TECHNICAL REPORT WA/92/1

Leeds: A geological background for planning and development

1:10 000 sheets SE 23 NW, NE, SE and
SE 33 NW, NE, SW, SE

Parts of 1:50 000 geological sheets 69 (Bradford), 70 (Leeds), 77 (Huddersfield) and 78 (Wakefield)

R D Lake, K J Northmore, M T Dean and
D G Tragheim

BRITISH GEOLOGICAL SURVEY

TECHNICAL REPORT WA/92/1

Onshore Geology Series

Leeds: A geological background for planning and development

1:10 000 sheets SE 23 NW, NE, SE and SE 33 NW, NE, SW, SE

Parts of 1:50 000 geological sheets 69 (Bradford), 70 (Leeds), 77 (Huddersfield) and 78 (Wakefield)

R D Lake, K J Northmore, M T Dean and D G Tragheim

Contributor R J Aldrick

Cover illustration

Aerial view of Leeds city centre (Leeds C C)

Geographical index

UK, England, West Yorkshire

Subject index

Land-use planning, mineral resources, geological constraints, thematic maps, Carboniferous and Permian rocks, Quaternary superficial rocks, engineering geology, hydrogeology

This study was commissioned by the Department of the Environment, but the views expressed in it are not necessarily those of the Department

Maps and diagrams in this book use topography based on Ordnance Survey mapping

Bibliographic reference

Lake, R D, Northmore, K J, Dean, M T, and Tragheim, D G. 1992. Leeds: A geological background for planning and development. *British Geological Survey Technical Report* WA/92/1.

Keyworth, Nottingham British Geological Survey 1992

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available through the Sales Desks at Keyworth and at Murchison House, Edinburgh, and in the BGS London Information Office in the Natural History Museum Earth Galleries. The adjacent bookshop stocks the more popular books for sale over the counter. Most BGS books and reports are listed in HMSO's Sectional List 45, and can be bought from HMSO and through HMSO agents and retailers. Maps are listed in the BGS Map Catalogue, and can be bought from Ordnance Survey agents as well as from BGS.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Overseas Development Administration.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottingham NG12 5GG

☎ Nottingham (0602) 363100 Telex 378173 BGSKEY G
Fax 0602–363200

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 031–667 1000 Telex 727343 SEISED G
Fax 031–668 2683

London Information Office at the Natural History Museum Earth Galleries, Exhibition Road, South Kensington, London SW7 2DE

☎ 071–589 4090 Fax 071–584 8270
☎ 071–938 9056/57

19 Grange Terrace, Edinburgh EH9 2LF

☎ 031–667 1000 Telex 727343 SEISED G

St Just, 30 Pennsylvania Road, Exeter EX4 6BX

☎ Exeter (0392) 78312 Fax 0392–437505

Bryn Eithyn Hall, Llanfarian, Aberystwyth, Dyfed SY23 4BY

☎ Aberystwyth (0970) 611038 Fax 0970–624822

Windsor Court, Windsor Terrace, Newcastle upon Tyne NE2 4HB

☎ 091–281 7088 Fax 091–281 9016

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS

☎ Belfast (0232) 666595 Fax 0232–662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ Wallingford (0491) 38800 Telex 849365 HYDROL G
Fax 0491–25338

Parent Body

Natural Environment Research Council

Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ Swindon (0793) 411500 Telex 444293 ENVRE G
Fax 0793–411501

Printed for the British Geological Survey by J E C Potter & Son Limited, Stamford, Lincolnshire

CONTENTS

FIGURES

PLATES

TABLES

PREFACE

This report describes the geology of the Leeds district covered by the Ordnance Survey 1:10 000 maps SE 23 NW, NE, SE and SE 33, and discusses its application in terms of land-use planning and development. The area is included in the 1:50 000 sheets, Bradford (69), Leeds (70), Huddersfield (77) and Wakefield (78). It was first surveyed at the 1:10 560 scale by W T Aveline, J R Dakyns, J Lucas, R Russell and J C Ward, and the maps published in 1873–1876. It was resurveyed between 1925 and 1938 by W Edwards. The present study was commissioned in 1989 by the Department of the Environment, in a contract jointly funded with the British Geological Survey, to provide an up-to-date geological database. Field mapping at the1:10 000 scale was carried out by Mr M T Dean, Mr R D Lake and Dr D G Tragheim. The collection and collation of borehole and geotechnical data was undertaken by Mr J P Hollands in association with the Department of Earth Sciences, University of Leeds; a further collation was carried out by Mrs G Bridge. The engineering geology study was carried out by Mr K J Northmore, and a hydrogeological contribution provided by Dr R J Aldrick (National Rivers Authority). The project leader was R D Lake and the programme managers Dr A J Wadge and Mr J I Chisholm. The Department of the Environment nominated officers were Dr S Cosgrove and Dr B R Marker.

The willing cooperation of landowners, tenants and quarry companies in allowing access is gratefully acknowledged. We are also grateful to all the holders of data for allowing us to transfer their information into the National Geosciences Data Centre. We are especially grateful to British Coal Deep Mines, North Yorkshire Area for provision of borehole data and seam mine plans, to the Mines Records Office, Wath-upon-Dearne, for allowing us to photograph abandoned mine plans, and to the Opencast Executive for access to exploration data. We acknowledge the advice provided by the officers of Leeds City Council and by Mr B Mason, Leeds Mineral Valuer. We also acknowledge the assistance provided by many organisations, including the National Rivers Authority (Yorkshire Region) and Norwest Holst Soil Engineering Ltd (see also Appendix V).

Notes to users

This report is divided into two sections. The first describes the study area, and discusses planning considerations in relation to the geology. This is done mainly in the context of the description of eight thematic maps which accompany the report, each highlighting a specific aspect of the geology relevant to planning land-use and development. It is presented in a form that requires little prior geological knowledge. The second section contains appendices describing the geology in more detail and providing additional data on other specialist themes.

There is considerable variation in the quality and reliability of the source data used to compile this report and the accompanying thematic maps, as well as great disparity in the density of site investigation data within the study area. Therefore the accuracy and reliability of the interpreted information reflects that of the source data. However, emphasis has been placed throughout on the most reliable data, particularly those derived from authoritative sources such as geotechnical engineers and geologists.

The component geological sheets were surveyed from 1989 to 1990. No information made available after mid-1991 has been used in this compilation, and thus the report and maps are to be regarded as the *best interpretation of the information available at the time of the surveys. They should be used for preliminary studies only and are not intended as a substitute for on-site investigations or local searches.* The responsibility for assuring that geological, geotechnical and mineral resource data for any given site are as indicated on the maps and in the figures and text of this report must remain solely that of the user.

The possibility of undetected anomalous site conditions should always be anticipated. The indicated occurrence of mineral deposits does not imply an economic resource. The possible presence of unmapped superficial deposits and made ground of variable thickness, particularly within the urban areas, should also be taken into account when formulating development proposals.

There is no substitute for the knowledge provided by a detailed site investigation that takes into consideration the extent, nature and location of a proposed development. Therefore the report and maps are primarily intended to give guidance on when to seek specialist advice, and to aid developers in formulating effective site investigations. The statutory authorities with responsibilities for planning and development should always be consulted at the earliest stage.

All National Grid references in the report lie within the 100 km square SE. Grid references are given to either eight figures (accurate to within 10 m), or six figures for more extensive locations.

Data used in preparing this report and associated maps are lodged at the British Geological Survey, Keyworth. Any enquiries concerning these, or about the purchase of the report or maps should be directed to Information Services, British Geological Survey, Keyworth, Nottingham NG12 5GG.

EXECUTIVE SUMMARY

This study, carried out between 1989 and 1991, was commissioned by the Department of the Environment and funded jointly by the Department and the British Geological Survey. Its principal aim was to produce a synthesis of geological information relevant to the land-use planning for development and redevelopment for a large part of the Leeds district. This report is aimed at those involved in planning and development. Much of the information is provided on a series of thematic maps, each of which concentrates on a specific aspect of the geology relevant to land-use. These are suitable for use in forward planning for development and conservation, and as a background to desk studies, prepared in advance of specific development proposals. However, they must not be used in place of results of adequate site investigations when development is being considered. In addition to the information contained in the report, sources of other more detailed data are indicated.

The study area

The study area comprises much of urban Leeds together with some rural tracts to the north-west and east; it covers an area of 175 km^2, mostly to the north of the River Aire. Considerable expansion of the urban area has taken place in recent years, together with some redevelopment of the inner city and derelict industrial land.

Sources of information

The information used in this report was acquired in two ways. Firstly, geological data were sought and compiled from various sources, most notably from the databases and archives of BGS, British Coal Corporation, Leeds City Council and that deposited by the late Mr J S Turner with Leeds University. A number of geotechnical consultants and private companies were also consulted. These data were mostly in the form of memoirs, maps, underground mine plans, borehole, shaft and trial pit records, and site investigation reports. Secondly, a detailed field geological survey was undertaken by BGS geologists at a scale of 1:10 000.

Geology

The bedrock of the Leeds area comprises mainly sandstones and mudstones with coal seams of Upper Carboniferous age; dolomitic limestones of Upper Permian age occur towards the eastern margin of the district. Overlying the bedrock in the Aire valley and in areas to the north, there are superficial or drift deposits which represent the loosely consolidated deposits of rivers, slope processes and glacial action, in the form of clay, silt, sand and gravel. As a result of mineral extraction and construction work there are locally extensive tracts of deposited fill materials and disturbed ground. The survey has resulted in a considerable improvement to the geological knowledge of the district. Much new detail has been added to the geological map and this provides a better understanding of the structures present.

Mineral and water resources

There are few remaining geological resources within the area because of sterilisation by urban development and near-exhaustive mining of the better quality coals. It is probable that future extraction of coal will be incidental to the stabilisation of ground, affected in the past by partial exploitation in shallow mine workings. There are resources of sandstone (for aggregate) and brick clay in the remaining rural areas, but it is not possible to provide an indicative assessment of the limestone resource.

The underground water resources of the area are reviewed with particular regard to water quality. Although there are presently ample resources, future prospects may be limited to localised extraction for industrial purposes, although the removal of some chemical elements may be required.

Geological constraints

Potentially adverse ground conditions are the main geological constraint for consideration in planning and development. Assessment of ground conditions includes not only the properties and stability of bedrock and drift deposits, but also the changes brought about by man, such as mining and any consequent subsidence, quarrying and landfill. These various factors are considered separately in this report. The results presented are based on data from a total of 7698 test or sample points.

A long history of quarrying and shallow coal mining in the district has left a legacy of shafts, adits, shallow workings and backfilled quarries which present problems for land use. Much of this is poorly documented. To the east and south of the city in particular, there are tracts where unrecorded former coal workings may occur at shallow depth. Only those shafts with recorded geological information are shown on the thematic map (No. 1) and responsibility for locating shafts rests on the site owner or developer. Tabulated information is presented for the backfilled quarries and other areas of made ground, providing information on these problem areas. Attention is drawn to the poor documentation relating to many of these sites, and the need for well-planned site investigations in such places. The special problems of fill as a foundation material are also considered.

Other geological factors examined include local geological structure, soft ground in the main valleys, rock types susceptible to development of high moisture content, localised high groundwater levels and slope stability.

References, glossary, appendices and thematic maps

This report concludes with appendices providing additional geological, geotechnical and hydrogeological details, together with glossaries, lists of data sources (including open file geological reports relating to the district) and references.

The thematic maps which accompany this report are as follows:

Distribution of borehole sites (Map 1)
Solid geology (Map 2)
Distribution of superficial deposits and levels of natural rock-head beneath (Map 3)
Distribution of Made Ground (Map 4)
Deep coal mining (Map 5)
Quarrying and shallow mining (Map 6)
Engineering geology (Maps 7 and 8)

Copies of this report and its maps can be obtained from the British Geological Survey, Keyworth, Nottingham NG12 5GG. Archival data is held by Information Services at the same address.

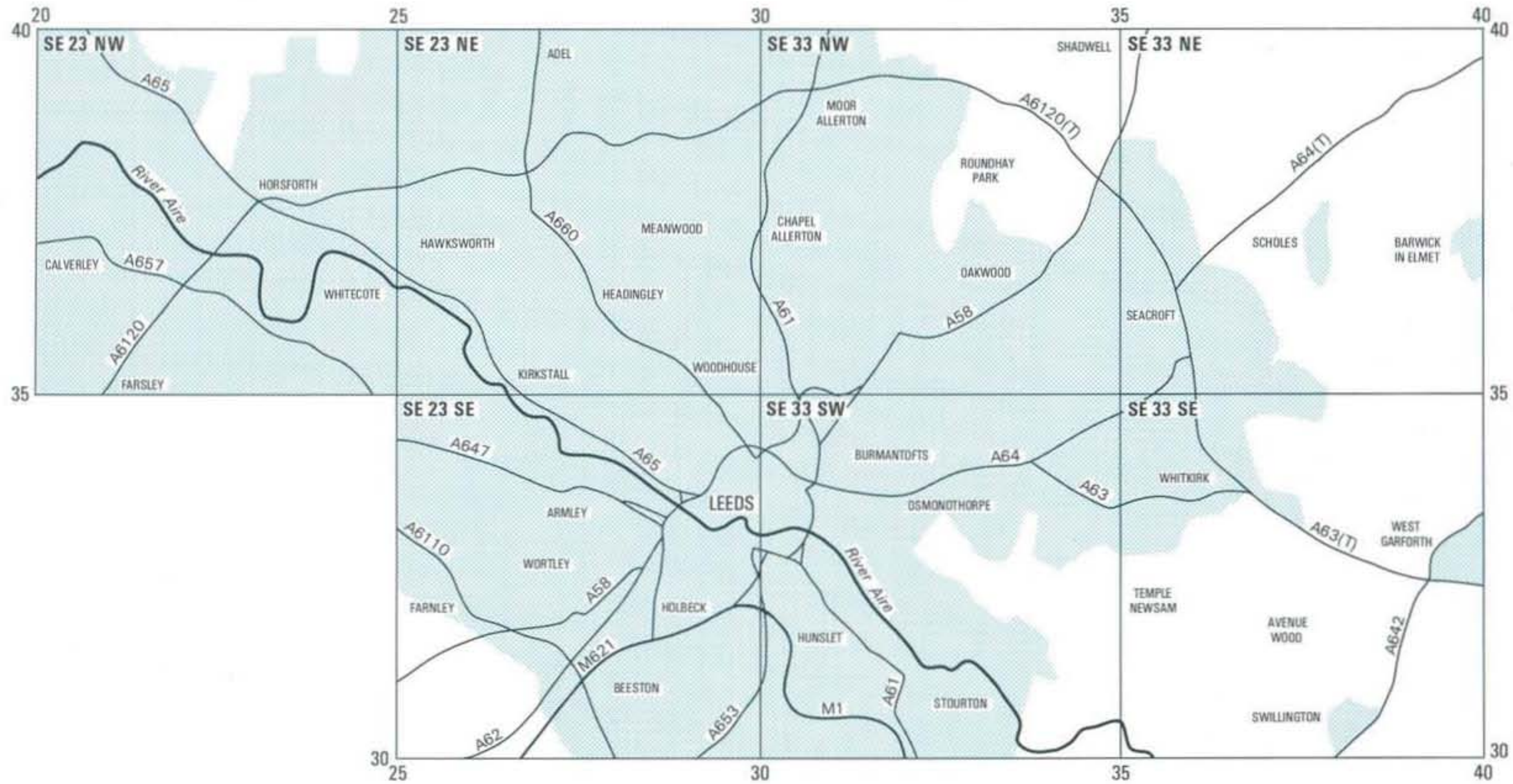


Figure 1 Location map.

INTRODUCTION AND PHYSICAL SETTING

The data provided in this report were obtained largely during a three-year contract, commissioned in 1989 by the Department of the Environment. Funding for the work was shared between the Department and the British Geological Survey.

The district under study comprises 175 km and relates to the urban area of south and central Leeds, together with some rural areas near Rawdon in the north-west, and around Barwick in Elmet and Swillington to the east (Figure 1). A substantial part of the district lies on part of the abandoned Yorkshire coalfield.

Aims and objectives

The study is one of a series commissioned by the Department of the Environment as part of the Geological and Minerals Planning Research Programme (Department of the Environment, 1988). The work carried out meets the remit of the British Geological Survey, which is to update the geological map, and the interest of the Department, which lies in areas of planning, development and conservation. It aims to provide an up-to-date geological database, including new geological maps, as a foundation for:

a) land-use planning for development and redevelopment, and
b) effective future geological research

The objectives were:

a) to collect, collate and index geological and geotechnical data in a form which allows it to be placed in a permanent archive and to be easily consulted

b) to carry out geological field mapping of the area to modern standards and present results in a set of revised geological maps with accompanying geological descriptions

c) to interpret and present results in a set of applied geological maps and accompanying reports which demonstrate the relevance of geological factors to: forward planning, development, development control and construction; and to indicate the nature, scale, and distribution of resources for, and constraints to, development.

d) to demonstrate the relevance of methods adopted to applied mapping studies in other areas

e) to identify the need for further investigations or specialist advice in relation to specific planning and development objectives and proposals, or to clarify important scientific factors.

The work programme

The geological mapping was carried out at a scale of 1:10 000 during 1989–90 and involved a complete revision of the existing maps. The fieldwork entailed systematic examination of exposures of solid rock and superficial deposits (drift), together with geological interpretation of topographic features and some hand augering to a depth of 1.4 m.

The field survey was augmented by an abundance of borehole and trial pit data, much of which was collected and/or collated during the programme. The bulk of these data relates to relatively shallow site investigation work. Much of the deep mining information, including colliery shaft sections, is of considerable vintage and was used in earlier surveys to establish the stratigraphy of this and surrounding districts.

Information gleaned from old topographic maps and aerial photographs was useful to determine former mineral workings and areas of landfill.

Reassessment of determination of fossils, housed in the Survey collection, has assisted in the correlation of Carboniferous strata.

The component 1:10 000 geological maps were constructed using a combination of the data outlined above. Each map depicts both lithological and structural variations in the bedrock, and the lithology and distribution of the superficial deposits. A three dimensional interpretation of each map is assisted by means of selected borehole and mining data, and a generalised vertical section. Each 1:10 000 scale map has an accompanying open file report, listed in Appendix VII, which provides more detailed information than is possible in this text.

The 1:25 000 scale thematic maps were compiled using data reduced and simplified from the 1:10 000-scale survey, and from a variety of other sources. Each map is designed to show one or more geological themes, in summary form, for the whole of the study area. Their main purpose is to provide an overview for each theme, and their accuracy is limited by the scale chosen. For more accurate or site-specific data, the 1:10 000 geological maps and other parts of the original database should be consulted. The latter includes topographic maps at 1:2500 scale on which most of the borehole sites have been plotted.

Presentation of findings

The study is intended to be of value to a wide range of users, from specialists in the earth sciences or related disciplines, to others who may possess only limited specialist knowledge, but who may use the findings as an aid to planning and development decisions. The findings are presented in this report together with its appendices and accompanying thematic maps.

The various themes portrayed on the maps are as follows:

Distribution of borehole sites (Map 1)
Solid geology (Map 2)
Distribution of superficial deposits and levels of natural rock-head beneath (Map 3)
Distribution of Made Ground (Map 4)
Deep coal mining (Map 5)
Quarrying and shallow mining (Map 6)
Engineering geology of the solid rocks (Map 7)
Engineering geology of the superficial deposits (Map 8)

For the specialist, a detailed description of the more salient aspects of the geology is provided in Appendix I. Attention is drawn to the most important advances in the understanding of the geology of the district and to the outstanding problems. Other appendices (II to IX) describe the engineering geology (Appendix II) and various aspects of the database; a glossary of geological terms and list of references are also provided.

Physical setting

The district described in this report includes much of the urban area of Leeds together with some rural areas to the north-west and east. The drainage of the area is largely directed towards the Aire valley which was a major transport route in historical times. The area has a long history of coal-mining since the twelfth century and the construction of the Leeds–Goole canal in 1704 provided the main stimulus for the extensive development of collieries in this part of the Aire valley. Other industries which were developed during the industrial revolution include those related to wool, leather, metals and engineering, particularly associated with railway equipment.

In the early days, the extractive industries provided brick-clay, ceramic clay, flagstone, limestone, ironstone and coal. With the depletion of resources coupled with expansion of the urban area and changing needs, the production of aggregates, brick-clay and coal is now limited to a few sites. Currently sandstone is quarried near Horsforth Woodside, brick-clay at Swillington and coal at Skelton (Grange) [3431].

The relief of the region is dominated by the Aire valley and broad ridges to the north and south; some of the tributary valleys are locally steeply incised. The highest ground occurs around Rawdon in the north-west (223 m OD) whereas the Aire valley falls to below 16 m OD downstream from Stourton. Much of the industrialised area, northwards from Hunslet to the River Aire lies on low ground at about 25 m OD.

GEOLOGICAL SEQUENCE AND FORMER MINERAL EXTRACTION

The geological sequence of solid rock formations which occur at the surface in the district are of Upper Carboniferous and Permian age. Much of the ground is underlain by Lower Coal Measures, with some Middle Coal Measures; the underlying Millstone Grit is present in the Aire valley, upstream from Kirkstall Abbey, and to the north, through Horsforth and Shadwell. The Magnesian Limestone (of Permian age) is represented patchily near Whinmoor and in the north-east, around Barwick in Elmet and northwards to Kiddal Hall. A generalised vertical section is given in Figure 2.

The Carboniferous strata, of Namurian and Westphalian age, were deposited by rivers and in deltas subject to periodic marine incursions. These oscillatory conditions gave rise to a broad cyclicity of bedding, commencing with a shelly (marine or lacustrine) mudstone and terminating with a coal (underlain by an ancient soil or 'seatearth'). The intervening beds show a coarsening-upwards trend from mudstone through siltstone to sandstone, although this sequence may be modified or interrupted by channelling, particularly in the Coal Measures, where the channel-fill sandstones are coarse at the base and pass upwards into finer sands.

At the end of the Carboniferous, during the Variscan mountain-building episode, uplift of former basins took place, accompanied by faulting and gentle folding. The folds are generally broad and open, with gentle dips and, regionally, the major faults show both easterly and north-easterly trends. After this period of deformation, a long period of erosion ensued, followed by the deposition of basin-margin marine sediments in Upper Permian times. The evidence for later, Mesozoic and Tertiary events is lacking in this district, but it is probable that some of the faults were reactivated during the Tertiary, when regional tilting towards the North Sea Basin also took place. The district was affected by glaciation during the Quaternary, with erosion of the landscape and deposition of superficial ('drift') materials. These deposits tend to be concentrated in the Aire valley and its tributaries, and on the higher ground, particularly around Horsforth and Adel.

The region lies across the northern margin of the exposed Yorkshire Coalfield. The regional dip of the Carboniferous rocks varies from 2 to 5° and is generally towards the south and south-east although there are significant local variations. As a consequence of the broad struc-

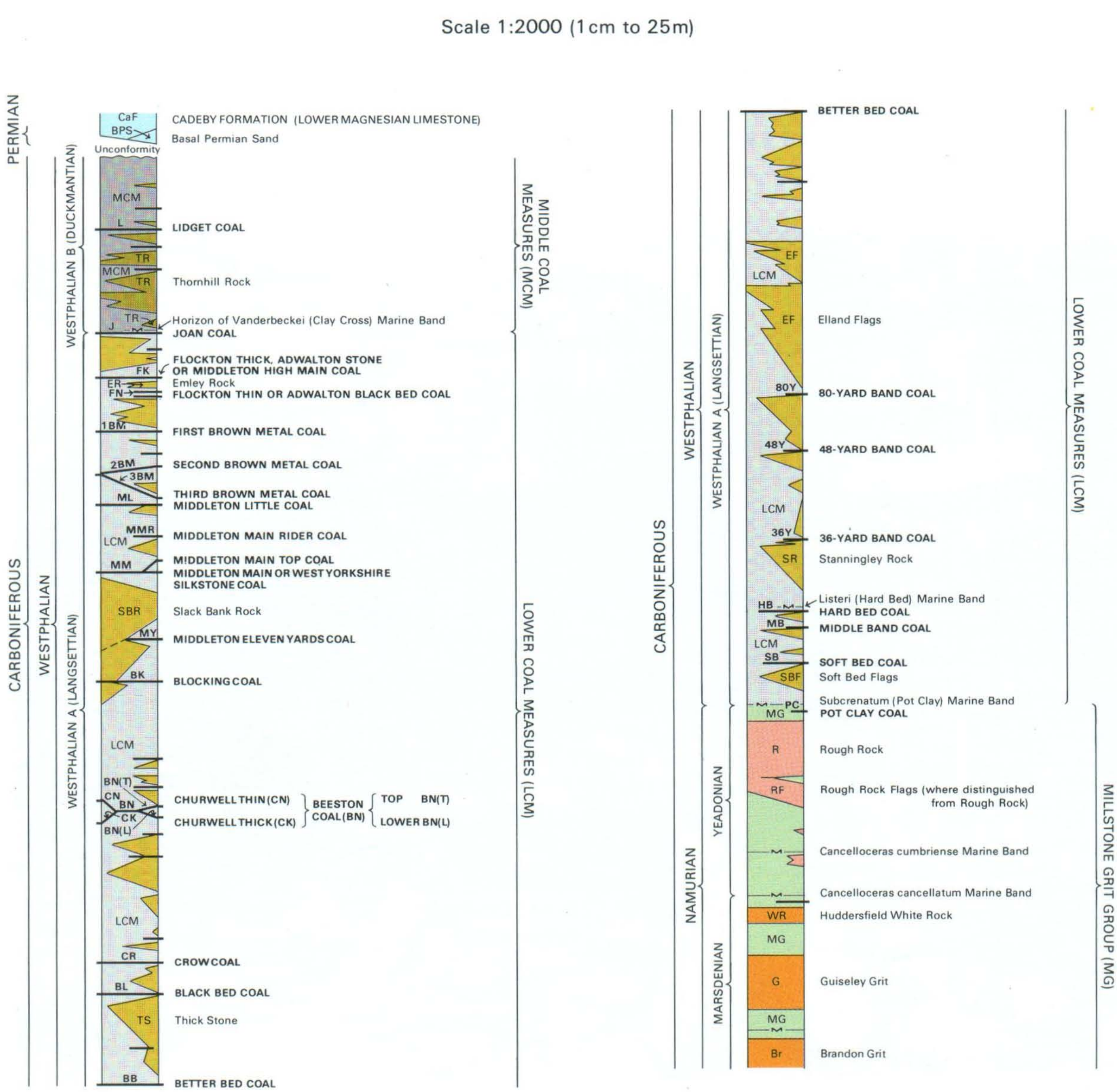


Figure 2 Generalised vertical section.

ture, the more productive Coal Measures, and the areas of intensive mining, tend to occur to the south and east of the city centre. The small outcrops of Permian strata lie near the western margin of a broad tract of limestone which extends eastwards to the Vale of York, with a generally easterly dip of about 1°.

Carboniferous: Millstone Grit

The exposed Millstone Grit comprises about 130 m of alternating sandstone ('rock' or 'grit') and mudstone beds. The former are named as follows in ascending order : Brandon Grit, Guiseley Grit, Huddersfield White Rock and Rough Rock. These sandstones are medium or coarse-grained and display flaggy or massive bedding. Only the Rough Rock is well exposed in this district and there is little information on the detailed lithologies of the other beds. The former is typically a cross-bedded, pebbly sandstone, up to 35 m thick. Locally a separate lower Rough Rock Flags division has been distinguished, which demonstrates a thin flaggy 'tilestone' lithology and is exceptionally up to 28 m thick (Plates 1 and 2).

The mudstones are medium to dark grey in colour and in places contain nodular ironstone. Thin coals may also occur in the beds close above the sandstone units. Four marine horizons are known to lie within the sequence from regional evidence: above the Brandon Grit (goniatites not determined), above the Guiseley Grit, (Bilinguites superbilinguis Marine Band) and two above the Huddersfield White Rock (Cancelloceras (Gastrioceras) cancellatum Marine Band and Cancelloceras (Gastrioceras) cumbriense Marine Band).

Carboniferous: Coal Measures

The Coal Measures consist of sequences of grey mudstone, siltstone, sandstone, seatearth and coal. A total thickness of about 530 m crops out in this area.

The mudstones are black to grey and commonly contain non-marine bivalves, particularly above some of the coal seams. These rocks weather to stiff to firm, orange-brown and pale grey mottled clays, the fossils being leached out. The typical depth of weathering is of the order of 3 m but this may extend down joints to at least 8 m. Nodules of sideritic clay ironstone, varying from less than 10 mm in diameter to about 0.5 m, are common in mudstones and silty mudstones. Where these nodules were of sufficient abundance, in the roof measures of the Black Bed Coal for example, they provided a source of iron ore in the past. Early shaft records describe mudstones as 'bind', 'blue bind', 'metal' or 'shale'.

A number of marine bands occur in this part of the sequence. These consist of thin black mudstone with a marine fauna (principally *Lingula mytilloides*) overlying a thin coal. The Coal Measures are divided for convenience into Lower, Middle and Upper divisions. The base of the Lower Coal Measures is taken at the base of the Subcrenatum (Pot Clay) Marine Band; the Lower-Middle Coal Measures boundary is at the base of the Vanderbeckei (Clay Cross) Marine Band.

Non-marine marker beds with characteristic faunas include the 'Cockleshell' horizon, which occurs below the Middleton Little Coal; the Low '*Estheria*' band, below the Blocking Coal, has not been recognised in this district.

Plate 1 Rough Rock Flags exposed at Woodside Quarry [2564 3853].

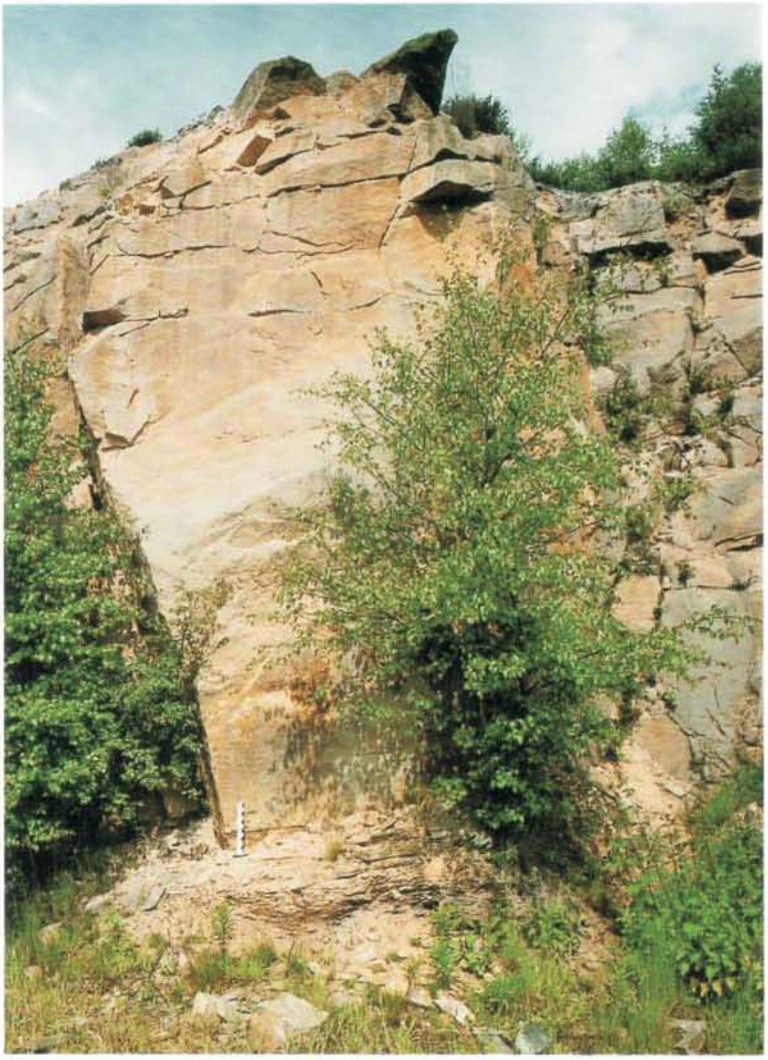


Plate 2 Rough Rock Flags exposed at Woodside Quarry, overlain by Rough Rock [2555 3857].

Siltstones are commonly pale to medium grey and contain plant debris. They grade both laterally and vertically into sandstones and mudstones. A common mixed lithology is that of an interbedded siltstone and fine-grained sandstone, with ripple lamination, small-scale cut and fill structures and evidence of soft sediment deformation. The equivalent old mining terms are 'stone bind' and 'slaty stone'.

Thick and regionally persistent sandstone units in this area are known as the Thornhill Rock, Slack Bank Rock, Thick Stone and (leaves of the) Elland Flags, in descending order. Below the Elland Flags, the sandstones include the Stanningley Rock and the Soft Bed Flags but these appear to be less extensive in their development. They all consist mainly of subangular to subrounded quartz with varying amounts of feldspar and mica. The grain size is generally very fine- to medium-grained but coarse-grained and conglomeratic beds occur locally. The sandstones are grey, weathering to brown (Plates 3 and 4), and giving a characteristic field brash of flaggy fragments. The old mining terms, 'galliard', 'strong stone bind' (probably a sandy siltstone) and 'rock' are synonymous with sandstone.

Seatearths are unbedded mudstones, siltstones and sandstones with *Stigmaria* roots. They typically occur beneath coals but may be laterally more extensive. Mudstone seatearths are generally pale grey and have been dug for use as pottery clay and fireclay in the past. The equivalent old mining terms are 'clunch' and 'spavin'. Sandstone seatearths may have been secondarily cemented by silica to form a hard white 'ganister' in places (Plate 6).

Coals are laterally extensive but vary in thickness depending on the amount of dirt (dirty coal) which locally may divide a coal seam into individually named beds of different composition. Where a coal seam becomes divided by mudstone or siltstone, the separate coals are known as leaves. The following seams have been deep mined in this area: Flockton Thick, Middleton Little, Middleton Main, Middleton Eleven Yards, Blocking (to a limited extent), Beeston, Crow, Black Bed, Better Bed and Hard Bed.

Tonsteins, thin, but laterally persistent, kaolinitic beds of volcanic ash (air-fall tuffs), are not common in the Coal Measures of Yorkshire but are important markers and were recorded in the Oxbow opencast workings [e.g. 3665 3034, 3644 3109], in the east of this area, beneath the top leaf of the Third Brown Metal Coal.

Permian: Magnesian Limestone

The Cadeby Formation (Lower Magnesian Limestone) rests unconformably on the Carboniferous strata and consists of buff, sparsely to moderately fossiliferous, marly dolomite and dolomitic limestone with local oolites and bryozoan-algal mats. The lowest few metres of beds tend to be sandy but the underlying Basal Permian Sand appears to be only patchily developed within this district, exceptionally up to 6 m thick. This latter unit is typically buff, friable and medium-grained.

Below the sub-Permian unconformity, the Carboniferous rocks are oxidised and reddened to a depth of a

Plate 3 Swillington brickworks showing Thornhill Rock overlain by mudstones with two sandstones and thin coals [385 315].

few metres. Locally this effect extends to greater depths and has been observed at some distance from the Permian crop, perhaps associated with enhanced weathering down fault-zones.

Superficial deposits

QUATERNARY DRIFT DEPOSITS

The superficial (drift) deposits present at the surface include glacial deposits, river terrace deposits, Head and alluvium (Table 1). Some of the categories are difficult to map in any consistent fashion so that the distribution of Head deposits, for example, as portrayed on Map 3, should not be regarded as fully representative.

The glacial deposits (till, glaciofluvial sand and gravel, glacial silt, moundy glacial deposits) are thought to be the products of more than one glaciation. The deposits which relate to the earlier (?Anglian) episode, show no con–structional features, are extensively weathered and typically occupy the higher ground. The moundy glacial drift and associated deposits, which occur in the Aire valley upstream from Leeds, belong to the Late Devensian glaciation, which affected the Pennine dales including Upper Airedale in the period 20 000 to 15 000 years before present. The till of the plateau areas comprises brown, ill-sorted, stony, sandy clay with clasts of locally derived sandstone together with some chert and ironstone. Limestone occurs where the till lies close to the Permian outcrop. The moundy drift is probably more varied in composition including both till and sandy gravels.

The river terrace deposits are variable in composition and range from sandy, fine to medium-grained, subrounded to rounded gravels, with some cobbles, to sandy clays with some rounded gravel. The sand content varies from fine to coarse-grained, but fine to medium-grained material is more common. The gravel fraction is mainly of locally-derived Carboniferous sandstone with some ironstone, shale and limestone. In the marginal areas the terrace deposits are locally sufficiently clayey to have been worked for brick-making.

The surface level of the terrace deposits within the Aire valley commonly lies about 5 m above that of the floodplain alluvium (c.25 m to 35 above OD), but near the margins, the upper surface climbs imperceptibly to higher elevations (for example near Hunslet Carr and Holbeck), probably as a consequence of the merging of these deposits with those of solifluction and possibly those of older fluviatile origin.

The lower flanks of the Aire valley, the floors of the tributary valleys and some of the isolated cols are mantled extensively by spreads of solifluction material and hillwash (Head). Typically the composition of these deposits reflects that of the parent materials upslope and commonly is of angular sandstone fragments in a matrix of sandy clay. A thickness of 2 to 4 m is thought to be fairly typical, although some drillers' logs do not distinguish between Head and weathered bedrock. Such deposits are commonly thicker on north and east-facing slopes. Thin patchy deposits of this material are probably widely present throughout the area, but it proved possible to map only certain occurrences.

Plate 4 Coal Measures sandstone, stratigraphically below the Beeston Coal, exposed at Gelderd Road [2600 3096].

The floodplains of the River Aire and its tributaries are underlain by channel-fills of two distinct deposits, commonly totalling up to about 10 m thick in the Aire valley. The upper unit (of Flandrian age) consists of soft to firm, brown and grey mottled, silty clays and clayey silts (alluvium). Locally, organic (peaty) horizons may be present and commonly there is a sand/gravel component which increases downwards. The lower unit (suballuvial gravels) shows a longer age range (Devensian to Flandrian), comprising fine to coarse-grained sands and angular to rounded, fine to coarse-grained gravels in varying proportions; a variable clay content is also present. The clast component is similar to that of the terrace deposits although there is a reduction in the less-durable materials. Lenses of organic silt or brown, pebbly, sandy clay are present in places within the sandy gravels.

At many locations, the soft upper unit of the alluvium has been removed prior to the construction of foundations, etc and commonly replaced by fill material.

MADE GROUND

Landfill material is very common in the urban area of Leeds, particularly in the alluvial tracts where soft clayey lithologies have been removed and partly replaced with other, generally granular, materials prior to construction work. Other more well defined locations, where made ground is thick, include backfilled clay-pits, quarries and opencast sites, infilled watercourses, man-made embankments in their various forms, former sludge beds and waste tips from mineral extraction sites, including collieries. Some of these areas have been subject to extensive landscaping.

The nature of the fill material in these various locations is poorly documented. In the Leeds district as a whole, for example, there are 19 opencast coal sites known to predate 1974. Of these, the date of backfill and/or restoration is known only for 14 sites (mostly falling within the range 1943–60). Although these workings would have been back-filled mainly with rock spoil, the possibility of 'topping up' with other materials cannot be discounted. It is probable that many of the older quarries were filled with waste material early in this century. Locally the landfill material is in excess of 20 m thick.

Former mineral extraction

Various geological horizons have been exploited in the past for brick clay, fireclay, coal, ironstone, limestone, sand and gravel, and sandstone (Plates 5–10). Early mining of coal and ironstone was from bell pits (p.19). For example, the ironstone about the Black Bed Coal was worked in this fashion, near what is now the Corn Exchange [304 334] in the city centre. Later, deeper mines extracted coal on a larger scale and, in some cases, ironstone and fireclay, from the beds above and below, respectively. The influence of old mine workings on planning, and on methods of foundation design, is discussed in more detail in a later section (p.19).

