Geotechnical engineering applications in opencast coal mining – case studies from Northern England

A collection of publications submitted for the degree of Doctor of Philosophy

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Volume 1

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ABSTRACT

Geotechnical engineering applications in opencast coal mining - case studies from Northern England
by David B Hughes

Opencast coal mining using mechanical excavators has taken place in Northern England for over sixty years. In the early years the excavations for coal were relatively shallow and of limited area, typically less than 20 m deep and 50 ha in plan. Nowadays, with the deployment of very large draglines and hydraulic shovels, opencast mines can be over 200 m deep and up to 1,000 ha in area. The investigations, excavations and earthworks failures associated with this activity have provided a unique opportunity to study several geotechnical engineering aspects of the drift and solid geology of Northern England, and how they impact on the mine planning, design and operations processes.

There are four shallow coalfield areas in Northern England where opencast mining has been carried out, namely Cumbria, Northumberland, Durham and Stublick. The geological conditions at each of these coalfields have influenced the nature of the geotechnical problems encountered therein. All four coalfield areas are overlain by glacial deposits, which are typically between 5 m and 40 m in thickness but can be up to 70 m. In the underlying Coal Measures strata the structural complexity varies with faulting and steep bedding being more prevalent in Cumbria, County Durham and Stublick areas than in Northumberland, although this later coalfield is dissected by a series of major east-west faults. Previous underground coal mining, especially shallow 'room and pillar' working, is also a feature of the whole region.

The research carried out in this study of opencast coal mining has led to thirty-one published papers covering the five themes of general opencast geotechnical, ground investigations, glacial deposits, Coal Measures, opencast backfill and groundwater. The papers are divided into three groups: nine that were written solely or mainly by the Candidate and are key to this submission, four that are secondary or tertiary authored, and eighteen earlier papers which provide further information to support the conclusions. This research has included exploratory investigations used in the design of excavations and spoil mounds, investigations following ground movements and failures in these earthworks structures, and the opportunity to study fresh exposures of the drift and solid geology of Northern England. This has led to two main achievements or conclusions. The first is that the work has resulted in an improved understanding of the depositional processes and the variability in the succession in the glacial deposits together with how these processes and variations have affected the engineering properties of the soils, and the impact they have on geotechnical engineering applications. The second emphasises the impact that the structure of the Coal Measures (especially faulting) has upon excavation design and the stability of excavated slopes. The opportunity to study one of the largest slope failures in the UK at St. Aidans opencast mine has highlighted the need to accurately locate faults, and to understand the effects of ground strains from mining subsidence as well as groundwater pressures and recharge. A theme that runs throughout this work is the need to have adequate ground investigations supported by a full understanding of the geological processes.

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THE CANDIDATE

David Bryn Hughes MSc, CEng, CGeol, FICE, FGS

After studying civil and structural engineering at Bolton Institute of Technology, David Hughes began his professional career with Lancashire County Council in 1964, initially designing sewerage and drainage works, followed by the design and construction of major highways and bridges. He later specialised in geotechnical engineering, firstly with Lancashire County Council, and subsequently with West Yorkshire Metropolitan County Council. Projects included the M6, M18, M60, M61, M62 (including the Trans-Pennine section), M63 and M66 motorways. During this period he also completed an MSc degree in Rock Mechanics and Excavation Engineering at the University of Newcastle upon Tyne (1974-75), where he presented a dissertation on "the shear testing of jointed and intact rock samples". This included the design and construction of a direct shear apparatus, which is still in use today.

In 1977 he joined the NCB Opencast Executive in West Yorkshire as a Resident Engineer on opencast coal mining sites, and then as Geotechnical Engineer for sites in the East Midlands. In 1979 he became Regional Geotechnical Engineer (Northern England) for the NCB and later British Coal Opencast, until his (early) retirement in 1994. As Head of the Geotechnical Department he was concerned with about 100 opencast projects including some of the largest in the UK (e.g. Butterwell and Stobswood). This work involved a very large programme of ground investigations, geotechnical reporting and contract document preparation, site inspection and monitoring, plus appointing and supervising consulting firms for a wide range of civil engineering projects. During this period he established research links with the Universities of Newcastle and Nottingham, and with the Building Research Establishment. He also represented BCO on Code of Practice drafting committees set up by the Health and Safety Executive.

In September 1994 he joined the Geotechnical Group at Newcastle University (part-time) as Senior Research Associate/Testing Manager continuing to work on the geotechnical aspects of surface mining, the engineering geology of glacial deposits, and laboratory testing procedures. He is author and co-author of many published papers on these topics. In September 2002, he became a 'guest' (unpaid) member of staff in the newly-formed School of Civil Engineering and Geosciences.

Note on 'higher degree' registration

The Candidate became a part-time staff member at the Newcastle University in September 1994, and initially registered to read for a PhD degree relating to the 'engineering properties of glacial deposits' by the more usual thesis route. However, the Candidate continued to publish journal and conference papers on 'the geotechnical aspects of opencast coal mining'. During 1996/97 a change of topic was discussed and agreed with his Supervisor, and a re-start via the publications route (regulations first published in August 1997) was made by agreement with the Registrar's Office. The new registration was formally accepted in March 1998.
"Geotechnical engineering applications in opencast coal mining – case studies from Northern England"

This is a collection of thirty-one geotechnical publications for which David Bryn Hughes (the Candidate) is either the sole author or a joint author, and is presented herein in pursuance of Membership of the Degree of Doctor of Philosophy at the University of Newcastle upon Tyne (under Staff Regulations, University Calendar 2002-2003).

A complete list of the published works submitted (Regulation 23a) is given immediately following this Doctoral Statement (Lists A, B and C) and the whole contents of the publications are reproduced in Appendices A, B and C.

The greatest emphasis is on the nine publications which date from 1996 onwards, with the Candidate as principal or sole author (List A and Appendix A, Volume 1), as these represent the main works carried out during his period of registration for a higher degree. These main works, where jointly authored, are covered by 'joint publication forms' (as required by Regulation 25) showing the percentage share of the work attributable to the Candidate. The other twenty-two publications are included as secondary or earlier works (Appendices B and C, Volume 2).

Several of these publications have contributed to either the 2001 Higher Education Funding Council for England (HEFCE) Research Assessment Exercise (RAE), or are likely to be included in the 2007 HEFCE RAE.
The Candidate has contributed to a total of thirty-one geotechnical publications. He is the sole or main author for seventeen of these, and a secondary or tertiary author for the other fourteen publications.

LIST A includes all the post-1996 publications where the Candidate is the sole or main author, and are the main papers in this higher degree submission. A note has been made after each publication of the percentage contribution by the Candidate (Regulation 25).

LIST B includes those remaining post-1996 publications where the Candidate is the secondary or tertiary author.

LIST C includes all the publications prior to 1996, i.e. prior to the Candidate's registration to read for a higher degree by the publications route.

The full texts of all of these publications are included in APPENDICES A, B and C respectively.

For ease of later reference each of the publications has been given a reference number and shortened title, followed (in brackets) by a brief subject category.

(A note has been made after those papers which have been presented by the Candidate, in person, at conferences and learned society meetings etc. – see Regulation 34.)
LIST A: Main publications - from 1996 onwards (9 in total – 7 refereed)

PAPER A1 PLENMELLER (Q.J.E.G.) (General Opencast Geotechnical)

PAPER A2 ENGINEER'S VIEW (Glacial Deposits)

PAPER A3 SPOIL MOUNDS – NORTHERN ENGLAND (Glacial Deposits)

PAPER A4 GLACIAL SUCCESSION (Glacial Deposits)

PAPER A5 FAULTING – UK (Coal Measures)
Hughes, D.B. 1998. The effect of faulting in UK opencast coal mining operations. Proceedings of Fifth BGS Young Geotechnical Engineers' Conference. (Paper presented at this Conference, and led visit to Herrington opencast site for Conference.) (Candidate's contribution – 100%)

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PAPER A6 HERRINGTON  *(Glacial Deposits)*
(Candidate's contribution – 95%)

PAPER A7 ST. AIDANS  *(Coal Measures)*
Hughes, D.B. and Clarke, B.G. 2001. The River Aire slope failure at St Aidans Extension Opencast Coal Site, West Yorkshire, United Kingdom. Canadian Geotechnical Journal 38(2), 239-259. *(Adjudged "Honourable Mention" (i.e. the runner-up) in the 2001 R.M. Quigley Awards of the Canadian Geotechnical Society for the best paper published in the Canadian Geotechnical Journal.)* *(Presented to IMMM meeting at Newcastle in March 2001.)*
(Candidate's contribution – 99%)

PAPER A8 FAULTING - NE ENGLAND  *(Coal Measures)*
(Candidate's contribution – 99%)

PAPER A9 RECLAMATION  *(Opencast Backfill)*
(Candidate's contribution – 99%)
LIST B: Secondary publications - from 1996 onwards (4 in total - 3 refereed)

PAPER B1 TILLS FRAMEWORK (Glacial Deposits)

PAPER B2 GLACIAL HISTORY (Glacial Deposits)

PAPER B3 TILLS IN EARTHWORKS (Glacial Deposits)

PAPER B4 NETDATA (Glacial Deposits)
List C: All publications - prior to 1996 (18 in total - 12 refereed)

PAPER C1 HORSLEY 1 (Opencast Backfill)
settlement of backfill at Horsley restored opencast coal mining site, 1973-1983. Third
International Conference on Ground Movements in Cardiff, Wales. J.D. Geddes (ed).

PAPER C2 GENERAL (Q.M.) (General Opencast Geotechnical)
Hughes, D.B. and Leigh, W.J.P. 1985. The stability of excavations and spoil mounds in
relation to opencast coal mining. Institute of Quarrying Transactions (Quarry
Management), April 1985. 223-232. (Presented to North of England Branch of IoQ
in September 1984.) (Updated presentation given to Institution of Civil Engineers –
North West Geotechnical Group, Liverpool, March 1988.) (Also presented at several
BCO/BMCL courses and seminars and at several Newcastle University MSc courses
'guest lectures'.)

PAPER C3 DEWATERING (Groundwater)
dewatering scheme at an opencast coal site in Northumberland. Groundwater in

PAPER C4 NORTHERN BACKFILL 1 (Opencast Backfill)
groundwater recovery and backfill consolidation in British surface coal mines.
Symposium on Surface Mine Hydrology, Sedimentology and Reclamation, University
of Kentucky, December 1985 (no page nos.).

PAPER C5 SITE INVESTIGATION (Ground Investigations)
Hughes, D.B. 1985. Site investigation in relation to opencast coal mining in Great Britain,
Part 1 and Chapter 3 of Part 2. In Norton, P.J., Hughes, D.B., McManus, R., Sturman,
J., Coats, H. and McLean, A.A. Geotechnical Engineering Guide, National Coal
Board, Opencast Executive, H.Q. Production Department, Mansfield, Notts., UK, 6-43,
115-139. (Presented to several British Coal/British Mining Consultants Ltd courses
and seminars during 1980s.)
PAPER C6 DERWENT-TYNE CONFLUENCE (Glacial Deposits)

PAPER C7 GENERAL (B.G.) (General Opencast Geotechnical)

PAPER C8 FAULTING - BUCKHEAD (Coal Measures)

PAPER C9 DRILLEX '87 (Ground Investigations)

PAPER C10 NORTHERN BACKFILL 2 (Opencast Backfill)

PAPER C11 NORTHERN BACKFILL 3 (Opencast Backfill)

PAPER C12 NORTHERN BACKFILL 4 (Opencast Backfill)

PAPER C13 GEOTECHNICAL STABILITY REPORT (Ground Investigations)

PAPER C14 SPOIL MOUNDS – DESIGN & CONSTRUCTION (Glacial Deposits)

PAPER C15 HORSLEY 2 (Opencast Backfill)

PAPER C16 PLENMELLER (Q.M.) (General Opencast Geotechnical)

PAPER C17 NORTHUMBERLAND TILL (Glacial Deposits)

PAPER C18 NORTHUMBERLAND TILL DISCUSSION (Glacial Deposits)
CRITICAL APPRAISAL

Geotechnical engineering applications in opencast coal mining
— case studies from Northern England

A compilation of geotechnical publications by David Bryn Hughes submitted for the degree of Doctor of Philosophy to the University of Newcastle upon Tyne, under staff regulations

Regulation 47(d): A critical appraisal of at least 10,000 words will be required incorporating:

(i) a review of the literature, setting the works in a broader context,
(ii) a drawing out of the linkages between the publications,
(iii) a conclusion.

