem. Some materials such as ashes and industrial wastes may contain sulphate and other products that are potentially injurious as far as concrete is concerned. Waste materials disposed of in sanitary landfills have dry densities varying from 160 to 350 kg m^{-3} when tipped, but after compaction the density may exceed 600 kg m^{-3}. Moisture contents range from 10 to 50%, with average specific gravities of the solids varying from 1.7 to 2.5 and low bearing capacities between 19.2 to 33.5 kPa. Settlements associated with landfills are likely to be large and irregular. The initial mechanical settlement of waste disposal fills is rapid and is due to a reduction in the initial void ratio. It takes place with no build up of pore water pressure. Settlement continues due to a combination of secondary compression (i.e. material disturbance) and physico-chemical and biochemical action. However, determination of the amount and rate of settlement of a landfill is not a simple task and a traditional soil mechanics approach for settlement prediction generally is unsatisfactory. Watts & Charles (1999) discussed the settlement characteristics of landfills and suggested various ground improvement techniques that could be used, notably the use of surcharge loading, to reduce post-construction settlement.

Unlike some other waste fills, colliery spoil heaps usually have well defined boundaries. Their distribution in the Nottingham area is shown in Figure 6. They consist of coarse material that reflects the various rock types discarded during coal mining operations. Obviously, the characteristics of coarse colliery discard differ according to the nature of the spoil. The method of tipping also influences the character of coarse discard. In addition, some spoil heaps, particularly those with relatively high coal contents, may be burnt, or still be burning, and this affects their mineralogical composition and physical properties. The moisture content of spoil increases with increasing content of fines. Generally, it falls within the range 5 to 15%. The range of specific gravity depends on the relative proportions of coal, shale, mudstone and sandstone in the spoil, and tends to vary between 1.7 and 2.7. The proportion of coal is of particular importance, the higher the coal content, the lower the specific gravity. The bulk density of material in spoil heaps shows a wide variation, most material falling within the range 1.5 to 2.5 Mg m^{-3}. Low densities are mainly a function of low specific gravity. Bulk density tends to increase with increasing clay content. As far as the particle size distribution of coarse discard is concerned there is a wide variation, often most

material falls within the sand range but significant proportions of gravel and cobble range also may be present. Subsequent breakdown on weathering reduces the particle size. The angle of shearing resistance of coarse discard usually varies from 25° to 45°. With increasing content of fine coal, the angle of shearing resistance is reduced. Also, as the clay mineral content in spoil increases, so its shear strength decreases. The angle of shearing resistance is higher in spoil that has been burnt. The shear strength of discard within a spoil heap, and therefore its stability, is dependent upon the pore water pressures developed within it. Pore water pressures in spoil heaps may be developed as a result of the increasing weight of material added during construction or by seepage though the heap of natural drainage. The relationship between permeability and the build-up of pore water pressures is crucial. In materials with a coefficient of permeability of less than 5×10^{-9} m s^{-1} there is no dissipation of pore water pressures, whilst above 5×10^{-7} m s^{-1} they are completely dissipated. The permeability of colliery discard depends primarily upon its grading and its degree of compaction. It tends to vary between 1×10^{-4} and 5×10^{-8} m s^{-1}, depending upon the amount of degradation in size that has occurred.

Spontaneous combustion of carbonaceous material, frequently aggravated by the oxidation of pyrite, is the most common cause of burning spoil. In fact, hot spots may occur within spoil heaps that have temperatures around 600°C or occasionally up to 900°C (Bell 1996). Spontaneous combustion may give rise to subsurface cavities in spoil heaps, the roofs of which may be incapable of supporting a person. Burnt ashes also may cover zones that are red-hot to appreciable depths. When steam comes in contact with red-hot carbonaceous material, water gas (hydrogen and carbon monoxide) is formed, and when the latter is mixed with air, over a wide range of concentrations, it becomes potentially explosive. Noxious gases are emitted from burning spoil. These include carbon monoxide, carbon dioxide, sulphur dioxide and, less frequently, hydrogen sulphide. Acid mine drainage may be associated with colliery spoil heaps.