Forms of pillar-and-stall or 'retreat' mining were also used in the exploitation of the Elland Flags in the Brighouse and Bradford districts (Godwin, 1984). Workings in the Gamble Hill area [247 337], which may just impinge on this district and which were probably reached from adits from a quarry, were described in Godwin's paper (p.7).

Quarrying activity was formerly extensive in the Leeds district, mainly for clay and sandstone. The shape of the excavations was in many cases determined by the local

Table 1 Geological succession of superficial deposits of Quaternary age

Approximate years before present	Stages	Deposits
0		
	Flandrian	Landslip Alluvium Suballuvial gravels (part) Head (part)
10 000		
	Devensian	Head (part) Suballuvial gravels (part) River Terrace Deposits Till, mouldy glacial deposits, and associated sediments
70 000		
	Ipswichian	Derived fossil bone material at Wortley
130 000		
	?Anglian	Till, and associated sediments 'Older Drift'

needs and geology. Thus, flagstone workings concentrated on bands of better quality stone, which provided even splitting. Clay pits may have developed faces which optimised on the secondary extraction of coal to reduce fuel costs. Some ganister and freestone workings may have exploited beds beneath a thin capping of clay and so obtained relatively unweathered stone.

The documentation of the extent of mining and quarrying is incomplete for this district. Prior to 1872 there was no statutory obligation to record plans of mines, there are few records, and the extent of old workings is largely unknown. The knowledge of former quarries is largely based on old topographic maps and site investigation borehole data.

In the early years of intensive mining near the city centre, it appears that there was a preferred tendency to exploit the more productive shallow seams, such as the Beeston Coal, and thence to work this seam and latterly lower horizons down-dip and at greater depths in a generally easterly or south-easterly direction. Much of the workable upper leaf of the Beeston Coal in Leeds was exhausted by the end of the 19th Century: its lateral equivalents, the Churwell Thick and Thin coals, were worked out by 1912.

It is thought that coal mining in the floor of the main Aire valley, in the vicinity of the city centre and Pottery Field, was restricted because the technology for mine drainage at shallow depth beneath water-bearing alluvial deposits was not available at the time. However, there is evidence for some working of the Beeston Coal in the Hunslet area beneath terrace deposits. The extent of the take of the Gibraltar Colliery [3181 3192], at Knowesthorpe, sited on alluvium, is not known; one shaft here encountered the base of the Beeston Coal at 40 m depth.

Plate 5 Quarry in Rough Rock at Calverley Wood, as seen in 1937. The lowest 15 m of strata are Rough Rock Flags.

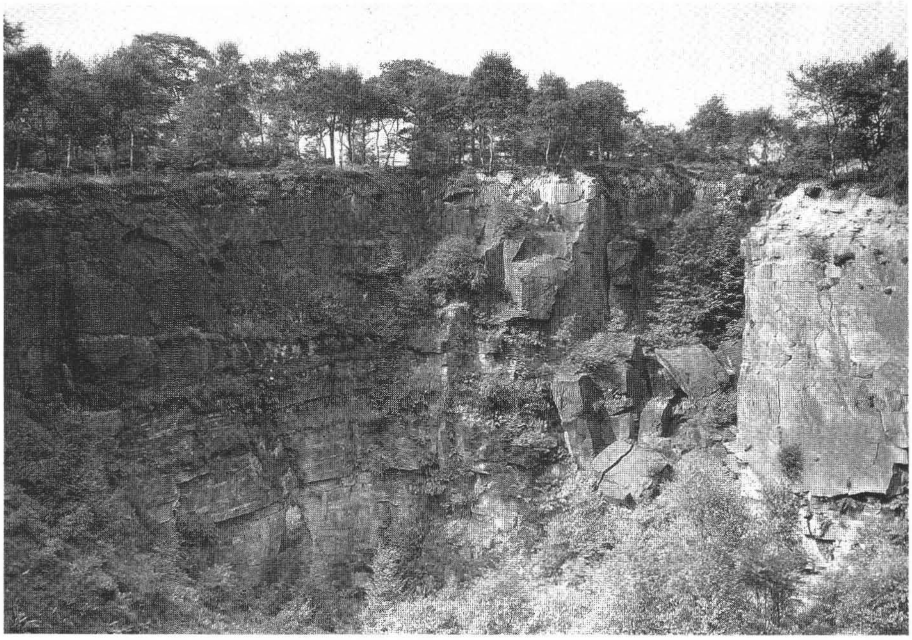
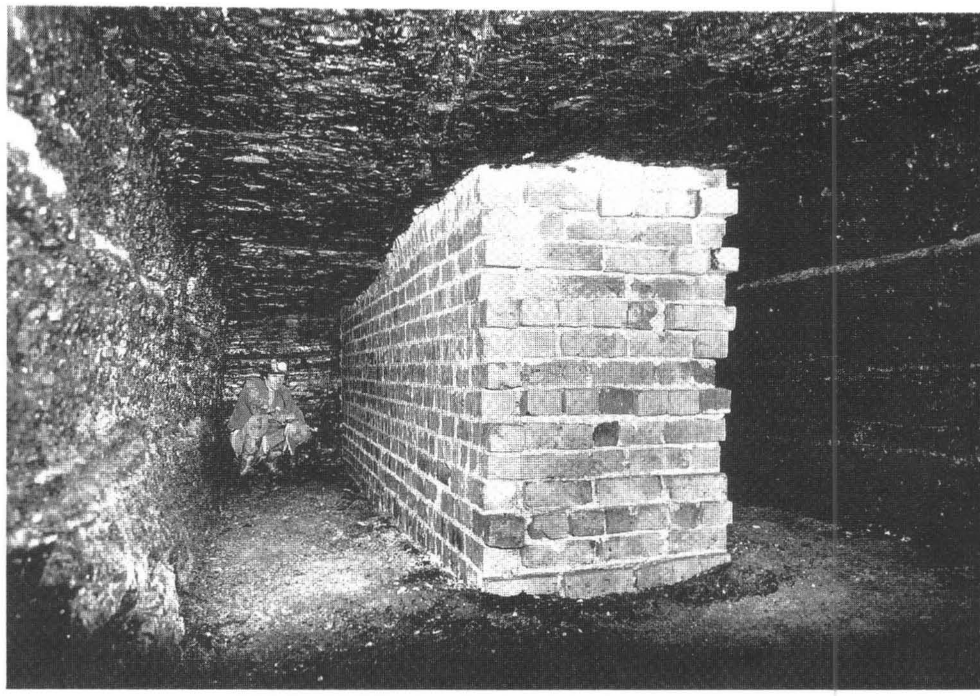


Plate 6 Ganister quarry in Stanningley Rock, showing beds folded up against a fault, near Meanwood Road in 1894. (British Association for the Advancement of Science Photographic Collection.)

Plates 7 and 8 Former pillar and stall workings, inspected in 1983, in the Beeston Coal at Richmond Hill [313 331]. Note the supporting brickwork pack in the upper photograph. (Courtesy: Wardell Armstrong/Leeds City Council)



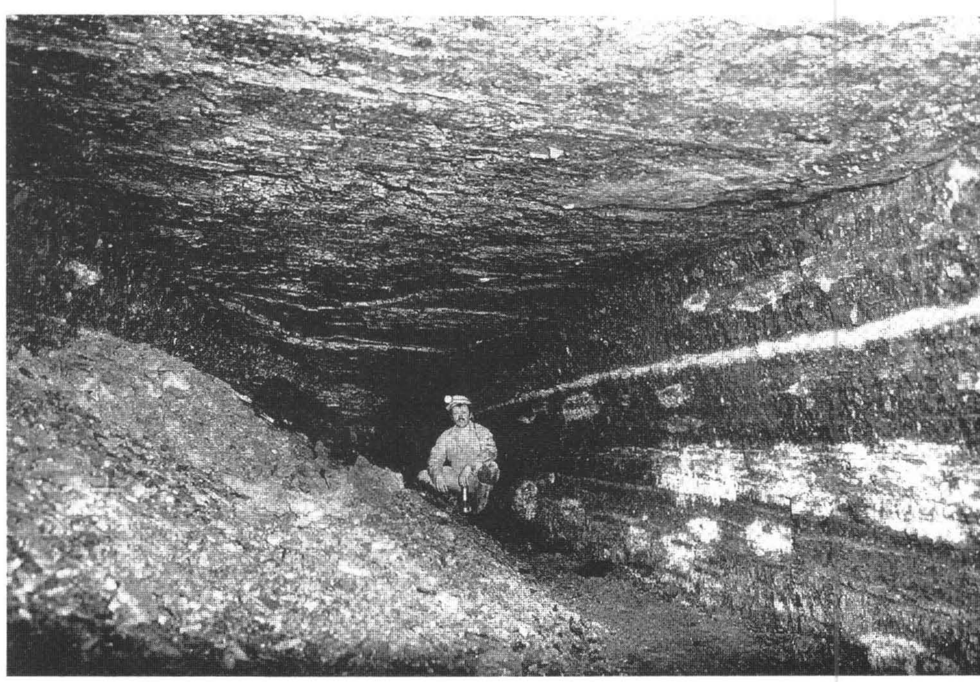
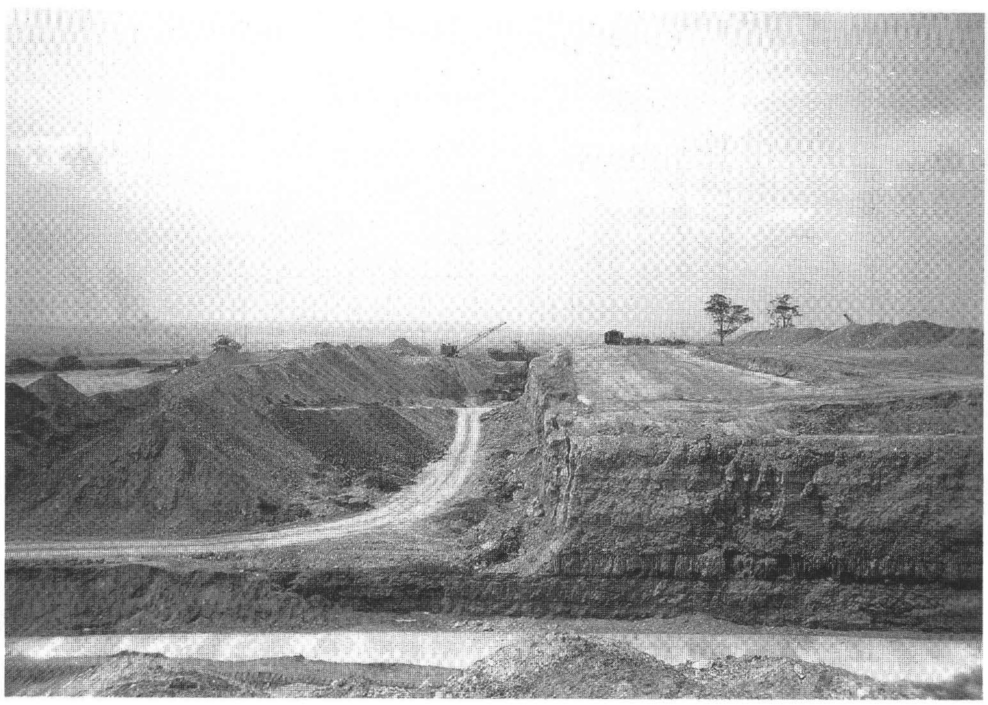


Plate 9 Brick pit in mudstones, above the Beeston Coal, at Hunslet, 1891, precise location uncertain. Note the former shaft (brick-lined) to the right of the scene. (British Association for the Advancement of Science Photographic Collection.)

Plate 10 Spring Wood opencast coal site [348 318] as seen in 1945: backfill area to the left: excavation in the Middleton Little Coal far centre.



GEOLOGICAL IMPLICATIONS FOR PLANNING AND DEVELOPMENT

This section of the report sets out the main categories in which geological conditions may have an influence on land-use planning and development. Further information relating to these categories is provided in the description of the thematic maps. The main items which should be considered in the planning stages are mineral resources, water resources and engineering geology.

Mineral resources

There remain few geological resources within the district because of sterilisation by urban development and extensive former coal-mining.

Brick clay

Brick clay has been worked extensively in the past, from a number of geological horizons, mainly in the Coal Measures (Plate 9) and resources of brick clay are extensive in the eastern part of the district. Currently only the works [386 314] near Swillington is active (Plate 3) and economic considerations are unfavourable to the establishment of new plants.

Coal

Underground mining in this district had ceased by 1981 with the closure of the local workings from the Ledston Luck colliery [4293 3083]. Prior to this, much of the activity ended in the post-war years, although Primrose Hill colliery [3874 2973; 3898 3136] was worked until 1970. Much of the district, to the south and east of the city centre, has been mined at some stage.

Opencast mining has been extensive since its inception in the 1940's. Whereas the early workings exploited seams close to crop at shallow depth (Plate 10), deeper excavations now permit mining beneath considerable thicknesses of overburden. Currently the large Skelton (Grange) site [3431] is being worked (Plates 11–13). Some smaller sites have worked ground where shallow mining had left underground cavities, thus restoring potentially unstable ground.

Limestone

Magnesian Limestone has been worked within and to the east of the district as a source of aggregate, building stone and agricultural lime. There is insufficient information to provide an indicative assessment of the resource within the district, although in general it is probably too thinly developed for commercial exploitation.

Sand and gravel

Although sands and gravels are present extensively within the river terrace deposits and beneath the alluvium of the Aire valley, much has been sterilised by urban development. A substantial resource remains downstream, in the Oulton-Castleford area (Giles, 1988).

Plate 11 Opencast coal working at Skelton showing faulted strata above the Middleton Main Coal [3492 3106].

Plate 12 General view of Skelton opencast site [3499 3085].

Plate 13 Extraction of folded Third Brown Metal Coal near a fault at Skelton opencast site [3486 3082]

SANDSTONE

Sandstones within the Carboniferous sequence have been dug extensively in the past for building, roofing, flagstone and general aggregate. In particular, much of the outcrop of the Elland Flags was exploited for flagstone. At present the Rough Rock and the Rough Rock Flags are dug at Horsforth Woodside [255 376] for flagstone and aggregate (Plates 1 and 2).

SECONDARY SOURCES OF AGGREGATE

Some materials excavated from construction sites are suitable for bulk fill purposes, such as the construction of embankments. The sources include unweathered Cadeby Formation, selected sound Carboniferous sandstones and sands and gravels of the river terrace deposits. Mudstones may also be suitable if emplaced immediately after excavation.

Aspects of the excavatibility and suitability as fill of these various materials are detailed further in Appendix II.

Water resources

HYDROGEOLOGY

The main aquifers providing groundwater for industry in the Leeds area are the sandstone units of the Millstone Grit (the Guiseley Grit, the Huddersfield White Rock and the Rough Rock/Rough Rock Flags), and the sandstones of the Elland Flags in the Lower Coal Measures (Figure 3). The sandstones of the Millstone Grit are commonly coarse-grained, though locally of limited thickness (10–20 m), separated by shales and siltstones of somewhat comparable thickness, whereas the Elland Flags comprise about 50 m of fine-grained sandstones with siltstones and mudstones.

Parts of the outcrops of the aquifers and hence the recharge areas are shown on the Solid Geology map (Map 2). The structure of the ground and, in particular, the southerly dip of the strata cause each aquifer to lie at increasing depth southwards. The Rough Rock and Elland Flags, the main aquifers in Leeds, crop out under the northern suburbs of Leeds. The Elland Flags form extensive dip-slopes towards central Leeds near Armley, Headingley, Scott Hall, and Roundhay, and these are delineated by the locally steep-sided tributary valleys of the Aire such as Meanwood Beck.

Most water boreholes are less than 100 m deep, though some early ones were 300 m deep. As a combined result of the depth of the boreholes, and the disposition of the strata, most boreholes in north Leeds (north of gridline — northing 35) reach the Millstone Grit, commonly the Rough Rock/Rough Rock Flags, and to the south of this line, are usually into the Elland Flags. The geological details of selected boreholes are shown on the component 1:10 000 geological maps and in some of the accompanying BGS open file reports. Many of the boreholes are now abandoned and their sites uncertain.

The hydrogeology of the Leeds district is strongly influenced by faulting. A number of faults trend generally NE-SW, approximating to the general strike of the aquifers. Because some of the gritstone aquifers are generally relatively thin, faults with a significant throw may restrict groundwater movement southwards, as the aquifers become deeper. As a result of the faulting, the Huddersfield White Rock has a restricted outcrop in north Leeds. There is evidence from a number of boreholes that the fractured rock, adjacent to some faults, may provide enhanced yields.

Groundwater flow paths in the complex multi-aquifer system of the Leeds district are almost impossible to define, but on the broad scale, groundwater levels in boreholes indicate a general flow pattern towards central Leeds, as a result of groundwater abstraction in that area.

Yields from boreholes in the sandstones may be variable, depending particularly on the interception of fissures. However, rest and pumping water level data in the well records indicate transmissivities, for both the Rough Rock and the Elland Flags, of typically 5–40 m^2/d with consequent yields of up to 40 m^3/h. Very few new boreholes have been drilled for industrial use in Leeds in the last 15 years and thus there is only a limited amount of new relevant data.

GROUNDWATER ABSTRACTION

Water abstractions are licensed by the National Rivers Authority under the 1963 Water Resources Act. There have been considerable changes in the numbers and quantities of licensed groundwater abstractions since this Act came into force in 1965. From a total of 72 licensed groundwater abstractions in the area of grid-sheets SE 23 and SE 33, no less than 45 have been revoked, and the licensed quantity of groundwater abstraction has been almost halved from 8573 megalitres per year (Ml/ann) (1886 million gallons per year (mga)) to 4455 Ml/ann (980 mga) in 1991. Many of the licenses were revoked in the later 1960's and early 1970's and this reflects the decline of the textile and leather industries in the Leeds district. Individually, many of these industries had small abstractions, typically 68–136 Ml/ann (15–30 mga).

The boreholes still in use are mostly for the chemical and engineering industries and also for brewing, and are often typically licensed for 136–545 Ml/ann (30–120 mga). Abstraction sites are now concentrated in the Calverley Bridge area and the Kirkstall Road area, west of Leeds city centre, and the Hunslet area south-east of the city centre. In the past, abstraction sites were spread along the Aire valley from Rawdon to Leeds where, historically, many mills had been sited for water power during the Industrial Revolution. A number of industries sited close to Leeds city centre also had boreholes but these have been lost in urban redevelopment.

There are no groundwater abstractions for public supply in the study area, though extensive use was made of the Millstone Grit aquifers for public supply in the Guiseley–Yeadon area to the north-west of Leeds.

The sites of licensed boreholes (both active and revoked) are shown in Figure 3. The licensed abstractions are tabulated in Appendix V.

GROUNDWATER QUALITY

An extensive study of groundwater quality was undertaken by Marsland (1975) who analysed many water samples from the Carboniferous sandstones of the Leeds district. His studies indicated that water quality deteriorates down-dip in the aquifers. Groundwater quality is generally better in the Millstone Grit aquifers, particularly in the Rough Rock north of gridline northing 35, with a moderate hardness of 200–300 milligrams per litre (mg/l) and sulphate content approximately of 100 mg/l. Boreholes that reach the Rough Rock at a greater depth are likely to have more elevated levels of sodium and chloride, a phenomenon more noticeable in the boreholes in the Elland Flags, especially around Leeds city centre, where the sodium content may be more than 100 mg/l and the chloride content may also exceed 100 mg/l. The groundwater in the Elland Flags is also more likely to have a higher hardness, increasing down-dip from 200 mg/l to more than 400 mg/l in the city

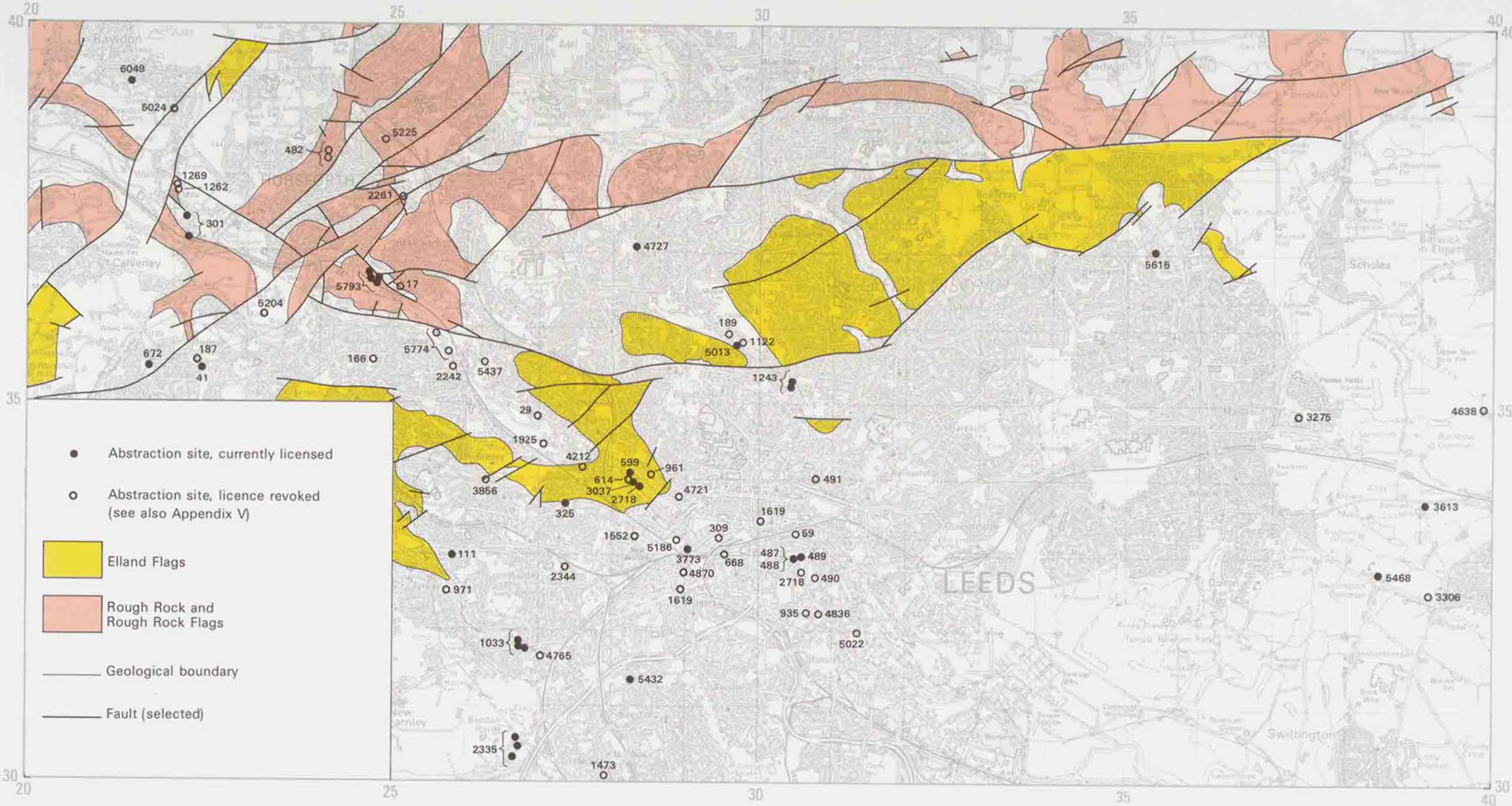


Figure 3 Groundwater abstraction sites and principal aquifers.

centre; the sulphate content increases similarly from 150 to more than 200 mg/l.

The available groundwater analyses indicate there may be a marked deterioration in water quality in the Elland Flags on the down-dip (southern side) of the narrow trough-fault which trends SW-NE through Leeds city centre. The general trend in water quality is of an increasing mineral content down-dip with some evidence of ion exchange of sodium for calcium/magnesium, probably facilitated by the clay minerals of the mudstones. The presence of naturally softened water, though possibly with a high mineral content, in deep grit aquifers was often exploited in the West Yorkshire textile industry in the past, though to a lesser degree in Leeds than in the neighbouring Huddersfield and Bradford districts.

Where the aquifers are confined, the groundwater frequently contains iron and manganese, in their reduced state. Hydrogen sulphide and methane may also be present (the latter is believed to have caused an explosion at one site). Borehole headworks thus require adequate ventilation to allow dispersion of gases. The poor quality of the groundwater may limit its value for industrial uses without suitable treatment, especially where the aquifers are confined by considerable thicknesses of mudstones.

Groundwater protection

The National Rivers Authority is currently preparing an Aquifer Protection Policy to protect the quality of underground waters. This is generally achieved by seeking to control the activities that take place on the aquifer outcrop particularly in the groundwater catchments of public supply boreholes or boreholes that are used for potable water. The policy is intended chiefly for application in major aquifers, and has the following limitations in a district such as Leeds:

a) The outcrops of the aquifers are narrow, and the complex geology and faulting make it very difficult to determine the groundwater catchment of boreholes.

b) Boreholes usually penetrate more than one sandstone and the descriptive logs may not precisely identify the horizons that are aquifers.

c) The recharge areas (outcrops of aquifers) and hence protection zones may be some distance from the boreholes and not encompass the borehole site itself.

d) The recharge areas lie mostly within the urban development. The recharge to the aquifer is therefore likely to have some degree of urban pollution.

e) The quality of uncontaminated groundwater over large parts of the Leeds district is probably on the borderline of potable standards.

Because of the nature of the structural geology of the aquifers, there may be a considerable distance between the recharge area and the abstraction point, so travel times are long and the risk of bacteriological pollution is therefore reduced. The confining mudstones may serve to protect the abstraction point from surface contamination at the site, although the design of the headworks may still form an easy pathway for pollution of the pumped water.

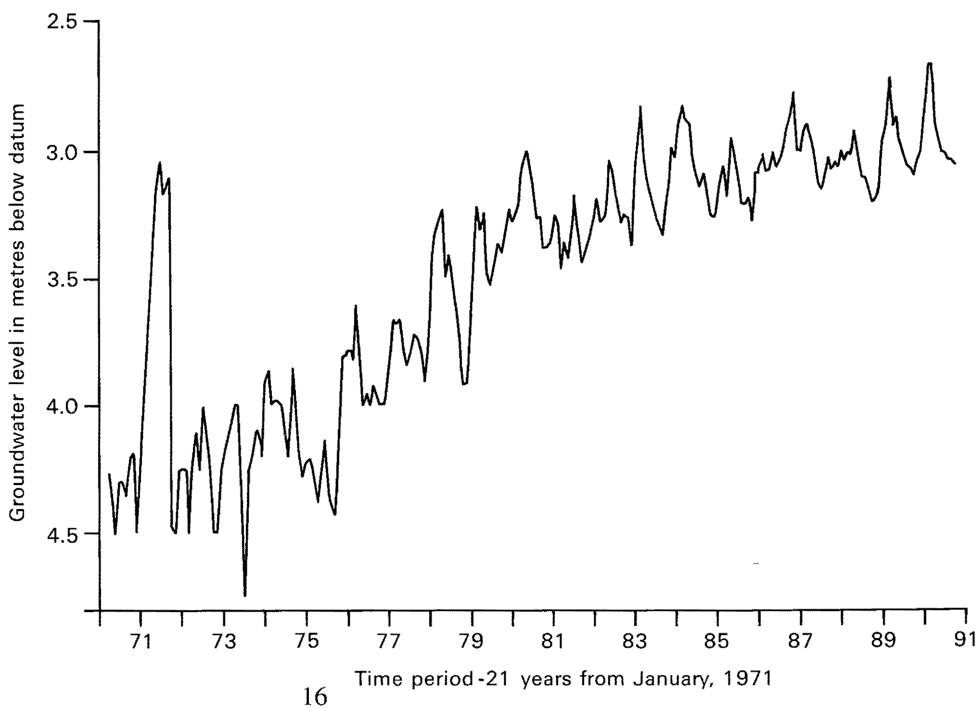
Effects of mining

The southern part of the Leeds district has been considerably affected by mining. The worked out coal seams sometimes form aquifers that may considerably enhance borehole yields. However, the withdrawal of hydraulic support in the old coal workings may give rise to subsidence and British Coal, who are liable for mining subsidence claims, may require boreholes to be cased and grouted through old coal workings. In the areas of suspected mine workings the NRA will refer proposed abstraction boreholes to British Coal for their comments before granting consent for a borehole to be drilled and test pumped.

Groundwater level monitoring

The NRA monitors the groundwater level monthly in the disused borehole at Trident House [285 341]. The hydrograph is shown on Figure 4. This is the only borehole monitored in the Leeds district, and is situated close to a number of licensed abstractions in the Kirkstall Road area. The figure shows a progressive rise of groundwater level in response to reduced local abstraction. This site should not be taken as representative of the district as a whole,

Figure 4 Groundwater level variations in Leeds.



but may be indicative of a general trend in terms of local demand.

SURFACE WATER ABSTRACTIONS

The River Aire is generally of poor quality and little used as a source of water, except for cooling purposes. Two major abstractions for cooling water have used shallow boreholes in the alluvial sands and gravels alongside the River Aire. No information is available on the quality of the water abstracted compared to the quality of the river water. One of these abstractions has now ceased.

FUTURE PROSPECTS

Water boreholes in the district are somewhat unpredictable in terms of groundwater yield and quality. Boreholes in Leeds have generally provided yields in the range 25 to 40 m^3/h, sufficient for most industrial uses. The water quality is commonly acceptable, in terms of mineral content, but the presence of iron and manganese, in their reduced state, in significant amounts may be troublesome. Some form of treatment may be required to remove these elements and this may have severe repercussions on the cost of private supplies.

Because of the large reduction in groundwater abstraction in Leeds over the last two decades, there are no restrictions on applications for groundwater licence abstractions subject to the normal provisos on derogation of existing sources. An application to drill and test pump a borehole must be submitted to the National Rivers Authority before construction of a water borehole.

Made Ground

The distribution of the principal areas of made ground is shown on Map 4 and, in so far as records exist, the nature, maximum thickness and dates of re-soiling of the fill materials are catalogued in Table 11. The areas of existing made ground are mainly:

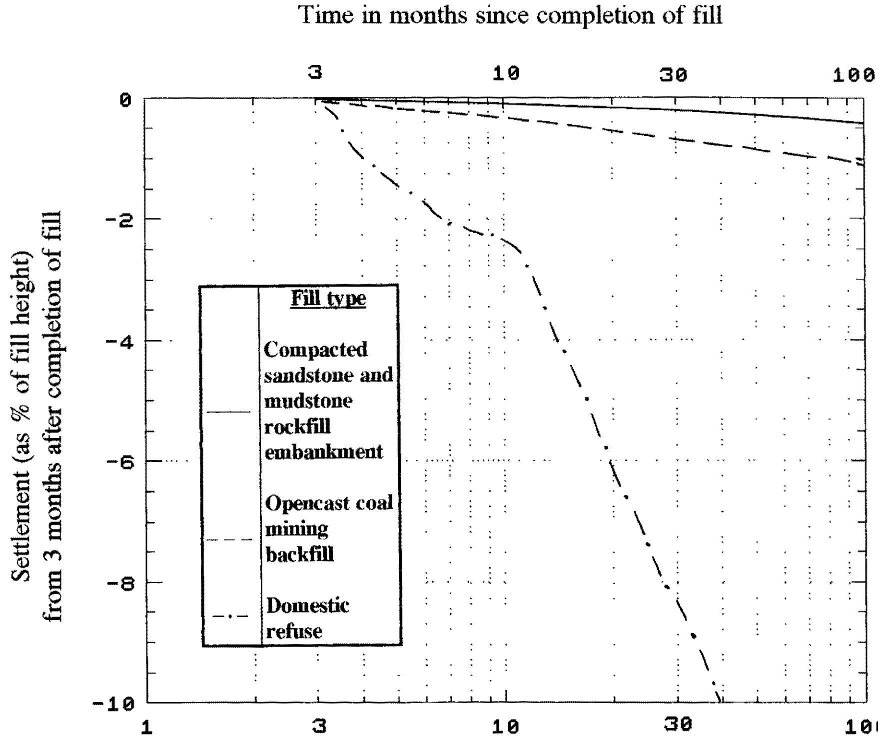
Infilled beck valleys
Made up ground levels on low lying, marshy or soft ground which was often prone to flooding
Backfilled sludge lagoons
Backfilled quarries, clay-pits and opencast sites
Demolished large industrial sites
Demolished areas of (predominantly terraced) housing stock.

The largest volumes of landfill are those of former opencast sites (Plate 14). Serious problems can arise where construction takes place on filled sites, and all made ground should be treated as suspect because of the likelihood of extreme variability in the composition of the fill materials (some of which may be hazardous to health or harmful to the environment or building) and their compaction/settlement characteristics. Not all made ground will present problems, as some of the fill material will be inert and possibly well-compacted, but the following points should be borne in mind:

a) where fill has been placed above ground level, as in infilled becks and made up levels of low marshy ground, it may rest on soft alluvial clays or peats which may themselves un-

Plate 14 Reinstatement of the former Gamblethorpe opencast coal site as a landfill area [368 306].

Figure 5 Settlement rates of different types of fill (vertical compression plotted against $\log_{10}$ time) [from BRE Digest 274].



dergo excessive differential consolidation settlement when loaded; this will be additional to that resulting from the compression of the fill itself. The stability of the ground underlying the fill may, therefore, need to be examined.

b) if structures are built on piles passing through the fill into underlying strata, 'drag-down' of the piles due to negative frictional forces caused by the fill settling under its own weight may be a major consideration in foundation design.

c) where the fill is deep, self-weight will often be the principle cause of long-term settlement. With granular fills and poorly compacted unsaturated fills of all types, the major compression occurs almost immediately and consequently most of the settlement due to self-weight occurs as the fill is placed. Nevertheless, significant further movements ('creep' settlement) do occur under conditions of constant effective stress and moisture content. With many fills the rate of creep compression decreases fairly rapidly with time and shows an approximately linear relationship when plotted against the logarithm of time elapsed since the deposit was formed (Figure 5).

It should be remembered that an increase in stress due to changes in applied load or moisture content may cause much greater movements than those shown in Figure 5.

d) compression of fills by building loads will be very variable depending on the nature of the fill, its particle size distribution, compactness, the existing stress level, the stress increment and the moisture content. Assuming the stress increments due to building loads do not bring the fill close to bearing capacity failure, settlements can be most simply calculated using a compressibility parameter related to one-dimensional compression. This parameter, the constrained modulus, is defined as $\Delta\delta_v / \Delta\varepsilon_v$, where $\Delta\delta_v$ is an increment of vertical stress, and $\Delta\varepsilon_v$ is the increase in vertical strain produced by $\Delta\delta_v$. Some typical values of constrained modulus for different fill types are shown in Table 2.

It should be realised that movements which occur during building construction are likely to be much less of a problem than those which occur after completion of the structure. The long-term creep component is therefore of particular significance (see 'c' above).

e) loose unsaturated fill materials are usually liable to collapse settlement following inundation with water. If this occurs after construction, a serious settlement problem may arise. It is believed that this is often a major cause of settlement problems in building development on restored opencast mining sites. Problems can also be caused by water penetrating into the fill from the surface through deep trench excavations for drains associated with building development.

f) when fine material is placed underwater, as in sludge lagoons, a soft cohesive fill is formed which is characterised by low permeability. Settlement is controlled by a consolidation process in which excess porewater pressures dissipate slowly as water is squeezed out of the voids in the fill. This type of fill may be susceptible to liquefaction, and often a firm but thin crust, overlying very soft material, may form over the surface of the lagoon deposit.

g) excessive differential settlements, leading to distortion and damage to buildings, are to be expected in highly variable poorer types of fill, or where the depth of fill changes rapidly. Where the made ground backfills a pit or quarry, it will invariably be less compacted than the surrounding natural ground, leading to differential settlement in foundations that straddle the edge of the filled area.

h) at sites in areas of demolished industrial buildings and housing, load-bearing walls may be present at or close to the surface of the fill. New foundations built across such walls and the surrounding fill are liable to severe differential settlements. Such sites may also contain basements, cellars, tunnels and service ducts which may be only partially filled with rubble and often remain as complete voids.

i) the problem of differential settlement may be compounded in cases where cavitation results from chemical or bacterial breakdown of the fill material.

Table 2 Compressibility of fills (from BRE Digest 274).

Fill type	Compressibility	Typical value of constrained modulus (kN/m2)
Dense well-graded sand and gravel	very low	40 000
Dense well-graded sandstone rockfill	low	15 000
Loose well-graded sand and gravel	medium	4 000
Old urban fill	medium	4 000
Uncompacted stiff clay fill above the water table	medium	4 000
Loose well-graded sandstone rockfill	high	2 000
Poorly compacted colliery spoil	high	2 000
Old domestic refuse	high	1 000 - 2 000
Recent domestic refuse	very high	--

j) fill comprising industrial waste may be potentially chemically active and capable of generating dangerous or combustible gases and toxic leachates.

k) domestic refuse will generate methane gas, which is highly combustible.

l) colliery spoil, which probably constitutes the greatest part of the made ground in this area, may be liable to spontaneous combustion, and tends to produce sulphate-rich acidic groundwater leachates causing corrosion problems in buried foundations. The leachates may also affect the quality of surface water.

Former mining

1) Opencast sites

These sites have been discussed under the category of 'made ground', and the implications for planning and development are as discussed above.

2) Bell pits, mine shafts (and well shafts)

Early mining of coal (and ironstone) was carried out from bell pits, initiated from shafts about 1 m in diameter and up to 10 m deep. The working of coal from the base of the shaft created a bell-shaped void, with an unsupported roof to the coal seam. The excavated area of coal was roughly circular in plan and up to 6 m in diameter. As examples, the Middleton Main Coal was worked in this fashion near Hunslet Carr (Figure 6) and Halton (the latter still visible).

In many cases the bell pits were only partly backfilled and the present state of compaction is almost certainly very variable. The fill materials usually consist of silty clay and moderately to completely weathered mudstone fragments with traces of coal and/or ironstone nodules. Rotting timbers are sometimes encountered. Weathering of pyrite in the fill may result in high levels of sulphate and acid conditions, but the limited chemical tests obtained in this study have not substantiated this.

Although bell pits have usually been backfilled to a greater or lesser degree, mine shafts have often been left empty. When shafts are backfilled, a poor state of compaction nearly always exists in the highly variable fill materials, and voids are common. Even when a mine or well shaft has been capped within the last 40 to 50 years, voids may not have been filled and old caps may be in a poor condition (although a number of mine shafts have been capped to standards set by British Coal over the last 50 years).