1. INTRODUCTION

Opencast coal mining presents a unique situation in the practice of geotechnical engineering, in that a very large proportion of the ground within the site area is excavated and therefore can usually be viewed directly, often from close quarters. This means that predictions of ground conditions made from direct or indirect investigations can be checked against what is actually exposed during the progress of the works. Also, the assessment of the stability of 'temporary' excavated slopes or spoil mounds, which are created during opencast mine operations, can be 'back analysed' because of failures that occur due to working with marginal Factors of Safety (FoS), and/or errors in the prediction of ground conditions or the measurement of geotechnical parameters. Therefore opencast mining represents a unique and valuable research situation.

In 1977 the Candidate joined the National Coal Board Opencast Executive (NCB/OE) as a Resident Engineer in charge of opencast coal sites in Yorkshire. Subsequently he acted as the Regional Geotechnical Engineer (RGE) for Central East-Region. He was appointed to the permanent post of RGE for Northern Region in 1979, and held this position until the demise
(re-privatisation) of British Coal Opencast in 1994 (BCO – from 1985 when NCB/OE was re-named).

The Candidate was involved in excess of 100 opencast projects during the period 1977 to 1994. The main papers (1996 onwards – Appendix A) presented herein include case studies or data from about 30 of these projects, and the secondary papers (1996 onwards – Appendix B) include data from a further 20 or so sites. The papers published prior to 1996 (Appendix C) refer to (or contain data from) at least another 20 sites. This collection of case studies has been published in the form of technical papers included in international geotechnical journals, learned society journals or in conference proceedings. These papers represent virtually the whole of the published geotechnical literature relating to opencast coal mining in Northern England, and include a very significant proportion of the literature for the UK as a whole. They show how this unique opportunity to monitor the geotechnical aspects of opencast coal mining has been used by the Candidate for research purposes.
2. A HISTORICAL AND GEOTECHNICAL PERSPECTIVE OF OPENCAST COAL MINING IN NORTHERN ENGLAND

This section explains how the impact of slope and mound failures has led to the introduction of improved specifications and legislation, codes of practice and geotechnical research, and includes the main references to these actions and events.

2.1 A brief history of opencast coal mining in the UK, with particular reference to Northern England

There is evidence that coal mining took place in the UK at the surface and at very shallow depths as early as Roman times. Hand-dug coal was for centuries obtained by people directly working outcrops or by means of bell-pits. However, opencasting (or surface coal mining – Note 1) as we know it today was really only started in 1941, when several civil engineering contracting firms began excavating shallow coal on behalf of the UK government. This came about because of the war effort (1939-1945) to meet the urgent need for fuel, and was overseen by the then Ministry of Fuel and Power (Directorate of Opencast Coal Production) following the introduction of the Defence (General) Regulations of 1939. Shortly afterwards the rules for opencast coal prospecting, land requisition, and 'authorisation' for excavating and mining coal by contractors were set out in Defence Regulation 51A (1942). These statutory arrangements continued for some years after the war ended, and initially the opencast coal industry was virtually unaffected by the 1946/1947 nationalisation of the UK deep mines (i.e. underground coal mines).

Opencast coal eventually became part of the overall nationalised coal industry in 1952, at which time annual opencast coal was recorded as 9.5 million tonnes. All opencast sites were taken into ownership by the National Coal Board (NCB), and the NCB Opencast Executive (NCB/OE) was established. Large scale participation by the private sector continued, in that all 'authorised' opencast coal projects were contracted out to 'approved' major civil engineering and earthmoving firms. In addition, private 'licensed' opencast coal sites, for yields up to 25,000 tonnes, were permitted under the nationalisation arrangements. Both authorised and licensed sites very often included the working of other minerals, particularly fireclays and brick shales, as well as coal.
The statutes and working arrangements outlined above were subsequently consolidated into planning law by the Opencast Coal Act (1958), in that planning applications to work coal by opencast methods were made to the then Secretary of State for Energy. The NCB/OE continued to use contractors for operating opencast sites, rather than develop its own large scale workforce and fleet of excavation and earthmoving plant. However, NCB/OE did purchase and (mostly) retain ownership of several large draglines for use on the larger sites. This was particularly so in Northern England, where these large items of plant were operated by the contractor as part of the contractual arrangements. The directors of NCB/OE took the view that the capital expenditure for such items was not reasonable for its contractors to make, especially as the contractors could not guarantee their winning future contracts on which to deploy large draglines; whereas NCB/OE could be sure that there would be continuous work for the draglines themselves.

Despite threats of down-turns in the required outputs from UK coal mining (particularly in 1949, 1958 and 1967), opencast coal became increasingly important as a supplement to the nation's deep mined coal output. Opencast output reached a peak of 14 million tonnes in 1958, but from about 1960 to the early 1970s annual outputs reduced to between 6 and 9 million tonnes. Then, following the effects of the 1973 OPEC decision to increase oil prices, the UK government, NCB and mining unions came to an agreement aimed at securing the future of the coal industry. This agreement was published in 1974 as the 'Plan for Coal', and included the raising of opencast coal output to a sustained 15 million tonnes per year by 1980.

Outputs of opencast coal were steadily increased from the mid-1970s, and 15.3 million tonnes was achieved in 1981. Thereafter outputs fluctuated between about 14 million tonnes and 17 million tonnes per year, until 1994. The Northern Region of NCB/OE (i.e. Northern England) was usually responsible for producing about a quarter to a third of the total national output. (The other UK opencast regions were Scotland, Wales, and two Central England regions.)

From the late 1970s, following 'Plan for Coal' and the steady increase in the number of opencast sites and coal output, there commenced a growing national trend in public opinion which was against opencast mining. This was primarily due to the perception that opencast mining causes environmental nuisance and damage (e.g. dust, noise, vibration and landscape damage). A particular consequence of this was that in 1985 the Government made a major change to the opencast coal planning application procedure. This change was introduced in
the form of a revision to the Mineral Planning Guidance Note No.3 (MPG 3) which required that applications to work opencast coal should no longer be dealt with by the Department of Energy (as in the Opencast Coal Act (1958)), but should be treated like all other mineral extraction schemes whereby planning applications were then (and still are) made to the Mineral Planning Authority (MPA), which is usually the local County or District Council (i.e. as per the Town and Country Planning Act (1971)) (H.M.S.O. 1981). This has led to many opencast coal planning applications being refused on environmental nuisance grounds, with subsequent appeals against refusal being made to the Secretary of State for the Environment. The overall effect of this 1985 change to the opencast planning procedure has been to make it much more difficult to obtain approval for new projects. Another change made in the mid-1980s was that NCB/OE changed its name to British Coal Opencast (BCO).

The latest major change for opencast coal mining was the re-privatisation of the UK coal industry in 1994. BCO's interests in the English Coalfields (including Northern England) were taken over by RJB Mining (UK) Ltd, which later became UK Mining Ltd. It is obvious that the 1985 change in opencast planning application procedures plus the 1994 re-privatisation has led to the present cut-back in the number of working sites and reduction in opencast coal output. In Northern England there were 22 working opencast sites in 1990, 19 sites in 1992, and only 6 sites by the end of 2001.

In the 1940s the maximum excavation depth at opencast sites was generally less than 15m, and excavation ratios (overburden to coal) were generally around 5 to 1 or 6 to 1. In 1952, for the whole of the UK, it was recorded that 40 civil engineering contracting firms were working 22 sites, and that a further 63 sites had been identified. Over the last 50 years excavation and earthmoving plant has become very much larger and more economical to operate, resulting in larger and deeper opencast mining projects. Nowadays maximum excavation depths can be up to 200m or even 250m, with excavation ratios commonly 25 to 1 and up to 30 to 1.

The two largest sites to have been worked in Northern England are at Butterwell and Stobswood in Northumberland. These sites also hosted the two largest draglines ever to be deployed in western Europe, i.e. 'Big Geordie' (Bucyrus-Erie 1550W) at Butterwell, and the 'Ace of Spades' (Page 757) at Stobswood, both machines having bucket capacities of 50m³. Butterwell was worked between 1976 and 1993 and yielded 13 million tonnes of coal from a
maximum excavation depth of 135m. Stobswood, having started in 1990, is still working and has so far yielded 14 million tonnes of coal from a maximum excavation depth of 200m.

2.2 The development of geotechnical engineering in the UK opencast coal industry, including staffing and statutory aspects

During the late 1950s and 1960s, as opencast workings began to be dug to greater depths and to cover much larger areas, failures in the excavated slopes became fairly commonplace. Both NCB/OE and their opencast site contractors realised that these slope failures represented a serious safety hazard. Probably of even greater concern (to them) was that these failures resulted in extra costs arising from the deployment of extra plant and/or double handling of spoils, and interruptions to the coal production process. As a consequence, staff at NCB/OE began to pay more attention to the geotechnical and (especially) the slope stability aspects of opencasting. This then led to NCB/OE participating in a major geotechnical research programme at Imperial College in London, jointly with several other international mining organisations (Sharp, 1970; Stimpson and Walton, 1970; Ross-Brown, 1973).

Probably the most important and useful outcome from this research was the book 'Rock Slope Engineering' by Evert Hoek and John Bray (Hoek and Bray, 1974). This has now been released in three editions (1974, 1977 and 1981) and has become a standard text and slope stability manual used by geotechnical engineers worldwide. However, prior to 1975, NCB/OE only employed one geotechnical specialist on their staff. He was based in the headquarters (then located in Harrow) but spent much of his time on secondment to the Imperial College research project.

In 1972, the UK Health and Safety Executive (HSE) published 'The Law Relating to Safety and Health in Mines and Quarries, Part 4 Quarries' (Anon, 1972) which gathered together all the then current pieces of legislation that related to quarry working (including opencast coal mining – Note 2). The following items contained therein were particularly relevant to geotechnical matters.

(i) Mines and Quarries Act, 1954

Regulation 108(1) required that quarrying operations should be carried out so as to avoid danger from 'falls of ground' (i.e. no slope failures).
Regulation 108(2) required that the face and sides of the quarry should not be worked so as to cause any 'overhang'.

(ii) Quarries (General) Regulations, 1956

Regulation 2 required that daily inspections should be made of all quarry faces, sides and overburden, and that these inspections should be recorded on M&Q Form No.236. Regulation 3(1) required that the 'overburden' at or near the top of the face or sides of the quarry should be cleared back for a sufficient distance and depth to avoid danger from falls. For opencast sites 'overburden' was interpreted as superficial deposits (i.e. engineering soils) and this regulation therefore made the provision of rockhead safety benches a legal requirement.

This HSE Part 4, Quarries publication (Anon, 1972) also contained the then recently introduced legislation on mines and quarries tips, being the:

Mines and Quarries (Tips) Act, 1969;
Mines and Quarries (Tips) Regulations, 1971;

However, both the NCB/OE and their contractors disputed the application of these tips statutes to the temporary storage of topsoil, subsoil and overburden spoils at UK opencast coal mining sites, i.e. they contended that they were not 'permanent tips' but 'temporary storage mounds'. (See Hughes and Clarke (2002 – PAPER A8) for illustrations of the progressive operation (excavation, mounding and backfilling) of opencast coal workings, and particularly the temporary nature of storage mounds.)

On January 14th 1974, at Westfield opencast coal site in Scotland, a fatal accident occurred when a bulldozer and its driver were buried by a 'fall of ground'. This catastrophic slope failure was reported in the national press and was investigated by Her Majesty's Inspectorate of Mines and Quarries (HMIM&Q) which was part of HSE. Norton (1983) subsequently recorded the details of this failure as being "on the western wall, and approximately 92m high, by 230m wide, by 3 to 4m thick. The overall slope angle (elevation) was 35°, with a convex upwards roll-over at the base of the slab where dips in excess of 60° were observed." The mechanism of failure was "slab-buckling" (Hughes and Leigh, 1985 – PAPER C2). The
failure event was very rapid, probably only a few seconds, giving the bulldozer driver insufficient time to escape.