Backfilled excavations of various size and depth are widely spread across the Nottingham area. They may be opencast sites for coal, pits for sand, sand and gravel or brick clay, and quarries for aggregate, building stone or gypsum. Frequently, there is no surface indication of their former extent or, in some instance, their existence. Moreover, there usually are no data available regarding the nature of the compaction of the material backfilling these excavations. The types of former excavations and the problems they may give rise to are summarized in

Table 2. Opencast working of coal involves excavation to depths of up to around 100 m below the surface. However, restoration usually begins before a site is closed, which means that worked out areas behind the excavation front are filled with rock waste. This involves topsoil and subsoil being stripped and put into separate temporary dumps about the site. Because of high stripping ratios (often 15:1 to 25:1) coupled with bulking, there usually is enough spoil to more or less fill the void. Part of the M1 motorway runs over a 1960s opencast coal mine in the western part of the Parish of Strelley. The water table at many opencast sites is lowered by pumping in order to provide dry working conditions in the pit. This can present a problem because significant settlements of opencast backfill can occur when the partially saturated material becomes saturated by rising groundwater after pumping has ceased. In other words, settlement due to wetting collapse is more significant than that due to the self-weight of the backfill (Blanchfield & Anderson 2000).

Some brick pits and old quarries are used as landfill sites. Former gravel pits, along the River Trent, where the water table is high, are allowed to flood when extraction ceases and are used for amenity or recreational purposes such as marinas, water sports (Holme Pierrepont), nature reserves (Attenborough) and fishing (Gunthorpe).

Geohazards and constraints on development
The constraints on development in the Nottingham area include slope instability, flooding, collapsing mines and caves, land contamination and, to a minor degree, earthquakes.

Landslide
Steep slopes are common in the Nottingham area but in most places they present little hazard to development unless they are disturbed by human activity or undercut by rivers. Landslides, for example, occur along the bluffs and cliffs of the River Trent. Generally, mudstone and interbedded mudstone and sandstone, which are exposed over two-thirds of the area, are strong enough to sustain steep slopes (Charsley *et al*. 1990). However, weathered material, Head or colluvium on such slopes is susceptible to movement if it is weakened by the ingress of water. For example, landsliding has occurred on the Penarth Group escarpment at Cotgrave, and elsewhere, where the mudstones and black shales forming the slope have weathered to form clays of high to very high plasticity which, under the influence of water draining from minor limestones in the Lias at the top of the slope, have generated minor landsliding especially where undercut at the base. Furthermore, ancient slopes that developed

under different climatic conditions during wetter, colder Devensian times may be covered in Head that contains relict shear planes that can be reactivated by loading, undercutting or the ingress of water. Rockfall and slab slides have occurred in the sandstones of the Sherwood Sandstone Group and the dolomites of the Cadeby Formation. These types of failures have taken place on the exposed sandstone in Nottingham and are mainly related to the occurrence of planes of weakness such as joints, bedding planes and faults, undercutting by the erosion of weaker sandstone beds and tree roots growing in discontinuities. In 1969 a slab weighing 18 tonnes fell from Castle Rock, beneath Nottingham Castle, but this is exceptional and even much smaller failures from rock faces are uncommon.

Flooding

Major flooding of urban areas occurred in 1947 after which a programme of flood protection was initiated. Further peak flows occurred in 1955, 1960 and 1977 but did not result in serious flooding in built up areas. Then, in November 2000, major flooding affected the whole of the Trent valley, as well as its larger tributaries. This was of slightly lesser magnitude than the flood of 1947 but nonetheless was regarded as a 50 year flood. Housing and farmland were inundated and important communication routes were disrupted for days afterwards. In fact, the Midlands region experienced its wettest autumn on record, receiving 214% of the normal October rainfall, after the ground was saturated following an abnormally wet September. Much of the terrain in the catchment areas is underlain by impermeable mudrocks of Carboniferous, Triassic and Jurassic age covered with patches of till. These have low infiltration capacities and so aided extremely rapid rates of runoff. Hence, the river system quickly filled to its capacity and overflowed its banks. Although protective defences saved many places from inundation, they probably contributed to constriction and ponding elsewhere. However, parts of the valley remained dry due to the topography of the flood plain. For example, around Gunthorpe and Caythorpe the dry land corresponded closely with the sands and gravels of the Holme Pierrepont Terrace that stands 2.5 m above the alluvium of the modern flood plain (Figure 10). Further flooding occurred in June 2007 associated with heavy, intense rainfall. This tended to cause localised 'flash-flooding' in the Nottingham area caused, in part, by overland flow over desiccated ground, rather than inundation of extensive areas of the main flood plains. In response to the flooding, raising of the main flood embankments along the River Trent through Nottingham is being planned.