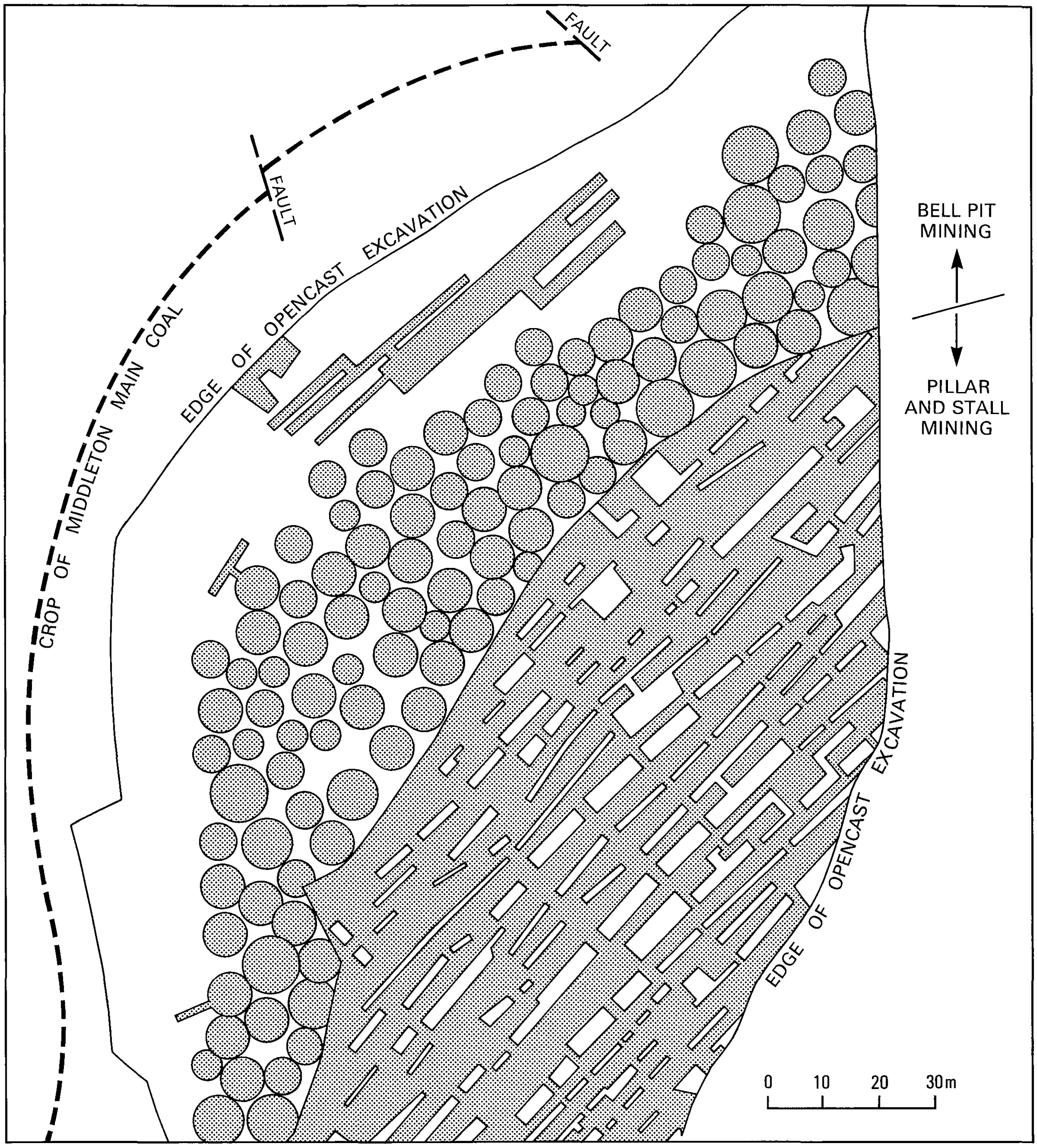
Collapse of shaft caps over empty shafts, collapse of the shaft fill leaving a void, and collapse of shaft linings into a void resulting in surrounding superficial deposits being drawn into the shaft are all potential threats to surface development. Building over shafts can result in severe differential settlement problems and, at worst, sudden ground failure is possible. Building over or close to shafts should be avoided, unless they have been treated to a standard suitable to safeguard the safety of the development, even though some structures have existed over such sites for centuries without damage (for example, Mount St. Mary's Church, Richmond Hill).

When located, shafts should be treated to a standard suitable for the subsequent use of the site, for example by filling with pea gravel, grouting and capping. Grouting of the generally cohesive backfill in old bell pits may not be successful. Treatment by vibro-replacement to support light structures is possible, but some differential settlements should still be anticipated. It may sometimes be cost-effective to opencast sites occupied by bell pits. Foundations can then be placed on underlying rock, or on overburden following its replacement in well-compacted layers.

In addition to adverse settlement characteristics, old shafts may also provide potential problems as pathways for noxious or explosive gases, or polluted groundwater.

It is essential that efforts are directed to locate the sites of old bell pits and mine/well shafts prior to construction and development. This is not always straightforward. Very few site descriptions given in site investigation reports for the Leeds area have noted the presence of open pits or hollow depressions in areas of old bell pit workings. This may be largely due to these 'tell-tale' features being obscured by centuries of agricultural, and other, activities. The locations of many shafts can be obtained from British Coal's shaft register, Leeds City Council (Architects Department),

Figure 6
The extent of shallow mining of the Middleton Main Coal, as revealed by part of the Middleton Broom Opencast site (courtesy of British Coal).



the Inland Revenue Valuation Office and the various editions of Ordnance Survey topographic maps. British Coal retains records of shafts properly filled and capped to prevent collapse. Where old bell pits or shafts are suspected, and no records exist, site investigations should consider and employ a combination of the following elements:

Aerial photographs The study and analysis of these is often very successful in identifying anomalous tonal features indicative of old shafts and pits.

Geophysical surveys (electromagnetic, magnetic and cross-hole seismic surveys and ground probing radar) These may be very successful where shafts are empty, contain significant voids, or where backfill material is significantly different from the natural ground. Less success is likely where insufficient contrast exists between the natural ground and the infill material (this is particularly likely in the case of bell pits). Useful guidance on the geophysical techniques appropriate to the location of shafts and mineworkings, located at different depths and overlain by varying thicknesses of fill cover, is given in the Geological Society Working Party Report on Engineering Geophysics (Anon, 1988).

Trial pitting/trenching This should be carried out as a matter of course and to confirm the presence of ground anomalies identified from aerial photography or geophysical methods. Where the fill cover is thin (<5 m) pitting and trenching may be employed as a relatively inexpensive alternative to a geophysical survey.

Boreholes Boreholes are an inefficient and expensive method of locating shafts, but once located, boring is essential to prove depths of shafts and composition and consistency of the backfill. If shell and auger tools meet suspected obstructions within the fill, the holes should be completed by rotary open-holing until the full shaft depth, and the presence or absence of voids, are ascertained.

3) SHALLOW MINE WORKINGS: PILLAR-AND-STALL (OR STOOP AND ROOM) WORKINGS

During the 15th and 16th centuries, the pillar-and-stall method of mining was developed to gain access to deeper reserves of coal. With this system, widely employed in the 18th and early 19th century, larger pillars are required to support the roof with increasing depth and thus it was self-limiting in terms of economic usage. In West Yorkshire the maximum feasible depth may have been about 30 m (Giles, 1988). General dimensions of these workings (Bell, 1978) are summarised below:

— Workings penetrated only about 40 m from the shaft in the 15th century, increasing to about 200 m by the 17th century.

— Room size increased with time from, usually, less than 2 m wide in the 15th century to a range of 1.8 to 5.0 m in the 19th century.

— Extraction ratio ranged from 30 to 70 per cent, showing a general increase with time.

In Leeds, the depth to the roof in uncollapsed workings is rarely less than 6 to 10 m, but in the vicinity of Mount St. Mary's Primary and Secondary Schools and Church, workings were encountered at depths of only 3 m below ground surface (in the Beeston Coal) due to exceptionally good mining conditions (Plates 7 and 8). It is probable, therefore, that the whole of Richmond Hill, where this seam occurs, is honeycombed with these workings (Hollands, 1990). The old workings may be dry or flooded.

These shallow workings did not totally collapse when mining ceased. They thus may pose serious problems for new construction work and are probably the single most common cause of structural damage in the Leeds area. Piggot and Eynon (1978) noted three principal mechanisms of failure of shallow mine workings:

a) squeeze of floor or roof strata

b) pillar failure

c) collapse of roof beds spanning adjacent pillars

Mechanism (a) is a relatively short-term effect unless influenced by changes in groundwater conditions. Mechanism (b), collapse of pillars, is comparatively rare unless the pillars were 'robbed' at a later date. Pillar collapse may result from deterioration due to weathering, but is a rare occurrence. Also, material from roof collapses provides lateral restraint which tends to enhance the strength of the pillars by 'buttressing'. Pillar collapse can be precipitated by longwall mining below old workings, but as much of the Leeds area lies within the abandoned coalfield, it is unlikely that further deep mining will occur. Pillar failure will tend to occur below about 30 to 50 m depth where the uniaxial compressive strength of the coal is exceeded by the pressure of overburden. However, as most of the workings are over 100 years old, 'crushing out' of the pillars, which leads to surface settlements, is likely to have ceased in all but a few cases.

Mechanism (c) is a major cause of ground instability problems as the collapse of roof beds spanning adjacent pillars may lead to upward propagation (migration) of a void. This can sometimes occur within a few months but, often, takes place many years after mining has ceased. When void migration occurs, the material involved in the fall 'bulks', which means that the migration is eventually arrested, but the bulked material never completely fills the void. At shallow depth, void migration may continue upwards to the ground surface leading to the possible formation of a crown hole. The height to which a void will migrate can, in general, be estimated by using the following expression (Bell, 1978):

$$H = t\left[\frac{\rho 1}{\rho} / \left(1 - \frac{\rho 1}{\rho}\right)\right]$$

where, H = height of migration
t = height of original void (usually the thickness of the seam worked)
ρ = bulk density of the roof rocks in place
ρ1 = bulk density of the collapsed roof materials

Piggot and Eynon (1978) showed that the maximum height of the zone of collapse is commonly up to 6 times the height of the mine void but may, exceptionally, exceed tenfold. In the Leeds area, local engineering experience suggests that between 5 and 7 times the height of the original mine void is a realistic figure (Hollands, 1990). Site investigation procedures in areas where old workings within c.30 m of the ground surface are suspected should include:

Rotary openhole drilling using air flush to search for voids and collapsed roof rock, and to prove the thickness of coal seams.

Trial pitting with a suitably powerful excavator if workings are at very shallow depth (less than 6 m).

Selected cored boreholes are useful to identify the lithologies overlying the workings, and to assess their strength and stability by laboratory testing of core samples. They are also useful to assess stability of pillars.

Geophysical methods (electrical resistivity soundings, gravity and cross-hole seismic surveys) may also be effective in locating and ascertaining the extent and dimensions of some old workings (Anon, 1988).

Once the old workings are identified and their extent and depth established, a number of options are available for site development and construction:

i) Avoid building over the potentially unstable area. This area includes a peripheral zone of influence, usually defined by projecting an angle of 25° to the vertical from the periphery of the workings at the worked level to the ground surface.

ii) Dig out the workings so that foundations may then be placed on exposed rock at the base of the workings or on replaced and compacted overburden. This may have the ancillary benefit of the extraction and sale of remaining coal, thus offsetting some of the reclamation or development costs.

iii) Use reinforced raft foundations. Rafts are often the best option for light structures. If crown hole formation is a possibility, rafts should be designed to span a void at least 2 to 3 m in diameter.

iv) Piling into sound rock below the worked coal seam is generally the best option for heavy structures. Bored, cast in situ piles are preferable to driven piles as the latter are prone to destabilise the workings and may be difficult to drive through Coal Measures rocks. Piles are at risk of being buckled or sheared by collapsing strata and appropriate pile diameters and suitable concrete, reinforced over the full pile length, should be used. Bored piles should be sleeved to avoid loss of concrete into voids and to reduce the 'drag-down' on the piles, should the strata overlying the workings subside.

v) The grouting of old workings and any migrating voids (including the peripheral zone defined by the 25° angle of influence) may be a suitable solution for ground improvement, particularly for expensive structures that can not tolerate even small differential settlements. A drawback to this method, however, is that it may be difficult to ensure that all the voids have been grouted. Also, delivery pressures, which are often necessarily high, can lead to ground heave, and a low viscosity grout (to ensure void penetration) may result in a high grout-take into the surrounding rocks if they are fractured. Further, groundwater, if flowing through the workings, may be dammed by the grout and result in an increase in the head of water, high pore pressures, uplift forces and erosion. It has been suggested by K. Wardell and Partners (unpublished report, quoted in Hollands, 1990) that, unless grout-take has been high, the bearing capacity of the grouted zone is unlikely to exceed 150 kN/m^2. It may, therefore, be necessary to ensure that heavy 'point' loads (eg. from pad foundations) are not sited in or so close to the grouted zone as to induce high settlements or shear failure.

The treatment of disused mine openings was detailed further by Freeman Fox Ltd (1988).

4) LONGWALL MINING

The longwall method of mining, which involves total extraction of a panel between two parallel headings, enabled deeper seams to be mined after its introduction late in the 19th century. Subsidence from longwall mining is usually rapid (within days of extraction) and residual subsidence is generally completed, typically, within 2 years of the cessation of coal extraction. Maximum subsidence, up to 80 per cent of the seam thickness, occurs when the width of the panel exceeds 1.4 times the depth of the seam below surface (Healy and Head, 1989).

Longwall mining has ceased in the Leeds district. No further mining is, at present, contemplated and most of the past longwall mining took place at considerable depth. In most areas, therefore, the presence of past longwall mining beneath a site is unlikely to compromise the integrity of future structures. In those areas where longwall mining occurred at relatively shallow levels (less than about 50 m below ground surface), site investigation techniques should be the same as for those suggested for pillar and stall workings. However, where the stowed waste ('goaf') is well compacted, it may be difficult to recognise the workings by rotary openhole drilling. In such cases it will be necessary to selectively 'spot' core (ie. openholing to an estimated 1 to 3 m above the suspected level of the workings, followed by core drilling until the workings are fully penetrated).

Where shallow longwall workings exist, roadways may still remain open and there is the possible risk of void migration above them. Also, the 'goaf' is much weaker than the natural adjacent strata and heavy structures which stress the goaf may experience larger than anticipated settlements. End-bearing piles terminated just above the level of the workings could 'punch through' when loaded. If the repositioning of planned structures away from the affected area is not a viable option, grouting of open roadways should be a relatively simple and successful solution, but the cost of such work should be compared with the use of reinforced foundations (e.g. rafts) within the localised area of risk. Where the goaf is likely to be stressed due to heavy foundation loads, allowances should be made in design to cater for additional settlements. Bored piles should be keyed into the floor rock (i.e. at or below the base of the workings). Light structures are unlikely to be affected.

Natural ground conditions

Few serious problems should be experienced in most undisturbed ground, particularly for light to moderately loaded structures, provided adequate site investigation is undertaken. However, particular difficulties may be encountered in the following situations:

1) SOFT GROUND (ALLUVIUM AND HEAD DEPOSITS)

Areas of soft ground are encountered in areas of alluvial clays and silts (i.e. in the floodplain of the River Aire and its tributary valleys). Due to artificial straightening of the River Aire channel, abandoned meanders (which may contain soft, compressible organic clays and silts hidden beneath made ground) occur at several locations. It is important that these features are identified during site investigations prior to planned development. Poorly-drained, clayey Head deposits are also likely to give rise to soft conditions, but the patchy development and usually limited thickness of these deposits should not cause undue difficulty provided they are identified during site investigations and removed or appropriately accounted for in foundation design prior to construction.

Soft ground is characterised by low shear strengths and bearing capacities, is highly compressible and prone to excessive total and differential settlement when stressed. Where it is economic to do so, wholesale removal and replacement with suitable granular fill should be considered, otherwise special attention must be given to foundation design (e.g. piling to sets in underlying gravels or sound bedrock for moderately to heavily loaded structures or, for lighter structures, reinforced concrete rafts with edge beams). For piled foundations in thick alluvial deposits 'drag-down' of the loaded pile by consolidation of the alluvial clays should be anticipated.

2) HIGH GROUNDWATER LEVELS IN ALLUVIAL SANDS AND GRAVELS (ALLUVIUM: LOWER UNIT AND SOME RIVER TERRACE DEPOSITS)

Severe water inflow problems will be encountered in excavations in highly permeable alluvial sands and gravels and whenever possible, foundations and services should be placed well above the water table. Diaphragm walling, grout injection and ground freezing are possible, but expensive, options for the exclusion of groundwater from excavations. Sheet piles are a less expensive alternative but may prove difficult to drive through dense gravels or gravels with included cobbles and/or boulders. All these techniques need to be applied through the full depth of the deposit. Drawdown of the water table using well point rings may be feasible but may be ineffective due to very high permeabilities. Drawdown may also cause settlement damage to existing nearby structures. Pumping tests should be carried out to assess in-situ permeabilities during site investigation.

3) MOISTURE SUSCEPTIBLE MUDROCKS

Mudstones of the Coal Measures and Millstone Grit are susceptible to rapid deterioration and softening when relieved of overburden pressure following excavation and in the presence of water. Increased moisture content can result in a reduction of shear strength, marked reduction in bearing capacity and loss of side friction for piles. Auger drilling for cast-in situ piles under wet conditions may also remould the mudstone lining the borehole walls to a soft clay. The deterioration of mudstones has been observed in foundation excavations in the centre of Leeds, where the exposed rock has altered to a slurry (0.2 to 0.3 m thick) in a matter of days. In the Adel district, contractors had to repeatedly deepen excavations that rapidly deteriorated to a mud slurry when the foundation level was reached.

Suspect mudstones should be subject to slaking tests during site investigation and be protected from water ingress during excavation by cut-off drains, sheet piling or similar measures. Borings for piles should be cased through water-bearing strata and, often, engineers aware of the problem will undertake pile design based on end bearing values only. To prevent deterioration in open excavations, the mudstone should be covered with a blinding layer of concrete as soon as formation level is reached and the side slopes protected by spraying with bitumen or other methods.

Variations in the depth and grade of weathering give rise to differing soil thicknesses and foundation conditions in the mudrock lithologies, and variable bearing capacities are to be expected in the weathered zone. It is recommended that during site investigations for shallow foundations, trial pitting is carried out as a matter of routine in order to ascertain the variation in weathering profiles.

Mudrocks may also pose a problem to shallow foundations during prolonged periods of drought, when they are prone to drying, shrinkage and cracking. Foundations should therefore be sufficiently deep to prevent this.

4) Geological faults

Geological faults are planes about which adjacent blocks of rock strata have moved relative to each other. Movement may be vertical, horizontal or, more likely, a combination of the two. Fault movements may be reactivated by mining, occasionally causing earth tremors. Faults are commonly complex, sheared zones rather than discrete planes, and such zones contain weakened, fractured and brecciated rock which promote deep weathering profiles and therefore varying bearing capacities. Lithologies with differing strengths and settlement characteristics may lie juxtaposed on either side of a fault. Foundations straddling this contact may therefore suffer differential settlement. This may not be a severe problem for light to moderately loaded structures, but heavy structural loads should be taken down to levels where differential settlements are of an acceptable magnitude.

Most structures cannot withstand the magnitude of movements initiated along faults by mining subsidence, and buildings should not be placed across faults unless the workings can be stabilised or it is certain that any existing subsidence is complete. It is therefore important that the precise positions of faults (and underground workings) are established prior to any future development.

5) Coal at foundation level

When coal is encountered, it should be removed to at least a metre depth below foundation level, and a suitable inert fill placed between the foundation and the coal as a precaution against spontaneous combustion. An alternative approach may be to opencast the site, which is advisable if previous partial extraction has left potentially hazardous ground conditions. The sale of coal from opencasting may help to defray the costs of remedial works.

6) Karstic features in Magnesian Limestone

Karstic features are formed by the dissolution of the soluble limestone by surface and ground waters percolating along joints and fissures. This results in highly variable rockhead levels, with hollows, depressions and channels in the limestone surface, commonly infilled with superficial deposits of variable thickness, lateral extent and composition. At depth, dissolution results in the formation of voids, cavities and enlarged open or partially filled channels following faults, fractures, joints and bedding planes. These features can lead to severe differential settlements below heavy structures and may preclude the use of shallow foundations except for light structures. Water inflow problems may also be encountered in excavations.

These might be a potential problem only in the localised limestone outcrops of the north-east corner of the study area.

7) Landslips and other superficial movements

Natural landslipping does not present a significant problem to development in the area. A few, generally shallow, dormant debris slides/flows and rotational slumps have been recognised during the geological mapping (see for example Map 3); the landslip deposits generally occur on or near the middle to lower parts of slopes, with angles over about 8 to 10°, in weathered mudstone below a coal seam and/or a capping sandstone (e.g. near Meanwood Grove [2815 3842]). Construction on these areas should be avoided wherever possible. If this is not feasible, it is essential that site investigations are undertaken to adequately define the geometry and current stability of the landslip (and adjacent ground) in order that suitable stabilisation measures can be designed and implemented prior to construction.

Minor, shallow slope movements (too small to be indicated as individual landslips on the geological maps, but identified from the presence of low arcuate scars above hummocky ground) are probable fairly common in the weathered mantle and/or Head deposits on mudstone slopes (e.g. at Farnley, north of Billey Lane [2552 3201]). Site investigations preceding development on, or near, these areas should ascertain the depth, areal extent and type of movement associated with these features so that appropriate remedial measures can be implemented. In some cases, small areas of landslip deposits may be removed completely and replaced with a free-draining granular fill. However, the mechanisms leading to initial failure must be ascertained and the likelihood of future potential movements in the affected areas and adjacent ground investigated in order to determine the best course of action.

The effects of cambering (p.39) may give rise to fissuring within sandstones, on the upper flanks of the deeper tributary valleys. Although such sandstones exist in the Leeds district, there is little documentary evidence to show that such fissures are a local problem.

THE THEMATIC GEOLOGICAL MAPS

Distribution of borehole sites (Map 1; Figure 7)

This map shows the borehole sites registered in the BGS database in the following categories:

1. Borehole sites with geological data only, including water wells.
2. Borehole sites with geotechnical data, in addition to standard penetration tests, not used in this study.
3. Borehole sites with geotechnical data, included in this study.
4. Shafts, with geological data.

For reasons of confidentiality and clarity, boreholes sunk for opencast coal exploration are not included. The non-confidential records may be examined at the BGS National Geosciences Data Centre, Keyworth, Nottingham, NG12 5GG, by prior appointment, or copies of records may be made available by post on receipt of the current fee. Confidential records may be examined only after permission has been granted by the owner of the information. The type, quality and quantity of information available for any one site may vary according to the original purpose of the borehole investigation.

Solid geology (Map 2; Figure 8)

This map depicts the distribution and nature of the bedrock lithologies, together with the areas affected by landslips. The vertical distribution of the solid formations is shown on the generalised section of strata.

It should be noted that at rockhead, the strata are generally weathered to material that is not 'rock' in engineering terms. The weathered mantle of the mudstones comprises clay, whereas that of the sandstones is variously sandy clay and silt with sandstone fragments. No drift deposits are shown here: their distribution and the levels of rockhead are shown on Map 3.

The location of geological boundaries is rarely a precise exercise, unless they are exposed in excavations or encountered in boreholes. The boundaries shown on the map are, therefore conjectural, but as accurate as possible, given the information available at the time of survey.

The portrayal of any fault as a single line on the geological map is a generalisation because such structures may consist of zones, perhaps up to several tens of metres wide, containing several fractures. The position of a fault is based on consideration of surface information and underground mining data, if available. In urban areas, and particularly beneath drift deposits, the evidence may not be sufficient to locate the fault precisely. On Map 1 only the surface positions of faults are shown. Where underground information has been used to locate a fault, an upwards projection on a 70° inclination, in the upthrow sense, was generally used for this estimation. Faults of small or indeterminate throw, recorded in mine workings, are not generally shown in this fashion, because these are likely to be impersistent.

Distribution of superficial deposits and levels of natural rock-head beneath (Map 3; Figure 9)

This map shows the distribution of the drift deposits and levels on the natural rockhead surface relative to 'sea level' (Ordnance Datum). Contours on the rockhead are plotted at intervals of 2.5 or 5 m (above Ordnance Datum) according to the amount and reliability of the available data. The effects of man-made excavations through drift deposits and into the bedrock are not generally taken account of. Exceptionally, however, near Newsam Green, such data are not shown where extensive opencast coal workings were carried out.

The map shows the deposits which occur at the surface. These may persist throughout the total thickness of beds down to rockhead. However, other deposits may intervene so that, for example, the alluvial clays are commonly underlain by gravels, and till deposits locally contain other lithologies, such as laminated clays or sandy gravel.

The limits of drift deposits are difficult to define, because such sediments are readily affected by soil creep, downwash, solifluction and cryoturbation (disruption by freeze/thaw activity). The excavation of trial pits is generally necessary to obtain a three-dimensional appreciation of the disposition of drift deposits.

It may be apparent that, at the feather edges of the drift deposits, the rockhead contour values do not necessarily accord with the contours of the adjacent surface topography, as might be expected. In practice, such a mismatch may be caused by the presence of thin, unmapped made ground or hillwash, resting on the bedrock.

Distribution of Made Ground (Map 4; Figure 10)

This map shows the distribution of man-made deposits as far as could be determined at the time of survey. Two categories are distinguished:

1. Deposits that lie on the original ground surface and in sludge lagoons, of uncertain history: termed unspecified fill.
2. Deposits that fill, or partly fill a former or existing pit, quarry, or other excavation: known as backfill.

A general criterion of minimum thickness (3 m) has been applied in this compilation in order to eliminate potentially very localised or ill-constrained areas of backfill, such as routes of service mains and infilled cellar-work, which may be detected by borehole investigations in redevelopment areas. The criterion cannot always be applied rigorously, because there is a need to depict some generally shallow, but extensive, backfilled quarries. Some road and railway embankments are not shown, for reasons of clarity. Most areas of landscaped ground are also excluded.

The maximum recorded thickness of fill in metres is shown by an arrow (not relating to any one specific point) where the available data are regarded as meaningful.

Deep coal mining (Map 5; Figure 11)

This map shows the areas recorded on mine plans as undermined in one or more seams at depths greater than 30 m. This information was collated from the data held by British Coal. The workings in much of the district are of considerable antiquity and their development was in places quite complex. The notification of coal abandonment plans was made compulsory in 1872 and so information is largely lacking for the earlier mines.

In order to highlight other areas of past mining, the positions of shafts which are known to extend to 30 m below rockhead but are outside the areas documented on plans, are also shown on this plot. Such sites may not be shown comprehensively, in that only the information available at the time of survey can be shown.

Quarrying and shallow mining (Map 6; Figure 12)

Shallow mining is here defined arbitrarily as that which penetrates less than 30 m below rockhead. This depth was selected because it is generally considered to be the maximum thickness of solid strata likely to be affected by collapse of pillar-and-stall workings in coal seams of a probable maximum thickness (i.e. 10 × maximum void height of 3 m: see p.21). Where there is more than 30 m of overburden, the effects of collapse are unlikely to reach the surface and create crown holes.

This map shows areas of shallow coal mining, opencast coal extraction and other quarries. There are evidently areas where shallow coal mining was attempted on a localised scale in less economic seams, as demonstrated by more recent opencast workings: these are emphasised on the map. It is important to be aware that, on a comparable scale, it is probable that adits were driven from the faces of clay pits which also exposed such coal seams.

The shallow coal workings are shown graphically in four categories:

1. where coal workings are known or inferred to be present, using the evidence of known workings, shafts, bell pits, etc. from original documentation and other sources
2. where localised coal workings are known to be present from subsequent opencast excavations or other evidence
3. where workable coal may occur but there is no evidence of workings from original documentation or other sources
4. where coal has been opencast mined.

Other workings, presently undetected, may be present near the crops of some inferior seams: these are annotated appropriately on the map. It is assumed that shallow mining was restricted, beneath the alluvium of the Aire valley, near the city centre (p.8).

It is essential that the British Coal Corporation is consulted for any site-specific enquiry.

The areas of quarrying for other materials are also shown on this map; there is generally some uncertainty concerning the internal and lateral extent of these features. The influences on the configuration of these excavations have been discussed previously (p.7). It should also be noted that some (poorly-defined) crop workings of coal may have exploited the underlying fireclay as well and thus the disturbed ground may now extend beyond the relevant coal crop. The term 'clay' is here used in the economic sense to embrace all argillaceous deposits including mudstone.

Engineering geology (Maps 7 and 8; Figures 13 and 14)

These maps classify the rocks of the area in terms of their engineering geological properties, and thus, depict areas where geotechnical conditions are broadly consistent. They are, however, only summary presentations and cannot reflect detailed conditions on a site-specific basis. The maps, together with the detailed discussion of the engineering geology, summary values of geotechnical parameters and descriptions of the geotechnical tests for which results were assessed (given in Appendices II, III and IV), present information that provides a better understanding of the general engineering geology of the area so that potential constraints on development can be identified and site-specific site investigations better designed.

The engineering geological units represent groupings of materials with similar geotechnical properties and anticipated engineering behaviour, which were identified from data extracted from site investigation reports for locations within the Leeds district. The distribution of the units is based on the geological maps produced during the study. Map 7 shows the engineering geology of the solid rocks and Map 8 that of the superficial (drift) deposits.

Both maps should be examined to obtain an indication of ground conditions in a specific area, and Map 3 should be examined to derive an approximate thickness of any superficial (drift) deposits. It should be noted that in areas shown as being drift-free, a mantle of weathered material and thin superficial deposits may be present. It is also possible that undetected pockets of thicker drift deposits may occur. Map 4 should be examined to ascertain if any made ground is present.

It is emphasised that these maps present only a general guide to the ground conditions in the study area, and they should not be used as a substitute for detailed site investigation to ascertain the conditions prevailing at any specific site. However, the maps provide a useful aid to efficient site investigation design and are a valuable source of general information relevant to planning issues.

Engineering geology of the solid rocks (Map 7;Figure 13). This map is based on the solid geology (Map 2). The relationship between the engineering geological units and the solid rock formations (mapped geological units) are shown in the map key and Table 3. The engineering geological characteristics of each unit, also described in the map key, are shown on Table 4, along with summary comments on engineering design considerations related to slope stability, excavatability, foundations and suitability as fill material. Brief comments highlighting potential geological constraints to engineering development are also given.

Most of the units shown on this map consist of 'engineering' rocks. However, because of weathering, some gradation between the states of rock and soil (in engineer-

Table 3 The relationship between the engineering geological units and the solid rock formations.

Engineering geological unit	Geological unit
Limestones	Cadeby Formation (Lower Magnesian Limestone)
Moderately strong sandstones	Lower and Middle Coal Measures sandstones Millstone Grit sandstones
Mudrocks	Lower and Middle Coal Measures mudstones and siltstones Millstone Grit mudstones and siltstones

Table 4 Explanation of engineering geological units: solid geology.

ENGINEERING GEOLOGICAL UNIT	GEOLOGICAL UNIT	DESCRIPTION / CHARACTERISTICS	PLANNING AND DEVELOPMENT CONSIDERATIONS				
			Slope Stability	Excavation	Foundations	Engineered Fill	Geological Constraints
Limestones	Cadeby Formation (Lower Magnesian Limestone)	Thinly to thickly bedded, fine to coarse-grained dolomitic LIMESTONE. Usually moderately weak when fresh or slightly weathered. Variable geotechnical properties due to variations in lithology and weathering. Topmost 0.5 to 1.5 m often weathered to calcareous silty clay with rock fragments. Zones of highly weathered rock may extend to at least 7 metres below ground surface.	Instability likely to be confined to minor rock falls and long-term degradation of rock faces. Cut faces of 1V:1H, regraded to 1V:2H in weak dolomites and highly weathered/faulted zones, are recommended as a guide.	Dependent on joint spacing. Ripping often required; thickly bedded rock with widely-spaced joints will require pneumatic breakers or minor blasting. Well-jointed, thinly-bedded or highly weathered and/or brecciated rock is generally diggable.	Use of shallow foundations, except for light structures, may be precluded due to excessive differential settlements and inadequate bearing capacities at shallow depth, arising from variable rockhead levels, solution cavities and highly weathered zones.	Suitable as rockfill provided care is taken in selection and extraction. Weaker, weathered material may be suitable as bulk fill only.	No major constraints. Use of shallow foundations may be unsuitable for all but light structures.
Moderately Strong Sandstones	Sandstones of the Millstone Grit and Coal Measures	Moderately to well-jointed, thinly to thickly-bedded, fine to coarse-grained SANDSTONES, with mudstone and siltstone interbeds and coal partings. Moderately strong when fresh or slightly weathered with medium to high mass permeability depending on joints. Depth and intensity of weathering is variable. Where exposed, topmost 1.5 to 5 m may be weathered to a silty, clayey sand/sandy clay. Highly weathered rock may be present to depths in excess of 12 m in the vicinity of faults.	Cut faces in fresh to slightly weathered, moderately-jointed rock may remain stable at steep angles. Where interbedded mudstones and siltstones are present, side slopes of 1V:2H have been used in design. Excavations in fault zones may need immediate support.	Dependent on joint spacing. Ripping and, in confined spaces, pneumatic tools are often required. Blasting needed for major excavations in massive rock. Highly weathered rock is usually diggable.	Dependent on bed thickness and depth of weathered zone. Generally good founding medium, but care needed not to overstress any underlying weathered mudrocks. In situ loading tests are advisable to assess selected sites. Possible undermining at shallow depth is overriding factor in assessing appropriate foundation requirements.	Suitable as high grade fill provided care is taken in selection and excavation. Suitable as bulk fill if uneconomic to separate from mudstone/siltstone interbeds.	No major constraints but presence and extent of any shallow mine workings must be ascertained prior to all construction.
Mudrocks	Mudstones and siltstones of the Millstone Grit and Coal Measures	Moderately fissured, weak to moderately strong, MUDSTONES and SILTSTONES. Weathering commonly alters rock to a firm to stiff mottled clay of low to high plasticity within 2 to 6 m of ground surface. Highly weathered mudstone clasts in a silty clay matrix may occur to depths of 10 to 15 m, and possibly deeper in fault zones. Tendency to deteriorate and soften when relieved of overburden pressure and in the presence of water.	Mudstones tend to soften and deteriorate when wetted. Side slopes of 1V:2H are suggested for preliminary design but drainage and regrading to 1V:4H may be needed where sandstone interbeds and perched water tables are present.	Weathered mudrocks are diggable; ripping or pneumatic breakers may be required at depth or for major excavations. In open excavations, foundation levels in moisture-susceptible mudstones need protection (eg. by blinding with concrete) to prevent rapid deterioration.	Dependent on nature and thickness of weathered zone. Foundation levels in moisture-susceptible mudstones should be protected in open excavations. In situ loading tests are advisable at selected sites. Possible undermining at shallow depth may be overriding factor in assessing appropriate foundation requirements.	Suitable as general fill under controlled compaction conditions. Should be placed as soon as possible after excavation and subject to minimum construction traffic when wet.	No major constraints, provided moisture-susceptible mudstones are properly engineered and presence and extent of any shallow mine workings are ascertained prior to all construction.

Table 5 The relationship between the engineering geological units and the superficial deposits.

Engineering geological unit	Geological unit
Made ground/fill	Made ground
Mixed, soft to firm cohesive / loose to medium dense non-cohesive soils	Head Alluvium
Mixed, stiff cohesive / dense non-cohesive soils	Till (boulder clay, moundy glacial deposits) with glaciofluvial sand and gravel
Non-cohesive sand and gravel deposits	River terrace deposits
Landslip deposits	Landslip

ing terms) occurs, particularly in the case of highly to completely weathered mudrocks of the Millstone Grit and the Coal Measures which weather to soft to stiff, silty clay.

Summary values of geotechnical parameters for each engineering geological unit are presented in Tables 12 to 18 in Appendix III. Detailed descriptions of the engineering geological units are given in Appendix II.

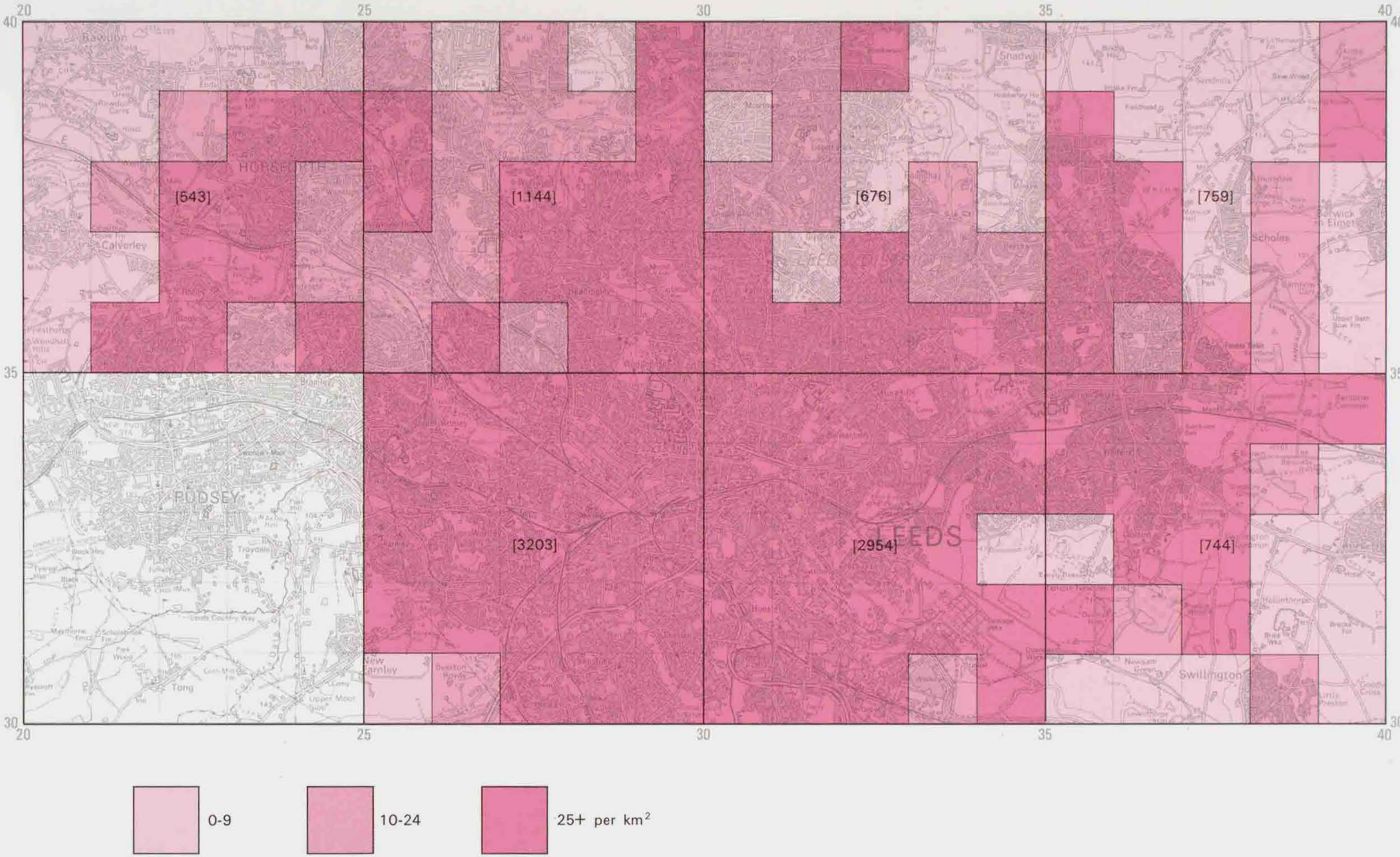
Engineering geology of the superficial (drift) deposits (Map 8; Figure 14). This map is based on the drift (superficial) geology (Map 3) and the distribution of made ground (Map 4). The relationship between the engineering geological units and their geological equivalents are shown in the map key and Table 5. The engineering geological characteristics of each unit, also described in the map key, are shown on Table 6, along with summary comments on engineering design considerations related to slope stability, excavatability, foundations and suitability as fill material. Brief comments highlighting potential geological constraints to engineering development are also given.

Made ground is a superficial deposit and an indication of its distribution and mention of its engineering characteristics are appropriate here. The materials comprising these areas can vary markedly from site to site across the study area and this variability is highlighted in the map key and Table 5, together with the potential for serious constraints to planning and development.

Summary values of geotechnical parameters for each engineering geological unit are presented in Tables 19 to 24 in Appendix III. Detailed descriptions of the engineering geological units, including made ground, are given in Appendix II.

Table 6 Explanation of engineering geological units: superficial deposits.