Following their investigations into the Westfield slope failure, HMIM&Q held several meetings with the directors of NCB/OE. These resulted in the post of Regional Geotechnical Engineer (RGE) being created in each of the five UK regions (i.e. three in England, plus one each in Scotland and Wales – Note 3), but this was still only a small number of specialists in a major excavation and ground engineering organisation with an annual turnover of about £500 million (i.e. at 1974 prices – Note 4). Also, the headquarters specialist geotechnical post was terminated and never re-introduced (Note 5).

At this time there were important additions and changes made to the NCB/OE standard opencast mining Contract Specification. These included that the newly appointed RGEs would provide a pre-contract geotechnical report for each new opencast project which would be called the Initial Stability Assessment (ISA). In addition, tenderers for opencast contracts would provide details of their proposed excavation slope profiles (face heights and elevations, and bench widths etc.) on plans and sections to be included with their Method Statement.

In further response to the Westfield disaster and the subsequent pressure from HMIM&Q (HSE), NCB/OE sponsored a number of PhD research projects at Nottingham University starting in 1976. The main topics researched included slope stability and slope monitoring, groundwater, diggability and backfill settlement, and resulted in theses by Young (1979), Rao (1980), Cobb (1981), Hassani (1981), Scoble (1981), Denby (1983), Muftuoglu (1983), Norton (1983), Stead (1984) and Reed (1986). In the NCB/OE Northern Region research into backfill settlement was carried out in conjunction with the Building Research Establishment (Charles et al, 1977, 1984 (PAPER C1) and 1993 (PAPER C15)). Later, research was done in conjunction with Newcastle University into groundwater (Minnett, 1987; Blythe, 1990) and into 'intraformational shear zones' (Jameson, 1995).

The next major geotechnical development was in 1980 when the HSE indicated that they were not in agreement with the NCB/OE and its contractors (who were now represented by the Coal Committee of the Federation of Civil Engineering Contractors (FCEC)) about the UK Mines and Quarries Tips legislation not being applicable to opencast coal sites, and threatened to go to the courts over this issue. Indeed there had been several spoil mound failures at UK
opencast sites, including some in Northern England (Rostron, 1976; Babakhanians, 1977; Blythe et al., 1993 (PAPER C14); Hughes and Clarke, 1997 (PAPER A3)). This resulted in NCB/OE and FCEC jointly proposing and drafting a code of practice about the siting and construction of temporary spoil mounds at opencast coal sites (FCEC, 1982) which was accepted by the HSE as being equivalent to their tips legislation.

The 1982 spoil mounds code of practice was divided into two parts. Part 1 required that the NCB/OE's RGEs (as Competent Person for Part 1) should carry out ground investigations in all areas of a proposed opencast site where spoil mounds could be located, particularly in the superficial or drift deposits, and especially where the MPA had indicated that they should be located following the planning application process. The RGE would then assemble all the available ground information and carry out outline designs for the spoil mounds. All of this information would be included in the opencast site tender documents. Under Part 2 of the code of practice, the successful tenderer was required to appoint a second Competent Person (i.e. a suitably experienced geotechnical engineer) to design the spoil mounds in detail, to carry out inspections and to provide geotechnical reports on the spoil mounds at specified time intervals after their construction.

The introduction of a small number of specialist geotechnical engineering staff by NCB/OE in the mid-1970s, plus the extra geotechnical safety requirements in the Contract Specification and the spoil mounds code of practice (FCEC, 1982), did appear to bring about some overall improvements in the safe working of UK opencast sites. However, sites were becoming even larger and deeper than before, and were being worked through ground conditions that were becoming ever more difficult and geologically complex. Consequently, throughout the late 1970s and 1980s, large slope failures still continued to occur (Leigh et al., 1980; Scoble, 1981; Hughes and McLean, 1986 (PAPER C8); Hughes and Clarke, 2001 (PAPER A7); Hughes and Clarke, 2002 (PAPER A8)).

One of the largest and most publicised slope failures at a UK opencast site occurred in March 1988, when a massive (600,000m³) failure took place adjacent to the River Aire in West Yorkshire (Hughes and Clarke, 2001 (PAPER A7)). This resulted in the rapid flooding of the working void at St Aidans Extension Opencast coal site. Unlike the Westfield failure of 1974 (Norton, 1983) nobody was injured, but considerable damage occurred to the banks and bed of the River Aire watercourse, and the security of a nearby major navigation canal was
seriously threatened. Coal production at St Aidans Extension Opencast site was suspended for 10 years, and the total remedial and recovery costs came to £56 million (Hughes and Clarke, 2001 (PAPER A7)).

Following the River Aire slope failure, both BCO and HSE set up inquiry panels and produced reports (BCO, 1988; Davies, 1988). The HSE then presided over a 'panel of experts' (which included the Candidate) which drafted a new geotechnical code of practice and this was introduced into the UK opencast coal mining industry at the end of 1989. The title was 'The stability of excavated slopes at opencast sites' (FCEC, 1989) and provided guidance on the ground investigation and design of stable excavations. The format was similar to the earlier spoil mounds code of practice (FCEC, 1982) in that a Competent Person for Part 1 provided the ground investigation data and outline designs, and a Competent Person for Part 2 carried out the detailed designs and inspections. Under this code the BCO RGEs provided a major geotechnical report with many appendices (geotechnical site investigation reports and borehole logs, underground mining and subsidence reports, prospecting geology reports and borehole logs etc. – see later) such that the total weight of hard copy data was usually between 10 and 30 kilos dependent upon the size and complexity of the mining project.

The introduction of the 1989 'excavations' code of practice resulted in a very large increase in workload for the BCO geotechnical staff, which led to the recruitment of small geotechnical teams in each region. The management structure for Northern Region for the period 1990 to 1994 is shown in Table 1. It can be seen that the RGE and the Geotechnical Department were part of the Regional Projects Group under the direction of the Regional Projects Manager (who was also the Deputy Regional Director). The involvement of geotechnical engineering in an opencast project, following the 1989 excavations code, is illustrated by Hughes and Norbury (1996 (PAPER A1)) in a case study for Plenmeller opencast coal site. Table 4 of that paper shows how geotechnical engineering contributes to the planning, prospecting, operations and restoration phases of a project. Table 3 of that paper shows the expenditure on each aspect of the geotechnical investigations for the Plenmeller project. Once the full extent of the BCO geotechnical obligations under the new code were fully understood, and started to be complied with, the annual geotechnical investigation budget for Northern Region amounted to between £0.5 million and £1.0 million (i.e. at 1990s prices).
TABLE 1: BRITISH COAL OPENCAST – NORTHERN REGION – ORGANISATION (1990/94)

Number of operating sites = 20-24
Annual coal production = 4.5-5.0 million tonnes

Cumbria, Northumberland
Co Durham, Tyne and Wear

Annual profit = £50 million approx.
Annual turnover = £250 million approx.

- Regional Opencast Director
  - Regional Operations Manager
    - Assistant Regional Operations Manager
  - Regional Projects Manager
    - Regional Geotechnical Engineer (RGE)
      - Projects Manager (3 No)
  - Regional Land Manager
  - Regional Commercial Manager
    - Regional Accountant
      - Regional Staff Manager
        - Regional Marketing Manager
        - Regional Contracts Officer
        - Regional Computer Apps. Officer
        - Regional Licences Mines Officer

- Senior Works Engineer
  - Works and Plant Engineers and Assistants
    - Surveyors
      - Assistant Site Engineers
        - Surveying Assistants
  - Site Managers (5 No)
    - Senior Surveyors
    - Site Engineers
      - Geotechnical Engineers (2 No)
  - Senior Geotechnical Engineer
    - Engineering Geologist (Cumbria – part-time)
  - Senior Engineers
    - Senior Engineers Geologists Planners (2 No)
    - Senior Lands Offices (2 No)
  - Geotechnical Technician
    - Projects Technician
      - Lands Technician
      - Lands Officers
        - Assistant Lands Officers
      - Surveying Assistants
  - Site Supervisors
  - Clerical and Administrative Staff

Departments for:
- Finance
- Marketing and Preparation
- Purchasing and Contracts
- Staff and Administration
- Drawing Office
- Computer Applications
As stated previously, the demise (privatisation) of BCO came at the end of 1994 (Note 6). Ownership and responsibility for the remaining opencast sites in Northern England passed to RJB Mining (UK) Ltd, which subsequently became UK Mining Ltd. After 1994 the HSE began drafting new regulations for health and safety at quarries (which includes opencast sites) which were published and applied from 1999 (Health and Safety Commission, 1999). An 'approved code of practice' which includes geotechnical requirements is included with these latest regulations. It appears that most of the ideas and requirements of the now superseded opencast geotechnical codes (FCEC, 1982 and FCEC, 1989) are included in this new quarries legislation.

2.3. Geotechnical reporting for opencast coal projects

As stated previously and illustrated by Hughes and Norbury (1996) for the Plemmeller site, geotechnical input is required at all stages of the planning and operation of an opencast coal site. These stages include prospecting, statutory planning, design and construction of all infrastructure works including coal processing and disposal facilities, design and excavation of rock and soil slopes, design and construction of spoil storage mounds and water treatment lagoons, and restoration aspects. Ground investigation works are required to provide the geotechnical input data for the analyses and designs required at the above listed stages of a project. The details of how geotechnical ground investigations are carried out and applied are given by Hughes and Blythe (1987) (PAPER C9) and Hughes (1991) (PAPER C13). The structure of the Geotechnical Stability Report (GSR), which contained all the geotechnical information supplied at tender stage, is summarised in Table 2 (from Hughes, 1991 (PAPER C13)).

The GSR was always signed personally by the RGE (as the Competent Person for Part I for both geotechnical codes of practice) and was expected to contain the details of all the investigations and findings of the BCO Regional Geotechnical Department for that project up to going out to tender. The next task for the RGE and his team was to assess the 'Method Statements' of the tenderers to ensure that the data provided, and any problems described in the GSR, had been understood, and that adequate solutions had been devised or designed.

Once work began on site, then legally the main geotechnical responsibility rested with the successful contractor's 'Competent Person' (for Part 2 of the codes), who was always an
experienced geotechnical engineer. However, BCO still had responsibilities under the Town and Country Planning legislation to the MPA, and to adjacent landowners etc. In practice this meant frequent site visits by the RGE and his staff to monitor progress, and regular meetings with the contractor's geotechnical representative(s). Hence, this resulted in the RGE (the Candidate in this case) obtaining detailed knowledge of the operational aspects of each project.

The gathering of all this pre-tender geotechnical information, and post-tender involvement in site operations, has enabled the Candidate to record and publish the detailed case studies which form the main part of this submission for a higher degree.

Note 1: In the UK 'opencast mining' is also referred to as 'opencast quarrying', especially in legal or statutory documents; but worldwide 'surface mining' is the term most commonly used. Also, in the UK, the term 'site' rather than 'mine' is frequently used when referring to opencast coal operations.

Note 2: As far as the Candidate was able to ascertain both NCB/OE and its contractors were mostly unaware of the existence of much of the 'Quarries' legislation prior to the publication, in 1972, of 'The law Relating to Safety and Health in Mines and Quarries, Part 4 Quarries' (Anon, 1972).

Note 3: A particular feature of the exposed coalfields of Northern England (comprising Cumbria, Northumberland, Tyne and Wear, and County Durham) is that they are generally covered by a thick layer of glacial deposits, usually between 5 m and 40 m depth (Hughes et al, 1998). The Candidate took up the post of RGE in Northern Region from February 1979 and, due to the size and geological conditions in this region, an assistant geotechnical engineer was also appointed.

Note 4: Inflation to today's (2003) values would increase this amount by at least five-fold to around £2,500 million.