Coal mining subsidence and collapse

Coal has been mined in the Nottingham area since at least the Middle Ages and has left behind a legacy of shafts, adits, subsurface workings and backfilled opencast pits over much of the area. These cause problems for the development and redevelopment of land, in particular, subsidence of the ground surface that takes place above the workings when coal is removed or subsequently when old workings collapse. Unfortunately, subsidence can have serious structural effects on surface buildings, can be responsible for flooding due to the lowering of the ground surface below the water table and, consequently, it can lead to the sterilization of land due to the need for special constructional design in site development or extensive remedial measures in developed areas (Bell 1988). One of the problems associated with old workings is that there may be no record of their existence. In Britain the first statutory obligation to keep mine records dates from 1850 and it was not until 1872 that the production of mine plans for retention by the Mines Inspectorate became compulsory. Even if old records exist, they may be inaccurate.

In the case of pillared workings although the intrinsic strength of coal varies, the important factor as far as the pillars are concerned is that their ultimate behaviour is a function of bed thickness to pillar width, the depth below ground and the size of the extraction area. Slow deterioration and failure of pillars may take place long after mining operations have ceased. Even if pillars are relatively stable, the surface may be affected by void migration as the roof between the pillars collapses. This can take place within a few months or many years after mining ceased. The process can, at shallow depth, continue upwards to the ground surface leading to the sudden appearance of a crown hole. The maximum height of migration in exceptional cases might extend to 10 times the height of the original stall. However, it generally is 3 to 5 times the stall height.

As far as old shafts are concerned, they may be unfilled or filled but in the case of the latter there can be no guarantee of the effectiveness of their treatment unless it has been carried out in recent years. The location of a shaft is of great importance in terms of the safety of a potential structure for, although shaft collapse is fortunately an infrequent event, its occurrence can prove disastrous. Moreover, from the economic point of view the sterilization of land due to the suspected presence of a mine shaft is unrealistic. However, the number of shafts at a site can be large. Gunn *et al.* (2008) reported 36 recorded mine shafts at the Nottingham Business Park development near Strelley. Figure 11 shows one of these shafts exposed by partial collapse of

infill/cover material. The site is approximately 0.8 km by 1.8 km in size, giving a maximum area of about 1.44 km^2. This gives a shaft density, for known shafts, of 1 per 0.04 km^2. They also observed that the recorded locations should not be regarded as having a precision better than ± 20 m in an easterly and a northerly direction.

In longwall mining the coal is exposed at a face of up to 300 m between two parallel roadways. The roof is supported only in, and near, the roadways, and at the working face. After the coal has been won and loaded the face supports are advanced leaving the roof rocks, in the areas where coal has been removed, to collapse. Subsidence at the surface more or less follows the advance of the working face and may be regarded as immediate. As longwall mining has ceased in the Nottingham area it is assumed that subsidence due to this cause is unlikely in the future. Residual subsidence, however, may take place for a number of years after working has ceased. Ground movements induced at the surface by longwall mining activities are influenced by variations in the ground conditions, especially by the near-surface rocks and superficial deposits. However, the reactions of surface deposits to ground movements are usually difficult to predict reliably. Indeed, some 25% of all cases of mining subsidence undergo some measure of abnormal ground movement that, at least in part, is attributable to the near-surface strata. Faults tend to be locations where subsidence movement is concentrated, thereby causing abnormal deformation of the surface. Whilst subsidence damage to structures located close to, or on, the surface outcrop of a fault can be very severe, in any particular instance the areal extent of such damage is limited, often being confined to within a few metres of the outcrop.

Fault reactivation due to mining subsidence can occur during active mining or after mining has ceased. In the 1950s, during mining from Clifton Colliery, some houses in West Bridgford suffered severe damage as a result of differential subsidence associated with a major fault. Donnelly (2000) described a number of instances of fault reactivation in the Nottingham area, most related to active mining. A number of problems, in addition to fault reactivation, can arise once mining operations have ceased. These include the rise of water levels in a mine after the cessation of the pumping that kept the workings dry and possible problems due to acid mine drainage, the escape of gas from poorly sealed mine shafts, and landsliding.