ENGINEERING GEOLOGICAL UNIT	GEOLOGICAL UNIT	DESCRIPTION / CHARACTERISTICS	PLANNING AND DEVELOPMENT CONSIDERATIONS				
			Slope Stability	**Excavation**	**Foundations**	**Engineered Fill**	**Geological Constraints**
Made ground/fill [See also Map 4]	Made Ground	Highly variable in composition, depth and geotechnical properties from site to site.	Not Applicable	Usually diggable.	Highly variable bearing capacity and settlement characteristics.	Variable. [See text comments]	Serious constraints possible. [See text comments]
Mixed, soft-firm cohesive / loose to medium dense non-cohesive soils	(i) Head (ii) Alluvium	(i) Soft to firm sandy silty CLAY with stones, of low to medium plasticity and compressibility; locally may be silty sand or gravel. Clayey Head may contain pre-existing shear surfaces. (ii) Very soft to firm, occasionally laminated, sandy, silty and organic CLAYS and SILTS of low to high plasticity, with impersistent layers or pockets of peat; and loose to dense, water-bearing, fine to coarse-grained SANDS and GRAVELS with variable clay lenses.	Lower/middle slopes with veneer of Head deposits are often marginally stable (ie. factor of safety at or close to 1)	Diggable. Immediate trench support required. Heave may occur at base of excavations in alluvial clays; running conditions likely in granular alluvial deposits; high water tables and risk of severe water inflows. Cut-offs and/or dewatering usually required.	Presence of soft, highly compressible zones with risk of severe differential settlements. Raft foundations or mini-piles bearing in basal alluvial gravels are suitable for light to moderately loaded structures. Heavy structures require piling to basal gravel or bedrock.	Generally unsuitable. Head may be suitable as bulk fill, but may be too wet to achieve satisfactory compaction.	Constraints on medium to heavy structures (must be founded on competent underlying strata). High groundwater levels in alluvium may preclude all building in some areas.
Mixed, stiff cohesive / dense non-cohesive soils	Till (boulder clay, moundy glacial deposits) with glaciofluvial sand and gravel	Variable lithologies, ranging from very stiff, stony, sandy CLAY (boulder clay) of low to medium plasticity, with bands of laminated clays and interbeds and lenses of sand and gravel; grading to slightly cohesive, clayey, silty SANDS and non-cohesive, medium to very dense, highly permeable, water-bearing sandy GRAVELS with lenses of silt and clay developed locally.	Cut slopes of 1V:2.5H are generally adequate for long-term stability in relatively homogeneous Boulder Clay.	Diggable. Ponding of surface water on low-permeability Boulder Clays may cause problems during working. Excavations in stiff clays generally stable in short term. Support required where lenses or interbeds of sand occur, or in granular deposits	Generally good founding medium. However, local lithological variations (particularly the presence of laminated silts and clays, or water-bearing sand layers) should be determined during site investigation stage.	Suitable if care taken in selection and excavation. Laminated clays may prove unsuitable, as may Boulder Clay occurring near water-bearing beds of sand and gravel.	No major constraints.
Non-cohesive sand and gravel deposits	River terrace deposits	Medium dense, fine to coarse-grained SANDS and medium dense to dense, fine to medium GRAVELS with occasional cobbles. Sandy clays and silts, sometimes laminated, occur locally, usually at terrace margins. In some areas, deposits may infill buried channels.	No information regarding performance of cut slopes. Stability dependent on lithological variations, presence of seepage zones and depth of cut.	Diggable. Trench support required. May be water-bearing.	Generally good founding medium. Care needed in some areas (eg. near Hunslet) to identify and ascertain depth, composition and bearing characteristics of any underlying infilled channels.	Sands and gravels suitable as granular fill. Terrace clays and silts are generally unsuitable.	No major constraints.
Landslip deposits	Landslip	Mainly remoulded clayey debris derived from weathered mudrocks and/or head. Generally soft, poorly drained and may contain one or more slip surfaces of low shear strength. Possible perched water table(s).	Construction activity is likely to reactivate slope movement unless appropriate stabilisation measures are undertaken. Detailed site investigation is essential, with extensive use of trial pits.			Unsuitable.	No major constraints (occurences are isolated). Where present, building should be avoided.



The numbers in brackets show the total number of borehole records for each quarter sheet.

Figure 7 Density of distribution of borehole sites. For full detail of sites see Map 1.

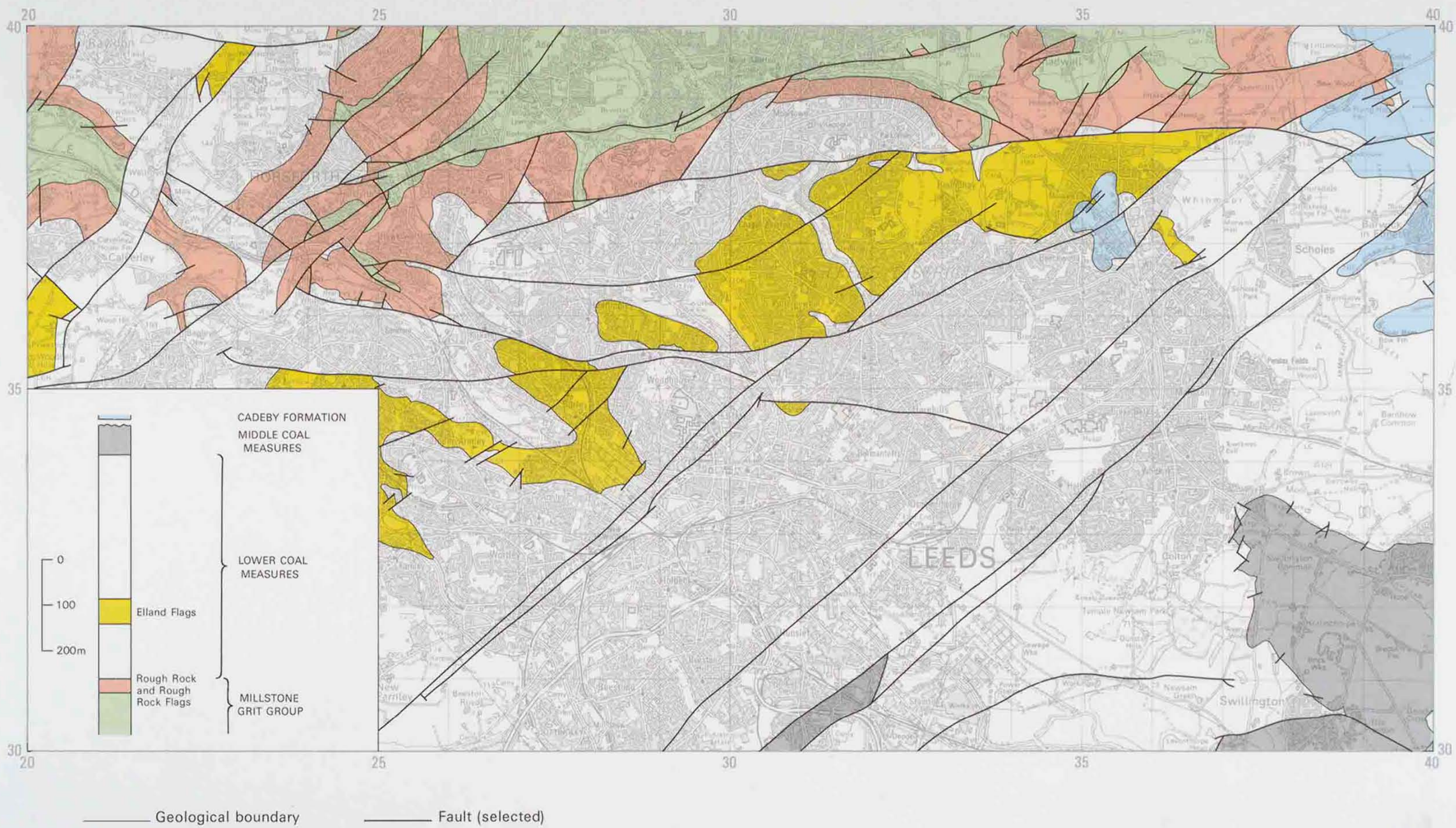


Figure 8 Simplified solid geology. For full detail see Map 2.

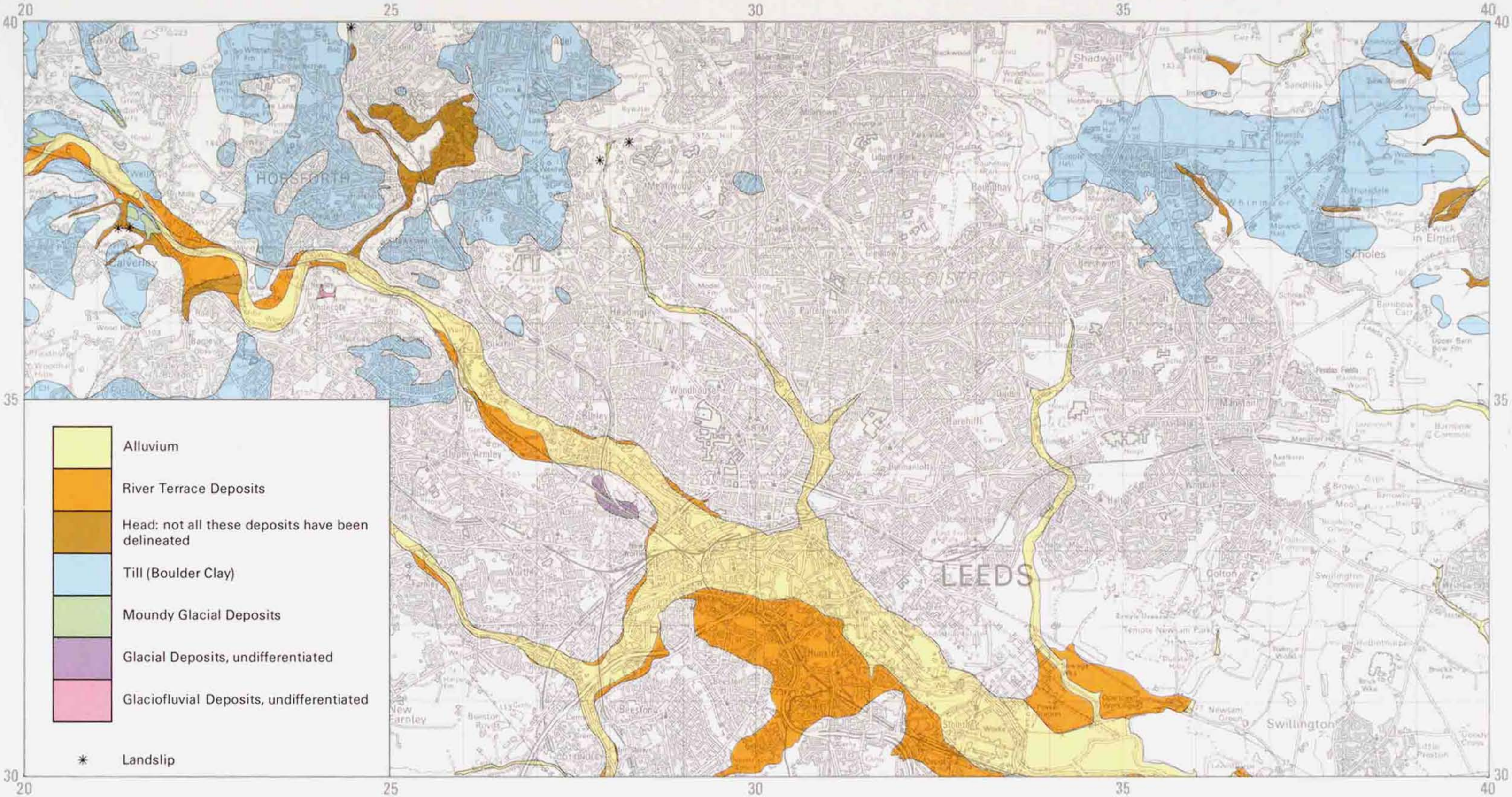


Figure 9 Superficial deposits. For full detail see Map 3, on which this generalised figure is based.

Figure 10 Distribution of made ground. For full detail see Map 4, on which this generalised figure is based.

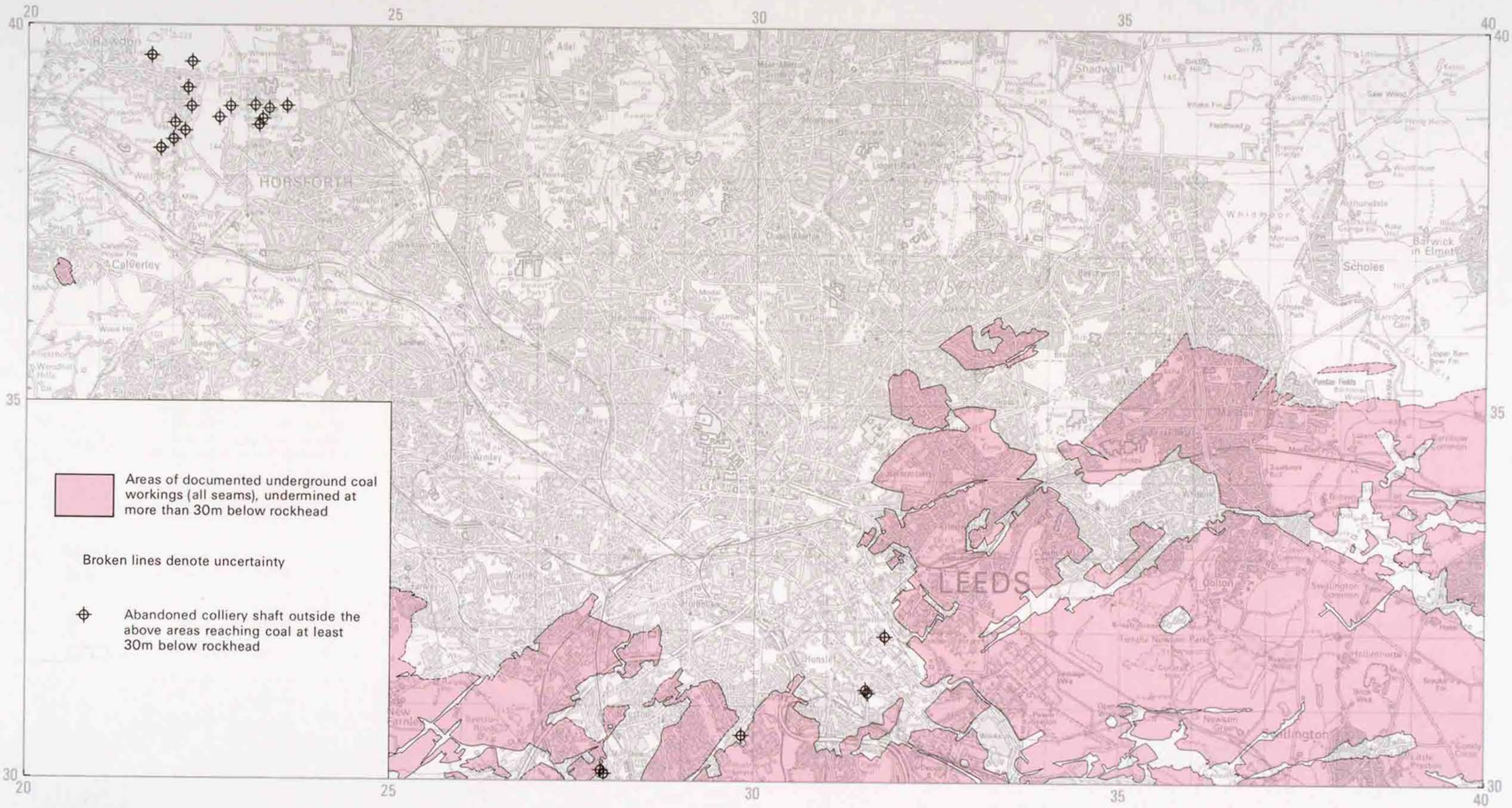


Figure 11 Deep coal mining. For full detail see Map 5, on which this generalised figure is based.

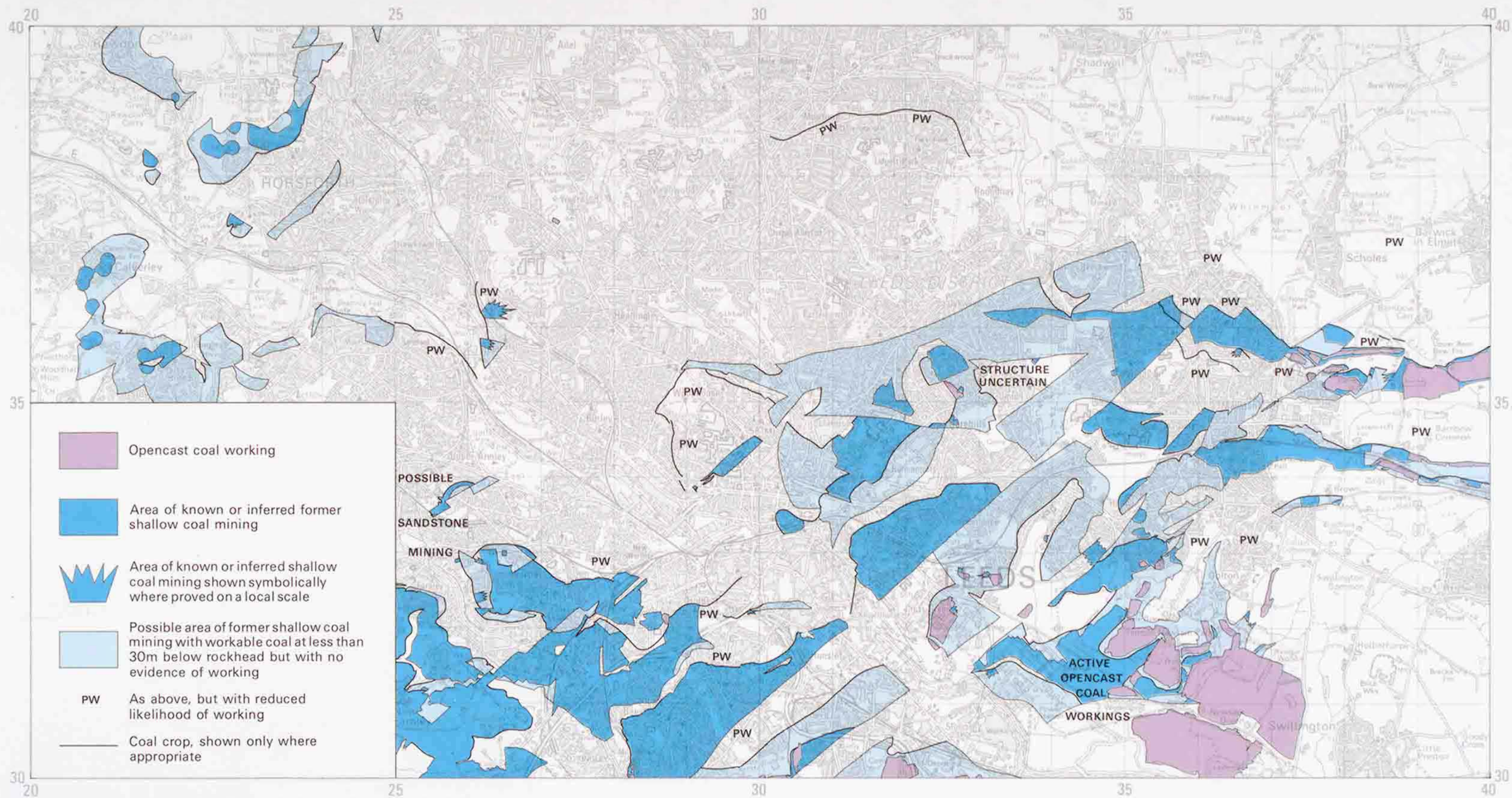


Figure 12 Shallow mining. For full detail, also including quarry locations, see Map 6, on which this generalised figure is based.

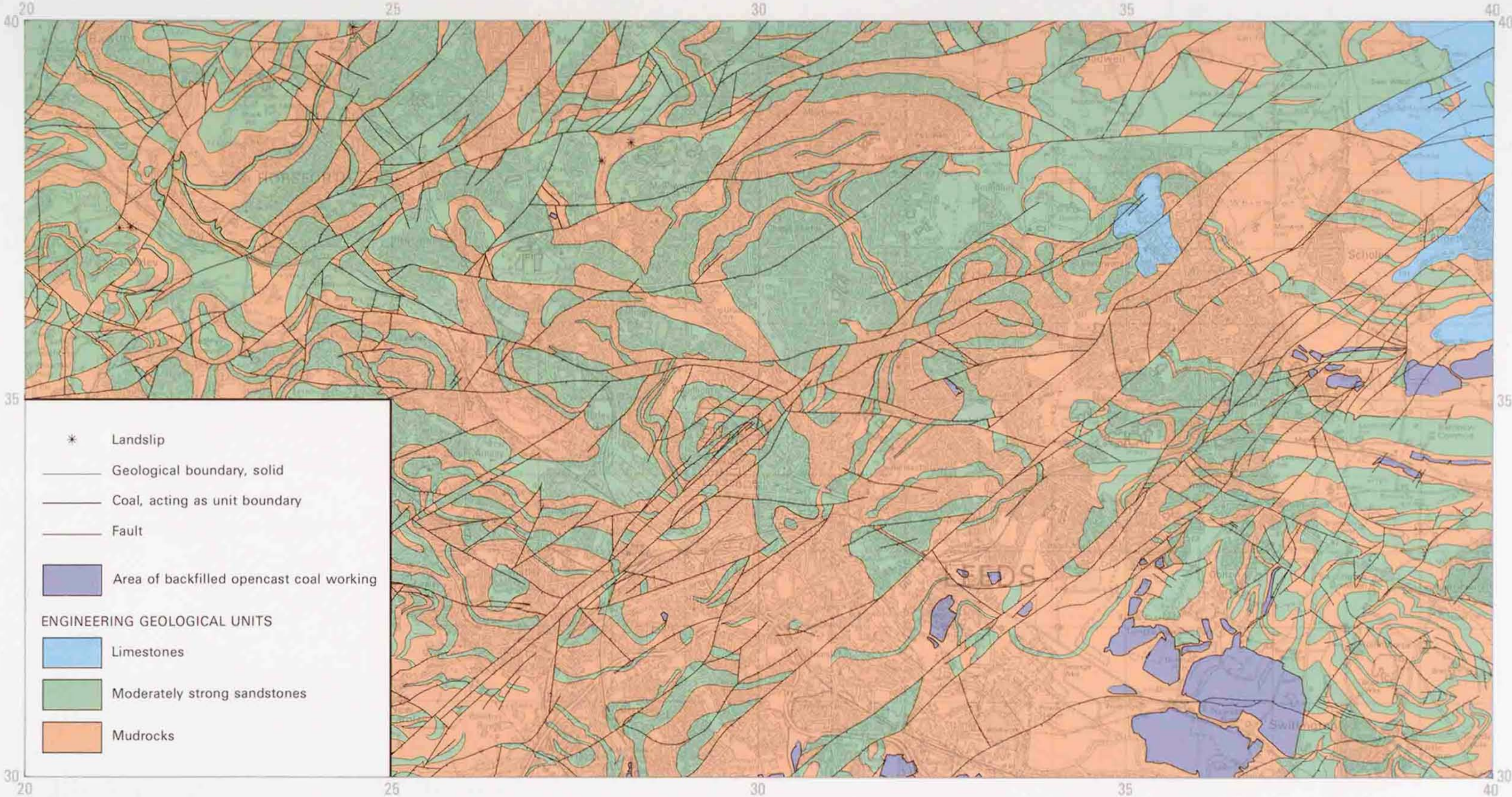


Figure 13 Engineering geology of the solid rocks. For full detail see Map 7, on which this generalised figure is based.

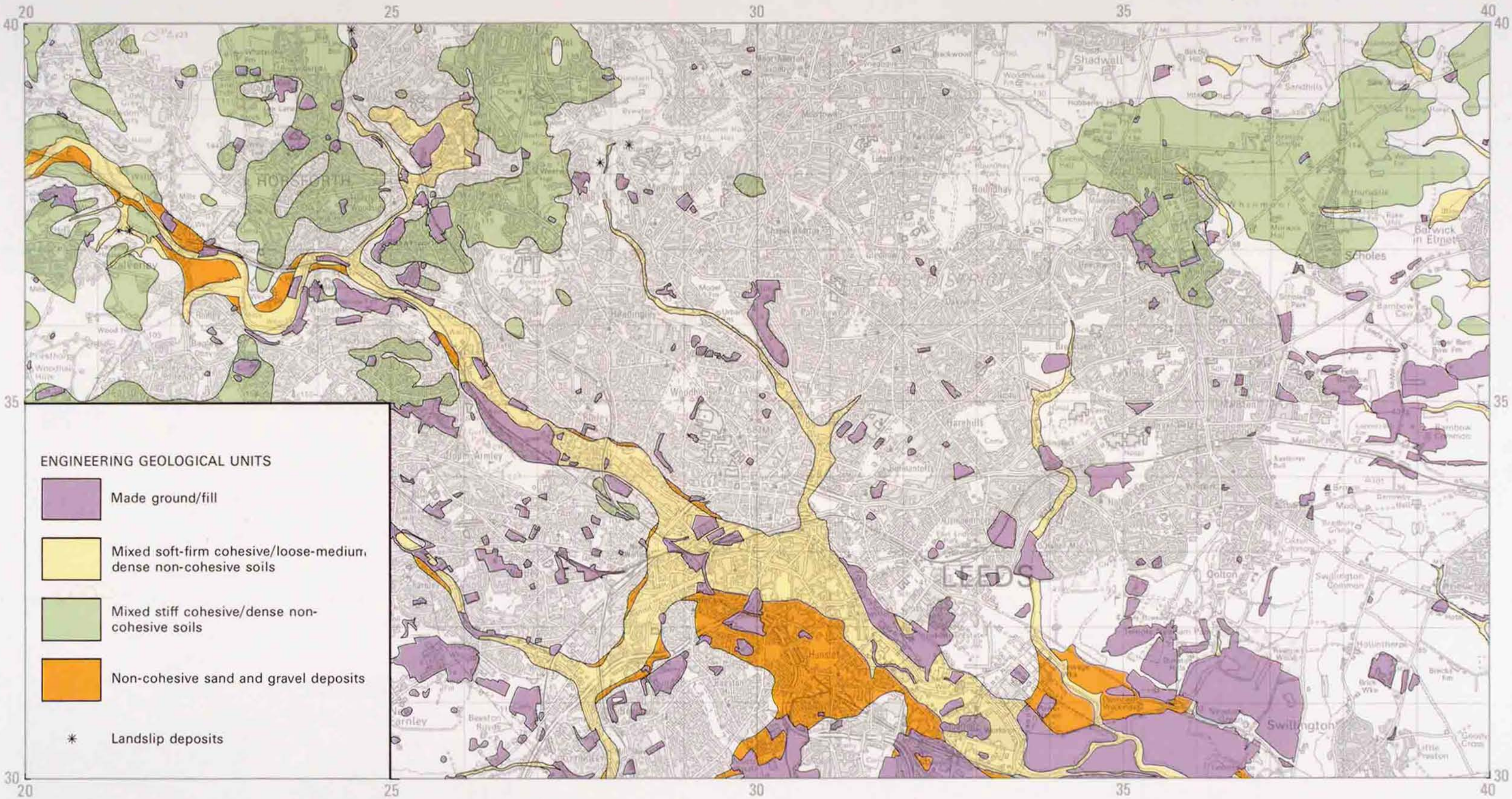


Figure 14 Engineering geology of the superficial deposits. For full detail see Map 8, on which this generalised figure is based.

APPENDIX 1: GEOLOGY

The following is a brief account of the geology of the district, which supplements that provided by way of introduction in a previous section (p.3). Further details are available in the open file technical reports for the constituent 1:10 000 sheets listed in Appendix VII.

Millstone Grit

The identification of individual sandstones below the Rough Rock is still somewhat conjectural in this district because of lack of exposure and structural complexity. The Cancelloceras cancellatum Marine Band was recorded in a pipeline trench [3245 3976], dug near Shadwell Lane, and the Cancelloceras cumbriense Marine Band occurs in the banks of The Gorge at Great Heads Wood, Roundhay Park [3340 3895 to 3364 3879]. The precise horizon of the marine shales recorded at the reservoir [3064 3950] at Moor Allerton is not known. The evidence of the trench section [3253 3990 to 3251 3938] at the first locality indicates that the internal structure of the fault segments in this vicinity may be more complex than that portrayed on the published map. Of the sandstone units, the Rough Rock, together with the underlying flags in some cases, has been extensively exploited in the district, throughout the crop. The larger workings include those at Calverley Wood [205 378], Hawksworth Wood [248 370], Newlay [243 364], Horsforth Woodside [255 376] and several near Meanwood Grove (Plates 1, 2, 5).

Surface springs were once evident at many places on the crop of the Millstone Grit, apparently associated with faulting or at sandstone-mudstone contacts. In some cases, seepages occur within extensive hillwash deposits, downslope from the sources.

Coal Measures

From the point of view of land-use planning, one of the main concerns relates to the extent of former shallow mining, which in turn was controlled by the extent of the workable coal seams and their structure. The following description is largely focused on these aspects, both to provide detail and to highlight areas where problems of interpretation still exist. The more general aspects of the geological succession were detailed by Godwin and Calver (1974). Some information on the thicknesses of coals is provided in Table 7.

The lowest seam worked on any significant scale in the district is the **Hard Bed Coal**. A number of shallow shafts were sunk to this coal north of Horsforth and to the east of Woodlands Orthopaedic Hospital [at 217 382]. It was also exploited patchily between Calverley and Farsley. Workings in the Kirkstall area are evidenced by pit shafts and spoil-heaps in Morris Wood [263 362]. Other possible workings include those near Sandford [258 356].

Former shallow mining of the **Better Bed Coal** and its seatearth was extensive to the south-west of the city, particularly in the Farnley and Wortley areas. The results of site investigations suggest some evidence of working to the west of the University. Further afield, shallow workings, possibly in the Better Bed, have been recorded east of Scholes [at 386 371].

The **Black Bed Coal** and the overlying ironstone were also extensively worked from shallow pits including bell pits in the Farnley and Wortley areas, and to the north and north-west of Beeston. 'Washouts' caused problems in workings at depth in the Beeston area.

Near the city centre, the more productive shallow coal seams were apparently worked in a patchy fashion. For example, the Black Bed Coal was worked at The Calls [304 333] and near Quarry Hill, whereas the ironstone in the overlying beds was also dug, perhaps more extensively, in this general area.

In the Potternewton area, the northern extent of workable coal (in the beds above the Elland Flags) was shown by a borehole [3096 3566] in Grange Avenue, which encountered 1.0 m of coal and seatearth at 13.3 m depth. The structure and stratigraphy of the tract from here to Oakwood and Gipton, which is segmented by faults, is imperfectly known. The Crow and Beeston coals are known to have been mined to varying degrees, but the extent of shallow workings in these and the Black Bed coals is un-

Table 7 The maximum and minimum recorded thicknesses of coals in the district

	Seam thickness (including dirt partings)	
Seam	minimum	maximum
Lidget	0.5	0.9
Unnamed	0.4	0.6
Joan	0.1	0.9
Flockton Thick	0.1	2.8
Flockton Thin	Absent	1.8
1st Brown Metal	Absent?	3.6 (three leaves)
2nd Brown Metal	0.2	2.9
3rd Brown Metal	0.2	2.1
Middleton Little	0.3	1.6
Middleton Main	0.4	2.0
Middleton 11 Yards	Absent	1.1
Blocking	0.03	2.8
Beeston (Top and Low)	0.7	4.6*
Churwell Thin	0.4	0.6
Churwell Thick	0.8	1.9
Crow	0.1	1.2
Black Bed	0.1	1.1
Better Bed	0.1	0.9
Hard Bed	Absent	1.0
Soft Bed	Absent	1.0
Pot Clay	Absent	?0.4

* 6.4 m thick where split: see text

certain. Near the Fearnville Sports Centre [338 358], a thin coal and bell pits have been recorded close to a fault. It is unclear if these occurrences lie within a fault zone or may be of more widespread significance.

On the east side of Leeds, the Black Bed Coal and ironstone, and the Crow Coal, have been extensively mined by bell pitting south-west from their outcrop at Seacroft and The Green. At Seacroft Town Centre the pits were proved to have been worked for ironstone alone (Edwards and others, 1950). Old shallow pits and workings in these beds have also been recorded south of Scholes [at about 379 359] though their south-westerly extent remains uncertain. Shallow working of the Black Bed and Crow Coal may possibly have occurred in the general area south of the Barnbow Lane/Bog Lane junction [387 358].

The **Crow Coal** occurs commonly as two leaves about 8 m above the Black Bed Coal. This close association, together with the presence of a sandstone within the intervening mudstones, forms a useful 'marker' group.

To the south-west of Leeds, the **Beeston Coal** has been worked, perhaps exhaustively, at shallow depth near Beeston and south-east of New Farnley. Near Farnley Wood Beck [about 265 301] this coal was worked in two leaves, an (upper) Churwell Thin seam and (lower) Churwell Thick seam. To the south of Beeston the seam also splits into upper and lower leaves (see below).

Near the city centre, evidence of shallow workings of the Beeston Coal has been noted in excavations for the Ring Road (see Godwin and Calver, 1974, p.422), at Park Lane [291 339] and at Wortley recreation ground [278 326].

Unlike other shallow workings east of the city centre, the pillar-and-stall workings in the Beeston Coal near Richmond Hill are definitely known to survive as voids (Plates 7 and 8). This coal occurs as two thinly separated leaves in central and eastern Leeds: a pronounced split occurs south-eastwards, associated with a deterioration of the lower seam. The extent of shallow workings beneath the drift deposits in the Hunslet-Thwaite Gate area is uncertain. Crop workings in the eastern part of the district were extensive near Swarcliffe and east of Pendas Fields. Thin coals above the Beeston Coal may have also been mined near Swarcliffe.

The **Blocking Coal** is of inferior quality and appears to have been exploited only on a small scale, perhaps from speculative workings. For example, there were limited workings near Beeston and localised pillar-and-stall workings in the Blocking Coal were exhumed in opencast sites near Cross Green.

Where the **Middleton Main Coal** lies at shallow depth, it was exploited at an early stage from bell pits, notably near Halton and Hunslet Carr (Figure 6). This seam was worked extensively between Killingbeck and south of Barnbow Common. The 'Cockleshell' horizon, with bivalve species of *Carbonicola*, the ostracod *Geisina arcuata* and the fish *Rhabdoderma* sp., occurs above a thin coal, perhaps 19 to 23 m above the Middleton Main Coal and 9 to 10 m below the Middleton Little Coal, near Stourton.

The Middleton Main Coal and succeeding seams up to the Flockton Thick Coal were worked in the large, deep, opencast pit at Oxbow [365 310]. Earlier and shallower workings at Temple Newsam Park extracted the Middleton Little, Third and Second Brown Metal seams (Plate 10).

The interval including the **Middleton Little Coal** and the **Brown Metal Coals** is not completely known in detail; this part of the sequence is characterised by marked variations in inter-seam thicknesses. Thus apparently the separation between the Middleton Little and Third Brown Metal coals varies from about 13 to 2.5 m between Stourton and Temple Newsam; eastwards these seams merge to form the 'Oxbow Coal'. The separation between the Second and Third Brown Metal coals is also variable over relatively short distances. The First Brown Metal Coal consists of two main leaves with minor leaves below. Where the Third Brown Metal and Middleton Little seams occur close together, they were locally exploited east of Halton.

The beds above the Brown Metal coals in this district are known only from the vicinity of the fault-bounded tract between Woodhouse Hill and Halton and from the south-eastern area, around Austhorpe and Swillington. The **Flockton Thin** and **Flockton Thick** coals both commonly occur in two leaves. (The Brown Metal coals and Flockton Thin Coal were formerly known as the Firthfield coals in the Garforth area to the east).

The **Vanderbeckei (Clay Cross) Marine Band**, which marks the base of the Middle Coal Measures, has only been positively recognised in borehole cores from the Swillington area. In this vicinity, the **Thornhill Rock** occurs as multiple units of sandstone, within some 28 m of strata. The topmost part of the Thornhill Rock and succeeding measures are exposed in the Swillington Brick-pit [386 314] (Plate 3).

In the Swillington Common area, the surface topography still reveals evidence of subsidence features, consequent on the former deep mining. The highest seam worked hereabouts was the Middleton Little Coal, at or near Ordnance Datum.

Permian strata

Up to about 15 m of Upper Permian strata are preserved within the district. An exceptional (and incomplete) thickness of 5.5 m of fine-grained sandstone (Basal Permian Sand) was recorded in a borehole to the north-west of Barwick in Elmet [3912 3830]. This sand unit was only previously noted at outcrop north of Seacroft [at about 351 377].

The dolomitic limestones of the Cadeby Formation (Lower Magnesian Limestone) commonly give rise to a low escarpment at the margin of the outcrop. Former quarries in this formation include those at Lime Pits Wood [352 374] and Ramshead Wood [353 370].

Structure

Dip values in the Carboniferous strata are generally low, less than 8°, to the south-eastern quadrant, except within some fault-blocks where different vectors and increased values may be observed. Gentle north-west trending folds also influence the pattern locally. The dominant structural style is of fairly evenly spaced, north-east trending, normal faults (Figure 8). Many of these downthrow to the south-east although some parallel faults throw in the obverse sense, to form relatively narrow grabens. Other major faults are aligned generally in a more easterly sense and may be of earlier origin. Minor cross-faults of varying trend also occur, apparently acting as accommodation structures between the other examples.

From regional evidence, it is known that most of the large faults, which cut the Carboniferous rocks, also affect the Permian strata with a reduced throw and steep dip. The minor faults are commonly truncated by the sub-Permian unconformity.

Joints are common, particularly in the thicker Carboniferous sandstones and in the Cadeby Formation. They are typically very steep or vertical and generally comprise at least two orthogonal or conjugate sets at any one locality. There is insufficient information to provide a pattern of trend, but proximity to faults evidently influences joint orientation.

Superficial structures

The solid strata are thought to be affected locally by the associated processes of cambering and valley bulging, though not on any great scale. Cambering may occur where sandstone or limestone overlies mudstone and caps the higher ground. Valleyward movement of the upper unit results in a draping effect, with consequent fracturing to form dip-and-fault structure. Fissures between the individual blocks may be filled with drift, or remain as open voids. Lateral pressures on mudstone in the valley-floor may result in the formation of sometimes faulted, anticlinal structures or valley bulges, which are characterised by aberrant steep dips in poorly exposed stream-beds. Such features are probably more common in the more deeply incised tributary valleys. Elsewhere, freeze-thaw activity has caused the disruption of bedrock beneath alluvial deposits.

The topography of the district is generally subdued and localised natural landslipping usually only affects the surface materials. The few landslips identified are dominantly shallow mudslides with associated mudflows, although, at Meanwood Grove [279 382], the slope failure may be deeper seated. In some areas, such as south of the Ring Road Meanwood [290 385], there may be a gradation between hillwash deposits and mudflows, which are difficult to distinguish in the hummocky ground.

It is possible that, beneath the steeper slopes, which have been subject to camber movements, the mudstones may contain bedding-plane shears which could be reactivated by excavation work.

Dissolution of the Cadeby Formation (Lower Magnesian Limestone) by surface and ground waters probably has given rise to concealed karstic features over the area of outcrop, particularly where the marl content is reduced. Corrosion of the carbonate results in variable rockhead levels on a localised scale: hollows and depressions in the surface of the dolomitic limestone are commonly filled with superficial deposits of varying thickness and lateral extent. At depth, joints and fractures have been enlarged by the movement of groundwater locally. Where conduits formed by this process are sufficiently large, collapse of the surface strata may produce shallow depressions, or 'solution hollows', in the ground surface. These are more commonly formed in the floors of dry valleys and may be filled (and thus masked) by superficial deposits. However, no solution hollows have been positively identified in this district.

Quaternary

The nomenclature and classification of the Quaternary deposits are summarised in Table 1.

The glacial deposits which occur in the plateau area between the Aire and Wharfe valleys in places include lithologies in addition to till. Locally a thin basal sand and gravel is present and near the waterworks [2730 3758] near Weetwood, for example, firm grey and brown laminated clayey silts and silty clays are present within the till. The younger (Devensian) moundy glacial deposits which occur in the Aire valley possibly also contain similarly varied sediments, although detailed information is lacking. Upstream from Whitecote [240 360], the alluvial sediments are underlain locally by glacial deposits, so that the gravels here may be of composite origin.