Note 5: Following the St. Aidans disaster in March 1988, and the completion of the subsequent investigations, BCO commissioned an independent consulting engineer to review its geotechnical engineering capabilities. One of the main recommendations from this review was that a Chief Geotechnical Engineer post should be created within the BCO headquarters management team to co-ordinate the work of the RGEs within the Regions. This proposal was adopted by BCO directors, but unfortunately the start of the re-privatisation process (around 1990) meant that an appointment was never made. However, the Candidate carried out many of the duties which had been assigned to this headquarters post on a part-time basis.

Note 6: The re-privatisation of the UK coal industry (British Coal) in 1994 ended the Candidate's employment in that industry.
### TABLE 2: STRUCTURE OF GEOTECHNICAL STABILITY REPORT

**MAIN BODY OF REPORT**

1. **PRELIMINARIES**
   - Location and size of site
   - Codes of practice – Contract Clause nos.
   - Reference documents and Appendices

2. **FIELD AND LABORATORY INVESTIGATIONS**
   - (Factual data and summaries)
   - Geological and prospecting summaries
   - Records from nearby sites
   - Surface and shallow features
   - Superficial deposits and rockhead
   - Bedrock
   - Previous workings (surface and underground)
   - Surface water and groundwater

3. **ASSESSMENT OF FACTORS AFFECTING STABILITY**
   - Method(s) of working
   - Surface and shallow features
   - Construction of spoil mounds
   - Construction of lagoons
   - Construction of ancillary works (highway or service diversions etc.)
   - Excavations in superficial deposits
   - Excavations in bedrock
   - Previous workings
   - Surface water and groundwater

4. **OTHERS**
   - e.g. Contaminated Land

**SIGNATURE OF COMPETENT PERSON**

**APPENDICES**

**INTERNAL APPENDICES**

- Description and diagrams of types of slope failure in bedrock and superficial deposits
- Lists of all archive and other documents referred to for information on:
  - e.g. shaft and adit locations etc.
  - old mining and quarrying records
  - underground and overhead services
  - industrial archaeology
  - contaminated land etc. etc.

- Rainfall records
- Groundwater level records (piezometer and standpipe details)

**EXTERNAL APPENDICES**

- Geotechnical Site Investigation Report(s) for Superficial Deposits (may be several volumes) including:
  - Borehole log sheets
  - In-situ and lab. test results
  - Schematic borehole sections
  - (For bedrock the details of the geotechnical)
  - (investigation part of the prospecting)
  - (programme are given with the geological)
  - (documents listed below and in the)
  - (appropriate internal appendices. However,)
  - (separate geotechnical bedrock)
  - (investigations are sometimes carried out.)

- Final geological report
- Borehole schedule (prospecting)
- Geological plans and sections:
  - e.g. Geological key plan
  - Structure plans and sections
  - Superficial deposits thickness plan
  - Rockhead level plan
  - Seam old workings plan(s)
  - Fully cored borehole details

- Contract site plan
- Contract specification
- Schedule of estimated quantities

- Other relevant reports:
  - e.g. Deep mines tip site investigation reports
  - Mineral Valuer’s report
3. REVIEWS OF PUBLICATIONS AND LINKAGES (INCLUDING KEY REFERENCES, IMPACTS AND CITATIONS)

In this section each of the Candidate's thirty-one publications is briefly reviewed and its relationships (linkages) with some of the other publications is shown. List A papers (being the main works) have generally been discussed at more length than List B and C papers.

All of the publications given in Lists A, B and C have been assigned to one of five main subject categories or themes, which are *General Opencast Geotechnical, Ground Investigations, Glacial Deposits, Coal Measures, Opencast Backfill and Groundwater*, and these represent the majority of geotechnical applications in opencast coal mining. Many of these publications contain information which falls into two or more categories, and hence it has been necessary to assign each one on a 'best-fit' judgement.

The overall linkage between the publications is the geotechnical aspects of opencast coal mining in the UK (mainly in Northern England). Many years have been spent researching, investigating, designing and specifying over a hundred major opencast projects. The work is based on many thousands of hours spent actually present on sites inspecting the exposed geology, examining slope and mound failures, and observing site operations including restoration and remedial works.

### 3.1 General Opencast Geotechnical

The following four papers are included in this category

- **PAPER A1** PLENMELLER (Q.J.E.G.)
- **PAPER C2** GENERAL (Q.M.)
- **PAPER C7** GENERAL (B.G.)
- **PAPER C16** PLENMELLER (Q.M.)

PAPERS A1 and C16 are specifically about Plemeller site, whereas PAPERS C2 and C7 are more generally about geotechnical engineering and the UK opencast coal mining environment. The purpose of these four papers has been to illustrate to other geotechnical engineering...
professionals the particular problems encountered in the UK opencast mining industry. These include the planning procedures and constraints, the HSE involvement (previously Codes of Practice, and now Quarries Regulations (Health and Safety Commission, 1999)), the particular ground conditions (specifically Coal Measures bedrock, and the overlying glacial materials), ground investigations (both for geotechnical purposes and for coal prospecting), the types of failures encountered in excavated slopes (both bedrock and superficials), spoil mound stability, groundwater problems and control, and finally backfill settlement and site restoration.

In the above paragraph the topics of ground investigation, glacial deposits, Coal Measures bedrock, opencast backfill settlement and groundwater are all listed as constituents of these general papers. Therefore these papers illustrate the overall linkages between the several topics within opencast mining geotechnical engineering, and which are the subjects of the remaining twenty-seven papers discussed hereafter.

3.1.1 PAPER A1 PLENMELLER (Q.J.E.G.)

"Plenmeller opencast coal site: a geotechnical and planning case study" (1996),
by D.B. Hughes and D.R. Norbury

This paper shows the contribution of geotechnical engineering in a large and complex opencast mining project, from the initial identification of the coal deposit, through the prospecting and engineering design, the planning application, the award of the contract and site operations, and finally the restoration and aftercare stages. The paper also shows the costs of the geotechnical investigations and identifies every aspect of geotechnical design where ground investigations are necessary. The geological succession and stability aspects are described, including the glacial deposits and the Coal Measures bedrock. An account of the previous underground workings is given. Also, the stability aspects of working in the vicinity of the Stublick Fault are discussed. This paper, therefore, may be viewed as a suitable guide to anyone whose experience in opencast geotechnical engineering is such that they need an example to follow.

The Candidate and the second author (D.R. Norbury) were the 'Competent Persons' for Parts 1 and 2 (respectively) for the opencast industry geotechnical codes of practice (FCEC, 1982;
FCEC, 1989) for the Plenmeller opencast coal site in SW Northumberland. This site was one of the first to go out to tender following the introduction of the 'excavations code' (FCEC, 1989), and therefore was covered by a Geotechnical Stability Report (GSR). The site was especially interesting due to the complex bedrock geology (faulting, steep bedding, old coal workings, groundwater) overlain by thick glacial deposits and peat, and a moorland location necessitating extensive infrastructure works.

Eight references are cited in this paper, the two main ones being the two geotechnical codes of practice referred to above (FCEC, 1982 and FCEC, 1989 (which are labelled Anon, 1982 and Anon, 1989 in the paper)). These codes/references are discussed in SECTION 2. Also, the paper by Hughes (1991 – "The Geotechnical Stability Report") is an explanation of the BCO input into these codes of practice.

The impact of this publication can be shown by the fact that two Regional Groups of the Geological Society invited the Candidate to present his paper in their programmes of technical meetings (these being the Northern Group and the West of Scotland Group). Also, the Northern Geotechnical Group held a technical visit to Plenmeller site. Therefore, this paper has been of particular interest to Engineering Geologists and Geotechnical Engineers in professional practice.

3.1.2 PAPER C2 GENERAL (Q.M.)

"The stability of excavations and spoil mounds in relation to opencast coal mining" (1985),
by D.B. Hughes and W.J.P. Leigh

and PAPER C7 GENERAL (B.G.)

"Geotechnical engineering in opencast mining" (1986),
by D.B. Hughes

Both papers were written entirely by the Candidate.

PAPER C2 is a technical account of the practice of geotechnical engineering in UK opencast coal mining up to the mid-1980s. It includes descriptions of excavation operations and
various slope and spoil mound failure mechanisms. There is also an account of the legislation and contractual aspects relating to that period. It has been presented to the Institute of Quarrying (North of England Branch), the Institution of Civil Engineers (NW Branch) and the North West Geotechnical Society. This paper had a major impact on the UK opencast mining industry at that time and sections of it were reproduced in GSRs and BCO technical handbooks, as well as other citations.

PAPER C7 is a shortened version of PAPER C2, but with additional emphasis on the NCB/OE organisation and potential career aspects. This paper was presented to the Institution of Geologists/Geological Society (North of England Group).

3.1.3 PAPER C16 PLEMELLER (Q.M.)

"Plenmeller OCCS – a ground engineering case history" (1994),
by D.B. Hughes and D.R. Norbury

This paper was in fact an early draft of PAPER A1 PLENMELLER (Q.J.E.G.) (Hughes and Norbury, 1996). This 1994 version was produced by the Candidate for presentation at a joint Geological Society/Institute of Quarrying seminar at Keyworth in March 1994. The Technical Editor of 'Quarry Management' asked if it could be published in that journal in its then early form. Subsequently, the two authors reviewed and considerably extended the paper before successfully submitting it to the Quarterly Journal of Engineering Geology, which had always been their target publication.

3.2 Ground Investigations

The three papers included in this category are as follows:

PAPER C5 SITE INVESTIGATION
PAPER C9 DRILLEX '87
PAPER C13 GEOTECHNICAL STABILITY REPORT

All the papers relate to acquiring geotechnical information about the ground through which it is intended to carry out major excavations or construct foundations. PAPER C9 concentrates
mainly on drilling and boring techniques. PAPER C13 extends this further by bringing in the examination of other relevant records (topographical, aerial photographs, walk-over surveys, weather, mining, other ground investigations and industrial archaeology etc.). PAPER C5, although the earliest of the three papers, also includes several ground investigation case histories related to the opencast mining industry.

The ground investigations for opencast coal sites in Northern England mainly involve drilling and sampling and testing in glacial deposits and Coal Measures bedrock. Therefore considerable overlap (or linkage) of subject matter and content with papers in the following sections (especially 3.3 Glacial Deposits and 3.4 Coal Measures) is inevitable.

3.2.1 PAPER C5 SITE INVESTIGATION

"Site investigation in relation to opencast coal mining in Great Britain" (1985),
by D.B. Hughes

Following the introduction of the "Spoil Mounds Code of Practice" (FCEC, 1982) into the UK opencast coal mining industry, the senior management at NCB/OE decided to produce a geotechnical engineering manual or guide for issue to all its staff, and to make it available to other participants in the industry (e.g. Contractors, HM Inspectorate, Planning Authorities etc.). The Candidate was a regular lecturer on geotechnical topics at courses and seminars given on behalf of NCB/OE and British Mining Consultants Ltd, and his lecture notes were adapted to become chapters in the "Geotechnical Engineering Guide". This "site investigation" chapter describes in detail the methods of drilling and boring for engineering soils and rocks, in-situ and laboratory testing, and includes several case histories to illustrate the use of geotechnical parameters in opencast mining related design and analysis situations. The Candidate was also the main author of a lengthy introductory chapter included in this same "Geotechnical Engineering Guide".

3.2.2 PAPER C9 DRILLEX '87

"Sub-surface investigations by drilling and boring for opencast coal mining projects in the United Kingdom" (1987),
by D.B. Hughes and D.A. Blythe
This paper describes in some detail the drilling and boring methods used by the UK opencast coal industry to prospect for coal, and for geotechnical investigation purposes, including some 'down-the-hole' geologging techniques. The paper has been cited in other opencast geotechnical and site investigation publications.