Gypsum mining subsidence and collapse
Subsurface mining of gypsum has taken place at East Bridgford, Cropwell Bishop, East Leake, Bunny and on Gotham and Thrumpton hills. Satinspar was mined at East Bridgford.

This occurs as impersistent veins and was probably worked by following the veins. Accordingly, voids left by mining may have an irregular shape. Neither the actual depth nor extent of the workings is known except that they are shallow and some abandoned shafts have been located. Abandoned mine plans are held confidentially by British Gypsum for the workings at Cropwell Bishop but there is a possibility that mining extended north of the recorded workings. Mining probably took place in several seams within the Newark Gypsum, mainly by the pillar and stall method. Shallow outcrop workings are common at Gotham Hill extending towards Thrumpton, and workings from adits and shafts, which generally consist of a series of randomly orientated tunnels and chambers, also are present. Gypsum was extracted by the pillar and stall method at Weldon Mine (one of the four mines beneath Gotham Hill, just west of Gotham) and the abandonment plan for the mine is available. Hence, the potential for subsidence does exist in these areas although there is little evidence to suggest that workings have collapsed.

Gypsum is much more soluble than limestone because 2200 mg l^{-1} of calcium sulphate can be dissolved in non-saline water compared with 400 mg l^{-1} of calcium carbonate. The solution rate of gypsum is controlled principally by the area of its surface in contact with water and the flow velocity of water associated with a unit area of the material. Hence, the amount of fissuring in a rock mass, and whether gypsum is enclosed by permeable or impermeable beds, is most important. In fact, widespread dissolution of gypsum has taken place within the Mercia Mudstone in a zone a few metres in thickness beneath the subsoil or superficial deposits, much of the solution having occurred along discontinuities (Firman & Dickson 1968). However, the depth of the solution zone may extend to a depth of some 30 m along faults and heavily jointed areas (Elliott 1961). Solution depressions, accordingly, are present in parts of the Nottingham area and gypsum rarely is exposed at outcrop. Nonetheless, much of the gypsum in the Mercia Mudstone below the solution zone occurs as veins and thin nodules except for the Tutbury Gypsum and Newark Gypsum in the Cropwell Bishop Formation. This means that sizeable voids could only develop in these two gypsum horizons if suitable groundwater flow conditions existed. Because there is little evidence of solution hollows resulting from the sudden collapse of cavities it would appear that sizeable voids have not developed. An exception may occur near Bradmore where some steep sided hollows may be due to sudden collapse. Unconsolidated deposits that have accumulated in solution depressions may be highly compressible and could give rise to excessive settlement if loaded.

Sandstone cave collapse

Over 400 man-made caves or cave systems are present in the sandstone beneath central Nottingham (Figure. 12). Most of the caves are between 200 and 800 years old but some may be over 1000 years old. They have been used for a variety of purposes such as storerooms, dwellings, breweries, tanneries, sources of building and domestic sand, waste disposal etc. A register of those caves for which documentary evidence exists has been prepared by Owen and Walsby (1989). However, because of their age and the rebuilding that has been done over the centuries it is likely that unknown caves are present in the sandstone. The distribution of the caves closely reflects the outcrop of the Nottingham Castle Sandstone Formation, although they do not all occur in that formation (Figure 13). The sandstone is friable and can be excavated easily with hand tools but because bedding and jointing are very widely spaced it can stand with vertical sides and support wide voids (Figure 14). Generally, the caves are 3 to 5 m in width and less than 10 m long. Many of the roofs are flat although some are arched and some of the wider caves have a central pillar to provide roof support.