The terrace deposits may postdate the glaciation of Upper Airedale, although one radiocarbon date appears to argue against this. A mammoth tusk found at the Oxbow Opencast site [3618 3026] beneath Flandrian alluvium yielded an age (if valid) of 38 600 + 1720 to -1420 years Before Present (Gaunt and others, 1970), i.e. before the Late Devensian. At this site the drift deposits comprised a sixfold sequence of alternating sandy gravels and silts. The tusk occurred within silts, up to 0.68 m thick, above the lowest sandy gravel; the same silts also contained arctic insect and plant remains. The contours on the rockhead, in the vicinity, indicate that this unit overlies a bench comparable to that of the terrace deposits which are in turn overlapped by Flandrian alluvium. It is necessary to invoke some degree of recycling of material from older deposits in order to reconcile the otherwise anomalous age or, more likely, the deposits in question are composite in origin. Another exposure in these drift deposits nearby revealed an 'anticlinal ridge' of bedrock, up to 3.7 m high and with a WNW-ESE trend, protruding into the deposits as a result of freeze-thaw movements.

Previous authors have recognised that the terrace deposits in the lower Aire valley may occur as two facets, a lower (First) unit with a topographic surface about 1m above the floodplain and an upper (Second) terrace about 5 to 6 m above this datum (see for example Barclay and others, 1990). On these criteria most of the outcrops of the terrace deposits within this district probably relate to the Second Terrace, whose basal surface lies between about 5 and 7.5 m above the minimum bedrock level of the valley floor near the Oxbow site. This differential possibly reduces upstream.

Slope deposits possibly yielded the remains of hippopotamus (indicative of the Ipswichian interglacial) found in 1852 at a clay pit [c.2837 3318] near Wortley. The bone material was obtained from dark blue clay at a depth of 2.74 to 3.05 m. An 'infinite' radiocarbon age was obtained from one assay (Harkness and others, 1977), which is compatible with an Ipswichian age and thus may indicate local derivation from a nearby source, no longer extant.

APPENDIX II: ENGINEERING GEOLOGY

Geotechnical database

The combination of the geological units into groupings with similar engineering properties (engineering geology units) was carried out using geotechnical data extracted from site investigation reports on sites within the study area. The reports are mainly of three types, connected with:

(1) Building/construction sites in and around the urban areas

(2) Infrastructure construction and improvement works (i.e. roads and sewerage schemes)

(3) Land reclamation sites, landfill sites and existing or potential waste disposal sites (limited in number).

Geotechnical data were obtained from 173 site investigation reports, selected because these were considered to contain data of sufficient quantity and quality to warrant incorporation into the geotechnical database. These reports presented data relating to 1666 boreholes, the distribution of which are presented on Map 1. An assessment of the geological formations in terms of engineering geology was undertaken by analysis of the geotechnical database. This was supplemented by taking account of comments recorded in the site investigation reports, relevant to engineering behaviour, problems and hazard, to provide a summary appraisal of engineering experience in the area.

As part of the area is rural, the coverage of the site investigation reports is geographically restricted and the spread of data across the outcrop and subcrop areas of most formations is generally uneven, even for those formations for which a large number of geotechnical data have been obtained. The geotechnical data used here to classify geological formations in engineering terms are not, therefore, necessarily comprehensive nor representative of the entire outcrop of any particular deposit or formation. For some deposits (for example the superficial 'moundy glacial deposits') no geotechnical data are available. For others (for example the Lower Magnesian Limestone, or Cadeby Formation) data are limited to those from a small number of boreholes. In part, this lack of data reflects the limited areal extent to which these deposits crop out in the study area.

The various tests, from which the data were obtained, should have been carried out to the appropriate British Standard. However, experimental and operator error may have resulted in variation in results between one contractor and another, and between one report and the next. As very little information is presented in the site investigation reports relating to these possible errors, the compiled data will inevitably be of variable accuracy, resulting in a greater spread of results than would probably be found within any one site investigation report. However, during assessment of the site investigation data prior to databanking, efforts were made to reject clearly erroneous test results, the remaining records being accepted as valid. Despite this limitation, the resulting statistical assessments remain useful guides to the engineering properties of the various formations provided the above points are considered and over-interpretation is avoided. Summary values of the geotechnical parameters are presented in Appendix III, Tables 12 to 24. It should be stressed that these provide only a general guide and must not be used as a substitute for adequate site investigation, or in detailed design calculations.

Geotechnical test data were obtained from 7698 borehole 'samples', including in situ field measurements. Results from the following tests were entered into the database:

(a) *In Situ* (Field) Tests
1. Standard penetration test (SPT)
2. Rock penetration test (RPT)
3. Permeability
4. Rock Quality Designation (RQD)
5. Fracture spacing index (If)

(b) Laboratory Tests
1. Moisture content
2. Liquid limit
3. Plastic limit
4. Bulk density
5. Dry density
6. Specific gravity
7. Particle size analysis
8. pH (acidity/alkalinity)
9. Sulphate content (of soil and/or groundwater)
10. Triaxial compression (undrained and/or drained)
11. Uniaxial compressive strength
12. Point load (axial and diametral)
13. Consolidation
14. Compaction
15. California Bearing Ratio (CBR)

Only rarely was a full range of test results available for any particular engineering geology unit. Tables defining various parameter classes recorded in the summary geotechnical data are presented in Appendix III, Annex A and a glossary of the geotechnical tests in Appendix IV.

The geotechnical data were entered on to manuscript proforma and then keyed into a computer database. For this purpose an IBM compatible micro-computer and commercially available software were used for database creation and storage. Backup copies of the database are held by the Engineering Geology and Geophysics Group of the British Geological Survey. The validation and analysis of the stored data set to provide a statistical assessment of the geotechnical properties and the relevant graphical plots, were carried out using a commercial statistics and graphics software package. Results from this analysis were used to produce the summary geotechnical data in Appendix III, Tables 12–24 and as a basis for the assessment of the engineering geological characteristics of the various geological formations. For each geotechnical parameter in the tables, the values quoted are dependent on the number of samples (observations) as follows:

Number of samples	Parameter values
≥5	50th percentile (Median)
≥10	25th & 75th percentile (lower & upper quartiles)
≥25	10th & 90th percentile
≥100	2.5th & 97.5th percentile

These values are considered to represent the spread of data for each parameter more reliably than by quoting the mean, standard deviation and range, because the latter are sensitive to atypical values, often giving rise to misleading results (Hallam 1990).

The distribution of the main areas of 'made ground' is presented on Map 4. No assessment is made in this section of the report of the engineering characteristics of specific sites because the material and geotechnical variability of these spreads, coupled with the lack of sufficient data, make them difficult to classify in general engineering terms (but see p.17 and p.47). For planning purposes, the suitability of any potential development site will be dependent not only on the engineering characteristics of the in situ rocks and soils but also on the nature, thickness and proximity of areas of made ground.

Engineering classification of rocks and soils

The grouping of the rocks and soils of the area into classes of like engineering characteristics (engineering geological units) has been based on an assessment of the recorded geotechnical parameters and those lithologies identified on the geological maps. The distribution of the engineering geology units (Maps 7 and 8) do not necessarily correspond with the divisions presented on the geological maps. For example, the Millstone Grit and the Coal Measures are shown separately on Map 2, and the Coal Measures are further divided into the Lower and Middle Coal Measures. Each stratigraphical unit consists predominantly of interbedded mudstones, sandstones and siltstones. In engineering geological terms, a two-fold division has been made into 'moderately strong sandstones' and the dominantly argillaceous mudstone ('mudrock') sequences because the Millstone Grit and Coal Measures each comprise similar lithologies with broadly corresponding engineering characteristics. Similar groupings based on dominant lithologies and like engineering characteristics apply to the Quaternary superficial deposits. However, in Appendix III, Tables 12–24, geotechnical data are presented for the major lithologies in each stratigraphical unit to allow summary geotechnical information to be extracted on the basis of the divisions shown on the geological maps and in borehole logs.

Over significant parts of the study area, the bedrock is obscured by a variable thickness of superficial deposits. A broad distinction has been made, therefore, between the engineering geological characteristics of the solid rocks (Map 7) and those of the superficial, or drift, deposits (Map 8).

Engineering geology of the bedrock formations

The bedrock formations of the Leeds area have been divided into three engineering geological units based on their geotechnical and lithological characteristics. The relationship between these units and the geological (lithostratigraphic) units are shown below.

Engineering Geological Units	Geological Units
1. Limestones	Cadeby Formation (Lower Magnesian Limestone)
2. Moderately strong sandstones	i) Lower and Middle Coal Measures sandstones ii) Millstone Grit sandstones
3. Mudrocks	i) Lower and Middle Coal Measures mudstones and siltstones ii) Millstone Grit mudstones and siltstones

The 'Mudrocks' unit includes those dominantly argillaceous deposits with geotechnical characteristics bordering on those of a 'weak' rock and a 'strong' (highly overconsolidated) engineering soil. The siltstones of the Coal Measures and Millstone Grit grade laterally and vertically into mudstones and sandstones and, geotechnically, straddle the boundary between the 'Moderately strong sandstone' and the argillaceous 'Mudrocks' units. They are included in the latter unit because they are not distinguished separately on the geological maps. However, summary geotechnical data for the siltstones are given in Appendix III (Tables 17–18). Weathering of the bedrock formations has caused breakdown and softening of the fresh material into an engineering soil and the degree and depth of weathering is of particular importance with regard to engineering behaviour. The variability of the weathering products precludes the identification of distinct profiles in a study such as this. However, the effects of weathering on the engineering properties of the bedrocks are described and, where sufficient records exist, the geotechnical data presented in Appendix III, Tables 12–18 distinguish between those obtained for 'fresh to slightly weathered' and for 'moderately to completely weathered' rock.

1. Limestones

This unit comprises the dolomitic limestones of the Cadeby Formation (Lower Magnesian Limestone) which crop out to a limited extent in the north-east of the study area. The formation dips gently to the east and consists of a slightly to completely weathered, buff, fine to coarse-grained, marly dolomite or dolomitic limestone with local oolitic horizons. Bed thicknesses tend to range from 0.06 to 0.6 m (thinly to medium-bedded), but beds over 2 m (thick-bedded) may also occur. Joint spacings range from between about 60 and 200 mm (closely-spaced) to over 2 m (very widely-spaced) and the joints are steep to vertical.

The lowest few metres tend to be sandy but unlike in the Castleford-Pontefract area to the south-east, the underlying Basal Permian Sand appears to be only patchily developed within this district. However, in 1981 a site investigation for the proposed A1-M1 link encountered at least 5.5 m of Basal Permian Sand (overlying Coal Measures) about 1.5 km north-west of Barwick in Elmet. Here the deposit was described as an 'off-white, highly weathered, thinly-bedded, fine-grained weak sandstone'.Geotechnical data relating to this sand in the study area are sparse and the reader is directed to the *British Geological Survey Technical Report* No. WA/90/3 for a geotechnical appraisal of this deposit as encountered in the Castleford-Pontefract area.

At outcrop, the topmost 0.5 to 1.5 m of the Lower Magnesian Limestone is often recorded as being weathered to a firm silty calcareous clay with limestone fragments. Below this zone the deposit may be weakened by weathering to permit a further 3 to 4 m of penetration by shell and auger boring. The depth to which weathering extends below rockhead is variable, but zones of highly weathered rock (with SPT N-values of about 50 or less) have been recorded to depths of c.7 m below ground surface. The porosity and permeability of the limestone generally increase with the degree of dolomitisation, but permeability is primarily dependent on the size and concentration of fractures and joints. A single recorded field permeability value of 10^{-4} m/sec is indicative of a moderately permeable rock mass, but values may be expected to vary widely both areally and with depth. The percolation of water along joints and bedding planes has resulted in widening of these discontinuities and the creation of significant cavities by dissolution, leading to karstic rockhead conditions.

The limited geotechnical data obtained for the limestones in the study area are given in Appendix III, Table 12, where parameter ranges are principally controlled by lithology (particularly degree of dolomitisation) and weathering grade. Standard penetration test (SPT) results obtained for depths down to 7 m below ground surface range from 13 to 130 and show a clear trend of increasing N-value with depth and decreasing weathering grade.

The very few plasticity data reflect values typical of inorganic silts and clays of low to medium plasticity. Intermediate plasticity values relate to more marly material, whereas the low plasticity values probably reflect data for dolomitic limestone weathered to slightly cohesive silt.

No strength data were obtained for the limestone in the study area. However, twenty-four values of unconfined compressive strength for fresh to slightly weathered Cadeby Formation limestones in the Castleford-Pontefract area ranged from 2.4 to 36 MPa, with median and mean values classifying the rock as moderately weak. It should be stressed that strength tests carried out on intact material in the laboratory cannot properly represent the in situ rock strength if the rock is jointed or fractured. It is important that the influence of such discontinuities is taken into account in the assessment of strength and deformability for design purposes.

Design considerations

i) *Foundations*

Because of the limited extent and rural location of the Magnesian Limestone outcrop in the study area, no major foundation difficulties have been recorded in the collected site investigation reports. However, should development of these areas be considered in the future, potential foundation problems similar to those encountered in the Castleford-Pontefract area may arise. These are briefly summarised in Table 8. A limited number of tests for groundwater sulphate content have provided values which fall within Class I of the Building Research Establishment classification for sulphate-bearing soils and groundwaters (BRE Digest 250, 1981), indicating that the use of sulphate-resisting cement for buried foundations may not be required, but concentrations should be checked during site investigation. Shattered or highly weathered soft clayey zones should be removed and backfilled with suitable compacted material or concrete. For fresh to slightly weathered rock at depth, anticipated allowable bearing capacities of 1000 to possibly 2000 kPa may be used in design.

ii) *Slope stability*

No natural landslips have been recorded in the limestones. Because the dip of the bedding is low, slope stability prob-

Table 8 Potential founding problems in the Cadeby Formation (Lower Magnesian Limestone).

Geotechnical Consideration	Potential Foundation Problem
Wide range of measured engineering properties, particularly strength and deformability.	Difficulty in assessing representative values of bearing capacity and anticipated settlements.
High porosities and the presence of voids and cavities. Possible karstic conditions locally developed in rockhead.	Likely to reduce bearing capacity and cause excessive differential settlements below heavy structures. May require ground treatment or special foundation design before placing structures. May cause water inflow problems in excavations.
Local presence of highly weathered zones.	Likely to reduce bearing capacity. May preclude use of shallow foundations except for light structures.
Variable rockhead level and possible presence of infilled solution holes and channels.	Problems in achieving adequate bearing capacity at shallow depth. May result in excessive differential settlements unless deep foundations are used. Pile foundations of variable lengths may be required.
Local artesian groundwater conditions.	Likely to locally result in basal heave of excavations close to base of formation, or lead to stability problems of foundations in weathered rock if taken below water table.
Likelihood of previous or current subsidence of limestone associated with collapse of workings in the underlying Coal Measures. Also subsidence of superficial deposits associated with faulting/fracturing of underlying limestone.	May result in excessive differential settlements. May require treatment before placing foundations.

lems in engineering works are likely to be confined to rockfalls and long-term degradation of rock faces rather than large scale instability. The most important factors influencing the stability of excavations are the presence of steeply inclined or vertical joints, natural cavities, highly weathered zones, brecciated limestones and weak, highly porous dolomites, which are particularly susceptible to weathering on exposure. Groundwater problems may also occur locally where mass permeabilities are high and the water table is at shallow depth. Where water ingress occurs in highly to completely weathered and brecciated rock or in fault zones, immediate support of excavations may be needed.

In general, the more resistant fresh to slightly weathered, bedded limestones can maintain stable slope angles of 70° to near-vertical, to heights in excess of 10 m, where no inclined joint surfaces are present or the cuttings are orientated such that discontinuity-bounded blocks are stable. Slopes of 1V:1H are recommended as a preliminary guide for excavations and cuttings in most of the limestone area, but regrading to 1V:2H may be necessary for highly weathered, brecciated or faulted zones and for long-term stability in beds particularly prone to degradation on exposure.

iii) *Excavatibility and suitability as fill*

Highly to completely weathered, brecciated and broken rock may be excavated by mechanical scraper or machine shovel; fresh to slightly weathered, jointed and fractured rock will require machine ripping. Massive limestone with widely spaced joints will need pneumatic breakers or minor blasting. Fresh to slightly weathered rock is suitable as rockfill. Highly weathered and fractured rock is generally unsuitable as rockfill but may be used as a bulk fill material. The limestone should be assumed to be frost-susceptible for design purposes, and this should be taken into account for calculations of minimum pavement thicknesses.

2. MODERATELY STRONG SANDSTONES

These are the sandstones of the Millstone Grit and Coal Measures groups. They are grey to greyish brown, moderately to well-jointed, moderately strong, variably micaceous, locally conglomeratic, medium to coarse-grained (in the Millstone Grit) and fine to medium-grained (in the Coal Measures) quartzose sandstones, with occasional siltstone and mudstone interbeds and coal partings. Bedding separation ranges from about 20–200 mm (very thinly to thinly bedded, or 'flaggy') to over 2 m (thickly bedded), and well-developed cross-bedding is common. Individual units range in thickness from thin impersistent bands within the mudrock lithologies to thick regionally persistent units such as the Rough Rock and the Thornhill Rock.

The depth and intensity of weathering is variable, but where exposed the complete weathering of the sandstones to a silty clayey sand or very sandy clay containing weathered sandstone fragments is often encountered to depths of 0.5 to 1.5 m, although residual sandy soils up to 5 m thickness are not uncommon in the Coal Measures. The change from residual soil to weathered rock is generally fairly distinct. Although the weathering grade decreases with depth, the thickness and character of the weathered zone may vary markedly in the vicinity of faults where locally steep bedding dips and fracturing have enhanced permeabilities. In these areas, 'pockets' of highly weathered sandstone rock have been encountered to depths in excess of 11 to 12 m below ground surface. The degree of weathering is a major factor in controlling engineering behaviour and summary geotechnical properties for 'fresh to slightly weathered' and 'moderately to completely weathered' sandstones of the Millstone Grit and Coal Measures are shown separately in Appendix III, Tables 13–14.

Standard penetration test (SPT) results vary widely according to weathering grade. A tentative correlation (Meigh, 1968) between SPT values and rock strength indicates that slightly weathered sandstone rock in the Leeds area falls into the 'medium strong' class with N-values generally between 100–250. N-values for moderately to completely weathered rock generally range from about 20 to 200, straddling the 'weak to moderately strong' classes. Where the residual soils developed over the sandstone outcrops are granular, the SPT values are generally indicative of medium dense to dense sands with values, and hence bearing capacities, improving with depth.

Soils developed over the sandstones are generally of low to intermediate plasticity. Some recorded data values do, however, indicate high plasticity materials and these may reflect the presence of mudstone layers or laminae within the weathered sandstone sequences or, more likely, the presence of Head deposits, which are difficult to distinguish from the in situ sandstone weathering profiles on borehole logs.

Insufficient data have been obtained to assess the in situ permeability of the sandstones but permeabilities can be expected to vary markedly across the outcrops depending on the degree of weathering, the size and spacing of joints and the presence of fault-zones. Where large or closely spaced discontinuities occur, moderate or high permeabilities (10^{-5} to 10^{-2} m/sec or higher) can be expected. Intact sandstone, with no or few joints or fractures, is generally only slightly to moderately permeable.

Uniaxial compressive strengths and point load indices for intact fresh to slightly weathered rock generally range from about 22 to 55 MN/m^2 and 1.0 to 2.5 MN/m^2, respectively, thus classifying the sandstones as 'moderately strong' (Anon, 1972; Hoek and Brown, 1980). It is uncertain, however, whether all these test data relate to samples tested at their natural moisture content. If the samples were allowed to dry out prior to testing, anomalously high laboratory strengths may have been obtained which bear little relation to field values. Conversely, saturated test specimens may have yielded strength values up to 50 per cent lower than those for dried or partially saturated samples. However, tentative correlation of the recorded uniaxial strengths with SPT N-values (see above) suggests that the summary strength values presented in Appendix III, Tables 13–14 are generally representative of the in situ field strengths of intact sandstone in the study area. Rock strength decreases with increased weathering, and it should be remembered that tests on intact laboratory specimens do not represent the in situ strength of the rock mass, which is largely influenced by the frequency, orientation and nature (e.g. if infilled or 'clean') of the discontinuities.

Design considerations

i) *Foundations*

In general discussion of the bearing capacity and settlement characteristics of the Upper Carboniferous rocks, consideration must be given to existing or potential areas of mining subsidence, because in some cases this may be an overriding factor when calculating settlements, and the presence of shallow mine workings may affect bearing capacity considerations. The potential hazard from shallow mine workings (usually within 30–40 m of rockhead), shafts and bell pits are discussed further on pp.19–22. Adequate provision should be made in any proposed site investigation to ascertain not only the thickness and founding characteristics of the sandstones, but also the extent and depths of these workings, before consideration is given to the appropriate foundation design. The Millstone Grit and Coal Measures rocks are also extensively faulted and the presence of shattered rock in fault zones may give rise to adverse groundwater conditions in addition to differential settlements. Pretreatment of the ground (e.g. dewatering, grouting or excavation and replacement) may be necessary and site investigations should aim to delineate these problem areas as accurately as possible, prior to placing foundations.

A variable thickness of Head deposits is widespread, but patchily developed, over most of the sandstones. Although these deposits are probably less than a metre thick in most areas, increased thicknesses may be expected at or near the foot of slopes. The Head deposits are extremely variable in composition and can give rise to excessive differential settlements. Below, or on, slopes, they may also contain numerous shear surfaces and the deposits should be removed prior to placing foundations.

Where the bedrock profile consists of (usually thin) alternating bands of sandstone and mudstone, the weathered zone may include bands of stiff clay, derived from decomposed mudstone, underlying less weathered and more resistant sandstone. Such a situation could have important implications for foundation design if the residual clay layer is not proved by penetration of the sandstone during site investigations.

Due to the wide range of rock conditions found in the Upper Carboniferous rocks, recent practice has been to use the results of in situ testing (e.g. plate loading tests) to assess the bearing capacity and settlement characteristics at any particular site. For shallow foundation levels in the weathered zone, allowable bearing pressures of between 250–500 kPa have frequently been used, increasing in some cases to as much as 2000 kPa in thick layers of unweathered massive sandstone. Both driven piles and bored cast in situ piles have been used to carry foundation loads into the Upper Carboniferous rocks. Driven piles have disadvantages in that they tend to cause shattering and may 'hold up' on thin sandstone layers underlain by severely weathered shale or mudstone. Heave is also likely where driven piles are emplaced close together. Bored cast in situ piles are generally to be preferred as they can more readily penetrate the weathered zone and the materials passed through can be identified (in some cases, inspection of the base can also be carried out to confirm sound bedrock). It should be emphasised that the site investigation should be sufficiently detailed to give adequate knowledge of the rocks below the toes of piles. The allowable pile loading can often be equivalent to the maximum allowable stress in the concrete, usually 5 MPa of pile cross-sectional area using normal concrete. The penetration necessary to develop this capacity will vary with the rock conditions but where the founding medium consists of a sufficiently thick layer of sound sandstone, a penetration of about one pile diameter is usually satisfactory, reducing to about half a pile diameter where the sandstone is very hard. Pile loading tests should be carried out prior to the main work to confirm chosen loadings and penetrations. Where the number of piles involved in the construction may be insufficient to justify the expense of pile loading tests, it is prudent to use more conservative loadings. Where the weathered zone persists to appreciable depths or where there are steeply dipping strata (e.g. near fault zones), it may be necessary to terminate piles in material which is outside the category of sound unweathered bedrock. In such cases it is probable that reduced loadings of about 3 MPa of pile cross-sectional area can be used, again subject to confirmation by pile loading tests.

Data obtained for soil and groundwater sulphate concentrations in the study area nearly all fall into Class 1 of the BRE classification (Digest 250, 1981: *Concrete in sulphate-bearing soils and groundwaters*). However, sufficiently high sulphate concentrations have been recorded in the vicinity of colliery tips (Crutchlow, 1966; Meigh, 1968) to warrant special measures, such as the use of sulphate-resisting cement, to avoid concrete attack.

ii) *Slope stability*

With the exception of a dormant, relatively shallow, rotational failure in the Rough Rock Flags near Mosely Wood [2447 3994], no natural landslips have been recorded in the sandstones.

In excavations for construction works, cut faces in massive to moderately-jointed, fresh to slightly weathered sandstone may remain stable at steep angles, but the presence of interbedded siltstones and mudstones will reduce stability and side slopes of 1V:2H have been suggested for preliminary design purposes. Perched groundwater tables may give rise to high hydrostatic pressures, causing heave at the base of excavations, and dewatering will be required where groundwater seepage is encountered. Excavations in fault zones may require immediate support due to the presence of shattered or brecciated rock and clay gouge.

iii) *Excavatibility and suitability as fill*

Weathered sandstone may be excavated by mechanical scraping or digging. Fresh or slightly weathered rock may require ripping and, in confined spaces, pneumatic tools for excavation. Blasting may be needed for major excavations in massive sandstone.

Sound sandstone rock is suitable for embankment fill if care is taken in selection and excavation. Although suitable as bulk fill, use as a high grade fill can be limited due to the variable amounts of clay and silt size particles, which may form the cementing medium of many of the sandstones, and to the common occurrence of argillaceous bands. For compaction purposes, the sandstones are generally classed as a graded granular soil.

3. MUDROCKS

This unit encompasses those dominantly argillaceous formations with engineering characteristics bordering on those of a 'weak' rock or a 'strong' overconsolidated soil. It includes the mudstones, siltstones, coals and seatearths of the Upper Carboniferous (Coal Measures and Millstone Grit groups). The siltstones, which grade laterally and vertically into mudstones and sandstones, are not distinguished on the geological maps and are here included in this unit despite having geotechnical characteristics which straddle those of mudstones and moderately strong sandstones. Coal seams and seatearths (unbedded mudstone or siltstone rootlet beds generally underlying coals) form only a small proportion of the Upper Carboniferous strata and the lack of geotechnical data relating to these lithologies precludes a regional assessment of their engineering properties here. Coal seams may cause problems for construction because they are commonly highly permeable and thus weather and weaken rapidly on exposure. They also pose the potential hazard of spontaneous combustion if exposed at proposed foundation levels (see p.23).

The 'Mudrocks' unit consists predominantly of medium to dark grey, moderately fissured, weak to moderately strong mudstones, silty mudstones and siltstones. These are particularly susceptible to weathering processes and completely weathered firm to stiff, orange-brown and pale grey mottled clay soils commonly occur within 2 to 6 m of ground surface, followed by a gradual transition through less severely weathered material into unweathered bedrock. Zones of highly weathered material, comprising softened mudstone clasts in a silty clay matrix, may occur to depths of about 10 to 15 m, and possibly deeper in fault zones. As the degree of weathering is a major factor in controlling engineering behaviour, summary geotechnical properties for 'fresh to slightly weathered' and 'moderately to completely weathered' mudstones of the Millstone Grit and Coal Measures are presented separately in Appendix III, Tables 15–16. Summary geotechnical properties for the siltstones are shown in Tables 17–18.

Standard penetration test (SPT) results vary widely depending on weathering grade, but N-values for fresh to slightly weathered rock generally range from about 75 up to 250, approximating to weak to medium strong rock. For highly to completely weathered mudrocks, N-values of 40 or less are frequently recorded.

Plasticity data (Figure 15) for the moderately to completely weathered mudstones cluster around the A-line in the manner typical of silty clays/clayey silts of low to high plasticity. For fresh to slightly weathered material, the few plasticity data plot as silty clays of generally low plasticity. These latter data may relate specifically to very silty mudstones which are less susceptible to breakdown on weathering to plastic clays than the less silty mudstones. The A-line plot for the siltstones (Figure 16) indicates materials of generally low to medium plasticity. Consolidation data show the mudrocks to be of generally low to medium compressibility although high consolidation settlements have been recorded locally. In general, the effect of increased weathering results in enhanced plasticity and moisture content and decreasing density and shear strength.

Figure 15
Plasticity diagram for Coal Measures and Millstone Grit mudrocks.

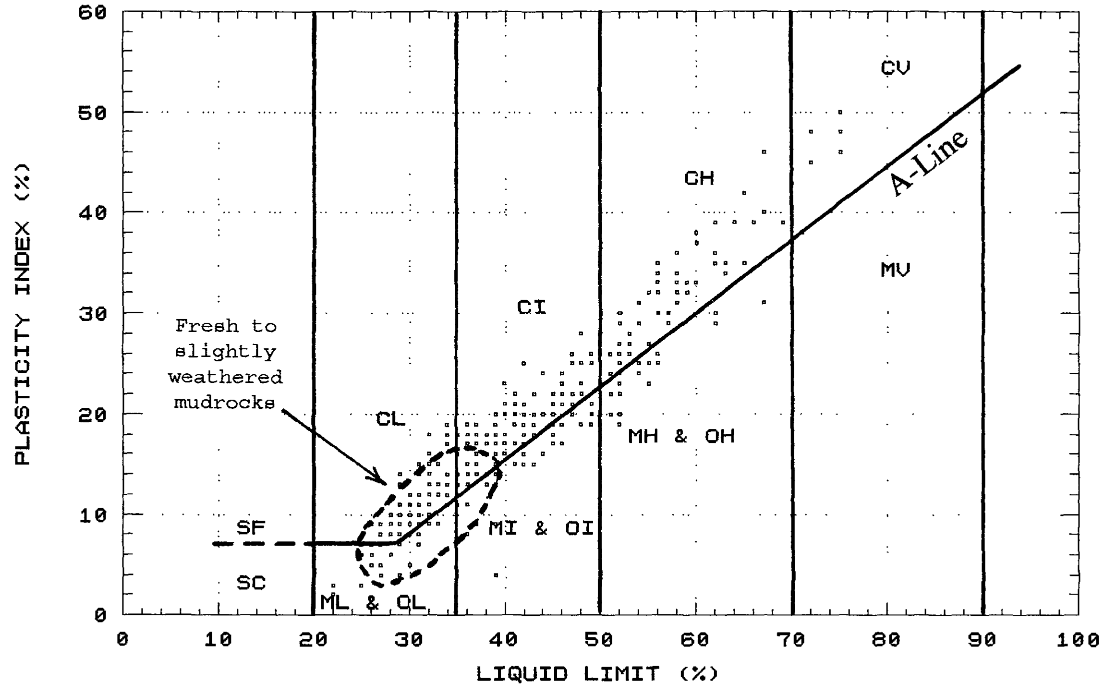
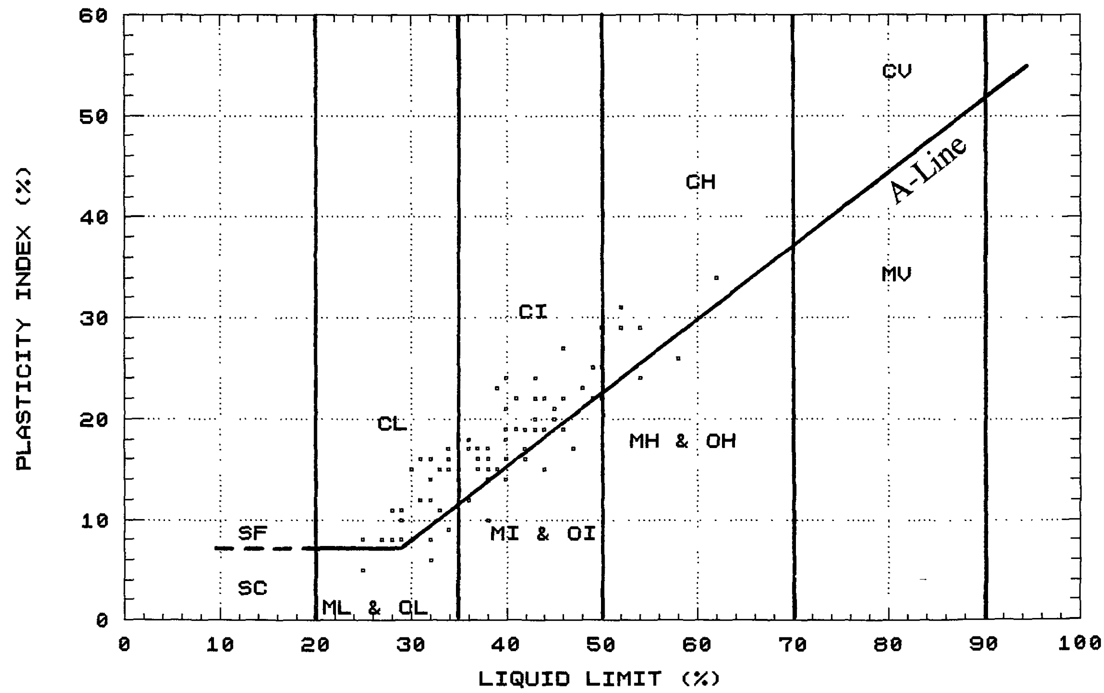


Figure 16
Plasticity diagram for Coal Measures and Millstone Grit siltstones.



The few field permeability values for the mudstones, ranging from 10^{-4} to 10^{-6} m/sec, classify the rock mass as slightly to moderately permeable (Anon, 1972), but this may vary depending on weathering grade, fissuring and the presence of interbedded siltstones, sandstones and coal horizons. Waterlogging of the ground may occur locally where the mudrocks are weathered to clay and also where mudstone seatearths crop out.

Design considerations

i) *Foundations*

Shallow mine workings present a potential foundation problem throughout much of the Coal Measures outcrop, and any site investigation should ascertain the presence, depth and extent of these. Once the workings have been accurately delineated, piled foundations set in sound rock below the worked level present the safest option for all but the lightest structures, although ground pre-treatment by grout injection has been successfully employed in some cases. Problems for development in areas of shallow mining are discussed further on p.19.

For shallow strip foundations within the weathered zone, allowable bearing pressures of 50 to 300 kPa have been considered to be satisfactory, increasing to 500 to 1000 kPa at depths greater than 1.5 m in fresh to slightly weathered competent mudstone or sound siltstone. Working loads of about 600 kN are suggested for 0.5 m diameter piles set in sound mudstone, with bored cast in situ piles being preferred to driven piles. In most cases, penetration of three to four pile diameters into sound mudstone bedrock is necessary to develop sufficient bearing capacity.

When exposed to wet conditions, the mudstones swell, lose strength and rapidly deteriorate to clays. Mudstones with a low silt content appear to be most susceptible to this weakening process which may result in a marked reduction of bearing capacity and loss of side friction for piles. Such lithologies should be subject to slaking tests during site investigation and be protected from water ingress during excavation by cut-off drains, sheet piling or similar measures. Borings for piles should be cased through water bearing strata and engineers, aware of the problem, will often base pile design on end bearing values only. Fault-zones comprising shattered rock and clay gouge may present problems in terms of low bearing capacity and excessive differential settlements and the location of these zones should be part of any site investigation and taken account of in planning and design.

Sulphate concentrations recorded in this study fall into Class 1, and occasionally Class 2, of the BRE classification (BRE Digest 250, 1981). However, as noted previously, locally high groundwater sulphate concentrations have been recorded in the Upper Carboniferous rocks elsewhere, particularly in the vicinity of colliery tips, and special measures may be required at some locations to avoid attack on buried concrete.

ii) *Slope stability*

A few, generally shallow, dormant debris slides/flows and rotational slumps have been recognised during the geological mapping. The landslip deposits generally occur on or near the middle to lower parts of slopes with angles over about 8–10°, in weathered mudstone below a coal seam and/or a capping sandstone. Minor, shallow slope movements (too small to be indicated as individual landslips on the geological maps, but identified from the presence of low arcuate scars above hummocky ground) are probably fairly common in the weathered mantle and/or Head deposits on such slopes. These minor, usually very shallow, slope movements should pose no serious problems to development provided they are identified during site investigation. The larger (mapped) slope movements are relatively isolated and are discussed in more detail on p.23 and p.53.

Temporary excavations in fresh to moderately weathered mudrocks should be stable but slumping may occur in the highly weathered zone or the completely weathered clay mantle. The mudstones are highly susceptible to deterioration and softening when relieved of overburden pressure and in the presence of water. Siltstone and sandstone beds may give rise to water seepages and accelerated deterioration of cut faces by rain and heavy construction traffic may exacerbate these processes. To prevent deterioration in open excavations, the mudrock should be covered with a layer of blinding concrete as soon as formation level is reached; temporary cut slopes may need protection by spraying with bitumen or covering with plastic sheeting or tarpaulins. Side slopes of 1V:2H are recommended for preliminary design of excavations and cuttings but perched water tables may present considerable difficulties and in some cases regrading of cut slopes to 1V:4H with suitable drainage may be required.

iii) *Excavatibility and use as fill*

The mudrocks can be readily excavated by mechanical scraping or digging, but ripping or pneumatic breakers may be required at depth or for major excavations. Although successfully used as embankment fill, the material should be placed as soon as possible after excavation and subjected to minimum construction traffic when wet. Soaked and unsoaked CBR test results confirm the sensitivity of mudrock fill to compaction moisture contents. Remoulded undrained shear strengths of 150 to 350 kPa have been quoted in embankment design for material compacted at in situ moisture contents between 15 and 22 per cent, but these values may reduce markedly with an increase in moisture content of only 2 per cent of dry weight in wet conditions. Checks on 'field' moisture contents should therefore be maintained during construction. Plastic limit versus moisture content plots for in situ material indicate that near surface, highly weathered mudstones/clays may be classified as cohesive for compaction purposes. Less weathered mudstones, below about 6 to 7 m depth, are generally classified as dry cohesive.

Engineering geology of the superficial deposits

The superficial deposits of the study have been divided into five geotechnical units. The relationship of these units to the geological divisions of the natural and man-made deposits are shown below:

Engineering Geological Units	Geological Deposits
1. Made ground/fill	Made ground
2. Mixed soft-firm cohesive/ loose-medium dense non-cohesive soils	i) Head ii) Alluvium
3. Mixed stiff cohesive/ dense non-cohesive soils	Till (boulder clay, moundy glacial deposits) with glaciofluvial sand and gravel
4. Non-cohesive sand and gravel deposits	River terrace deposits
5. Landslip	Landslip

Geotechnical units 2 and 3 (and in some areas unit 4) consist of variable and/or mixed deposits of clays and non-cohesive sands and gravels of contrasting engineering characteristics. However, interdigitation and impersistent layering and lensing of these lithologies make it virtually impossible to refine their characteristics by geological mapping. The geotechnical units are, therefore, selected to reflect this variability in the superficial (drift) deposits as shown on the geological maps.

1. MADE GROUND

Made ground is ubiquitous in many parts of the Leeds urban area. Reflecting the industrial and residential development of the region, these areas, some of which have been subject to extensive landscaping, are mainly:

- Infilled beck valleys
- Made up ground levels on low lying, marshy or soft ground which was often prone to flooding
- Backfilled sludge lagoons
- Backfilled quarries, clay-pits and opencast sites
- Demolished areas of (predominantly terraced) housing stock
- Demolished large industrial sites

The distribution of existing made ground, generally over 3 m thick, is shown on Map 4 (see also Map 8). As an engineering geology unit, made ground, also known as fill or backfill, is variable in composition, geotechnical properties and thickness (1–2 m thicknesses are common but locally, in areas such as old quarries and opencast sites, thicknesses of 10 to over 20 m occur). In so far as records exist, the nature of the fill material and dates of re-soiling for the various made ground sites are presented in Table 11. Infill materials at these sites may consist of chemical, mining and quarry waste, domestic refuse, and construction materials such as bricks, concrete and other rubble, in addition to bulk fill derived from the bedrock formations.