3.2.3 PAPER C13 GEOTECHNICAL STABILITY REPORT

"The Geotechnical Stability Report" (1991),
by D.B. Hughes

Following the introduction of the 'Excavations Code of Practice' (FCEC, 1989), the Health and Safety Executive arranged a conference at Leicester in 1991 to allow the participants in the UK opencast coal industry to discuss the progress of the implementation of this code. The Candidate was asked to prepare and present a paper about the Geotechnical Stability Report, and particularly about the acquisition and presentation of factual geotechnical data as required by Part 1 of the (then) new Code of Practice. This paper has been cited in other publications relating to opencast geotechnics.

3.3 Glacial Deposits

With twelve publications relating to research on glacial deposits, this topic represents by far the largest expenditure of research effort by the Candidate on any aspect of opencast coal mining.

PAPER A2 ENGINEER'S VIEW
PAPER A3 SPOIL MOUNDS - NORTHERN ENGLAND
PAPER A4 GLACIAL SUCCESSION
PAPER A6 HERRINGTON
PAPER B1 TILLS FRAMEWORK
PAPER B2 GLACIAL HISTORY
PAPER B3 TILLS IN EARTHWORKS
PAPER B4 NETDATA
PAPER C6 DERWENT-TYNE CONFLUENCE
Although the common theme to all of the above papers is the engineering geology or geotechnical aspects of Northern or North East England glacial deposits, several different aspects are included. However, all the papers discuss the glacial succession to a greater or lesser degree.

PAPER A2 is a general introduction to the engineering geological aspects of the glacial deposits in Northern England and was written as a summary of a lecture which was given to the Cumberland Geological Society. PAPER A4 is a detailed account of the development of our knowledge of the glacial history of Northern England, which is followed by a description of the engineering geological aspects of the glacial deposits based mainly on the Candidate's own research on opencast coal sites. PAPER B2 is an account of the glacial history of North East England (main author D. A. Teasdale) and cites from PAPER A4. PAPERS A3, A6, C6 and C14 are all case histories about excavated slopes and spoil mounds. PAPERS B1, B3, B4, C17 and C18 are all papers which present and discuss engineering parameters for the layers or units within the glacial succession as found in Northern England.

3.3.1 PAPER A2 ENGINEER'S VIEW

"The glacial deposits of Northern England: an engineer's view" (1996),
by D.B. Hughes

This paper is a set of notes supplied by the Candidate following his lecture to the Cumberland Geological Society in September 1996, and subsequently published in the Society's journal. Just a few days prior to the lecture date there had been announcements in both the national and local news about plans for a "Great North Canal" linking Port Carlisle to Tynemouth, a distance of some 110 km across northern England. Such a waterway, if constructed, would have to be cut through glacial deposits for virtually its entire length. Although this proposal has found very little public or government support, it did provide a topical way to introduce the research being carried out by the Candidate at Newcastle University into the engineering aspects of the glacial deposits in Northern England. This included illustrations of exposures
of the glacial geology (particularly at opencast coal sites) and the acquisition of geotechnical
data from ground investigation boreholes and soil mechanics laboratory testing. Examples of
design and construction problems encountered in projects which involved working on or in
glacial deposits were also described.

3.3.2 PAPER A3 SPOIL MOUNDS – NORTHERN ENGLAND

"The glacial tills of Northern England in relation to the stability of screening and spoil
mounds at opencast coal mines" (1997),
by D.B. Hughes and B.G. Clarke

This paper shows a very simplified sequence of working for opencast coal sites, which is then
used to introduce the siting of storage and spoil mounds (topsoil, subsoil and overburden).
The glacial successions for Cumbria and North East England are included, which are
somewhat abridged versions of the detailed accounts given in PAPER A4 GLACIAL
SUCCESSION (Hughes et al, 1998), thus demonstrating the link with that paper. Some spoil
mound design considerations are discussed, and finally three anonymous case studies of spoil
mound failures are described.

There are 9 references given in this paper, of which 5 are the Candidate's own papers. These
are Blythe et al (1993 – PAPER C14), Hughes and Leigh (1985 – PAPER C2), Hughes and
presented in Glasgow)) and Robertson et al – PAPER C17 (1994). The first two deal with
spoil mound construction, the third with ground investigation techniques, and the last two
with glacial deposits.

Boulton et al (1997) describe a British ice-sheet model for the Late Devensian. Eyles and
Sladen (1981) propose the 'weathering theory' for Northumberland tills instead of separate
'upper' and 'lower' tills (i.e. the whole glacial succession was deposited from a single ice sheet
as lodgement till). Both of these papers are discussed in some detail in PAPER A4
GLACIAL SUCCESSION (Hughes et al, 1998). The two opencast industry geotechnical
codes of practice (i.e. for 'spoil mounds' (Anon, 1982) and for 'excavations' (Anon, 1989))
have been referenced in this 'Critical Appraisal' as FCEC (1982) and FCEC (1989), and have
been described in detail in Section 2.
Note: The initial version of this paper was somewhat longer and more detailed, as it was intended to be a journal paper. However, when details of the International Engineering Geology Conference (in Athens) were received it was decided to target the paper there, and so it had to be reduced to just six A4 pages. Also, the regulations for the 'staff PhD by publications route' were not known at that time (these were first published in August 1997). These regulations emphasise the requirement to publish in peer-reviewed journals, and had this been known in time, this paper would have been kept nearer its original length and submitted to a suitable journal. However, the paper was anonymously reviewed for the conference, and a copy of the reviewer's report is available (which rated the paper as "good").

3.3.3 PAPER A4 GLACIAL SUCCESSION

"The glacial succession in lowland Northern England" (1998)
by D.B. Hughes, B.G. Clarke and M.S Money

This paper started as a presentation to the 'Glacial Geology and Engineering' seminar in Glasgow in October 1996 (organised by the West of Scotland Regional Group of the Geological Society). The presentation mainly comprised the photographic evidence from opencast coal mining sites showing the glacial succession in Northern England. The editor of Quarterly Journal of Engineering Geology (QJEG) and the seminar organisers asked if a paper could be prepared for publication in QJEG. They particularly wanted a review of the history of glacial geology research for the region, together with the evidence from opencast mining which the Candidate had presented. The preparation of this paper therefore required a major review of the literature. In the paper 83 references have been cited, but well over 200 articles, papers, theses and books were consulted whilst carrying out this review.

In reviewing the historical development of the concepts of the glacial succession for Northern England several late nineteenth and early twentieth century publications were referred to. In particular Wood and Boyd (1863) plotted the locations of deep drift filled valleys in County Durham, and Howse (1864) promoted the idea of the 'Glacial Theory' by explaining the significance of land-based ice sheets and their erosive power. Goodchild (1875) concluded that ice which had accumulated on the western side of the region had flowed eastwards through both the Tyne Gap and the Stainmore Pass. Mackintosh (1877) was the first to
identify a tripartite succession in Cumbria and NW England, and Kendall (1902) was probably the first to identify a tripartite succession in NE England with his work in the Cleveland area. The tripartite succession in both the NW and NE is generally referred to a lower boulder clay (lower till), middle sand (and/or laminated clay), upper boulder clay (upper till). British Quaternary ice sheet modelling, glacial deposition and ice flow directions have all been the subject of publications by Boulton (1972) and by Boulton et al (1977, 1985 and 1991).

For the western side of the region the Geological Memoirs published by the British Geological Survey (BGS) have developed the concept of the tripartite succession and these included Dixon et al (1926), Eastwood (1930), Eastwood et al (1931), Trotter et al (1937), Eastwood et al (1968), Taylor et al (1971) and Barnes et al (1988). Huddart and Huddart et al (8 publications between 1970 and 1997) have named the lower boulder clay/till as the Lowca till, and they have presented the evidence for Late Devensian re-advances of the ice sheet, southwards, along the Cumbria coast. Eyles and McCabe (1989) suggested that these coastal deposits were of glaciomarine origin, but later work by BGS on behalf of NIREX (Anon (1997) and Merritt (1997)) refuted the glaciomarine theory in favour of the re-advances.

On the eastern side of the region all of the BGS memoirs (Fowler (1935), Smith and Francis (1967), Taylor et al (1971), Land (1974), Mills and Hull (1976), Lawrence and Jackson (1986), Lawrence and Jackson (1990), Smith (1994)) also support the idea of the tripartite succession. For NE England several views have been presented on the formation of the upper (red/brown) till as distinct from the lower (grey) till. Carruthers (1939, 1946 and 1953), Smith and Francis (1967), Smith (1981, 1982 and 1994) and Catt (1991a and b) favour the idea that an earlier western ice stream deposited the lower till and that a later northern ice stream deposited the upper till, thus explaining the different clay matrix colours and clast suites and orientations in the two till layers. Eyles and Sladen (1981) and Eyles et al (1982) presented their ideas which involved a single but complex till deposit and that the red/brown colour (rather than grey) for the upper till was due to post-glacial weathering. Lunn (1995) discussed these two different views and came out in favour of the 'weathering' theory. However, a third explanation (at least for some areas where an upper till occurs) is that there could be solifluction effects (Anson and Sharp (1960), Taylor et al (1971), Smith (1981 and 1994), Douglas (1991) and Turner and Smith (1995)).
About 60% of the paper is devoted to discussing the Candidate's own evidence for the Northern England glacial succession based on his records and photographs obtained from the many opencast coal sites with which he has been involved. Figures 3 and 7 show, in engineering terms, a schematic succession for the glacial deposits for both the west and east sides of the region.

Although this paper was only published in August 1998, it has been cited in several recent publications (apart from being cited in the Candidate's own subsequent papers). Examples include the BGS Quaternary geology – towards meeting user requirements (Foster et al, 1999); plus papers by Clarke et al (1998), Bell (2002) and Davis and Horswill (2002). The newly published Geological Conservation Review Series – Quaternary of Northern England (Huddart and Glasser, 2002) cites the paper many times and includes some of the Candidate's original diagrams. Therefore, it appears that this paper has made a very significant contribution in the fields of glacial geology and engineering geology for Northern England.

3.3.4 PAPER A6 HERRINGTON

"Herrington Colliery opencast coal site" (1999),
by D.B. Hughes and D.A. Teasdale

In April 1999 the Quaternary Research Association (QRA) held their annual field meeting in North East England. The QRA asked the Candidate to organise a site visit to view Late Devensian glacial deposits exposed at an opencast mine and to write an account for their Field Guide. The site at Herrington had very good exposures of these deposits which included the Tyne-Wear Complex (as named by Smith, 1994). The Candidate's collaboration with D.A. Teasdale (of Durham University) led to two papers being published in the QRA North East England Field Guide (1999) (Hughes and Teasdale, 1999 – this one (PAPER A6); and Teasdale and Hughes, 1999 – PAPER B2).

This paper discusses the glacial geology exposed at Herrington Colliery opencast coal site which is located on the edge (an embayment) of the former Glacial Lake Wear (the Tyne-Wear Complex). The glacial succession is described in engineering geological terms, and this is related to the glacial ice flows.
The site visit took place on 9th April 1999, and involved about 90 QRA members. At that time the excavation face in the superficial deposits almost exactly coincided with the section line in Figure 4 (in this paper) which had been the intention/prediction of the Candidate and site staff when the paper was being written. Several earthworks ramps and platforms were constructed by the site contractor to allow close examination of the freshly exposed glacial deposits, especially the Tyne-Wear Complex (glaciolacustrine) formation. Of particular interest on the day of the visit was a series of overthrusts in the upper levels of the glaciolacustrine (laminated) deposits, which were overlain by a thin layer (0.5m to 1.0m thickness) of red/brown till (lodgement?). This indicated a possible late re-advance or surge in the coastal (northern source) ice. These features are not described in the published paper because they were not exposed until after the QRA Field Guide had been printed. The site visit overran by about 1½ hours as the QRA members found this location to be of very great interest and they were reluctant to leave. The advantage of visiting very large excavations (i.e. opencast voids) for inspecting till exposures was thus demonstrated.