According to Waltham (1993), three possible types of failure may be associated with the caves. Firstly, he maintained that building foundations may lose their integrity if less than 3 m of sound rock exists above the top of the caves. However, there is no record of building subsidence above the caves in more than 100 years. This probably is because building construction in Nottingham takes the presence of caves into consideration. It has meant that some caves have been filled prior to construction (Walsby *et al.* 1993). The design of the Broadmarsh Shopping Centre development (in the centre of Nottingham) ensured historically important caves beneath it were preserved by a concrete beam that spanned them while some of the minor caves were infilled. In another development, in the centre of the City, the caves beneath the site were retained for future use by carrying the frame of the building on reinforced concrete columns that extended through the cave roof onto concrete pad foundations cast into the floor of the cave. Secondly, Waltham indicated that unloaded roofs may undergo progressive failure and that this ultimately could lead to the development of crown holes. The latter is uncommon although Waltham quoted the case of Stanford Street where a crown hole appeared in the road surface in June 1990. Thirdly, Waltham suggested that sandstone roofs and walls could deteriorate rapidly where there are open entrances to caves. As pointed out above, these sandstones can suffer a significant loss of strength when saturated that can affect the behaviour of roofs adversely. Indeed, Waltham mentioned that in

three caves the saturated roof beds had sagged away from the ceilings. Thus, the ingress of water from construction sites to the sandstone should be prevented wherever possible, especially where the sandstone above a cave is known to be less than 3 m. The water table beneath the City has risen in recent years and this has meant that some caves that have been used as basements have been flooded. This may affect the foundations concerned adversely. In fact, water levels have been lowered by pumping in the Broadmarsh complex.

Subsidence investigation and remediation

If development is to be carried out at a site where natural or artificial voids are known or suspected, the ground investigation should aim to detect their presence so that precautions can be taken against their collapse. There are numerous references relating to how to undertake a ground investigation in areas of abandoned mine workings such as Taylor (1968), Healy and Head (1984), Bell (1988) and Anon. (1999); and of how to locate old shafts (Anon. 1976). One of the most difficult assessments to make is the possible effects of progressive deterioration of voids in the ground and the consequent risk of subsidence. The most obvious way of dealing with old workings is to place a proposed structure away from any voids but if this is not possible then an attempt can be made to stabilize the ground by grouting or to use specialized foundation structures such as rafts. Discussion of the methods by which voids in the ground may be dealt with is given by Anon. (1977), Healy & Head (1984) and Waltham *et al.* (2005) and of methods to deal with shafts by Anon. (1982).

Abandoned quarries and pits

Old quarries and pits occur throughout the Nottingham Area. In the past, they were smaller in size but more frequent than they are today when excavations, especially for sand and gravel and brickclay, are centred on a few large-scale workings. Former quarries and pits may have been filled or remain unfilled. Where they have been filled, the character of the backfill may differ from that of the host rock and the backfill may undergo more settlement when loaded than the surrounding host rock. Settlement at former opencast sites has been referred to above and if these are to be built over then, ideally, they should have been compacted properly. Quarries and pits frequently are used to dispose of waste, if the ground conditions are suitable. Not only are such landfills likely to settle but they also may generate methane if the waste contains organic material. Ideally, they should be developed as open spaces rather than be built over.

Groundwater pollution

Public water supply wells draw water from the Sherwood Sandstone Formation. The limestones of the Cadeby Formation also supply water locally to farms but not to public supply. The Coal Measures and other formations yield only limited supplies of groundwater for local use. To avoid groundwater pollution groundwater protection zones have been established within a radius of 1 km around wells in the Sherwood Sandstone Formation so that development likely to cause pollution is avoided. The location of waste disposal sites should be chosen with care so avoid the pollution of groundwater by leachates. Also, the extensive use of nitrogen based fertilizer has given rise to nitrate pollution, especially in rural areas where the limestone and sandstone is exposed. Acid mine drainage can cause pollution of aquifers in the Coal Measures. However, abandonment of the South Nottinghamshire Coalfield and the cessation of pumping minewater raise concerns over the security of the Sherwood Sandstone Formation that overlies the concealed part of the coalfield. Dumpleton *et al.* (2001) suggested that possible discharge of acid mine drainage both to the surface and into the Sherwood Sandstone might take place some 20 years after the end of dewatering.