Although fill materials show a wide range of engineering properties, properly engineered fills, such as those typically used in the construction of highway embankments, may have excellent engineering properties. Recently-placed domestic refuse would be at the opposite end of the range. It is important that site investigations make it possible to initially classify the fill, in a qualitative manner, in terms of this wide range of behaviour. Classification should be carried out under the headings listed in Table 9. From a classification of this type, deductions can be made about the causes and possible magnitude of settlement of the fill subsequent to construction. Field loading tests should then be carried out to enable quantitative estimates of settlement to be made with more confidence. On the basis of these estimations, it is useful to distinguish between three different situations:

a) **Small movements** (vertical compression of the fill subsequent to construction everywhere smaller than 0.5 per cent) This is likely with granular fill that has been placed under controlled conditions and received adequate compaction. Such a material forms a good founding medium and there should be few problems.

b) **Significant movements** (vertical compression of the fill subsequent to building estimated to have a maximum value between 0.5 and 2 per cent) A granular fill placed without compaction, with little organic matter and which has been in place for some years, may come into this category. In this situation special attention must be given to foundation design. If piling is considered to be uneconomic, basic alternatives are either to use some ground treatment technique to improve the load carrying properties of the fill or to design the foundations to withstand differential movements caused by settlement. Reinforced concrete rafts with edge beams have been used for two-storey dwellings, but where large differential settlements are likely, very substantial foundations may be needed and buildings should be kept small and simple in plan.

c) **Very large movements** (vertical compression of the fill subsequent to building estimated to exceed 2 per cent) This category may include recently-placed domestic refuse with high organic content liable to decay and decomposition, and fine-grained materials which have been discharged into lagoons, as a suspension, to form highly compressible cohesive fill which might be susceptible to liquefaction. Severe settlement problems are likely and ground improvement techniques may have limited effect. With recently-placed domestic refuse methane emission may also be a major problem and such sites may be prohibitively expensive to develop.

Insufficient data are available to enable a geotechnical assessment to be carried out for the made ground areas in this study, but the general problems and implications for development on made ground are discussed further on p. 17. The reader is also directed to the Building Research Establishment Digests 274 (1983a) and 275 (1983b) for a general appraisal of construction on existing filled areas.

2. MIXED SOFT-FIRM COHESIVE/LOOSE-MEDIUM DENSE NON-COHESIVE SOILS

Head

Head deposits are superficial materials derived from bedrock and other superficial deposits by the action of periglacial freeze-thaw processes and hillcreep, solifluction and gelifluction. Such deposits are variable but the most common lithology is that of a soft to firm sandy, silty clay with stones; locally it may be a gravelly silty sand or clayey sandy gravel. The variable composition reflects the local derivation. Head commonly forms an extensive cover on the lower slopes of all the exposed bedrock formations, usually as a thin veneer less than a metre thick, but greater thicknesses may have accumulated at the foot of slopes and in hollows. Thicknesses ranging from less than 1 m to about 6 m (and occasionally more) are recorded in many site investigation reports, but the distinction between in situ soil (derived from completely weathered bedrock) and Head is generally unclear, the one grading into the other. The mapped distribution of Head as shown on Map 3, is not fully representative. It should be assumed to occur elsewhere as a patchy veneer of varying thickness, which should be ascertained, and its geotechnical characteristics established, prior to the design of foundations or cut slopes.

Summary geotechnical properties for all Head deposits are shown in Appendix III, Table 19. No distinction has been made between the Head developed over the Upper Carboniferous and Magnesian Limestone lithologies owing to the broad overlap of recorded parameter values and the substantial statistical bias towards data obtained for the Head developed over the Upper Carboniferous rocks, which crop out over the major part of the study area.

Table 9 Qualitative classification of fills (from BRE Digest 274).

Classification	Description
Nature of material	Chemical composition. Organic content. Combustibility. Homogeneity.
Particle size distribution	Coarse soils, less than 35% finer than 0.06 mm; fine soils, more than 35% greater than 0.06 mm (BS 5930: 1981).
Degree of compaction	Largely a function of method of placement: thin layers and heavy compaction - high relative density: high lifts and no compaction - low relative density; end tipped into water - particularly loose condition; Fine grained material transported in suspension and left to settle out produces fill with high moisture content and low undrained shear strength (eg. silted up abandoned dock or tailings lagoon).
Depth	Boundary of filled area. Changes in depth.
Age	Time that has elapsed since placement; If a fill contains domestic refuse, the age of the tipped material may be particularly significant, since the content of domestic refuse has changed considerably over the years. During the last 40 years the ash content has decreased whilst the paper and rag content has increased. The proportion of metal and glass in domestic refuse has also increased. It may be that more recent refuse will be a much poorer foundation material than older refuse not only because there has been a shorter time for settlement to occur, but also because the content of material which can corrode or decompose is greater.
Water table	Does one exist within the fill? Do fluctuations in level occur? After opencast mining a water table may slowly re-establish itself within the fill.

Plasticity data (Figure 17) indicate that the Head deposits can be classified as sandy or silty (sometimes very silty) clays and clayey silts of low to intermediate plasticity. The absence of high plasticity clays is unusual as the weathered mudrocks typically degrade to highly plastic clays: clays of high to very high plasticity are recorded in Head deposits overlying Coal Measures rocks in the nearby Castleford-Pontefract area (Barclay and others, 1990). In the Leeds area, the predominance of low to medium plastic clays may result from the extensive development of arenaceous beds in the Upper Carboniferous bedrock formations and their potential as a source material for Head deposits.

A profile of moisture content versus depth for the Head deposits (Figure 18) indicates a sharp decrease in the range of recorded moisture contents from 10–50 per cent (from ground surface to about 3 m) to 10–20 per cent (which remains fairly constant from 3 m to the maximum recorded depth of Head below ground surface, about 8 to 10 m). This may partly reflect the difficulty of distinguishing Head from in situ residual soil which commonly shows a gradual decrease in moisture content with depth, reaching an average of about 16 per cent at the weathered bedrock surface. In contrast to the weathered in situ soils, Head deposits tend to show more variable and generally higher compressibilities, more variable rates of consolidation settlement, and generally low shear strengths.

Design considerations

i) *Foundations*

The presence of soft, highly compressible zones giving rise to low bearing capacities and excessive differential settlements, and the ponding of water in depressions (locally caused by mining subsidence) due to effectively impermeable clays, present the main problems for foundation design on Head deposits. In general, weathered bedrock lies within about 1.5 m of the ground surface and where feasible the Head should be removed prior to placing foundations or, where thicknesses are excessive, loads transferred to sound underlying bedrock by piling. For shallow foundations on dominantly clayey Head, the loading criteria shown in Table 10 may be used as a guide.

The recorded sulphate concentrations indicate that no special precautions are normally needed to prevent sulphate attack on concrete. However, as for the Upper Carboniferous rocks, increased groundwater sulphate contents may be encountered in the vicinity of colliery waste tips and checks at specific sites should be undertaken during site investigations.

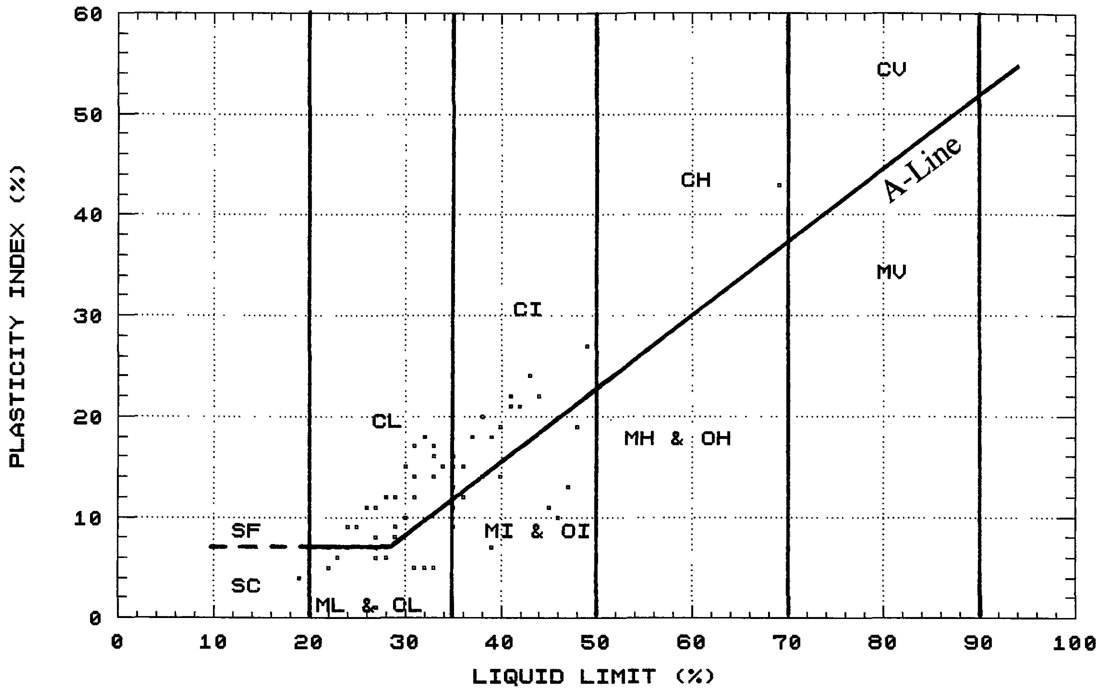


Figure 17 Plasticity diagram for Head deposits.

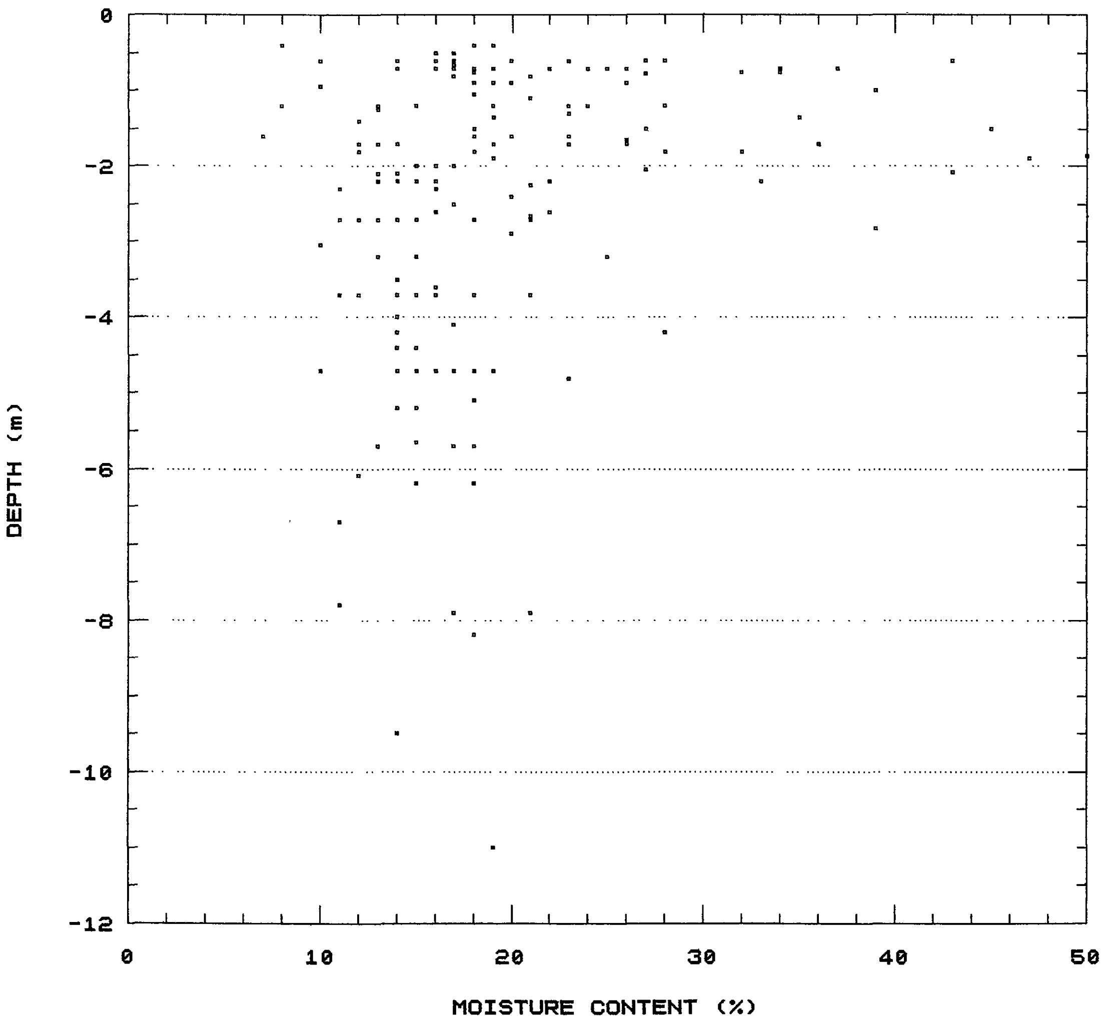


Figure 18 Profile of moisture content versus depth for Head deposits.

Table 10 Loading criteria for shallow foundations in Head deposits.

Foundation Type	Depth (m)	Nett Safe Bearing Capacity (kPa)	Factor of Safety	Differential Settlement
0.5m STRIP	1.0	100	3	19 mm
0.5m STRIP	1.0	150	2	29 mm
RAFT	0.5	100	3	40 mm
RAFT	0.5	150	2	60 mm

ii) *Slope stability*

Minor natural slope failures, often comprising areas of hummocky ground, may occur in the Head deposits. Such movements are too small and isolated to show on the geological maps. Even on low angle slopes, Head deposits may also contain relic shear surfaces (resulting from solifluction and multiple sliding movements during its formation under periglacial conditions). Shear strengths on these surfaces will be at or near residual values and this should be accounted for in slope design calculations. Cutting side slopes of 1V:2H are suggested as a guide for preliminary design in Head with no identified shear surfaces.

iii) *Excavatibility and suitability as fill*

Head deposits may be easily excavated with normal soft ground excavating plant. Problems may be encountered locally due to ponding of water in depressions where impermeable clayey Head is present. Head may be suitable for use as bulk fill, but locally may be too wet to achieve satisfactory compaction. No CBR data were obtained for Head deposits in the area but values may be expected to increase if compacted at optimum moisture contents (ranging from about 10 to 16 per cent) and to reduce considerably as moisture contents increase above optimum.

Alluvium

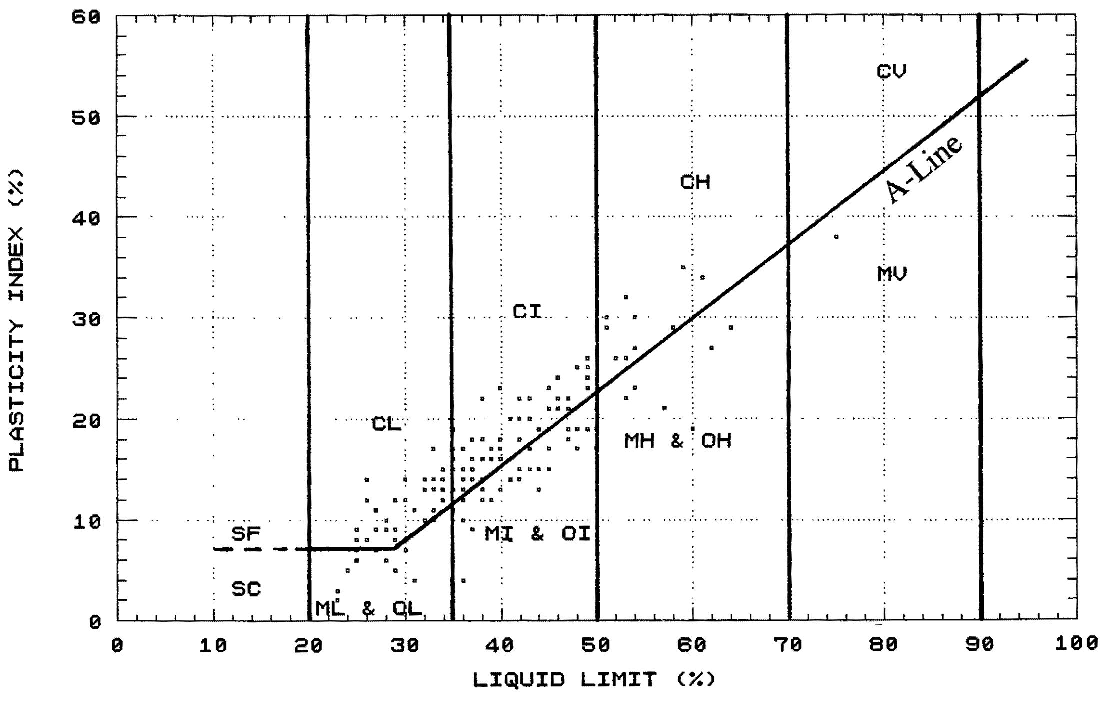
Alluvial deposits occur extensively on the valley-floor of the River Aire, and are also present in minor tributary valleys. Although extremely variable in terms of lithology on both a regional and local scale, and with highly variable geotechnical properties and engineering behaviour, the alluvial deposits may be broadly subdivided as follows:

'Upper Unit' Brown-grey mottled, soft to firm, silty CLAYS and clayey SILTS with local organic (peaty) horizons, and sand and gravel components becoming more common with depth.

'Lower Unit' Medium dense, fine to coarse-grained SANDS and angular to rounded, fine to coarse-grained GRAVELS with variable clay content and local lenses of organic silt or brown, pebbly, sandy clay.

The depths and thicknesses of the above units vary across the area. In the Aire valley combined thicknesses of up to 10 m are commonly recorded in site investigation reports, but thicknesses of c.14 m may occur locally (e.g. in a meander loop of the River Aire near Rodley sewage

Figure 19 Plasticity diagram for alluvial silts and clays.



works). At many locations the soft upper unit of the alluvium has been removed and replaced with fill. Summary geotechnical properties are presented separately for the two units in Appendix III, Tables 20–21, but lithologies (and engineering properties) may vary markedly at specific sites due to local layering and lensing.

Standard penetration test (SPT) N-values for the sands and gravels range widely from below 10 (loose) to over 100 (very dense), the great majority falling within the medium dense/dense range (N-values of 20 to 40) and showing an overall increase with depth. SPT N-values for the silts and clays are consistently below 40 (median 10) with no clear trend of increasing N-values with depth. These consistently low values reflect the low shear strengths of these materials.

The data for the silts and clays when plotted on the plasticity chart (Figure 19), indicate materials ranging from low to high plasticity, but zones of organic clay and peat (not recorded in the current database) will have very high plasticities. The silt/clay units may be expected to exhibit medium to very high compressibilities with very slow rates of consolidation settlement, particularly where soft organic clays and peat are present.

Design considerations

i) *Foundations*

Low bearing capacities (undrained cohesion commonly around 20 to 40 kPa), high compressibilities, high groundwater tables and water uplift pressures, and the likelihood of excessive total and differential settlements pose problems for foundations in the alluvium. Where limited thicknesses occur, wholesale removal and replacement of the alluvium with suitable fill may be an economic option, but elsewhere alternative solutions are required. Of these, piling and raft foundations are most commonly used in the Leeds area. For heavy structures, bored or driven piles should be used to transfer loads to the basal gravel or into the underlying bedrock. Minipiles bearing in the granular alluvial deposits should be suitable for light to moderately loaded structures. For piles in thicker alluvial deposits, consolidation of the clays may cause 'drag-down' of the loaded pile and this should be anticipated. Raft foundations have been successfully employed for light structures where large settlements need to be allowed for in design.

Maximum embankment heights of about 4 m with 1V:2H side slopes have been suggested for construction on alluvium. Very low rates of consolidation settlement may be partly overcome by the use of lightweight embankment fill or staged surcharging, for both embankments and light structures. Monitoring of settlements during construction should be undertaken and the likelihood of differential settlement accounted for in pavement design.

Due to the artificial straightening of the River Aire channel, abandoned meanders occur at several locations. It is important that these features (which may contain soft, compressible organic clays and silts hidden beneath made ground) are identified during site investigations prior to planned development.

The recorded groundwater sulphate concentrations in Class 2 of the BRE classification indicate that care is needed in the selection of buried concrete.

ii) *Slope stability*

High groundwater levels mean that excavations in the alluvium are subject to severe water inflow problems and immediate support is normally required to maintain the stability of trench sides and cut faces. Running sands may also be encountered below the water table.

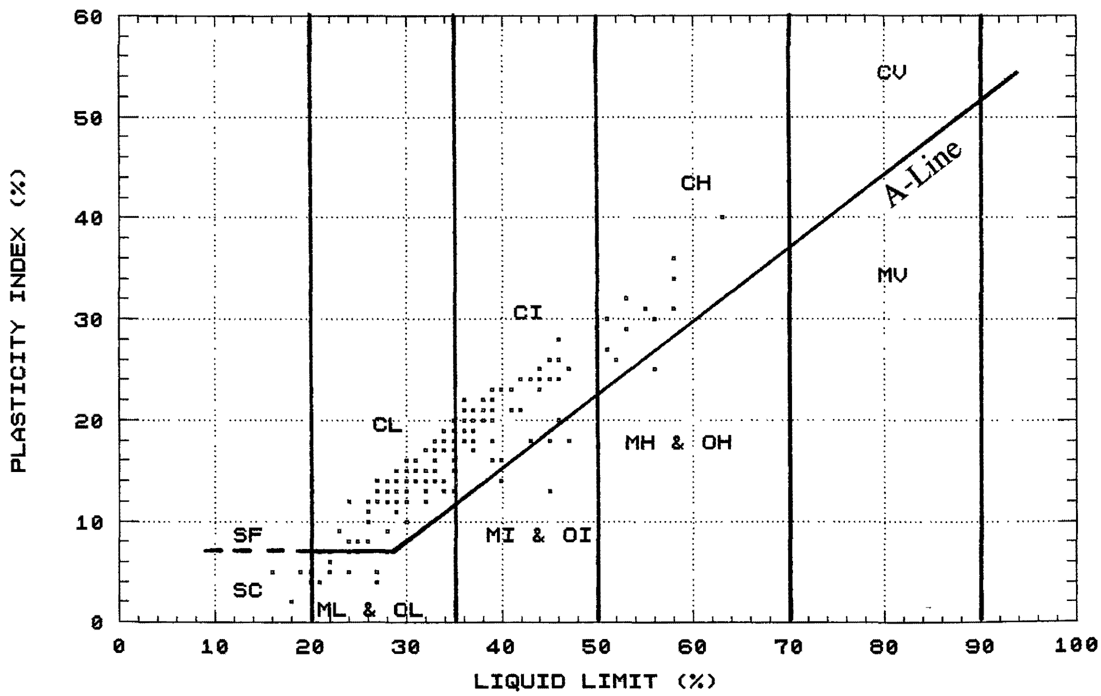
iii) *Excavatibility and suitability as fill*

Alluvial deposits are readily excavated using normal soft ground excavating plant but severe water inflow problems may be encountered during working. These deposits are generally unsuitable as fill material.

3. MIXED STIFF COHESIVE/DENSE NON-COHESIVE SOILS

This engineering geological unit comprises glacially derived material termed 'till' and 'glaciofluvial sand and gravel' on the geological maps. The till in the area is lithologically variable, but includes dominantly boulder clay and, at some localities, laminated silts and clays. It also includes moundy glacial deposits (morainic drift) which occur as low, elongated mounds over a small area in the Aire valley upstream

Figure 20
Plasticity diagram for till (boulder clay).



from Leeds. No geotechnical data were obtained for these latter deposits and no engineering assessment of them is made here. It is likely, however, that they were never subjected to substantial ice loading and, as such, their engineering behaviour may be more akin to gravelly clayey Head rather than an overconsolidated boulder clay. The glaciofluvial sands and gravels grade into the till deposits.

Boulder clay, found mainly on the higher ground, typically comprises brown, stiff to very stiff, stony, sandy clay with clasts of sandstone, chert and ironstone. Limestone clasts are present where it lies close to the Magnesian Limestone outcrop. The deposit is often variable and lenses of sand, intercalations of laminated clays and interbedded sandy gravels may occur locally. Summary geotechnical data for the boulder clay (till) is shown in Appendix III, Table 22. SPT results mainly range from 15 to over 60 (median 31), with N-values increasing with depth. Depending on the sand/silt content, the till matrix consists of clays ranging from low to high plasticity (Figure 20), with low to medium compressibility and generally high shear strength (typical undrained cohesions of around 100 kPa and angle of shearing resistance 10°).

Glaciofluvial sands and gravels may grade laterally and vertically into boulder clay. They range from slightly cohesive, clayey silty sands to highly permeable, dense/very dense non-cohesive sandy gravels with layers and lenses of silt and clay developed locally. Summary geotechnical data for these deposits are shown in Appendix III, Table 23. SPT N-values rarely fall below 30 and show a general, but erratic, increase with depth which possibly reflects variable clay contents and local silt/clay layering and lensing. Insufficient data were obtained to tabulate summary geotechnical results for laminated glacial/glaciolacustrine silts and clays. Limited SPT results recorded N-values ranging from 14 to 40 with a median value of 25.

Design considerations

i) *Foundations*

Till should present no major problems for shallow foundations provided lithological variations are determined during site investigations (particularly the presence of laminated silts and clays) and potential differential settlements are accounted for in design.

ii) *Slope stability*

Temporary cuts or excavations in 'homogeneous' boulder clay should remain stable, but the presence of layers or lenses of laminated clays may necessitate side support. Bands of silt and sandy gravel may result in perched water tables and seepage and, where exposed, excavations will require support. Cut slopes of 1V:2.5H have been recommended for long-term stability in relatively homogeneous boulder clay. Excavations in glaciofluvial sandy gravels will require immediate support and where water-bearing, measures to regulate water ingress will be required.

iii) *Excavatibility and suitability as fill*

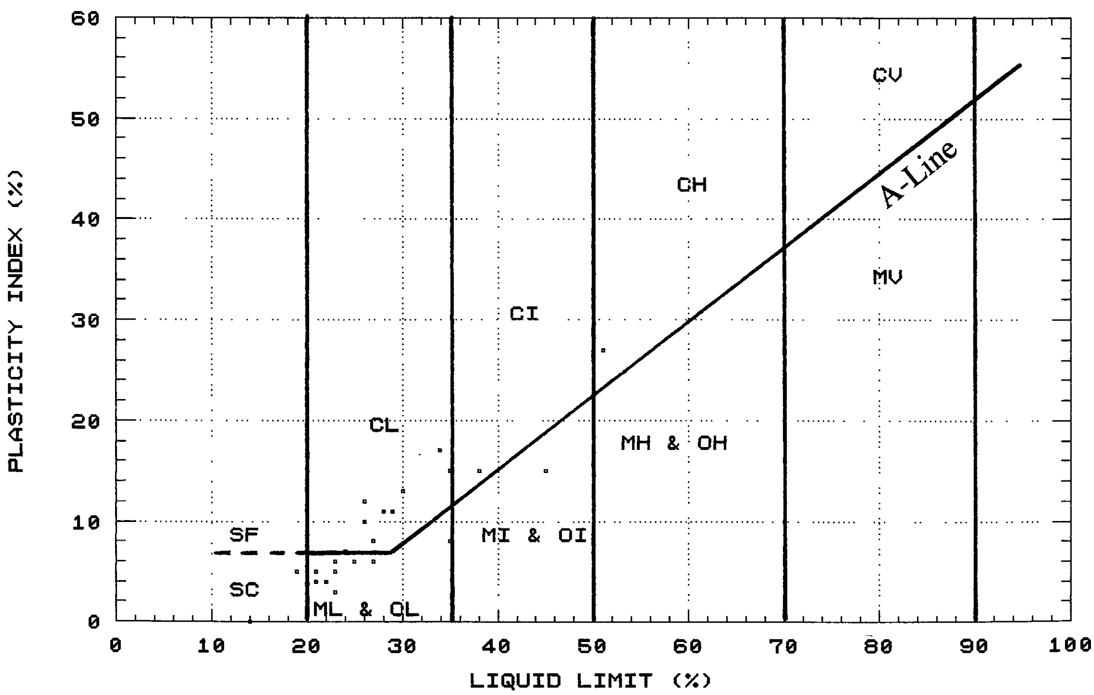
Till may be easily machine-excavated but ponding of surface water in low permeability boulder clay may cause problems during working. The laminated clays may prove unsuitable for use as fill, as may boulder clay occurring near water-bearing beds of sand and gravel.

4. Non-cohesive sand and gravel deposits

This unit comprises river terrace deposits, which occur as irregular but often elongated, impersistent low planar features along the Aire valley immediately upslope from the alluvium. The surface level of these deposits lies about 5 m above the alluvium (c.25 m above OD) and the surface climbs upslope imperceptibly to merge with hillwash and/or Head deposits on the lower Aire valley-slopes.

The terrace deposits consist mainly of medium dense, fine to coarse-grained sands and medium dense to dense, sandy, sub-rounded to rounded, fine to medium gravels with occasional cobbles. The gravel fraction is mainly of locally-derived Carboniferous sandstone with occasional ironstone, shale and limestone. Although these granular materials predominate, sandy clays and silts (in places, laminated or with included gravel) occur locally (e.g. in the Hunslet area), typically as a surface veneer over the sands and gravels and/or at the margins of the terraces where they merge imperceptibly with weathered clayey

Figure 21
Plasticity diagram for fine-grained terrace deposits.



slope deposits (hillwash/Head). In these marginal areas the terrace deposits are sufficiently clayey to have been worked for brick-making.

Summary geotechnical properties for the terrace deposits are shown in Appendix III, Table 24. For the granular materials, SPT N-values fall mainly between 10 to 50 (medium dense to dense) but loose deposits (N-values of 10 or less) are often found in the topmost 3 m below ground level. Limited plasticity data show the less dominant, fine-grained terrace deposits to consist mainly of low plasticity clays, silty clays and clayey silts, with some clays of intermediate plasticity (Figure 21). These materials can be expected to show low to moderate compressibilities and moderate shear strengths (typical undrained cohesion of about 50 kPa, and angle of shearing resistance of 9°). Horizontal shear strengths may, however, be much lower in laminated silts and clays.

Design considerations

i) *Foundations*

Provided lithological variations are identified, the terrace deposits should pose no major problem for most foundations. The deposits are well-drained, and shallow foundations should be above the water table. Care should be taken in some areas (e.g. near Hunslet) to identify and ascertain the depth and lithological composition of infilled channels below the terrace deposits, particularly during site investigations for heavier structures. Recorded groundwater sulphate concentrations generally fall into Class 1 of the BRE classification, indicating that no special precautions are normally required to prevent attack on buried concrete. However, checks should be made at specific sites during ground investigations.

ii) *Slope stability*

Excavations and cut faces will require immediate support and casing will be required to prevent collapse of granular material into bores. Water ingress should not present problems unless borings or excavations into channel infill are taken below river level (as hydraulic continuity may be anticipated).

iii) *Excavatibility and suitability as fill*

The terrace deposits may be readily excavated by machine digging. The sands and gravels should be suitable as granular fill but the terrace clays and silts are probably unsuitable for fill purposes.

5. Landslip deposits

The topography of the study area is generally low and subdued, and natural landslipping is not widespread. A few, generally shallow, dormant debris slides/flows and rotational slumps have been recognised during the geological mapping; the landslip deposits generally occurring on or near the middle to lower parts of slopes,. in excess of c.8–10°, in weathered mudstone below a coal seam and/or a capping sandstone (e.g. near Meanwood Grove, [2815 3842]). Minor, shallow slope movements (too small to be indicated as individual landslips on the geological maps, but identified from the presence of low arcuate scars above hummocky ground) are probable fairly common in the weathered mantle and/or Head deposits on such slopes (e.g. at Farnley, north of Billey Lane, [2552 3201]). Construction on these areas should be avoided wherever possible.

Remoulded clayey landslip debris is generally soft, poorly drained and may contain perched water tables. It also contains one or more shear surfaces, along which shear strengths are at or close to residual values. Construction activity (including excavations) on these deposits, even if the landslip is dormant and degraded, is always likely to reactivate movement and development on or close to these areas should be avoided wherever possible. If development on these areas is unavoidable, it is essential that site investigations are undertaken to adequately define the geometry and current stability of the landslip (and adjacent ground) in order that suitable stabilisation measures can be designed and implemented prior to construction. In some cases, small areas of landslip deposits may be removed completely and replaced with a free-draining granular fill. However, the mechanisms leading to initial failure should be ascertained and the likelihood of future potential movements in adjacent ground investigated.

Table 11 List of made ground localities

NATIONAL GRID SQUARE	NGR	MAXIMUM RECORDED THICKNESS (m)	NOTES
SE 23 NW			
2039	201 392	—	Apperley Lane: quarry
	2040 3975	—	Quarry Farm: quarries (see map)
2139	2175 3945	—	Intake Farm: quarry
	2195 3910	—	Mount Farm: landscaped area
2239	221 392	—	St Peter's Church: landscaped area
2339	230 394	—	near Whetstone Farm: landscaped area
	232 394		as above
	236 392	—	Beechwood: landscaped sports ground
	2307 3908	c.2	Southway: quarry
2439	2450 3975	—	Mosely Wood Croft: embanked area
	c. 247 394	c.3	Tinshill Road area: quarries (see map)
	2455 3905	c.7	Haigh Wood Road: quarries (see map)
2038	2025 3895	—	Cragg Wood Drive: quarry spoil
	205 388	—	Cragg Wood Drive: landscaped area
2138	2125 3860	—	Woodlands Drive: quarry
2238	2200 3845	—	Knott Lane: quarry

NATIONAL GRID SQUARE	NGR	MAXIMUM RECORDED THICKNESS (m)	NOTES
	2295 3840	—	West End School: landscaped area
2338	2335 3865	c.5	Hunger Hills: quarry
	237 385	—	Lee Lane East: landscaped area
	239 389	—	Westbrook Lane: landscaped sports ground
	239 382	5	Town Street area: quarries (see map)
2438	243 389	—	Lister Hill: infilled area
	2415 3860	c.7	Long Row area: quarries (see map)
	243 384	—	King George Avenue: landscaped area
	249 384	c.10	Low Lane: quarries (see map)
2037	206 377	—	Calverley Wood: quarry spoil
	2085 3715	—	St Wilfred's Church: landscaped area
2137	219 374	c.5	near Owl Bridge: embanked area
	219 371	7	Low Hall Road: embanked area
2237	225 370	—	Swaine Wood: embanked areas at River Aire bridge
2437	2445 3760	c.8	Cragg Hill area: quarries (see map)
2036	2015 3660	—	Carr Hill Drive: embanked area
2236	2285 3620	—	Rodley mills: embanked area
2336	237 365	—	Newlay: sludge beds
	238 363	c.5	Newlay: embanked areas near River Aire
2436	240 365	—	
	243 364	8	Newlay Quarry complex: spoil and backfill
	245 364	15	as above
	245 361	15	Whitecote: landscaped area ?of quarry spoil
	2430 3685	—	Newlay: former filter beds and embanked area
2035	2005 3550	3	Hill Top Farm: quarry
	204 351	c.4	near Woodhall Hills: landscaped area
	204 359	c.3	Crossfield House: quarry
2235	c. 225 359	5	Coal Hill: landscaped areas (see map)
	225 354	—	Farsley Beck Bottom: embanked area
	229 353	—	Intake Lane: landscaped area
2335	230 355	4	Intake: landscaped school playing fields
	232 358	6	Rodley Lane: embanked area
2435	2400 3573	4	Hillcourt Drive: infilled area
	2475 3555	c.5	Moorside mills: infilled area
SE 23 NE			
2539	2584 3903	3.6	Ireland Wood: quarry
2739	2785 3998	3+	Sir George Martin Drive: quarry
2939	2990 3935	3.2	Lingfield Approach: quarry
	2975 3935	2.4+	Lingfield Approach: quarry
2538	255 384	up to c.20	Woodside Quarry. Part now active landfill site. Methane detected in 1989.
	252 380	4.7	Low Lane: landfill area
2638	2663 3818	—	The Grange Road: quarry
	2669 3809	—	Wynford Grange: quarry, part backfilled
	269 383	2+	Otley Road: quarry
2537	251 373	8.5	White Hall Quarries, Hawksworth Wood
	2534 3746	—	Cragside Close: quarry
	2538 3743	c.5	Cragside Walk: quarry
	2546 3765	—	Butcher Hill: working quarry; about 10m of beds exposed, backfill of generated spoil
	2558 3774	c.11	Fillingfir Thicks: quarry
	257 374	c.26	Hawksworth Quarry
2737	2720 3741	c.4	Headingley Service Reservoir: opencast coal site; ceased coaling 1986
	276 379	11.1	Weetwood (Quarry Dene)
2837	282 379	9+	Meanwood Recreation Ground: quarry
	285 378	10.7	Hill Top: quarry
2937	2915 3755	4.6	Stonegate Road: clay (? and stone) pit
2536	2525 3667	c.25	Forge Quarry. Landfill completed 1979
	2560 3674	—	Vesper Gate Mount: quarry
	2566 3675	c.9.5	Vesper Road: quarries
	2572 3673	c.9.5	as above

NATIONAL GRID SQUARE	NGR	MAXIMUM RECORDED THICKNESS (m)	NOTES
	2515 3630	7.6	Toads Hole Wood: quarry
2836	2885 3640	6.1+	Walker's Road: quarry
	289 365	8.7	Stainbeck Side: quarry
2936	299 364	12.8+	Potternewton Mount: quarry(ies)
2535	2587 3532	—	Wyther Lane: brickworks
2635	2677 3559	10.0	Eden Crescent: quarry
2735	2785 3510	3+	Ashville Road: quarry(ies)
2835	289 357	7.7	Grosvenor Road: quarry
2935	292 358	10.7	Woodhouse Cliff Hostel: quarry
	293 357	14.7	Cliff Mount: quarry
	2935 3565	14.2	Lucas Street: quarry
	297 356	12.9	Rider Road: quarry; smaller examples nearby
	2970 3545	4.3	Melville road: clay pit
	2940 3515	3.4	St Mark's Road: 'brick pit'
SE 23 SE			
2634	268 349	?7+	Kirkstall Road: landfill area
2734	2732 3452	11.0	Redcote Lane: waste tip
	2765 3482	7.0	Burley Road: quarry
2934	291 348	—	Woodhouse Service Reservoir
2533	2502 3365	15.2	Gamble Hill: quarry
	2506 3369	3+	Gamble Hill: ?quarry tip and 'earthworks'
	2504 3353	—	Gamble Hill: quarry
	2552 3309	?c.9	Farnley Reservoir 'earthworks'
	2557 3304	3.4	Pipe and Nook Lane: landfill area
	2590 3376	—	Hill Top Moor: ?quarry
	2574 3366	—	Hill End Road: ?quarry
2633	2678 3300	6+	Cross Lane: ?backfilled brick-clay pit
	2685 3368	—	Theaker Lane: brick pit
2733	2711 3355	?c.10	Eyres Terrace: embankment
	2760 3385	—	Pickering Street: quarry
2833	281 339	9.0	Former Armley Bridge Works
2933	291 337	4.7	Duncombe Street: landfill area
2532	2542 3272	—	Bawn Avenue: ?brick pit
	2543 3237	3.4	Bawn Approach: landfill area
	2544 3298	4.8	Farnley Beck: landfill area. Asbestos and "gasworks" waste reported
2632	261 324	—	Blue Hill Lane sports ground: embankment
	2621 3298	c.10	Blue Hill (Fireclay) Quarry; used as a tip since before 1948
	2635 3280	c.9	Cliffs (Fireclay) Quarry; used as a tip since before 1948
	2667 3274	c.12	Cabbage Hill (Fireclay) Quarry
	2619 3216	7.3	Fawcett Way: clay pit
	2621 3213	—	Fawcett Way: clay pit
2732	2736 3261	—	Oldfield Lane: brick-clay pit
2832	2882 3290	5.5	Whitehall Road: fireclay pit
	2872 3213	40.1	Low Close Mine: opencast coal and fireclay site
2531	2515 3177	—	Coach Road: opencast ?coal site
	253 316	—	Whitehall Road: part of Barkers Well Farm Tip, and quarry
	256 316	c.16	Farnley Fireclay Works (Leeds Fireclay Company)
	259 314	—	?Farnley Fireclay Works
2631	262 319	5.4	?infilled channel of Wortley Beck
	264 312	c.6?	Ochre House Farm landfill site
2731	2723 3169	9.6	Leeds Fireclay Company
2831	288 314	c.28	Elland Road: brick pit
2931	2923 3187	—	Elland Road: ?brick pit
	2932 3185	—	Cambrian Street: ?brick pit
	2976 3181	4.7	Hunslet Hall Road: brick pit
	2984 3177	12+	Hunslet Hall Road: clay and gravel pit
	2970 3179	3.9	Lady Pit Lane: ?clay and ?gravel pit
	2972 3171	1.8	Lady Pit Lane: ?clay and ?gravel pit
	298 317	14.6	Disraeli Terrace: ?backfilled clay and gravel pit(s) and areas of tipped waste