Probably the most important reference is Smith (1994) which is a revised version of Smith (1981) in which he describes the various shorelines and levels of Glacial Lake Wear, together with the ice flow directions during the Late Devensian glaciation. Differing explanations of the history and patterns of glaciation have also been published by Carruthers (1953), Catt (1991a) and Eyles and Sladen (1981). In particular, evidence against the Eyles and Sladen 'weathering theory' (i.e. all the till was deposited as lodgement till by a single ice-sheet, with the upper red/brown till being in fact weathered lower grey till) is described where red/brown till was found beneath grey till. These alternating layers of the two main colours of till could perhaps be explained by the 'waxing and waning' of separate (northern and western sourced) ice flows, which vied for superiority (and therefore overran each other) during the latter stages of the Late Devensian. Huddart and Glasser (2002) in their massive book "Quaternary of Northern England" refer to this paper several times, particularly in relation to the sequence of the brown and grey till units.

In this paper, by reference to BS 5930: 1981, the use of engineering descriptions of soils is introduced as a way to consistently describe glacial materials. However, this has now been superseded by BS 5930: 1999.
3.3.5 PAPER B1 TILLS FRAMEWORK

by B.G. Clarke, E. Aflaki and D.B. Hughes

This paper is based on research done in North East England and highlights the variability of glacial tills. The glacial and depositional environment in which tills are formed is discussed in relation to their physical and geotechnical properties. The Candidate contributed the description of the glacial geology and some of the geotechnical data on which the paper was based.

3.3.6 PAPER B2 GLACIAL HISTORY

by D.A. Teasdale and D.B. Hughes

As the title suggests this is a brief account of the glacial history of north-east England. The paper was written almost entirely by D.A. Teasdale, although some of the information contained therein was taken from Hughes et al (1998) (PAPER A4 GLACIAL SUCCESSION). The paper is cited in Huddart and Glasser (2002) and Clark (2000-2001).

3.3.7 PAPER B3 TILLS IN EARTHWORKS

"Characteristic Parameters of Tills in Relation to Earthworks" (2002).
by B.G. Clarke, D.B. Hughes and S. Hashemi

The glacial geology and tills properties for North East England and Ireland (especially the Dublin area) are compared in relation to their use in earthworks and national roadworks specifications. This paper was written almost entirely by B.G. Clarke, but the Candidate contributed geotechnical data and information on glacial geology.
3.3.8 PAPER B4 NETDATA

"NETDATA — a relational database for the geotechnical properties of Northern England glacial tills" (2003?),
by S. Hashemi, D.B. Hughes and B.G. Clarke

This paper has been submitted to the journal Geotechnical and Geological Engineering, and is currently going through the review procedure. It describes a relational database which has been constructed to analyse ground investigations and soil mechanics test data for the glacial deposits of Northern England. The Candidate has contributed all of this data from his employment in the opencast coal industry. In the paper he contributed most of the "Introduction" and the sections on "Source of Data" and "Glacial Geology of the Northern Counties".

3.3.9 PAPER C6 DERWENT—TYNE CONFLUENCE

"Ground investigations and foundations in deep alluvial deposits near the Derwent-Tyne confluence (1986),
by D.B. Hughes

This paper describes ground investigations and foundation problems at Swalwell, where NCB/OE had a large coal disposal facility. The conditions encountered included made ground overlying glaciolacustrine and glaciofluvial deposits, with tills and bedrock down at 32 m to 38 m below surface level. Two new structures were to be constructed. The first was a large coal storage bunker which was founded on a shallow raft, and allowed to settle. The second was an elevated rail loading hopper (small coals plant) for which piled foundations were chosen. The paper describes the ground conditions, settlement monitoring and analysis, and pile installation and testing associated with these structures.

3.3.10 PAPER C14 SPOIL MOUNDS — DESIGN & CONSTRUCTION

"Design and construction of spoil mounds" (1993),
by D.A. Blythe, D.B. Hughes and B.G. Clarke
In 1990, geotechnical staff at BCO and at Newcastle University began a programme of collaborative research into the engineering geology and geotechnical properties of the glacial deposits, especially those found in Northern England. BCO's interest was particularly related to spoil mound and slope failures. This paper was the first publication which resulted from that joint research and describes two spoil mounds for which adequate ground investigation data was available for analyses, namely Acklington Extension and Colliersdean.

3.3.11 PAPER C17 NORTHERN TILL

"Classification and strength of Northumberland Till" (1994).
by T.L. Robertson, B.G. Clarke and D.B. Hughes

and PAPER C18 NORTHERN TILL DISCUSSION

"Classification and strength of Northumberland Till – reply to discussion by R.D. Boyd" (1995)
by T.L. Robertson, B.G. Clarke and D.B. Hughes

Since appearing in 'Ground Engineering' in 1994, this paper has had considerable impact, and has been cited several times in subsequent publications relating to UK glacial geology and glacial engineering geology/geotechnical parameters. The paper summarises the results from the compilation of a simple spreadsheet database and the analysis of geotechnical parameters for glacial deposits as sampled and supplied by BCO (the Candidate) from Northumberland opencast coal sites. The results are expressed as means and ranges for the various horizons (units) in the glacial succession. This paper is also a result of the research collaboration between BCO and Newcastle University.

The discussion by R.D. Boyd included a question about the moisture condition value (MCV) test, which is related to the use of glacial tills in highway earthworks construction. Compaction of fills is seldom carried out at opencast sites in Northern England, so the MCV test is rarely performed. The authors were able to express additional views on undrained shear strengths and glacial geology/geomorphology terminology.
3.4 Coal Measures

There are four papers included in this section, which are as follows:

- PAPER A5 FAULTING - UK
- PAPER A7 ST. AIDANS
- PAPER A8 FAULTING - N. E. ENGLAND
- PAPER C8 FAULTING - BUCKHEAD

The common theme to all these papers is bedrock (Coal Measures) faulting. PAPER A8 gives five case histories of slope failures due to faulting, and particularly relates slope failure potential to excavation methods and cut orientations. PAPER A5 also relates working methods and cut orientations to potential fault related slope failures. PAPER C8 is a detailed account of excavations through the Wigglesworth Fault zone at Buckhead site, and shows how ground movement monitoring was used to ensure stability. PAPER A7 is a detailed account of the major slope failure at St. Aidans site, which occurred along a zone of minor faulting that ran sub-parallel with the endwall of the excavation. However, ground strains from underground mining and continuously recharged hydrostatic pressures were also important factors at St. Aidans.

3.4.1 PAPER A5 FAULTING - UK

by D.B. Hughes

This is a very short paper which was presented to the 1998 "Young Geotechnical Engineers Conference" in Newcastle, to introduce opencast coal mining operations to the conference delegates prior to the Candidate leading a site visit to Herrington opencast site.

Table 1 of the paper shows the degree of tectonic disturbance in the UK coalfields, following work by Price et al (1967), but with input from the Candidate's own experience. The effect of faulting on the choice of cut orientations is explained, and case histories are referred to (Hughes and Leigh, 1985 – PAPER C2; Hughes and McLean, 1986 – PAPER C8; Hughes and Norbury, 1996 – PAPER A1).
This paper deals with one particular slope failure located adjacent to the River Aire in West Yorkshire. A comprehensive description of the site geology and strata succession is given, together with a detailed account of past underground mining and groundwater conditions. The main focus of the paper is the discussion of evidence about the size, geometry and causes of this massive slope failure. In particular the contributions from previous underground mining subsidence strains and from high groundwater pressures are emphasised. A detailed back-analysis was carried out which, together with photographic evidence, supported the Candidate's model of the failure.

Following the River Aire slope failure at St. Aidans in March 1988, the directors of BCO set up an internal inquiry panel of senior staff (who had not had any previous involvement in the St. Aidans Extension project) and the Candidate was included on this panel as the geotechnical expert. A draft confidential report relating to the probable causes of the slope failure was completed by the panel and the Candidate was the major contributor to this document (BCO, 1988). The BCO directors expressly forbade any publication or divulgence of the technical details of this slope failure at that time. However, following the UK coal industry re-privatisation in 1994, ownership of the site passed to RJB Mining (UK) Ltd (now UK Mining Ltd), and in 1999 they were asked for permission to publish this paper, which was subsequently granted.

The thesis by Scoble (1981 – reporting Walton's earlier work), the technical reports submitted to the Aberfan Tribunal (1969 – especially by Bishop), the papers by Forrester and Whittaker (1976), Walton and Taylor (1977) and Siddle et al (1985) all gave examples of how tensile strains due to underground coal mining had contributed significantly to instability in spoil mounds and in opencast excavations. With the exception of Siddle et al (1985) all of these publications pre-date the commencement of the St. Aidans Extension contract (1981) and
therefore the potential effects of these strains adjacent to the River Aire should have been known to the geotechnical staff who were involved in the project.

Case studies provided by Leigh et al (1980), Scoble (1981), Hughes and Leigh (1985 – PAPER C2) and Hughes and McLean (1986 – PAPER C8) all show the importance of locating zones or planes of faulting, even where the throws are fairly small as was the case at St. Aidans.


Two other key references are the accounts of investigations into the causes of the River Aire slope failure by Davies (1988 – for the HSE) and Farmer (1996 – I.W. Farmer Associates were retained by Leeds City Council (the MPA) to report to them because the planning conditions and the ownership boundaries had been breached as a result of the failure). Both of these authors stated that the lowest failure surface was through the Barnsley Rider seatearth. However, the Candidate's research proved that the basal failure surface was through the Barnsley Top Softs seatearth, both from photographic evidence and from back analysis of the failure itself.

This massive slope failure at St. Aidans led to major improvements in the statutory requirements for geotechnical engineering inputs in the UK opencast coal mining industry (FCEC, 1989; and Health and Safety Commission, 1999).

This paper was adjudged "Honourable Mention" (i.e. runner-up) in the 2001 R.M. Quigley Awards of the Canadian Geotechnical Society for the best paper published in the Canadian Geotechnical Journal for that year.

In the academic year 2001/2002, 4th year Civil and Environmental Engineering students at the University of Alberta, Calgary (Canada) used the St. Aidans paper as the basis of a major project and corresponded by e-mail because of the difficulty in obtaining some of the publications referenced therein. The Candidate supplied photocopies of these.
3.4.3 PAPER A8 FAULTING – N.E. ENGLAND

"Faulting and slope failures in surface coal mining – some examples from North East England" (2002)
by D.B. Hughes and B.G. Clarke

The purpose of this paper was to put forward the Candidate's own guidance on how to deal with faulting in large opencast excavations, by referring to some of his own slope failure case records from North East England. The paper contains several topics, including regional geology, ground investigations, faulting characteristics, opencast working methods, faulting induced slope failures, and the case histories themselves.

The cited references for the regional geology are the main standard texts for NE England, being Taylor et al (1971), Johnson (1995), Scrutton (1995) and Wam (1995). Figure 1 in the paper shows that the regional dip of the strata is eastwards, and that the main faults are mostly aligned approximately west-east. Table 1 shows the geological history and generalised downward succession. The Ninety Fathom – Stublick Fault system, which approximately follows the Tyne Valley, divides the Northumberland Basin (Northumberland Coalfield) from the Alston Block (Durham Coalfield).

The ground investigations section is a brief summary taken from Hughes and Blythe (1987 – PAPER C9). Faulting characteristics were mainly taken from the Candidate's experience, with reference also to Williamson (1967) and Knight (1990). Information on shear strengths of weak horizons and fault gouge has been taken from Stimpson and Walton (1970), Salehy et al (1977), Spicer (1981), Denby (1983), Robertson and Rodger (1990) and Jameson (1995).

The illustrations and descriptions of opencast working methods are again from the Candidate's own knowledge, and include references to Hughes and Leigh (1985 – PAPER C2) and Hughes and Clarke (2001 – PAPER A7). Reference is also made to Walton and Atkinson (1978) and Brook and Thornley (1985). The section on faulting induced slope failures is also from the Candidate's own work, some of it original to this paper, and some from Hughes and Leigh (1985). There is also reference to Hoek and Bray (1981).
The case histories are all the Candidate's own, and with the exception of Buckhead (Hughes and McLean, 1986 – PAPER C8) and Plenmeller (Hughes and Norbury, 1996 – PAPER A1) they are all new to the published geotechnical literature. A limit equilibrium analysis has been carried out for the Buckhead failure since 1986, and the Plenmeller failure is discussed in much more detail than in 1996. The Oasys: SLOPE (1997) program was used to carry out the actual stability analyses given in the paper.