Contaminated land

Contaminated land has been a constraint on development for at least the past 20 years. The shift in the local and national economic base away from old, heavy, extractive and manufacturing industries towards the light engineering and service industries has resulted in much redevelopment taking place on land affected by contamination. The long history of industrial activity in Nottingham has resulted in the contamination of shallow soils and water in both shallow and deep aquifers. Coal mining has created voids and opened discontinuities that both facilitate contaminant transport and act as a source of very low pH groundwater (Bell & Kerr 1993). Waste disposal sites may be sources of explosive and asphyxiating gases and pollutant-rich leachates. Such land requires a three-dimensional conceptual model to guide the design of a ground investigation that will refine the model and inform the appraisal of risk assessment and remediation options (Nathanail & Bardos 2004). Consequently, Nottingham has been at the forefront of risk-based approaches to managing land contamination. For example, the first soil washing project in the UK was used in the remediation of the Basford gasworks site, north of the City centre.

Seismicity

Earthquakes are occasionally felt in the Nottingham area. These usually are of low intensity and give rise to little or no damage. However, on 11 February 1957, the Derby earthquake, with its epicentre located near Diseworth, about 20 km south west of Nottingham, had an intensity of 6-7 on the European Macroseismic Scale (MSL) scale that affected the Nottingham area. The earthquake had a magnitude of 5.3 M_L. Such an earthquake can cause minor damage such as cracks in roofs and walls, broken windows and damage to, or the collapse of, chimney stacks. The earthquake of 27 February 2008 at Market Rasen (Lincolnshire) (some 70 km north east of Nottingham) had a magnitude of 5.2 M_L and an intensity of 6 (MSL). It occurred at an estimated depth 18.6 km and was felt across Nottingham. It caused damage to the steeple of St Mary Magdalene Parish Church at Waltham-on-the-Wolds about 30 km south east of the city as well as damage to chimney stacks and roofs in the epicentral area. Movement on major faults at depth is a cause of earthquakes and the Nottingham area is crossed by several major faults that extend into the Pre-Carboniferous basement. For instance, on 30 May 1984 the West Bridgford earthquake had its focus at a depth of 15 km. Mining-induced seismicity has been recorded in the Nottinghamshire coalfield but the risk of damage to properties by these events is low (Bishop *et al.* 1993).

Conclusions

Nottingham owes it origin to the fortuitous combination of geology and geography that resulted in the presence of a low, well-drained sandstone hill close to a crossing point of the River Trent. This was aided by the geotechnical properties of the sandstone that allowed rock shelters to be easily cut in the abandoned river cliff on the south side of the hill. This simple beginning was developed by slowly expanding westwards to a second hill when the Normans took advantage of its strategic importance to build a castle on its well-protected, cliff-bounded summit.

The City grew and industries developed supplied by an abundance of natural geological resources in the form of clean water, sandstone, limestone and coal, all within easy transportation distance of the City. Thus, by the early 20th century Nottingham was a major industrial centre of the East Midlands. However, after the middle of the 20th century the old heavy, dirty industries were in decline and were eventually superceded by lighter

manufacturing and service industries at the end of the 20th century. Along with this change came new attitudes to the protection of the environment, natural resources and the health of the population. Thus, Nottingham faced new challenges in its redevelopment that needed to deal with the poor ground conditions left by its industrial past. Challenges included contaminated ground, poor and uneven bearing capacity of made and infilled ground, underground voids, explosive and asphyxiating gases and rising groundwater.

Nottingham has risen to these challenges and employed appropriate geological and geotechnical expertise to deal with them and create a modern city with a vigorous economy and high quality of life for its citizens. Such an outcome is to be expected for a city at the heart of the area that houses the home of the British Geological Survey at Keyworth.

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List of figures:

1. The location of the City of Nottingham and the surrounding urban areas.

2. The bedrock geology of the Nottingham area.

3. North-west to south-east section across Figure 2 showing the regional dip (exaggerated) of the post Palaeozoic strata and the north-west facing scarp slopes of the Permian strata and the Penarth Group. (For a key to the formations present see Figure 2).

4. Cropwell Bishop Gypsum Quarry. The Quarry face shows beds and nodules of gypsum in the reddish brown Cropwell Bishop Formation below the blue-green Blue Anchor Formation, which is overlain by black shales and grey clays of the Penarth Group. In the centre of the face a minor fault displaces the strata by a small amount (photograph BGS © NERC).

5. Distribution of superficial deposits of the Nottingham area.

6. Distribution of artificial deposits in the Nottingham area.

7. Distribution of colliery-based underground coal mining.

8. A nodding donkey, a relict of its oil field past on the nature trail in the Dukes Wood Nature Reserve (photograph © A Forster).