NATIONAL GRID SQUARE	NGR	MAXIMUM RECORDED THICKNESS (m)	NOTES
2530	2525 3040	—	Farnley Wood Side: quarry
	258 300	8+	Farnley Wood Beck: embankment
2630	269 309	c.25	Gelderd Road: brick pit. Landfill site with industrial, inert, domestic and some notifiable wastes
2730	2708 3059	—	Gelderd Road: former railway cutting
	2704 3066	—	Gelderd Road: ?fireclay pits
	2706 3084	?c.12	Ravell's Pit: colliery waste tip
	2763 3026	4.3	Cottingley Drive: quarry
	2792 3077	?c.6	Crow Nest Lane: embankment
2830	2824 3014	6.4	Millshaw opencast coal site (part). Restored 1959
	283 301	10.4	Millshaw: ?opencast waste
	2824 3004	c.5 (14.1 in area of SE 22 NE)	Millshaw opencast coal site (part). Restored 1959
SE 33 NW			
3139	312 396	3.0	Moortown East Reservoir: former quarry
	319 396	3.0	Shadwell Lane: quarry
3239	321 396	3.0	Darkwood Close: quarry
3038	301 382	—	Woodbourne Avenue: quarry
3138	310 387	9+	Sportsman's Hall brickyard
3037	309 372	9.0	Allerton Park: quarry
3337	334 373	6+	Waterloo Lake: former ?quarry
3036	302 364	11.5	Scott Hall: quarries
	301 360	c.8	Scott Hall: quarries and backfill area
	300 367	8.5	Potternewton Lane: quarry
3136	320 368	c.15	Fitzroy Drive: quarry
3236	c. 322 368	c.15	Fitzroy Drive area: quarries (see map)
	324 367	22.5	Oakwood Crescent: quarries
	323 366	7.5	Ravenscar View: quarry
3035	301 351	10.5	Servia Drive: clay pit
3235	322 357	—	Hovingham Ave: colliery waste tip
	321 352	4.5	Lane Pit: colliery waste tip, undefined area, ?partly removed
	327 351	4.5+	Gipton (No 1) coal pit: ceased coaling 1917
3335	332 355	4.0	Gipton Colliery: waste tip (restructured)
3435	342 355	c.8	Fearnville recreation ground
	3495 3545	8.5	Seacroft playground: ?opencast coal working
SE 33 NE			
3539	3523 3953	—	Grove Lodge: ?quarry
	356 394	—	Birkby Hill: area includes a service reservoir
	c. 358 395	—	Birkby Hill: quarries
3639	3641 3901	—	Intake Farm: quarry
3739	c. 370 398	2.4	Carr Farm: quarries
	3730 3995	4.6+	Westfield Lane: quarry
	3759 3988		Main Street: ?quarry
	3703 3909	—	Intake Dairy Farm: quarry
	3710 3903	—	Holly Croft: quarry
	3785 3912	—	Thorner Bottoms Wood: quarry
	3795 3991	6.1	Littlemoor Lane: quarry
3839	3875 3911	—	Saw Wood: ?clay pit
	3887 3915	—	Saw Wood: quarry
3939	3934 3935	—	Kiddal Hall: quarry
	3950 3930	4.6	Kiddal ('limestone') Quarry Farm
	3946 3918	—	Kiddal ('limestone') Quarry Farm
	3912 3905	—	Kiddal Quarry Farm: ?'limestone' quarry
	c. 393 391	2+	Kiddal Quarry Farm: sandstone (and ?'limestone') quarries
3538	c. 351 389	6.1	Hobberley Lane: quarries
	3519 3873	—	Wetherby Road: brickfield
3638	3695 3883	—	Thorner Lane: quarry
3537	354 376	6.1	Coal Road: 'limestone' quarries
	352 374	4.9	Lime Pits Wood
	353 370	5.7	Ramshead Wood: 'limestone' quarries

NATIONAL GRID SQUARE	NGR	MAXIMUM RECORDED THICKNESS (m)	NOTES
3637	3623 3720	—	Grimes Dyke Farm: landfill area
	3650 3713	—	York Road: landfill area
3837	c. 385 372	—	Rakehill Road: quarries
3937	3925 3733	—	Rakehill Road: landfill area
	3993 3768	—	Wendel Hill: 'limestone' quarry
3536	3540 3681	—	Ramshead Approach: 'limestone' quarries
3636	365 365	?c.5	Farndale Approach: landfill area
3736	3738 3676	—	Wood Lane: brick pit
3836	3837 3605	—	Bog Lane: quarry
	c. 389 367	—	Limekiln Hill: 'limestone' quarries
3535	3557 3543	3.1	Inglewood Drive: quarry
	3585 3540	—	Inglewood Place: quarry
	3588 3531	—	York Road: quarry
3635	3628 3523	—	Victoria Pit: quarry
	3660 3530	—	Sandbed Lane: quarry
	3666 3512	4.6	Church Lane: quarry
3735	375 355	31.6	Stanks opencast sites and extensions (see map): restored 1956
	379 354	22.1	Cock Beck opencast sites: restored 1948
3835	384 357	21.2	Cock Beck Extension opencast site: ceased coaling 1948
3935	392 353	42.4	The Springs and Extensions 1 to 4 opencast site: restored 1964
	398 354	29.5	The Springs Extension 5 opencast site: ceased coaling 1967
	3918 3584	—	Upper Barn Bow Farm: 'limestone' quarry
	3938 3576	—	Upper Barn Bow Farm: 'limestone' quarry
	c. 396 358	—	Upper Barn Bow Farm: 'limestone' quarries
	3950 3554	—	Upper Barn Bow Farm opencast site
SE 33 SW			
3034	3015 3485	13.7	Servia Hill: clay pit
3134	3120 3465	?21.5 (10.7 proved)	Roseville Road brick pit
	315 346	10.7	Dolly Lane brick pit, 19.4 m of beds were exposed
	3165 3440	4.9	Beckett Street: brick field
	318 341	4.6	Burmantofts Brickworks: kiln area
3234	321 345	—	Harrison's Pit (coal and clay), Burton Way, 11.4 m of beds were exposed
	321 343	9.1	Trent Road: clay pit
	326 344	—	Lupton Avenue: brickworks
	328 341	—	Prince of Wales Pit: landscaped area of colliery waste and refuse
3334	340 342	8.5	Wyke Beck valley, York Road: embanked areas
3133	317 338	20+	Burmantofts brick pits
	316 334	4.1	Lavender Walk quarry (?enlarged)
	3175 3343	9.1	Pontefract Lane quarry
	3184 3337	9.4	Pontefract Lane quarry
3233	324 330	—	East End Park: colliery waste tips
3333	333 333	11.2	Osmondthorpe Colliery: waste tip
	337 330	7.3+	Halton Moor Ave: ?colliery and domestic waste tip
3433	347 340	17.3	Killingbeck Colliery: landscaped colliery and waste tip (industrial, inert, domestic)
3132	316 322	7.0	Knowsthorpe industrial estate (former railway yard) – ?including gravel working (industrial, inert, ?domestic waste)
3232	328 327	7.1	West View opencast site (west) ; restored 1954
	325 320	11.0	Knostrop opencast site; restored 1954
3332	332 326	6.6	West View opencast site (east); restored 1954
	3365 3220	14.0	Wyke Beck opencast site; ceased coaling 1951
3031	306 319	16.1	Jack Lane Pottery
	3065 3178	22.3	Hunslet Brickfields (central)
	3067 3172	24.7	Hunslet Brickfields (south)
	3085 3185	—	Hunslet Brickfields (east)
3131	318 315	—	infilled channel of River Aire
3231	327 314	—	Knostrop sewage works (west)
3331	336 314	—	Skelton Grange Power Station
	340 310	—	Knostrop sewage works (east)

NATIONAL GRID SQUARE	NGR	MAXIMUM RECORDED THICKNESS (m)	NOTES
3431	349 318	19.4	Spring Wood extension opencast site; restored 1946
	3490 3115	8+	Pontefract Lane opencast site
3030	304 308	5.2	Hunslet Carr: brickfield
	3090 3085	10.0	Arthington Ave: brick pit
	305 303	c.15	Middleton Broom opencast site; ceased coaling c.1977
	303 300	c.29*	Lockwood opencast site; ceased coaling 1980
	305 305	8.8	Hunslet Carr general area, excluding above
3130	318 301	c.20	East View opencast site (north); ceased coaling 1958
	311 307	22.1	Sandon Place: brick pit
	3100 3035	c.6	Belle Isle: quarry
3230	327 310	9.8	Thwaite Lane: gravel pit (industrial and inert waste)
	329 302	5.3	Stourton area excluding sites below
3330	330 307	5.9	Haigh Park Road: gravel pit
	331 303	c.9	Bison Works: gravel pit
	330 300	16.5*	Bell Hill opencast site; ceased coaling 1960
3430	343 303	11.2	Skelton Grange sludge beds: the thickness of made ground given may be exceeded where sand and gravel extraction has taken place. (Industrial, inert, domestic waste)
		* not in area of Sheet SE 33 SW	
SE 33 SE			
3534	3513 3495	5.3	Foundry Lane–York Road: infilled area
	354 346	c.11	Seacroft Hospital: landscaped area
	3571 3425 & 3577 3428	—	The Mount, Whitkirk: colliery spoil
3634	3680 3457	—	Austhorpe Lane: backfilled railway cutting
3834	386 342	c.16	Austhorpe opencast site: ceased coaling 1945
	389 343	c.9	Manston opencast site: ceased coaling 1945
	386 349	—	Cock Beck: private landfill site
	386 345	—	Manston Lane: colliery spoil
3934	396 342	c.9	Garforth opencast site: ceased coaling 1945
	391 346	6.2	Barnbow Pit: colliery spoil and landscaped ground
3633	3617 3331	4.2	Whitkirk: bowling green
	3686 3359	3.0	Whitkirk Lane End: embanked area
	364 338	c.4	Prince Arthur Pit: colliery spoil
3733	375 337	9.6	West Yorkshire Colliery: Austhorpe: colliery spoil
	3780 3385	—	Brown Moor Pit: colliery spoil
3833	381 338	—	Ellen Pit: colliery spoil
3532	352 323	19.0	Pump Wood opencast site: restored 1944
	353 325	<17.1	Beechwood opencast site: ceased coaling 1943: some fill later removed
	3522 3286	15.5	Temple Gate, West, opencast site: restored 1953
	3544 3279	15.8	Temple Gate, East, opencast site: restored 1953
3632	369 322	17.1	Colton opencast site: restored 1947
	366 329	—	Colton Pit: colliery spoil
	364 320	18.6	Dawson Wood opencast site: restored 1946
3832	3840 3235	—	Swillington Lane: quarry
3932	3935 3225	—	motel site: landscaped area of fill
	3947 3281	—	Wakefield Road: quarry
3531	352 314	5.5	Spring Wood Extension opencast site: restored 1947
	356 318	27.1	Dunstan Hills I and II opencast sites: restored 1947
	3572 3196	—	Temple Newsam: ornamental gardens
3631	365 315	c.77	Opencast sites: ceased coaling 1946 (Avenue Wood), 1979 (Charcoal), 1986 (Gamblethorpe), 1973 (Oxbow Extension); restored 1945 (Waterloo). Gamblethorpe is currently a landfill site (industrial, inert, domestic waste; also some notifiable waste materials)
	360 317	17.9	Park opencast site
3831	386 315	—	Swillington Brickworks: spoil from working quarry. Also spoil embankments to the east.
3931	390 313	—	Primrose Colliery: landscaped colliery spoil.

NATIONAL GRID SQUARE	NGR	MAXIMUM RECORDED THICKNESS (m)	NOTES
3530	358 303	56.5+	Oxbow, Newsam Green and Leventhorpe opencast sites: now Oxbow ash disposal site for pulverised ash and inert waste
3730	3725 3015	—	Newsam Green Road: spoil from Gamblethorpe opencast site
	3735 3025	3.7	Gamblethorpe landfill site screening embankment: colliery spoil
3830	3874 3010	—	Little Preston Hall Farm: levelled, infilled area
	387 306	—	Swillington Nurseries: levelled, infilled area
3930	3914 3010	—	Little Preston Hall: area of tip

Table 12 Summary gotechnical data for the Cadeby Formation (Lower Magnesian Limestone)

ENGINEERING GEOLOGY DESCRIPTION	ENGINEERING GEOLOGY COMMENTS
Buff, weathered, fine to coarse-grained, marly dolomitic LIMESTONE with local oolitic horizons. Thinly to massively bedded.	Variable rockhead level with possible karstic conditions. Highly weathered zones and solution cavities (infilled and open) may cause excessive differential settlements and inadequate bearing capacities for shallow foundations.

SUMMARY FORMAT

TEST PARAMETER		No. of Samples
	No of Samples	
50%		>5
25%	75%	>10
(percentiles)		
10%	90%	>25
2.5%	97.5%	>100

FIELD MEASUREMENTS

SPT N-VALUE	RPT (mm	RQD (%)	If (mm)
24	22	27	
56	77	17	
47 100	50 90	13 20	
		12 23	

INDEX AND CHEMICAL TESTS

MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
27	7	7	7			3	4
17	36	21	18			7.8	1
13 20	31 41	18 24	10 20				
12 23							

PARTICLE SIZE DISTRIBUTION

CLAY (%)	SILT (%)	SAND (%)	GRAVEL (%)

CONSOLIDATION AND COMPACTION TESTS

Mv class*	Cv class*	MDD (Mg/m3)	OMC (%)	CBR unsoaked (%)	CBR soaked (%)

STRENGTH TESTS

Cu (kPa)	ϕu (degrees)	UCS (MPa)	PT. LOAD diam. (MPa)	PT. LOAD axial (MPa)
5	5			
88	8			

* Classes defined in Annex A

Table 13 Summary geotechnical data for sandstones of the Millstone Grit and Coal Measures (fresh to slightly weathered)

ENGINEERING GEOLOGY DESCRIPTION	ENGINEERING GEOLOGY COMMENTS
Grey to greyish brown, moderately to well-jointed, moderately strong, variably micaceous and locally conglomeratic, fine to coarse-grained SANDSTONES of the Millstone Grit and Coal Measures.	Moderately strong to strong rock. Generally good founding medium but interbedded mudstones will cause local variations in settlement characteristics Potential problems with underlying shallow coal workings. Ripping/blasting required for excavations.

SUMMARY FORMAT

TEST PARAMETER	No. of Samples
No of Samples	
50%	>5
25% 75% (percentiles)	>10
10% 90%	>25
2.5% 97.5%	>100

FIELD MEASUREMENTS

SPT N-VALUE	RPT (mm	RQD (%)	If (mm)
11	64	222	
150	42	52	
64 200	20 75	28 81	
	0 99	14 100	
		0 100	

INDEX AND CHEMICAL TESTS

MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
64				49		17	17
4				2.42		6.7	1
3 8				2.36 2.49		6.1 7.4	1 1
2 14				2.26 2.57			

PARTICLE SIZE DISTRIBUTION

CLAY (%)	SILT (%)	SAND (%)	GRAVEL (%)

CONSOLIDATION AND COMPACTION TESTS

Mv class*	Cv class*	MDD (Mg/m3)	OMC (%)	CBR unsoaked (%)	CBR soaked (%)

STRENGTH TESTS

Cu (kPa)	ϕu (degrees)	UCS (MPa)	PT. LOAD diam. (MPa)	PT. LOAD axial (MPa)
		61	53	122
		35	1.1	1.55
		25 54	0.8 1.9	0.8 2.3
		17 64	0.3 2.5	0.4 3.2
				0.3 3.7

* Classes defined in Annex A

Table 14 Summary geotechnical data for sandstones of the Millstone Grit and Coal Measures (moderately to completely weathered)

ENGINEERING GEOLOGY DESCRIPTION	ENGINEERING GEOLOGY COMMENTS
Greyish brown, moderately strong to moderately weak, silty micaceous SANDSTONES and medium dense to dense silty, clayey SANDS. (weathered sandstones of the Millstone Grit and Coal Measures)	Variable depth of weathered zone. May be weathered to sandy soil within 5 m of ground surface. Zones of highly weathered rock may be present to depths in excess of 12 m below ground surface, particularly in fault zones.

SUMMARY FORMAT

TEST PARAMETER		No. of Samples
	No of Samples	
50%		>5
25%	75% (percentiles)	>10
10%	90%	>25
2.5%	97.5%	>100

FIELD MEASUREMENTS

	SPT N-VALUE	RPT (mm	RQD (%)	If (mm)
No of Samples	525	220	117	
50%	64	73	31	
25% / 75%	36 / 123	50 / 102	14 / 41	
10% / 90%	19 / 176	31 / 133	0 / 46	
2.5% / 97.5%	11 / 283	1 / 200	0 / 72	

INDEX AND CHEMICAL TESTS

	MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
No of Samples	670	182	182	165	348	57	219	223
50%	15	33	20	13	2.06	1.75	6.7	1
25% / 75%	12 / 19	28 / 38	18 / 22	9 / 18	2.00 / 2.13	1.66 / 1.82	6.1 / 7.1	1 / 1
10% / 90%	9 / 24	28 / 44	16 / 25	6 / 22	1.91 / 2.19	1.52 / 1.92	5.6 / 7.5	1 / 1
2.5% / 97.5%	6 / 30	22 / 58	14 / 30	2 / 29	1.81 / 2.25		4.5 / 8.2	1 / 2

PARTICLE SIZE DISTRIBUTION

	CLAY (%)	SILT (%)	SAND (%)	GRAVEL (%)
No of Samples	25	25	36	36
50%	7	25	36	32
25% / 75%	4 / 20	19 / 34	21 / 54	8 / 48
10% / 90%	3 / 23	15 / 40	12 / 64	1 / 70
2.5% / 97.5%				

CONSOLIDATION AND COMPACTION TESTS

	Mv class*	Cv class*	MDD (Mg/m3)	OMC (%)	CBR unsoaked (%)	CBR soaked (%)
No of Samples	28	29			67	6
50%	3	4			5	4
25% / 75%	3 / 3	3 / 4			3 / 7	
10% / 90%	3 / 3	3 / 4			2 / 8	
2.5% / 97.5%						

STRENGTH TESTS

	Cu (kPa)	ϕu (degrees)	UCS (MPa)	PT. LOAD diam. (MPa)	PT. LOAD axial (MPa)
No of Samples	347	346	13	69	33
50%	70	6	25	1	0.5
25% / 75%	38 / 105	0 / 18	20 / 32	0.6 / 1.3	0.3 / 1.0
10% / 90%	24 / 150	0 / 28		0.2 / 1.6	0.3 / 1.5
2.5% / 97.5%	13 / 250	0 / 36			

* Classes defined in Annex A

Table 15 Summary geotechnical data for mudstones of the Millstone Grit and Coal Measures (fresh to slightly weathered)

ENGINEERING GEOLOGY DESCRIPTION	ENGINEERING GEOLOGY COMMENTS
Medium to dark grey, moderately fissured, weak to moderately strong, silty and sandy MUDSTONES of the Millstone Grit and Coal Measures.	Fresh to slightly weathered rock of low to intermediate plasticity and medium compressibility. Tends to deteriorate rapidly in presence of water. Suitable as fill if placed under controlled compaction conditions

SUMMARY FORMAT

TEST PARAMETER	No. of Samples
No of Samples / 50%	>5
25% / 75% (percentiles)	>10
10% / 90%	>25
2.5% / 97.5%	>100

FIELD MEASUREMENTS

	SPT N-VALUE	RPT (mm	RQD (%)	If (mm)
No of Samples	89	26	9	
50%	156	50	54	
25% / 75%	94 / 202	40 / 75		
10% / 90%	71 / 260	12 / 102		
2.5% / 97.5%				

INDEX AND CHEMICAL TESTS

	MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
No of Samples	86	25	25	25	12	8	8	8
50%	9	31	21	10	2.15	1.915	6.7	1
25% / 75%	8 / 12	29 / 33	19 / 22	8 / 12	2.08 / 2.30	1.82 / 1.95	6.1 / 7.5	
10% / 90%	6 / 15	26 / 35	18 / 23	6 / 13				
2.5% / 97.5%								

PARTICLE SIZE DISTRIBUTION

CLAY (%)	SILT (%)	SAND (%)	GRAVEL (%)

CONSOLIDATION AND COMPACTION TESTS

Mv class*	Cv class*	MDD (Mg/m3)	OMC (%)	CBR unsoaked (%)	CBR soaked (%)

STRENGTH TESTS

	Cu (kPa)	ϕu (degrees)	UCS (MPa)	PT. LOAD diam. (MPa)	PT. LOAD axial (MPa)
No of Samples	9	9	65		2
50%	105	20	32		1.1
25% / 75%	76 / 110	12 / 23			
10% / 90%					
2.5% / 97.5%					

* Classes defined in Annex A

Table 16 Summary geotechnical data for mudstones of the Millstone Grit and Coal Measures (moderately to completely weathered)

ENGINEERING GEOLOGY DESCRIPTION	ENGINEERING GEOLOGY COMMENTS
Orange brown and pale grey, moderately strong, fissured silty MUDSTONES and firm to stiff, silty CLAYS of low to high plasticity (weathered mudstones of the Millstone Grit and Coal Measures).	Depth of weathered mantle variable but often within 2 to 6 m of ground surface. Highly weathered zones may occur to depths in excess of 10 to 15 m. Heavy loads may need piling to sound bedrock. May be too wet to achieve optimum compaction.

SUMMARY FORMAT

TEST PARAMETER	No. of Samples
No of Samples; 50%	>5
25% 75% (percentiles)	>10
10% 90%	>25
2.5% 97.5%	>100

FIELD MEASUREMENTS

	SPT N-VALUE	RPT (mm	RQD (%)	If (mm)
No of Samples	785	145	40	3
50%	66	102	27	12
25% 75%	40 100	75 135	11 43	
10% 90%	27 146	50 175	0 61.5	
2.5% 97.5%	14 195	20 230		

INDEX AND CHEMICAL TESTS

	MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
No of Samples	1198	296	296	296	778	111	335	334
50%	17	42	23	19	2.05	1.74	6.5	1
25% 75%	13 22	36 52	21 26	14 25	1.95 2.14	1.59 1.84	6 7	1 1
10% 90%	10 28	29 59	19 29	9 33	1.86 2.21	1.52 1.93	5.5 7.5	1 1
2.5% 97.5%	8 34	26 70	16 33	4 42	1.78 2.28	1.35 2.00	4.5 8.0	1 1

PARTICLE SIZE DISTRIBUTION

	CLAY (%)	SILT (%)	SAND (%)	GRAVEL (%)
No of Samples	22	22	22	22
50%	29	55	11	2
25% 75%	18 40	46 64	5 17	0 6
10% 90%	15 47	41 67	4 24	0 11
2.5% 97.5%				

CONSOLIDATION AND COMPACTION TESTS

	Mv class*	Cv class*	MDD (Mg/m3)	OMC (%)	CBR unsoaked (%)	CBR soaked (%)
No of Samples	27	27	17	17	47	12
50%	3	3	2.00	11	3	5.5
25% 75%	3 3	3 4	1.96 2.00	9 11	2 7	3 23.5
10% 90%	3 3	3 4			1 10	
2.5% 97.5%						

STRENGTH TESTS

	Cu (kPa)	φu (degrees)	UCS (MPa)	PT. LOAD diam. (MPa)	PT. LOAD axial (MPa)
No of Samples	748	748	5		6
50%	76	8	7		0.7
25% 75%	53 110	0 15	1 13		0.5 0.9
10% 90%	34 139	0 22			
2.5% 97.5%	18 190	0 30			

* Classes defined in Annex A

Table 17 Summary geotechnical data for siltstones of the Millstone Grit and Coal Measures (fresh to slightly weathered)

ENGINEERING GEOLOGY DESCRIPTION	ENGINEERING GEOLOGY COMMENTS
Grey to greyish brown, moderately strong, variably clayey SILTSTONES of the Millstone Grit and Coal Measures.	Rock of low plasticity and low compressibility. Grades laterally and vertically into mudstones and sandstones. Generally good founding medium but interbedded mudstone may cause local variations in strength and bearing capacity.

SUMMARY FORMAT

TEST PARAMETER		No. of Samples
	No of Samples	
50%		>5
25%	75%	>10
(percentiles)		
10%	90%	>25
2.5%	97.5%	>100

FIELD MEASUREMENTS

	SPT N-VALUE	RPT (mm	RQD (%)	If (mm)
No of Samples	4	32	39	
50%	136	91	28	
25% / 75%		55 / 115	14 / 46	
10% / 90%		40 / 130	6 / 54	

INDEX AND CHEMICAL TESTS

	MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
No of Samples	13				4		2	2
50%	9				2.4		7.6	1
25% / 75%	6 / 12							

PARTICLE SIZE DISTRIBUTION

CLAY (%)	SILT (%)	SAND (%)	GRAVEL (%)

CONSOLIDATION AND COMPACTION TESTS

Mv class*	Cv class*	MDD (Mg/m3)	OMC (%)	CBR unsoaked (%)	CBR soaked (%)

STRENGTH TESTS

	Cu (kPa)	ϕu (degrees)	UCS (MPa)	PT. LOAD diam. (MPa)	PT. LOAD axial (MPa)
No of Samples			5	3	24
50%			28	0.6	1.3
25% / 75%					0.8 / 1.75
10% / 90%					0.1 / 2.5

* Classes defined in Annex A

Table 18 Summary geotechnical data for siltstones of the Millstone Grit and Coal Measures (moderately to completely weathered)

ENGINEERING GEOLOGY DESCRIPTION	ENGINEERING GEOLOGY COMMENTS
Greyish brown, moderately strong to moderately weak clayey SILTSTONES and firm clayey SILTS and silty CLAYS (weathered siltstones of the Millstone Grit and Coal Measures).	Variable depth of weathered zone. May be weathered to silty clay soil within top 1 to 5 m of ground surface. Variable strength and bearing capacity associated with depth and grade of weathering.

SUMMARY FORMAT

TEST PARAMETER	No. of Samples
No of Samples	
50%	>5
25% 75% (percentiles)	>10
10% 90%	>25
2.5% 97.5%	>100

FIELD MEASUREMENTS

	SPT N-VALUE	RPT (mm	RQD (%)	If (mm)
No of Samples	178	57	48	
50%	83	110	0	
25% 75%	49 134	75 150	0 34	
10% 90%	32 164	43 225	0 0	
2.5% 97.5%	20 225			

INDEX AND CHEMICAL TESTS

	MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
No of Samples	260	88	88	88	178	28	72	72
50%	17	38	22	17	2.11	1.81	6.7	1
25% 75%	14 20	34 44	19 24	14 21	2.03 2.18	1.68 1.88	6.15 7.3	1 1
10% 90%	11 23	29 50	17 27	9 25	1.92 2.23	1.56 1.93	5.3 7.8	1 1
2.5% 97.5%	9 30				1.75 2.35			

PARTICLE SIZE DISTRIBUTION

	CLAY (%)	SILT (%)	SAND (%)	GRAVEL (%)
No of Samples	6	6	7	7
50%	14	44	20	22

CONSOLIDATION AND COMPACTION TESTS

	Mv class*	Cv class*	MDD (Mg/m3)	OMC (%)	CBR unsoaked (%)	CBR soaked (%)
No of Samples	32	32			8	4
50%	3	4			8	7
25% 75%	3 3	3 4			3.5 9	
10% 90%	2 3	3 4				

* Classes defined in Annex A

STRENGTH TESTS

	Cu (kPa)	ϕu (degrees)	UCS (MPa)	PT. LOAD diam. (MPa)	PT. LOAD axial (MPa)
No of Samples	152	152	2	9	29
50%	90	0	16.5	0.4	1.3
25% 75%	55 134	0 9		0.3 0.7	0.8 2.4
10% 90%	42 190	0 20			0.3 3.5
2.5% 97.5%	20 308	0 30			

Table 19 Summary geotechnical data for Head deposits

SUMMARY FORMAT

FIELD TESTS

ENGINEERING GEOLOGY DESCRIPTION
Soft to firm, sandy silty CLAY with stones (typically). Locally, may be a gravelly silty SAND or sandy GRAVEL.

TEST PARAMETER		No. of Samples
	No. of Samples	
50%		>5
25%	75%	>10
(percentiles)		
10%	90%	>25
2.5%	97.5%	>100

SPT N-VALUE	
	34
22.5	
15	35
7	51

INDEX AND CHEMICAL TESTS

MOISTURE CONTENT (%)		LIQUID LIMIT (%)		PLASTIC LIMIT (%)		PLASTIC INDEX (%)		BULK DENSITY (Mg/m3)		DRY DENSITY (Mg/m3)		pH		SO3 class*	
	164		61		65		61		121		13		44		48
17		33		20		12		2.08		1.57		6.4		1	
14	22	28	39	17	22	8	17	1.98	2.14	1.53	1.67	5.85	6.7	1	1
12	28	24	44	15	27	5	21	1.86	2.20			5.1	7.3	1	1
10	43							1.78	2.26						

PARTICLE SIZE DISTRIBUTION

CLAY (%)		SILT (%)		SAND (%)		GRAVEL (%)	
	12		12		13		13
8.5		26.5		42		20	
6	16	19.5	36	39	50	11	25

CONSOLIDATION AND COMPACTION TESTS

Mv class*		Cv class*		CBR unsoaked (%)	CBR soaked (%)
	6		6		
3		3			
3	3	3	4		

STRENGTH TESTS

Cu (kPa)		ϕu (degrees)	
	130		130
55		5	
36	84	0	14
116.5	20	0	20
9	175	0	28

*Classes defined in Annex A

ENGINEERING GEOLOGY COMMENTS
Variable lithology and thickness gives rise to variations in geotechnical behaviour. Generally low bearing capacities and variable rates of settlement. May contain relict shear surfaces where developed on slopes > 3° to 7°, with shear strengths approaching residual values.

Table 20 Summary geotechnical data for alluvial silts and clays

SUMMARY FORMAT

TEST PARAMETER		No. of Samples
No. of Samples		
50%		>5
25%	75% (percentiles)	>10
10%	90%	>25
2.5%	97.5%	>100

ENGINEERING GEOLOGY DESCRIPTION

Very soft to firm, occasionally laminated, sandy, silty and organic CLAYS and clayey, sandy SILTS, with impersistent layers or 'pockets' of PEAT.

FIELD TESTS

SPT N-VALUE	
No. of samples	63
50%	10
25% / 75%	6 / 24
10% / 90%	4 / 27

INDEX AND CHEMICAL TESTS

	MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
No. of samples	464	152	152	152	322	30	107	112
50%	26	38	23	15	1.95	1.415	6.8	1
25% / 75%	19 / 33	33 / 46	20 / 27	12 / 21	1.85 / 2.10	1.36 / 1.57	6.5 / 7.3	1 / 1
10% / 90%	15 / 39	28 / 53	18 / 30	8 / 26	1.74 / 2.21	1.30 / 1.68	5.7 / 8	1 / 2
2.5% / 97.5%	12 / 55	25 / 62	16 / 36	4 / 34	1.63 / 2.28		4.4 / 8.3	1 / 2

PARTICLE SIZE DISTRIBUTION

	CLAY + SILT (%)	SAND (%)	GRAVEL (%)
No. of samples	5	5	5
50%	22	39	29

CONSOLIDATION AND COMPACTION TESTS

	Mv class*	Cv class*	CBR unsoaked (%)	CBR soaked (%)
No. of samples	45	43		
50%	3	3		
25% / 75%	3 / 3	3 / 4		
10% / 90%	3 / 4	2 / 4		

STRENGTH TESTS

	Cu (kPa)	φu (degrees)
No. of samples	305	305
50%	40	0
25% / 75%	21 / 65	0 / 6
10% / 90%	15 / 104	0 / 12
2.5% / 97.5%	9 / 217	0 / 22

*Classes defined in Annex A

ENGINEERING GEOLOGY COMMENTS

Highly compressible soft silts, clays and peat, with low shear strengths and very low bearing capacities. Generally unsuitable founding medium due to large differential settlements. High groundwater levels pose severe water inflow problems for excavations.

Table 21 Summary geotechnical data for alluvial sands and gravels

ENGINEERING GEOLOGY DESCRIPTION
Medium dense to dense, fine to coarse-grained SANDS and angular to rounded, fine to coarse GRAVELS with variable clay content and local lenses of organic silt or brown pebbly sandy clay.

SUMMARY FORMAT

TEST PARAMETER		
	No.of Samples	No. of Samples
50%		>5
25%	75% (percentiles)	>10
10%	90%	>25
2.5%	97.5%	>100

FIELD TESTS

SPT N-VALUE	
	507
30	
22	42
15	71
7	114

INDEX AND CHEMICAL TESTS

MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
127	10	10	10	25	5	57	56
13	26	20	7	2.06	1.87	7.2	1
11 17	25 30	18 21	5 12	1.96 2.19		6.8 7.4	1 1
8 26				1.92 2.27		5.3 7.7	1 2
6 38							

PARTICLE SIZE DISTRIBUTION

CLAY (%)	SILT (%)	SAND (%)	GRAVEL (%)
78	78	125	125
2	5	28	63
0 3	1 11	15 38	47 81
0 6	0 20	11 53	34 88
		4 68	4 94

CONSOLIDATION AND COMPACTION TESTS

Mv class*	Cv class*	CBR unsoaked (%)	CBR soaked (%)
3	3		
3	4		

STRENGTH TESTS

Cu (kPa)	ϕu (degrees)
25	25
30	18
20 55	12 27
5 88	0 30

*Classes defined in Annex A

ENGINEERING GEOLOGY COMMENTS
Medium dense/dense basal alluvial gravels of sufficient thickness are often suitable as sets for piles, provided site investigations have proved the absence of clay, silt or organic lenses. Casing is required for bores to combat severe water inflows.

Table 22 Summary geotechnical data for till (boulder clay)

ENGINEERING GEOLOGY DESCRIPTION
Brown, stiff to very stiff, stony, sandy CLAY (boulder clay) with clasts of sandstone, chert, ironstone and limestone* (*where it lies close to the Magnesian Limestone outcrop).

SUMMARY FORMAT

TEST PARAMETER	
No.of Samples	No. of Samples
50%	>5
25% 75% (percentiles)	>10
10% 90%	>25
2.5% 97.5%	>100

FIELD TESTS

SPT N-VALUE
74
31
15 51
6 66

INDEX AND CHEMICAL TESTS

MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
527	158	175	158	208	123	75	76
16	34	17	16	2.10	1.92	6.6	1
13 19	29 39	16 19	13 21	2.03 2.17	1.8 1.98	5.9 7.3	1 1
12 23	24 46	15 23	8 26	1.95 2.23	1.74 2.02	5.3 7.6	1 1
11 28	20 58	14 27	5 31	1.81 2.30	1.65 2.08		

PARTICLE SIZE DISTRIBUTION

CLAY (%)	SILT (%)	SAND (%)	GRAVEL (%)
23	23	25	25
15	34	35	11
9 19	19 43	28 50	5 12
		22 73	1 29

CONSOLIDATION AND COMPACTION TESTS

Mv class*	Cv class*	CBR unsoaked (%)	CBR soaked (%)
19	19	37	8
3	3	9	4
3 3	3 3	7 17	
		5 21	

STRENGTH TESTS

Cu (kPa)	ϕu (degrees)
255	255
93	5
64 147	0 9
35 210	0 14
16 290	0 21

*Classes defined in Annex A

ENGINEERING GEOLOGY COMMENTS
Boulder clay is often variable with lenses of sand, bands of laminated clays and interbedded sandy gravels. Matrix clays of low to medium plasticity, and low compressibility and permeability. Few problems for shallow foundations provided lithological variations are established during site investigations.

Table 23 Summary geotechnical data for glaciofluvial sand and gravel

SUMMARY FORMAT

TEST PARAMETER		No. of Samples
	No.of Samples	
50%		>5
25%	75%	>10
(percentiles)		
10%	90%	>25
2.5%	97.5%	>100

ENGINEERING GEOLOGY DESCRIPTION
Glaciofluvial sands and gravels ranging from slightly cohesive, clayey silty SANDS to highly permeable, medium dense to very dense sandy GRAVELS with layers and lenses of silt and clay developed locally.

FIELD TESTS

SPT N-VALUE	
	44
44	
32	54
22	80

INDEX AND CHEMICAL TESTS

MOISTURE CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTIC INDEX (%)	BULK DENSITY (Mg/m3)	DRY DENSITY (Mg/m3)	pH	SO3 class*
25						10	10
15						6.85	1
9 16						6.7 7.0	1 1
8 20							

PARTICLE SIZE DISTRIBUTION

	CLAY + SILT (%)	SAND (%)	GRAVEL (%)
	24	24	25
	10	37	51
	4 22	21 53	30 73
			0 83

CONSOLIDATION AND COMPACTION TESTS

Mv class*	Cv class*	CBR unsoaked (%)	CBR soaked (%)

STRENGTH TESTS

Cu (kPa)	ϕu (degrees)

*Classes defined in Annex A

ENGINEERING GEOLOGY COMMENTS
Generally dense to very dense sandy gravels should provide few problems for most foundations, provided lithological variations are established during site investigations. Excavations will require immediate support and where water-bearing, measures to regulate water inflows will be needed.

Table 24 Summary geotechnical data for river terrace deposits

ENGINEERING GEOLOGY DESCRIPTION
River terrace deposits comprising medium dense fine to coarse SANDS and medium dense to dense fine to medium GRAVELS, with occasional cobbles. Granular materials predominate but sandy CLAYS and SILTS (sometimes laminated) occur locally, usually at terrace margins.

SUMMARY FORMAT

TEST PARAMETER		
	No. of Samples	No. of Samples
50%		>5
25%	75% (percentiles)	>10
10%	90%	>25
2.5%	97.5%	>100

FIELD TESTS

SPT N-VALUE	
	131
22	
12	32
9	47
4	95

INDEX AND CHEMICAL TESTS

	MOISTURE CONTENT (%)		LIQUID LIMIT (%)		PLASTIC LIMIT (%)		PLASTIC INDEX (%)		BULK DENSITY (Mg/m3)		DRY DENSITY (Mg/m3)		pH		SO3 class*	
No. of samples		149		25		25		25		93		7		57		56
50%	15		27		17		8		2.10		1.81		6.8		1	
25% / 75%	12	18	23	30	17	20	5	13	2.03	2.17			6.3	7.3	1	1
10% / 90%	9	23	21	38	14	24	4	15	1.89	2.24			6.1	7.7	1	1
2.5% / 97.5%	6	30											4.8	8.0		

PARTICLE SIZE DISTRIBUTION

	CLAY + SILT (%)		SAND (%)		GRAVEL (%)	
No. of samples		30		30		30
50%	13		28		58	
25% / 75%	4	16	22	42	43	70
10% / 90%	1	29	9	54	27	8

CONSOLIDATION AND COMPACTION TESTS

Mv class*	Cv class*	CBR unsoaked (%)	CBR soaked (%)

STRENGTH TESTS

	Cu (kPa)		ϕu (degrees)	
No. of samples		94		94
50%	51.5		9	
25% / 75%	28	90	0	17
10% / 90%	19	140	0	24

*Classes defined in Annex A

ENGINEERING GEOLOGY COMMENTS
Granular terrace deposits should prove a suitable founding medium for most light to medium structures, provided lithological variations are established during site investigations. In some areas, these deposits may infill buried channels which must be delineated prior to foundation design. Excavations/bores require immediate support/casing.