The discussion and conclusions in the paper particularly relate to choosing the correct method of working in relation to the fault zone structures and geometry.

This paper was only published in December 2002, and therefore its impact is, as yet, unknown.

3.4.4 PAPER C8 FAULTING – BUCKHEAD

"Stability monitoring of ground movements in faulted Coal Measures and Glacial Drift in Northern England (1986),

by D.B. Hughes and A.A. McLean

Buckhead site in County Durham was a particularly difficult site to work due to its high density of faulting, steep bedding dips, and a thick cover of glacial drift. The Wigglesworth Fault is the main fault in the area, and ran through the northern part of the site, at one location running beneath and sub-parallel with Esperley Lane. This paper describes the ground movement monitoring carried out adjacent to Esperley Lane, and the steps taken to ensure ground stability as the excavation works passed through this zone.

3.5 Opencast Backfill and Groundwater

Seven of the following eight papers were produced before the Candidate registered to read for this higher degree. The research was carried out over a considerable time-span during his direct employment in opencast coal mining.

PAPER A9 RECLAMATION
PAPER C1 HORSLEY 1
PAPER C3 DEWATERING
PAPER A9 mainly discusses the incorporation of colliery and quarry tips (and other landfills) within opencast backfills as a way of reclaiming derelict land. PAPERS C1 and C15 are accounts of backfill settlement monitoring at Horsley site which was a joint research project between BCO and the Building Research Establishment. PAPERS C4, C10, C11 and C12 (in chronological order) are accounts of backfill settlement monitoring at four sites in Northumberland. The theme of all the above six papers is the rates of settlement of the surface and within the body of the backfilling, and the effect of other factors such as method of backfill placement, placing and removal of surcharge material, and changes in groundwater levels. PAPER C3 DEWATERING is the only publication from this entire submission which is specifically about groundwater, although groundwater is a major factor in many of the other papers submitted (especially the papers listed in this SECTION 3.5 (above) and PAPER A7 ST. AIDANS (Hughes and Clarke, 2001)).

3.5.1 PAPER A9 RECLAMATION

"Surface coal mining and the reclamation of tips, landfills and quarries – some geotechnical case studies from Northern England" (2003)

by D.B. Hughes and B.G. Clarke

This paper describes public opposition to opencast mining (Benyon et al, 2000) and sets out to illustrate the potential benefits where reclamation of derelict land can be included in a project. Six case histories, from the Candidate's own experience and records, are described where reclamation has been (or in one case could be) incorporated into the works. These case histories involve both glacial and Coal Measures strata, and slope or spoil mound stability is a major factor in four cases. Detailed back-analyses are given for three of the sites.

The topic is introduced using Figure 2 in the paper which shows a relationship between underground and surface coal mining, quarrying, tips and spoil mounds, landfills and
contamination. This is followed by an introduction to the legislation, quasi-statutory codes, and industry guidance, e.g. National Coal Board (1968 and 1970), Health and Safety Executive (1972), FCEC (1982 and 1989), Institution of Civil Engineers (1993) and British Standards Institution (2001).


The conclusions of the paper highlight the positive value of opencast coal projects especially in facilitating the clean-up and remediation of derelict land in former coal mining areas.

This paper was published very recently in the International Journal of Surface Mining Reclamation and Environment, Volume 2 for 2003. Therefore its impact is, as yet, unknown.

3.5.2 PAPER C1 HORSLEY 1

by J.A. Charles, D.B. Hughes and D. Burford

and PAPER C15 HORSLEY 2

by J.A. Charles, D. Burford and D.B. Hughes
In 1973, at Horsley in Northumberland, the BRE and NCB/OE began monitoring settlement on five traverses at various locations corresponding to different backfilling and loading conditions during restoration of the site. Of particular interest was the collapse settlement which was induced by the rising groundwater levels as the water table was re-establishing, and the heave on unloading of backfilled ground which had been surcharged by a large overburden mound after the placement of the backfill. The Candidate was responsible for managing and supervising all site works (land access, ground surveys and instrument (extensometer) readings) and wrote the sections of the papers which described the history of the site workings and restoration. These papers have been cited many times in opencast mining and earthworks publications.

3.5.3 PAPER C4 NORTHERN BACKFILL 1

"An investigation into groundwater recovery and backfill consolidation in British surface coal mines" (1985),
by R.N. Singh, S.M. Reed, B. Denby and D.B. Hughes

PAPER C10 NORTHERN BACKFILL 2
"Backfill settlement of restored strip mines – case histories" (1987),
by S.M. Reed, D.B. Hughes and R.N Singh

PAPER C11 NORTHERN BACKFILL 3
"Research into the stability of restored opencast coal mines in the North East of England (1987),
by R.N. Singh, S.M. Reed and D.B. Hughes

PAPER C12 NORTHERN BACKFILL 4
"Long-term settlement of opencast mine backfills – case studies from the North East of England" (1990),
by S.M. Reed and D.B. Hughes

These four papers relate to backfill settlement monitoring at four restored sites in North East England, namely Radcliffe, Coldrife, Radar and Sisters, which were worked during the period late 1950s to late 1970s. The Candidate set up and supervised the monitoring at Radcliffe,
Coldrife and Sisters, whereas monitoring at Radar started earlier but was still supervised by the Candidate. The interim results were published in PAPERS C4, C10 and C11 (in chronological order) and PAPER C12 was the final assessment before backfill level monitoring at all these sites was terminated. All of these papers were mainly written by S.M. Reed as part of his PhD project (at Nottingham University – 1983 to 1986), but the Candidate was responsible for all the survey data collection, site access and maintenance. These papers have been cited many times in opencast mining/geotechnical publications.

3.5.4 PAPER C3 DEWATERING

"Analysis of an advanced dewatering scheme at an opencast coal site in Northumberland" (1985),
by S.T. Minett, D.A. Blythe, G.D. Hallam and D.B. Hughes

This paper describes an advance dewatering scheme at East Chevington site in Northumberland, which involved a single deep well drilled into old workings in the pavement seam in the north east corner of the site. An estimate was made of the total quantity of groundwater which occurred within the excavation area and which needed to be pumped out, together with the probable recharge. The main author, S.T. Minett, was a PhD student at Newcastle University, and the Candidate was his industrial supervisor (NERC – CASE Studentship with NCB/OE) (Minett, 1987).
4. CONCLUSIONS

Collectively the Candidate's papers illustrate most of the applications of geotechnical engineering which occur in UK opencast coal mining situations. Slope failure investigation and analysis (including prevention and remedial works) are the most common and important applications of geotechnical engineering in opencast mining, and all the main papers (List A) refer to this, with detailed back-analyses included in several cases. Two of the main research aspects and linkages have been the evidence for the strata succession for the glacial deposits, and the faulting and related slope failure models for the Coal Measures bedrock, and therefore this work has led to two principal achievements or generic statements:

(i) An improved understanding of the distribution and depositional processes for the glacial materials in Northern England, and some of the effects that these processes can have on their geotechnical properties.

(ii) A demonstration of the influence that faulting in Coal Measure bedrock can have upon the stability of excavated slopes, and on the design of opencast operations.

The conclusions for each paper are given in the papers themselves and can be read in the APPENDICES. The intention here is to briefly summarise the impact and usefulness of these publications, and what has been added to the knowledge of geotechnical engineering in connection with opencast coal mining operations, particularly in relation to the glacial deposits and Coal Measures bedrock of Northern England.

The same themes or topics (sub-headings) as used in the previous Section 3 to demonstrate linkages and groupings of the publications are used again here to illustrate what has been achieved by the Candidate's research.

4.1 General Opencast Geotechnical

The main work under this topic is PAPER A1 PLENMELLER (Q.J.E.G.) (i.e. Hughes and Norbury, 1996) and is unique in that it is a detailed account of the contribution from geotechnical engineering in the whole life-span of a complex opencast coal project, from initial planning and prospecting to final restoration.
All of the papers on this topic were written for the purpose of presentation at meetings of learned societies (Institute of Quarrying, Institution of Civil Engineers, Geological Society etc.). The fact that the Candidate was asked to present these papers on six separate occasions in the 1980s and 1990s shows the interest in UK opencast coal mining that existed within the geotechnical and engineering geology professions at that time. This was primarily due to the introduction of geotechnical codes of practice (FCEC, 1982 and FCEC, 1989) and new quarries legislation (Health and Safety Commission, 1999).

4.2 Ground Investigations

Standards of geotechnical investigations in the UK opencast coal industry were fairly poor or even non-existent during the 1960s and 1970s (see Section 2, and PAPER A7 ST. AIDANS (Hughes and Clarke, 2001)), and very much lagged behind the standards then found in the UK civil engineering industry. The three papers included under this topic show the huge improvements which resulted from the appointments of Regional Geotechnical Engineers in the late 1970s and the introduction of geotechnical codes of practice in the 1980s. In particular, the implementation of cable percussion boring and trial pitting in the superficial deposits (mainly glacial materials in Northern England) provided samples for geotechnical laboratory testing in connection with spoil mound design, following the introduction of the 'spoil mounds' code (FCEC, 1982). Also, a general increase in geotechnical drilling (in both superficiais and bedrock) followed the introduction of the 'excavations' code (FCEC, 1989).

All of the papers on this topic were published prior to 1996 (see List C and Appendix C) and therefore are not part of the Candidate's research at Newcastle University. However, they do complement the overall theme of geotechnical applications in opencast coal mining.

4.3 Glacial Deposits

The exposures of glacial deposits studied at opencast sites (Hughes et al, 1998; Hughes and Teasdale, 1999 (PAPERS A4 and A6)) have shown the complexity and variability of the depositional succession in Northern England. Many problems of instability, both of excavated slopes and spoil mounds, result because of this complexity (Hughes and Clarke, 1998; Blythe et al, 1993 (PAPERS A3 and C14)). Construction and foundation engineering
problems have also been experienced (Hughes, 1986; Hughes, 1996 (PAPERS C6 and A21)). Several papers have analysed the geotechnical parameters (particularly strength and classification) of these glacial materials and have attempted to define a simplified model for the succession of 3 or 4 units (Robertson et al, 1994; Clarke et al, 1997; Clarke et al, 2002; and Hashemi et al, 2003? (PAPERS C17, B1, B3 and B4)).

The publication of all of these papers has greatly added to the available data and information on the engineering geology and geotechnical parameters for these Northern England glacial deposits. This information has been useful to the civil engineering industry as well as the surface mining and quarrying industries (Bell, 2002; Davis and Horswill, 2002). Also, these papers have had a significant impact in the field of Quaternary geology research (Forster et al, 1999; Huddart and Glasser, 2002).

A general conclusion for all of this research, so far, is that the geological continuity and the physical properties of the materials in the glacial succession of Northern England are exceptionally variable both laterally and vertically. Hence, even a very comprehensive geotechnical database will not preclude the use of direct investigations (i.e. sampling and testing from boreholes and trial-pits) for any proposed civil or mining engineering works. The information from such a database should, however, enable the right investigation procedures to be chosen, and thus obtain the best geotechnical data to input into the project design.

4.4 Coal Measures

The key factor which has been brought out in the four papers linked under this topic is the significance of faulting. Three of these papers (Hughes and McLean, 1986; Hughes and Clarke, 2001; Hughes and Clarke, 2002 – i.e. PAPERS C8, A7 and A8) are instability case studies related to faulting. The importance of accurately locating all fault zones during the coal prospecting and geotechnical investigation stages is paramount, so that the most favourable excavation geometry (cuts) and sequence of working can be selected, and thus avoid instability (as far as possible).

The paper about the River Aire slope failure at St. Aidans (Hughes and Clarke, 2001 – PAPER A7) includes a very detailed account of the many factors which contributed to this
major instability including faulting, underground mining (especially subsidence and tensile strains), geometry and timing of the endwall exposure, groundwater pressures and recharge (from the River Aire). That this paper was nominated for a prestigious award by a major international geotechnical journal (i.e. won Honourable Mention for the R.M. Quigley Award, 2001, by the Canadian Geotechnical Journal/Canadian Geotechnical Society) emphasises the quality and impact of this paper.