9. The 'Oil Patch warrior' a statue in the Dukes Wood Nature reserve commemorating the 44 roughnecks who arrived from Oklahoma in 1942 to develop the Dukes Wood oilfield (photograph © A Forster).

10. Flooding of the Trent Valley around Gunthorpe (east of Nottingham) in 2000. The dry land corresponds to the Holme Pierrepont Terrace that stands 2.5 m above the alluvium of the modern flood plain (photograph BGS © NERC).

11. Approximately 2 m diameter shaft exposed at the site of the Nottingham Business Park near Strelley. The shaft is lined with dry-stacked red bricks and its collar is within 1.5 m of the ground surface. Infill material appeared to consist of soil, wooden logs and metal objects (photograph BGS © NERC).

12. Cave below the former Pearson's Department store with a wide stable roof and additional support from a carved pillar in the background. The style of the cave and the pillar indicate considerable age (photograph BGS © NERC).

13. Distribution of known caves in a) the Nottingham area and b) central Nottingham.

14. The Park Tunnel was built in 1855 to allow carriages access from a major residential area to Derby Road. The cutting shows massive cross bedded Nottingham Castle

Sandstone and the tunnel its ability to sustain stable wide spans for many years (photograph © A Forster).

List of tables:

Table 1. Bedrock geology – factors affecting ground conditions

Geological Formation	Geohazard	Potential source of contamination	Potential pathway	Potential barrier	Potential receptor
Lias Group	Landslides Shrink/swell clay	No	Fissure flow in limestone beds	Yes	
Penarth Group	Landslides Shrink/swell clay	No		Yes	Minor Aquifer
Mercia Mudstone Group	Collapse of workings in gypsum	Sulphate from gypsum		Yes	
Sneinton Formation		No	Fissure flow	No	Major aquifer
Nottingham Castle Sandstone Formation	Collapse of caves	No	Fissure flow	No	Major aquifer
Lenton Sandstone Formation		No	Fissure flow	No	Major aquifer
Cadeby Formation	Karstic features	Carbon dioxide	Solution-widened fissures	No	Major aquifer
Coal Measures	Collapse of workings, entrances	Methane, Acid mine drainage	Fissure flow; Old workings	Yes	Minor Aquifer

Table 2. Types and methods of coal mining and associated land-use issues.

Type of mining (Period used)	Location	Method	Land-use issues
Crop working (Middle Ages and earlier)	Exposed coalfield	Direct working of coal at surface	1. Very shallow workings 2. Line of subsidence along crop
Bell pits (Middle Ages)	Wollaton, Trowell, Strelley	Shaft c. 1.25 m diameter, up to 12 m deep; radial working to 10 m from shaft	1. Risk of voids remains 2. Shaft sites poorly known 3. Shaft infilling variable and doubtfully compacted
Pillar and stall (From 15th to 17th century)	Wollaton, Trowell, Strelley, Nuthall	Coal cut along grid of roads with rectangular pillars left for support	1. Up to 60% coal may be left, so site investigation may not detect workings 2. Moderately strong overlying beds (such as Cadeby Formation) may have resisted collapse, leaving large voids 3. Collapse of pillars may result in cavities and breccia pipes in rock above 4. Shaft sites poorly known 5. Shafts variably backfilled and doubtfully compacted
Panel working and longwall mining (From 18th century)	Progressively deeper workings from collieries on, and later to the east of, exposed coalfield.	Extraction along continuous coalface (up to 200 m wide). Temporary support of roof then collapse of all except lateral roadways	1. Collapse of face underground produces subsidence and lowering of ground surface. Effects usually immediate and assumed to be complete within a few years 2. Differential subsidence along faults can lead to severe damage 3. Faults may 'reactivate' due to minewater rise long after cessation of mining (years to decades) 4. Minewater rise may result in acidic minewater at surface 5. Mine gases may be driven ahead of minewater to surface 6. Variable backfilling and capping procedures applied to shafts
Opencast mining (From 1940s)	Wollaton, Strelley	Excavation of pit, extraction of coals; backfill with spoil; restoration of site	1. Compaction may be incomplete locally on earlier sites 2. Differential settlement possible along sides of former workings 3. Natural drainage altered