Annex A

Key Tables, defining parameter classes used for summary geotechnical test data presented in Appendix III, Tables 12 to 24.

Table 25 Sulphates in soils and Groundwater

Class	Total SO_3 (%)	SO_3 in 2 : 1 Soil : Water extract (g/l)	In Groundwater (g/l)
1	<0.2	<1.0	<0.3
2	0.2 - 0.5	1.0 - 1.9	0.3 - 1.2
3	0.5 - 1.0	1.9 - 3.1	1.2 - 2.5
4	1.0 - 2.0	3.1 - 5.6	2.5 - 5.0
5	>2	>5.6	>5

From BRE Digest 250 (1981)

Table 26 Scale of Point Load Strengths

Term	Point Load Strength KN/m²
Extremely Strong	>12000
Very Strong	6000 - 12000
Strong	3000 - 6000
Moderately Strong	750 - 3000
Moderately Weak	300 - 750
Weak	75 - 300
Very Weak	<75

After Anon (1972)

Table 27 Coefficient of Volume Compressibility, Mv.

Class	Description of Compressibility	Mv (m²/MN)	Examples
5	Very High	>1.5	Very organic alluvial clays and peats
4	High	0.3 - 1.5	Normally consolidated alluvial clays. (eg. estuarine clays)
3	Medium	0.1 - 0.3	Fluvioglacial clays, Lacustrine clays
2	Low	0.05 - 0.1	Boulder clays
1	Very Low	<0.05	Heavily overconsolidated 'boulder clays', Stiff weathered rocks

After Head (1982)

Table 28 Coefficient of Consolidation, Cv.

Class	Cv m²/year	Plasticity Index Range	Soil Type
1	<0.1	>25	Clays Montmorillonite
2	0.1 - 1		High plasticity
3	1 - 10	25 - 15	Medium plasticity
4	10 - 100	15 or less	Low plasticity
5	>100		Silts

After Lambe and Whitman (1979)

NB. California Bearing Ratio (CBR) Tests

CBR test results given in summary tables (Tables 12 to 24, in Appendix III) show values for soils compacted at natural moisture content.

APPENDIX IV: GLOSSARY OF GEOTECHNICAL TESTS QUOTED IN THE DATABASE AND THEIR APPLICATIONS

1. Field tests

THE STANDARD PENETRATION TEST (SPT)

The standard penetration test (SPT) is a dynamic test carried out at intervals during the drilling of a borehole. A standard 50 mm diameter split barrel sampler is driven into the soil at the bottom of the hole for a distance of 450 mm by the blows of a standard weight (65 kg), falling through a standard distance (0.76 m). The number of blows (N) required to drive the last 300 mm is recorded. Test details are given in BS 5930:1981.

A modification of the test for hard material and coarse gravel uses a solid cone instead of a cutting shoe and is called a cone penetration test (CPT).

Although this is a field test which is subject to operational errors, the SPT is widely used to give an indication of the relative density of granular soils (very loose to very dense) and the consistency of cohesive soils (very soft to hard). Correlations have also been made between SPT and the bearing capacity of a soil.

The SPT is also frequently used in harder materials, ie. rocks and heavily overconsolidated soils or 'mudrocks', in which case the test is normally terminated before the shoe has been driven the full 300 mm. Rather than extrapolate the number of blows to represent the full 300 mm of test, the amount of penetration in millimetres for 50 blows can be quoted. When the results are given in this manner the test is referred to as the Rock Penetration Test (RPT). The relationship between the two methods of quoting the results is tabulated below:

Relative Density/Consistency	SPT	RPT
Very loose/very soft	0–5	
Loose/soft	5–10	
Medium dense/firm	10–30	
Dense/stiff	30–50	
Very dense/hard	50	≤ 300
Rock/Heavily overconsolidated soils		200–≤ 100

PERMEABILITY

The permeability of a soil is its capacity to allow water to flow through it. It may be measured on laboratory samples or from boreholes. Laboratory tests do not take into account the effect of structural discontinuities in the soil or rock mass in situ and may not, therefore, give a true indication of the permeability of the ground *en masse*. Pumping tests using boreholes give more representative permeability values.

In field permeability tests, water may be pumped out of a borehole and the effect on the water level in adjacent boreholes monitored or if a single borehole is being used it may be pumped out and the water level recovery time recorded. An alternative approach is to pump water into a borehole under pressure and measure the volumes of water flowing into the borehole at a number of different pressures. Details are given in BS 5930:1981. Sections of borehole may be isolated by sealing with 'packers' in order to measure water flows over selected depth intervals. The data obtained from either method enable the coefficient of permeability (k, metres/second) to be calculated.

The permeability is used to predict the inflow of water during excavation or tunnelling and to design groundwater control schemes to deal with it. This parameter is important when assessing waste disposal sites or the siting and construction of water-retaining structures such as dams, lagoons and canals. The assessment of potential well yields requires field permeability determination for the formations concerned.

ROCK QUALITY DESIGNATION (RQD)

RQD is a quantitative index based upon core recovery by diamond drilling. The RQD is defined as the percentage of core recovered in intact pieces of 100 mm (10 cm) or more in length over the total length of the borehole. An RQD value would normally be established for each core run (of say 2 m). Hence:

$$\text{RQD}\ (\%) = 100 \times \frac{\text{length of core in pieces} > 100\ \text{mm}}{\text{length of core run}}$$

Deere (1964) proposed the following relationship between the numerical value of RQD and the engineering quality of the rock:

RQD	Rock Quality
25%	very poor
25–50%	poor
50–75%	fair
75–90%	good
90–100%	very good

FRACTURE SPACING INDEX (If)

The fracture spacing index gives a direct measure of fracture spacing, and refers to the average size of cored material within a recognisable unit, measured in millimetres. The 'unit' may be a geological or lithological unit, or a unit length with a similar number of fractures. When few fractures traverse the core, the index is the unit length divided by the number of fractures within the unit. If the core is very broken, the index is the average diameter of a number of separate rock fragments. For example, if a one metre long unit of core is cut by four fractures, the fracture spacing index (If) is 1000 mm/4 = 250 mm. For a half metre length of core fractured into pieces with an average size of approximately 3 mm, the index for that 500 mm long unit will be the average diameter of the core fragments = 3 mm.

2. Laboratory tests

MOISTURE CONTENT

The moisture content of a soil sample is defined as the ratio of the weight of water in the sample to the weight of solids, normally expressed as a percentage, ie:

$$\text{Moisture content, m} = \frac{\text{weight of water}}{\text{weight of solids}} \times 100\%$$

The standard test procedure is given in BS 1377:1990. The moisture content is a basic soil property and influences soil behaviour with regard to compaction, plasticity, consolidation and shear strength characteristics.

ATTERBERG OR CONSISTENCY LIMITS (PLASTICITY TESTS)

As moisture is removed from a fine-grained soil it passes through a series of states, i.e. liquid, plastic, semi-solid and solid. The moisture contents of a soil at the points where it passes from one stage to the next are known as 'consistency limits'. These limits are defined as:

Liquid Limit (LL) The minimum moisture content at which the soil will flow under its own weight.

Plastic Limit (PL) The minimum moisture content at which the soil can be rolled into a thread of 3 mm diameter without breaking up.

Shrinkage limit The maximum moisture content at which further loss of moisture does not cause a decrease in the volume of the soil.

The range of moisture content over which the soil is plastic is known as the plasticity index (Ip), and is defined as:

$$Ip = LL-PL$$

The test procedures are given in BS 1377: 1990.

The factors which control the behaviour of the soil with regard to consistency are the nature of the clay minerals present, their relative proportions, and the amount and proportions of silt, fine sand and organic material. A soil may be classified in terms of its plastic behaviour by plotting plasticity index against liquid limit on a standard plasticity (also known as a Casagrande or A-line) chart. The consistency limits also give an indication of soil strength and compressibility.

Density

The density of a soil, i.e. the mass per unit volume, may be measured in various ways.

The total or bulk density is the mass of the entire soil element (solids + water) divided by the volume of the entire element.

The dry density is the mass of dry solids divided by the volume of the entire soil element.

The saturated density is the mass of the entire soil element with its pore spaces filled with water (i.e. totally saturated) divided by the volume of the entire soil element.

Density measurements are simple if an undisturbed specimen of known, or easily measured, volume is obtained. If this is not possible in the field, the sand replacement method is used to determine the volume of a hole from which the soil sample is excavated by filling with a measured quantity of dry, uniformly graded sand of known density. Density measurements are usually expressed as Mg/m^3 and full test details are given in BS 1377:1990.

Soil density measurements may be used to assess various earth loads such as soil mass, overburden pressure, surcharge pressure and earth pressure on retaining walls.

Specific Gravity

The specific gravity of a soil is the ratio of the weight of dry solids to the weight of an equal volume of water (i.e. the weight of water displaced by the solids). It is, therefore a dimensionless parameter. Full test details are given in BS 1377:1990. Specific gravity is a basic soil property and represents an average for the particles of different minerals present in a soil sample. The parameter is used to enable calculation of other basic soil properties. For example: specific gravity (G), moisture content (m), voids ratio (e) and degree of saturation (S) are given by the useful relationship:

$$Gm = Se$$

Particle Size Analysis

The particle size distribution of a soil is determined by sieving and sedimentation. A sample of soil is dried, weighed and sieved to remove the fraction greater than 20 mm in size. It is then immersed in water with a dispersing agent such as sodium hexametaphosphate to break up soil aggregates. The sample is then wet sieved to remove particles less than 63 µm. The fraction retained on the 63 µm sieve is dried and passed through a nest of sieves of mesh size ranging from 20 mm to 63 µm. The fraction retained on each sieve is weighed and the cumulative percentage passing through each sieve is calculated. A grading curve of percentage passing against sieve size is plotted.

The fines passing through the 63 µm sieve are graded by sedimentation. A representative subsample is made up into a suspension with distilled water, placed in a tall jar and made up to a volume of 500 ml. It is then agitated vigorously and allowed to settle. Samples are removed by pipette from a given depth at specific times, dried and the contained solids weighed or, alternatively, hydrometer readings of the soil-water suspension are recorded at specific time intervals. The size distribution can then be calculated using Stokes' Law which relates settling time to particle size. The entire grading curve for coarse and fine material can then be plotted. Full details are given in BS 1377:1990.

Particle size distribution is used for classifying soil in engineering terms (BS 5930:1981) which in turn provides an indication of soil behaviour with regard to permeability, susceptibility to frost heave or liquefaction, and some indication of strength properties. Particle size analysis does not, however, indicate structure and will not distinguish between a sandy clay and a laminated sand and clay which may behave very differently in situ, but may show similar particle size distribution in a bulk test sample.

pH (Acidity)

In the pH test, about 30 g of soil are weighed and placed in 75 ml of distilled water in a beaker. The mixture is stirred and allowed to infuse for at least 12 hours. A glass electrode connected to a pH meter is then placed in the stirred mixture and the reading taken. The electrode and meter may also be used to determine the pH of groundwater samples; pH may also be determined colorimetrically. Details are given in BS 1377:1990.

The pH of soil or groundwater is important when designing concrete structures below ground surface. Ordinary Portland cement is not recommended in situations with a pH below 6; high alumina cement can be used down to pH 4 and supersulphated cement has been used to pH 3.5. Acidic groundwaters can also cause corrosion in buried iron pipes.

Sulphate

The sulphate content of a soil is determined by leaching a weighed sample of soil with hydrochloric acid and precipitating the dissolved sulphate by the addition of an excess of barium chloride. The precipitate is then filtered, ignited in a furnace and weighed.

The sulphate content of groundwater or an aqueous soil extract is determined by passing the water through a column of strongly acidic, cationic exchange resin activated with hydrochloric acid. The groundwater or soil-water washings are collected and titrated against standardised sodium hydroxide solution, using a suitable indicator. From the amount of sodium hydroxide used during titration the quantity of dissolved sulphates can be determined and expressed in terms of SO_3 content, as grams per litre or as parts per hundred thousand. Full test details are given in BS 1377:1990.

It is important that the sulphate content of groundwater and soil is known as ordinary Portland cement deteriorates in the presence of sulphate. Knowledge of sulphate concentrations enables a suitable sulphate resisting or high alumina cement to be used in appropriate concrete mixes for applications below ground level.

3. **Strength tests**

Triaxial Compression Test

The triaxial compression test is the most widely used test for determining the shear strength of cohesive soils and a number of different methods may be used depending on the application of the results.

In general terms, an undisturbed cylindrical specimen (usually 76 mm × 38 mm) is placed between rigid end caps and covered with a rubber membrane. The assembly is then placed in a triaxial cell which is filled with water, taking care that all air is removed. The confining water pressure in the cell is then maintained at a prescribed constant value while the axial load on the specimen is increased at a constant rate of strain. The test continues until the specimen shears or a maximum vertical stress is reached. Vertical displacement and axial load on the sample are measured during the test. The test is repeated on two further specimens (from the same sampling point) at different confining pressures. From the results obtained from the three tests, a standard graphical construction (based on the Mohr-Coulomb failure criterion) enables the measured principal stresses to be plotted so that the shear strength of the soil can be determined in terms of its cohesive and frictional components (i.e. cohesion, C, and angle of internal friction,ϕ).

The test may be carried out with the sample either drained or undrained (with or without pore pressure measurement), and the type of test will depend upon the site conditions and type of engineering works being undertaken.

An unconsolidated-undrained (UU) test is used for foundations on normally consolidated clay soils (where drainage would be slow). The test normally takes only a few minutes, as pore pressures are not allowed to dissipate, and is thus often known as a quick-undrained (QU) test. The strength parameters determined in this test are the total or apparent undrained cohesion and friction values (C_u and ϕ_u, respectively).

In a consolidated-undrained (CU) test, free drainage of the specimen is allowed under the cell pressure for 24 hours before testing (that is, the sample consolidates). The drainage valve is then closed and the load increased rapidly to failure. This test is applicable to situations where a sudden change in load takes place after a period of stable conditions (e.g. as a result of rapid drawdown of water behind an earth dam).

A consolidated-undrained test with pore pressure measurement may also be carried out. In this test, the measurement of pore pressure enables calculation of the effective strength parameters, C' and ϕ' (sometimes referred to as the "true" cohesion and "true" angle of internal friction), in addition to the undrained parameters, C_u and ϕ_u.

A drained (CD) test is suitable for sandy soils or for clay embankments in which drainage blankets have been laid. Free drainage of the sample is allowed during both the consolidation and loading stages of the test, with the sample loading applied at a rate slow enough to allow dissipation of pore pressures. The test conditions enable the determination of the effective strength parameters, C' and ϕ'.

Uniaxial Compression Test

This test measures the unconfined (uniaxial) compressive strength of rock samples of regular geometry and is mainly intended for strength classification and characterisation of intact rock.

Test specimens are required to be right circular cylinders having a height:diameter ratio of 2.5–3.0 and a diameter preferably of not less than 54 mm. The sides and ends of the specimen should be smooth and end surface treatment other than machining is not permitted. Samples should be stored and tested in such a way that the natural water content is preserved. If other moisture conditions are used, they should be reported with the test results.

The prepared rock cylinders are placed in a suitable load frame and the load applied continuously at a constant stress rate such that failure will occur within 5 to 10 minutes of loading, alternatively the stress rate should be within the limits of 0.5 to 1.0 MPa/sec. The specimen is loaded to failure and the maximum load recorded. The number of specimens tested should be determined from practical considerations, but at least 5 are preferred. The uniaxial compressive strength is calculated by dividing the maximum load carried by the specimen during the test, by the original cross-sectional area.

Point Load Test

The point load test provides a rapid, economical and reasonably accurate index of rock strength and strength anisotropy, the principles of which have been described by Broch and Franklin (1972) and Bieniawski (1975). The test involves loading a sample of rock to failure between two standard-shaped steel cones mounted in a portable hydraulically-operated press. The load at failure is determined from appropriately calibrated pressure gauges and the Point Load Strength (Is) calculated from the relationship:

$Is = P/D^2$, where D is the initial distance between the loading cones holding the sample; and P is the maximum pressure recorded on the gauge (i.e. the failure load).

The test is usually carried out on pieces of rock core placed both diametrically and axially between the loading cones to obtain an indication of strength anisotropy. For diametral tests the diameter:length ratio (D/L) of the core should be >1.4; for axial tests the D/L ratio should be 1.1 (where D is the axial distance between the cones). The test may also be performed, less accurately, on irregular lumps with D/L ratios of 1.0–1.4.

It is usual practice to correct the point load strength (Is) to a standard 50 mm reference diameter using a set of standard curves to give the Point Load Index, $Is_{(50)}$. This index is essentially equivalent to the point load strength multiplied by correction factors for shape and size. The Anisotropy Index (Ia) of the rock may be expressed as:

$$Ia = \frac{Is(50)\ [\text{diametral}]}{Is(50)\ [\text{axial}]}$$

5. **Consolidation and compaction tests**

Consolidation Test

If a saturated cohesive soil is subjected to an increase in loading, the pressure of the water in the pore spaces will increase by the same amount as the applied stress. The water will therefore tend to flow towards areas of lower pressure at a rate controlled by the soil permeability. The removal of water causes a decrease in volume of the soil, a process known as consolidation.

The consolidation parameters are measured in the laboratory by placing a disc of soil confined in a metal ring, in a water filled cell. A constant normal load is applied to the disc and its decrease in thickness measured with time. When it reaches a constant thickness for a given load, the load is increased (usually doubled) and the readings repeated. The loading is continued depending on the soil type and the structure for which the data is required. The coefficient of volume compressibility, M_v (m^2/MN), can then be calculated. This is a measure of the amount of volume decrease that will take place for a given increase in stress. The coefficient of consolidation, C_v ($m^2/year$) is also calculated, and is a measure of the rate at which the volume change will take place for a given increase in stress.

Consolidation test results are important for foundation design and the calculation of the likely settlements that will take place during and after construction. The test results also enable the planning of phased construction stages to allow full consolidation settlement (dissipation of pore pressures) to take place prior to successive load stages.

Compaction

The compaction test determines the moisture content (the 'optimum') at which a soil may be compacted to its maximum dry density. A quantity of soil (5 kg) is compacted in a standard (Proctor) mould using a standard (2.5 kg) or heavy (4.5 kg) rammer which is dropped from a standard height (300 mm or 450 mm) a standard number of times (27). The density of the compacted soil is then measured and its moisture content determined. The procedure is then repeated using the same soil at different moisture contents.

The dry density of the compacted soil is plotted against its moisture content and the moisture content at which maximum compacted density may be achieved is read from the curve. Details are given in B.S. 1377:1990.

The results of the compaction test are used to determine the optimum moisture conditions at which to place a given soil as general or embankment fill.

California Bearing Ratio (CBR)

The California Bearing Ratio test is an empirical test carried out in the laboratory, or in the field, which compares the resistance of a soil to penetration by a standard plunger to the resistance to penetration shown by standard crushed stone:

$$CBR = \frac{\text{Measured force}}{\text{'Standard force'}} \times 100\%$$

There are, however, various ways of preparing samples for the test. The samples may be either undisturbed or remoulded. Remoulded samples may be compressed into a standard CBR (or Proctor) mould under a static load, or dynamically compacted into it, at the required moisture content, either to achieve a specific density or by using a standard compactive effort. Undisturbed samples may be taken on site in a CBR mould, either from natural ground or from recompacted soil such as an embankment or a road sub-base. Specimens may be tested in the mould as prepared (or as received) or after soaking in water for several days.

For soaked CBR tests on remoulded soil at maximum compaction, for example, the test normally involves a series of samples which are compacted in a 152 mm diameter mould at moisture contents around the optimum. A surcharge weight is placed on the soil which is then immersed in water for four days. The mould is placed in a load frame and a plunger 48.5 mm in diameter is forced into the sample to a penetration of 2.5 and 5 mm. The CBR value is determined as the higher of the ratios of the resistance at 2.5 mm and 5 mm penetration to the standard resistance of crushed stone at the same penetrations. Details are given in B.S. 1377:1990.

The CBR value of recompacted soil is very sensitive to variations in moisture content and dry density. Some typical laboratory CBR values for British soils compacted at natural moisture content are indicated below:

Type of soil	Plasticity index (PI) Range (%)	Range of CBR* (%)
Clay	40–70	1–3
Silty clay	about 30	3–5
Sandy clay	10–20	4–7
Silt	0	1–2
Sand (poorly graded)	NP	10–20
Sand (well graded)	NP	15–40
Sandy gravel (well graded)	NP	20–60

*Lower values relate to water table depth <600 mm below formation level. Upper values to water table >600 mm below formation level. (From TRRL Road Note 29, 1970). NP= non-plastic

In the field test, the plunger is jacked into the ground against the reaction of a heavy lorry. Field values are usually lower than laboratory values and the results of these in situ tests are not directly comparable with laboratory test results. The laboratory test in the CBR mould is recognised as the standard test. The results of the CBR test are used to assess the suitability of soils for use as base, sub-base and sub-grade in road construction.

APPENDIX V

Table 29 Groundwater abstraction licences

Appn No	Licence No	Grid Ref	Name/Site	Licensed abstraction cu.m.h	cu.m.d	tcma	P*	Borehole diam mm	depth m	T* m^2/d
SE 23										
41	16/40	224355	Broom Mills	34.10	818.28	136.38	M	300	131	4
111	17/37	258330	Silver Royd Winery	4.55	27.28	6.82	C	200	76	
301	16/16	221371	Sandoz Products	92.51	2182.08	c568.00	M	375	82	7
								375	198	
325	17/5	273337	Phillips Yeast Products	18.18	436.42	90.92	M	150	101	40
599	17/12	283341	Jonas Woodhead & Sons	18.18	436.42	34.10	M	200	46	20
672(1)	16/34	216355	Sunny Bank Mills	9.09	90.92	22.73	M	275	183	
								914	21W	
742(2)	17/54	268318	Providence Dye Works	56.83	545.52	140.93	M	225	37	
1033(1)	17/15	267318	Wortley Low Mills	19.09	459.15	153.81	C	–	42	8
1614	16/33	218377	Low Mills	272.76	2273.00	500.06	M	500	92	70
2335	17/115	266307	Beeston Royds	31.82	159.11	15.91		200	152	17
		267305						250	45	
2718a(2)	17/136	284339	Yorkshire Chemicals	50.01	1136.50	409.14	C	300	61	22
3037	17/66	283341	Associated Dairies	95.47	381.86	139.38	C	300	46	112
3773	17/106	290330	Monk Bridge Ltd	68.19	1636.56	554.61	M/C	450	79	50
4727	17/141	283371	Highbury Works	18.18	309.13	77.28	M	200	120	2
5013	17/142	297358	Howard Cook Ltd	–	31.82	9.55		2134	12W	
5432	17/156	282313	Leeds United	37.00	296.04	10.00	SI	–	W	
5793	17/171	2436	GKN Axles Ltd	77.00	1640.00	575.07	C	Shallow wells		
6049	16/193	214392	J Penny & Sons	9.09	113.65	20.46		150	105	
SE33										
487	17/7	305330	Brewery, Hunslet Road	48.64	272.76	68.19	M	–	170	20
488	17/8	305330	Brewery, Hunslet Road	45.46	272.76	68.19	M	–	174	15
489	17/9	306330	Brewery, Hunslet Road	45.46	845.56	181.84	M	610	174	15
1243	17/91	304352	Sheepscar Tannery	84.10	409.14	22.73	M	250	76	5
2718	17/72	306328	Yorkshire Dyeware	50.01	1200.14	290.94		300	93	3
3613	17/131	391337	Barrowby Hall Farm	–	4.55	–	D&A	1200	12W	
5468	17/160	385328	Swillington Common Farm	4.55	27.28	10.00	SI	150	52	
5615	17/163	353370	Howson–Algraphy	8.50	195.02	60.01	M	230	180	
TOTAL LICENSED ABSTRACTION				1198.77	14236.95	4167.05				

* P = Purpose
C = cooling
M = manufacturing
SI = spray irrigation
D&A = domestic & agricultural
T = Transmissivity

Table 30 Leeds groundwater abstraction licences – revoked

Appn No	Licence No	Grid Ref	Name/Site	Licenced abstraction			R*	P*	Borehole		T*
				cu.m.h	cu.m.d	tcma			diam mm	depth m	m^2/d
SE 23 REVOKED											
17	17/95	251365	GKN Axles Ltd	45.46	590.98	147.75	83	C	200	55	14
29(2)	17/2	270348	Burley Mills	22.73	104.56	25.00	74	M	260	24	
96	17/74	285341	Silver Blades Ice Rink	29.55	65.01	227.30	can	C	200	46	
115(2)	17/42	239325	Troydale Mills	77.28	909.20	227.30	84	M	460	67	20
166	17/47	248356	Wellington Mills	17.05	168.20	40.91	77	M	430	107	12
187	16/49	223356	Bank Bottom Mills	10.00	120.01	35.91	76	C	150	18	
189	17/75	296359	Cliff Tannery	56.83	227.30	56.37	72	M	380	136	
226	17/60	251377	J Pickard, Tannery	4.55	27.28	3.64	70	M	1524	18W	
309	17/69	295333	Whitehall Soap Works	–	272.76	emergency	89	C	355	77	70
482	17/6	240382	Horsforth Steam Laundry	54.55	545.52	200.02	can	M	350	120	7
484	17/44	299379	Moor Allerton Golf Club	11.37	113.65	11.37	71	SI	200	58	6
614(1)	17/13	283340	Aire Place Mills	75.46	1818.40	454.60	84	M	300	46	15
688	17/114	296331	Hardings Ltd	2.27	2.27	–	73		–	46	
971	17/84	257325	Butterbowl Mills	45.46	454.60	109.10	69	M	300	198	175
1122	17/63	297358	Valley Mills	–	54.55	13.64	68	C	–	12W	
1262	16/66	220378	Woodbottom Mills	22.73	386.41	136.38	76	M	300	76	10
1269	16/52	220378	Woodbottom Mills	34.10	454.60	136.38	73	M	300	76	
1473	17/35	279301	Millshaw Leather Works	56.83	454.60	104.56	73	M	2134	46	
1552	17/29	284332	Wortley Gas Works	54.55	454.60	113.65	76	M	392	114	130
1619	17/97	289326	Victoria Mills	–	68.19	emergency	68	M	100	18	
1925	17/110	271344 269342	Kirkstall Power Station	–	5527.94	795.55	78	C	4x 1220	W	
2242	17/19	258355	Whitbread & Co.	45.46	340.95	68.19	68	C	1828	16W	
2344	17/39	273329	Crowther	–	13.64	3.55	87	M	200	92	
3856	17/127	263340	Winter Green Mills	0.91	8.18	2.05	75		–	–	
4212	17/130	275342	Armley Mills	13.64	54.55	1.64	72	M	100	213	
4721	17/51	289338	Joseph Clark Ltd	136.38	1363.8	329.58	–	M	–	122	
4765	17/105	270317	TRF Pland Ltd	2.27	18.18	4.80	87	M	200	65	
4870	17/138	290328	Leeds Ind. Co-op	34.10	1909.32	99.10	80	C	355	122	4
5024	16/162	219388	Park Mills	–	363.68	63.64	78	M	250	176	25
5186	17/146	289333	Thomas Bennett Ltd	22.73	227.30	70.92	79	C	200	97	
5204	17/148	237358	Ross Textile Mill	22.73	272.76	90.92	83	M	300	76	40
5225	17/149	248385	Woodside Dye Works	72.74	727.36	181.84	–	M	380	91	30
5437	17/157	262355	Abbey Printing Works	127.28	75.01	27.38			305	52	
			TOTAL SE 23	999.01	18195.36	3782.89					

* R= year licence revoked
P= Purpose
C= cooling
M= manufacturing
SI= spray irrigation
T= Transmissivity

Table 31 Leeds groundwater abstraction licences – revoked

Appn No	Licence No	Grid Ref	Name/Site	Licenced abstraction			R*	P*	Borehole		T*
				cu.m.h	cu.m.d	tcma			diam mm	depth m	m²/d
SE 33 REVOKED											
59	17/4	30453328	Hey & Humphries Ltd	4.55	36.34	9.09	can	C	150	49	10
490	17/10	308328	J P Simpson & Co Ltd	34.10	159.11	54.55	90	C	203	110	2
491	17/11	308340	Melbourne Brewery	52.28	1254.70	136.38	74	C	380	96	
935	17/48	306323	Fowler, Leathley Rd, Leeds 10	30.46	243.66	60.92	74	M	250	332	
1618	17/96	300346	Charge Court, Albion St	–	127.29	3.82	78		250	99	4
3275	17/49	373349	Cables & Plastics Ltd	6.82	45.46	11.37	87	C	150	90	1
3306	17/100	393325	J Wilson, Brookfield Fm	–	100.01	0.64	68	SI	1220	4W	
4638(1)	20/44	398350	Garforth Golf Club	9.09	45.46	4.55	72	SI	150	45	
4836	17/137	30803223	Specialloid Ltd	22.73	159.11	47.73		M	–	107	
5022	17/143	314321	Thomas Bennett & Sons	–	113.65	34.10	74	M	762	7W	
TOTAL SE 33				160.03	2284.79	363.15					
TOTAL REVOKED ABSTRACTION				1159.04	20480.15	4146.04					

* R= year licence revoked
P= Purpose
C= cooling
M= manufacturing
SI= spray irrigation
T= Transmissivity

APPENDIX VI: DATA SOURCES

The principal sources of data were as follows:

British Geological Survey, Information Services, Keyworth, Nottingham NG12 5GG.

The Chief Planning Officer, Leeds City Council, Planning Department, Headrow Buildings, The Headrow, Leeds.

The Regional Geologist, British Coal, North Yorkshire Area Office, PO Box 13, Allerton Bywater, Castleford, West Yorkshire WF10 2AL.

British Coal Opencast Executive, Thorncliff Hall, Thorncliff Park, Chapeltown, Sheffield S30 4PX.

British Coal Mines Records Office, Manvers Outstation, Golden Smithies Lane, Wath-upon-Dearne, Rotherham.

Norwest Holst (Soil Engineering Ltd), Parkside Lane, Dewsbury Road, Leeds LS11 5SX.

In addition, borehole data were obtained from a variety of sources. The drilling was mainly carried out by, or on behalf of, the following concerns:

Bradshaw, Buckton and Tonge, Ltd
Central Electricity Generating Board (now National Grid, National Power)
Civil Engineering Laboratory, Cardington
Eastwood and Partners
Exploration Associates
Ian Farmer Associates
Georesearch Ltd
Geotechnical Engineering (Northern) Ltd
Groundshire
HJT Solmek (formerly Hutter, Jennings and Titchmarsh)
JMP Consultants Ltd
Michael D Joyce Associates
KD Drilling Services
Pro-Soil Surveys
Soil Mechanics Ltd
Strata Surveys Ltd
Sub Soil Surveys Ltd (Manchester)
West Yorkshire Highways, Engineering and Technical Services (HETS) Joint Committee
Wimpey (Environmental) Ltd

Supplementary information on landfill sites was supplied by West Yorkshire Waste Management.

APPENDIX VII: LIST OF OPEN FILE REPORTS

Each component 1:10 000 geological map in the study area has an equivalent descriptive Open File Report. The reports are listed below together with their BGS Technical Report numbers in the WA Series, dated 1991.

SE 23 NW	Horsforth	WA/91/40	D G Tragheim
SE 23 NE	North-west Leeds	WA/91/41	M T Dean and R D Lake
SE 23 SE	South-west Leeds	WA/91/42	M T Dean
SE 33 NW	North-east Leeds	WA/91/43	R D Lake
SE 33 NE	Seacroft and Scholes	WA/91/44	M T Dean
SE 33 SW	South-east Leeds	WA/91/45	R D Lake
SE 33 SE	Swillington	WA/91/46	D G Tragheim

Other Technical Reports relating to adjoining areas are:

SE 43 SW	Garforth	WA/89/99	R A Ellison 1989
SE 22 NE	Morley		I C Burgess 1983
SE 32 NW	Rothwell		I T Williamson and J R A Giles 1984
SE 32 NE	Oulton		J R A Giles and I T Williamson 1985

The last three reports are entitled 'Geological notes and local details for 1:10 000 sheet....'

Copies of these reports may be ordered from BGS (Book Sales), Keyworth, Nottingham NG12 5GG.

APPENDIX VIII: GLOSSARY OF GEOLOGICAL TERMS

ALLUVIUM Sediments deposited by rivers or streams, during relatively recent geological time and deposited on the floodplain.

BRYOZOAN An invertebrate animal characterised by colonial growth and commonly a calcareous skeleton, synonymous with moss coral.

CLAST Rock fragment or pebble in a sedimentary rock.

CONGLOMERATE A coarse-grained clastic sedimentary rock with fragments larger than 2 mm in diameter: the consolidated equivalent of a gravel.

CONJUGATE Said of a joint system, the sets of which are related in deformational origin and angular disposition.

CROSS-BEDDING The internal layering of a bed of sediment, characterised by inclined minor beds disposed at various angles to the principle bedding planes.

DEVENSIAN The part of the Quaternary Period during which Britain was last glaciated.

DIRT A collective name for non-coal material found between leaves of coal within a seam, usually a mudstone or mudstone-seatearth.

DISTRICT The area covered by this report.

DOLOMITIC A term used to describe limestones containing more than 10 per cent calcium magnesium carbonate (the mineral dolomite).

DRIFT Unconsolidated sediments deposited during the Quaternary Period.

FINING-UPWARDS Applied to sedimentary sequences which show a progressive upwards reduction in overall grain-size.

FIRECLAY A mudstone which strictly should have a chemistry suitable for the manufacture of refractory ceramic products. The term is commonly applied more loosely to a rooty mudstone.

FLANDRIAN The present, post-glacial stage, part of the Quaternary period.

GANISTER A hard, even-grained sandstone will a siliceous cement, commonly found as the seatearth to a coal.

GONIATITE An ammonoid fossil characterised by an external shell that is symmetrical and coiled in one plane.

GRABEN An elongate relatively depressed block of strata bounded by faults on its long sides (trough-fault).

HEAD Unconsolidated sediment produced by a mixture of mass-movement processes including solifluction and slope wash, and commonly characterised by weak shear strengths.

INTERFLUVE High ground between streams or rivers of the same drainage basin.

IPSWICHIAN A temperate stage of the Quaternary Period, prior to the Devensian.

LACUSTRINE Relating to lakes.

OOLITE A rock composed of subspherical particles commonly of calcium carbonate, that were formed by accretion around a nucleus.

RESOURCE The total amount of potentially workable material.

SIDERITE A mineral composed of ferrous (iron) carbonate.

SOLIFLUCTION A process whereby sediment is transported downslope under the influence of alternate freezing and thawing.

TILL Sediment deposited directly by a glacier; commonly a stiff clay, with clasts of both local and exotic origin.

TUFF A compacted deposit consisting mainly of volcanic ash and dust.

UNCONFORMITY A surface between two groups of rocks which marks a major period of non-deposition or erosion.

WASHOUT In a coal seam, a mass of mudstone or sandstone filling a contemporaneous channel (mining term).

REFERENCES

ANON. 1972. The preparation of maps and plans in terms of engineering geology. Report by the Geological Society Engineering Group Working Party. *Quarterly Journal of Engineering Geology*, Vol. 5, No. 4.

— 1988. Engineering Geophysics. Report by the Geological Society Engineering Group Working Party. *Quarterly Journal of Engineering Geology*, Vol. 21, No. 3.

BARCLAY, W J, ELLISON, R A, and NORTHMORE, K J. 1990. A geological basis for land-use planning: Garforth–Castleford–Pontefract. *British Geological Survey Technical Report*, WA/90/3.

BELL, F G. 1978. Subsidence due to mining operations. 322–362 in *Foundation Engineering in Difficult Ground.* BELL, F G (editor). (Butterworths.)

BIENIAWSKI, Z T. 1975. The point load test in engineering practice. *Engineering Geology*, No. 9, 1–11.

BRITISH STANDARD 1377. 1990. *Methods of testing for soils for engineering purposes.* (London: British Standards Institution.)

— 5930. 1981. *Code of practice for site investigations.* (London: British Standards Institution.)

BROCH, E, and FRANKLIN, J A. 1972. The point load strength test. *International Journal of Rock Mechanics and Mineral Science*, No. 9, 669–697.

BUILDING RESEARCH ESTABLISHMENT. 1981. *Digest 250: Concrete in sulphate-bearing soils and groundwaters.* (Watford: Building Research Establishment.)

— 1983a. *Digest 274: Fill, part 1: Classification and load carrying characteristics.* (Watford: Building Research Establishment.)

— 1983b. *Digest 275: Fill, part 2: Site investigation, ground improvement and foundation design.* (Watford: Building Research Establishment.)

CRUTCHLOW, S B. 1966. The foundation properties of the Upper Shales. *Proceedings of the 1st International Conference on Rock Mechanics, Lisbon, September 1966.*

DEERE, D U. 1964. Technical description of rock cores for engineering purposes. *Rock Mechanics & Engineering Geology*, Vol. 1, No. 1, 17–22.

DEPARTMENT OF THE ENVIRONMENT. 1988. *Review of the geological and minerals planning research programme.* (London: Department of the Environment.)

EDWARDS, W, MITCHELL, G H, and WHITEHEAD, T H. 1950. Geology of the district north and east of Leeds. *Memoir of the Geological Survey of Great Britain.*

FREEMAN FOX LIMITED. 1988. Treatment of disused mine openings. *Department of the Environment, Planning Research Programme.*

GAUNT, G D, COOPE, G R, and FRANKS, J W. 1970. Quaternary deposits at Oxbow opencast site in the Aire valley, Yorkshire. *Proceedings of the Yorkshire Geological Society*, Vol. 38, 175–200.

Giles, J R A. 1988. Geology and land-use planning: Morley–Rothwell–Castleford. *British Geological Survey Technical Report*, WA/88/33.

GODWIN, C G. 1984. Mining in the Elland Flags: a forgotten Yorkshire industry. *British Geological Survey Report*, Vol. 16, No. 4.

— and CALVER, M A. 1974. A review of the Coal Measures (Westphalian) of Leeds. *Journal of Earth Sciences of the Leeds Geological Association*, Vol. 8, 409–432.

HALLAM, J R. 1990. The statistical analysis and summarisation of geotechnical databases. *British Geological Survey Technical Report*, WN/90/16.

HARKNESS, D D, GAUNT, G D, and NUNNEY, J H. 1977. Radiocarbon dating versus the Leeds hippopotamus — a cautionary tale. *Proceedings of the Yorkshire Geological Society*, Vol. 41, 223–230.

HEAD, K H. 1982. *Manual of Soil Laboratory Testing. Volume 2: Permeability, shear strength and compressibility tests.* (London: Pentech Press.)

HEALY, P R, and HEAD, J M. 1989. Construction over abandoned mine workings. *CIRIA Special Publication* 32, PSA Civil Engineering Technical Guide 34.

HOEK, E, and BROWN, E T. 1980. Classification of rock masses. Chapter 2, 14–36 in *Underground Excavations in Rock.* (London: The Institution of Mining and Metallurgy.)

HOLLANDS, J P. 1990. Foundation engineering hazards in the Leeds area. Unpublished MSc thesis, University of Leeds.

LAMBE, T W, and WHITMAN, R V. 1979. *Soil Mechanics, SI version.* (New York: John Wiley & Sons.)

MARSLAND, P A. 1975. Groundwater in Leeds. Unpublished MSc thesis, University of Leeds.

MEIGH, A C. 1968. Foundation characteristics of the Upper Carboniferous rocks. *Quarterly Journal of Engineering Geology*, Vol. 1, No. 2, 87–113.

PIGGOT, R J, and EYNON, P. 1978. Ground movements arising from the presence of shallow abandoned mineworkings. 749–780 in *Large Ground Movements and Structures.* GEDDES, J D (editor). (London/Plymouth: Pentech Press.)

TRANSPORT & ROAD RESEARCH LABORATORY. 1970. *Road Note 29: A guide to the structural design of pavements for new roads.* (London: HMSO.)