4.5 Opencast Backfill, and Groundwater

Anti-opencast coal mining views are firmly established within the UK Mineral Planning Authorities and apparently within the general public as well (Beynon et al, 2000). However, the case studies included in Hughes and Clarke, 2003 (PAPER A9 RECLAMATION) demonstrate that there is still an important role for opencast coal projects in facilitating the reclamation of coal mining related derelict land in Northern England.

Although published prior to 1996 (List C and Appendix C), the six papers on opencast backfill settlements (PAPERS C1, C4, C10, C11, C12, C15) contain all the research data produced on this topic for Northern England since that published by Kilkenny, 1968. This work made a major contribution to the 'state of the art review' by SWK in 1991.

Only the paper by Minett et al, 1985 (PAPER C3 DEWATERING) is specifically about the topic of groundwater management at an opencast coal site. However, groundwater features very significantly in all the papers about opencast backfill settlement where water table recovery correlates with accelerated settlement (i.e. collapse settlement?). The devastating effect of high hydrostatic pressures and groundwater recharge is illustrated by Hughes and Clarke (2001) for the massive slope failure at St. Aidans site (PAPER A7).

4.6 Further Research — Suggestions and Opportunities

With the demise of British Coal Opencast in 1994 and the very much reduced size of the reprivatised opencast mining industry both in Northern England and the UK as a whole, there are now far fewer opportunities to carry out research in connection with large opencast excavations (see Section 2). Therefore this collection of geotechnical papers provides a
unique record which is unlikely ever to be replicated. This work has, however, pointed to a few areas where further research could still be carried out.

Large opencast projects are still in progress at Maiden’s Hall and Blagdon in Northumberland, and there are a few smaller projects ongoing in Cumbria, Tyne and Wear, and County Durham. Descriptions of fresh exposures have given an insight into the deposition of glacial materials which sometimes challenge existing theories of the processes involved. A better understanding of these processes will assist geotechnical engineers in choosing the most appropriate methods for their ground investigations, and in designing mining operations and other earthwork and foundation structures. Research into the glacial geology of Northumberland is currently ongoing at Durham University (D.A. Teasdale – see ACKNOWLEDGEMENTS).

Further work is desirable to extend the NETDATA database for the geotechnical properties of glacial deposits (Hashemi, 2002 – PAPER B4) to include additional BCO data from County Durham, and then add data which have been offered or could be available from several civil engineering companies and organisations. This would probably also allow the extending of the existing geographical area from just Northern England, as at present, to include the whole of the UK.

Exposures at opencast coal sites have shown the effects that earlier underground coal workings (especially room and pillar workings) have upon the ground surface. The legacy of mine workings and the impact that they may have upon future surface developments could be explored from the records (especially photographs) and from historic mining subsidence records held in various archives.

4.7 Final Conclusions

It can be seen that the topics described in this Critical Appraisal, and in the papers included in full in the Appendices, cover a wide range of engineering geology and geotechnical applications. These papers illustrate the main geotechnical engineering applications in UK opencast coal mining, including ground investigations, design and analysis, and the execution and supervision of the works. The publication of the many case studies which have been included in the papers represents an important feedback aspect in a technical area where there
have been comparatively few geotechnical papers, especially relating specifically to Northern England. Putting these case studies of geotechnical failures and applications into the public domain has provided many examples and much information which can be used by others and may help to improve the practice of geotechnical engineering as applied to opencast coal mining in other locations.

If all the Candidate's publications are taken into account (Appendices A, B and C) then this collection of papers represents virtually the whole of the geotechnical literature on opencast mining in Northern England, and a very significant proportion of the publications for the United Kingdom as a whole.
5. ACKNOWLEDGEMENTS

In preparing and presenting the publications which constitute this submission for the Degree of Doctor of Philosophy at the University of Newcastle upon Tyne, the Candidate is deeply indebted and very grateful to the following.

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Finally, the greatest thank you to Hazel for her encouragement and support throughout this period.
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(Note: this list includes all the references contained in this Critical Appraisal and in the publications given in Appendix A)


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APPENDIX A

Main and sole authored papers – from 1996 onwards

PAPER A1  PLENMELLER (Q.J.E.G.)
PAPER A2  ENGINEER'S VIEW
PAPER A3  SPOIL MOUNDS – NORTHERN ENGLAND
PAPER A4  GLACIAL SUCCESSION
PAPER A5  FAULTING – UK
PAPER A6  HERRINGTON
PAPER A7  ST. AIDANS
PAPER A8  FAULTING – N.E. ENGLAND
PAPER A9  RECLAMATION
Hughes, D.B. and Norbury, D.R. 1996

Plenmeller Opencast Coal Site – a geotechnical and planning case study.

Plenmeller opencast coal site: a geotechnical and planning case study

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\textsuperscript{2}Soil Mechanics Ltd, Glossop House, Hogwood Lane, Finchampstead, Wokingham, Berks RG11 4QW

Abstract

Plenmeller is a remote upland opencast site in Northumberland designed to produce just over 2 million tonnes of coal during eight years of production. The complex ground conditions comprise thick peat and glacial deposits, overlying much faulted and steeply dipping Coal Measures strata. Previous underground workings, high groundwater levels and associated subsurface reservoirs of water are also present. In order to mine and export the coal off-site, extensive infrastructure works were necessary including impounding embankments for lagoons, public road diversions, an overland conveyor with a tunnel and major river crossing, coal screening and crushing plant and a rapid loading bunker with associated railway sidings.

A lengthy planning history included a public inquiry and a high court hearing before coal production commenced in August 1991. Imposed planning constraints required modifications to the development, additional construction works and restoration measures. The combination of the site location, infrastructure requirements and planning constraints gave rise to the need for a wide range of ancillary civil engineering works; this was one of the most extensive programmes in connection with an opencast project in the UK. These engineering works in turn required a substantial geotechnical input. This paper presents a general account of the extensive ground investigations and construction works carried out at Plenmeller, and briefly discusses some geotechnical aspects of the site operations and the construction works.

Keywords: case studies, coal mines, planning, site investigation, slope stability

Introduction

Plenmeller Opencast Coal Site is in southwest Northumberland, just south of Hadrian's Wall (Fig. 1) and close to the railway town of Haltwhistle. The site lies partly within the designated North Pennines Area of Outstanding Natural Beauty and is upland moorland which includes peat bog, heather moor, rough pasture, and enclosed improved pasture, and forms part of Plenmelland and Kingswood Commons. There has been previous mining activity as evidenced by pitfallen land, abandoned shafts, drifts and spoil heaps. The land was mainly used for sheep grazing and grouse shooting.

The site is an east--west depression within the catchments of the eastward flowing Kingswood Burn and westward flowing Level Sike (Fig. 2). The Blackcleugh Burn and the Willimontsyke Burn rise on the northern rim of the depression and flow north. Higher ground to the south prevents any drainage in that direction. Average annual rainfall is about 800 mm. Over most of the site the ground slopes range from 1 in 10 to 1 in 30, but gentler slopes of 1 in 50 to 1 in 70 are found across areas of peat bog. Steeper slopes up to 1 in 3 occur along the banks of the Kingswood Burn and the Level Sike.

The layout of the site is shown in Fig. 3, and an aerial view at an early stage of the mining works as Fig. 4. To develop this remote site, and to meet the planning conditions described below, extensive infrastructure works were required; these included a highway diversion, a system of lagoons and settling ponds, peat storage lagoons, coal crusher and screens and a conveyor, which involved a tunnel and a major river crossing, to the specially constructed off site railhead. The coal has a generally high calorific value, and is primarily bought by the power generators. Preliminary construction works for the coal processing and transportation facilities commenced in August 1989, and the main coaling contract followed in March 1991. The first coal was produced in August 1991. The stripped topsoils, peats and overburden all had to be separately stored for progressive restoration throughout the works, due to be completed in 2001, about 2.5 years after the completion of coaling. Some site statistics are given in Table 1.

TABLE 1. Outline statistics of the site

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal tonnage in contract</td>
<td>2,034,514 tonnes</td>
</tr>
<tr>
<td>Overburden to coal ratio</td>
<td>19.7 to 1</td>
</tr>
<tr>
<td>Site area</td>
<td>458 hectares</td>
</tr>
<tr>
<td>Excavation area</td>
<td>190 hectares</td>
</tr>
<tr>
<td>Maximum volume of spoil stored above ground</td>
<td>8,000,000 m(^3)</td>
</tr>
<tr>
<td>Expected coaling life of site</td>
<td>8 years</td>
</tr>
<tr>
<td>Rate of coal production (average)</td>
<td>5000 tonnes/week</td>
</tr>
<tr>
<td>Tender price for coaling contract</td>
<td>£35.6 million</td>
</tr>
</tbody>
</table>

Statutory planning

An application to work the Plenmeller site was made by British Coal Opencast (BCO) to the Secretary of State for Energy in December 1982 under the Opencast Coal Act 1958, but withdrawn in February 1984 as a consequence of new legislation. A new application was...
made to Northumberland County Council (the Mineral Planning Authority) in March 1985 under the Town and Country Planning Act 1971, and a public inquiry was held during June and July 1986. In January 1987 the Inspector reported to the Secretary of State for the Environment in favour of the project, and authorization was notified in June 1987, with a series of detailed planning conditions attached. However, the Mineral Planning Authority (MPA) appealed to the High Court against the decision. This hearing did not take place until February 1989 but confirmed the authorization. A brief summary of the imposed planning conditions which impact on the geotechnical aspects of the Plenmeller project is given in Table 2. The implementation of these conditions required close and continual co-operation and communication between the MPA and BCO.

Ground investigations

Ground investigations were carried out to prospect for coal, to enable design of the opencast mining operation (including cut slopes, spoil mounds and groundwater control) and for the infrastructure works (including coal processing, coal transportation and loading facilities, lagoons and highway diversions). These investigation activities are described briefly below and summarized in Table 3, with the timing of these activities being indicated in Table 4.

Coal prospecting drilling was carried out mainly between 1973 and 1981, with some further drilling in 1989. Around 2400 vertical boreholes were sunk, mostly by openhole air-flush rotary drilling techniques. Slimline geophysical logging (long spacing density, high resolution density and natural gamma) was applied down a
Fig. 2. Site topography.

Fig. 3. Site layout and operations.
The site in 1993 at an early stage in the works looking west. The diverted C322 highway dividing Areas A and B can be seen towards the far end of the site. (Courtesy AirFotos Ltd, Newcastle-upon-Tyne.)

### TABLE 2. Summary of planning conditions

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<table>
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<tbody>
<tr>
<td><strong>1. Maximum heights for the storage mounds limited:</strong></td>
<td></td>
</tr>
<tr>
<td>Topsoil and peat (not retained by clay bunds)</td>
<td>2 m</td>
</tr>
<tr>
<td>Baffle banks, topsoil, topsoil making material</td>
<td>6 m</td>
</tr>
<tr>
<td>Subsoil (all grades)</td>
<td>10–12 m</td>
</tr>
<tr>
<td>Peat (retained by clay and rock bunds)</td>
<td>7 m</td>
</tr>
<tr>
<td>Peat in partially backfilled areas (below ground level)</td>
<td>10 m</td>
</tr>
<tr>
<td>Clay and rock bunds</td>
<td>8 m</td>
</tr>
<tr>
<td>Overburden</td>
<td>30 m</td>
</tr>
</tbody>
</table>

The location of these mounds to be agreed by the MPA. Their design to be by the competent person appointed under Part 2 of the Code of Practice (Anon 1982). Base levels of all mounds to be agreed in advance.

| **2. An initial void to be formed in each of the coaling areas, with progressive excavation and backfilling of successive cuts. The batters of all excavations to be designed and supervised by the competent person appointed under Part 2 of the Code of Practice (Anon 1989).** |                        |

| **3. The C322 highway to be diverted so that coal could be removed from beneath the original route. These works to be completed within 18 months of the start of site operations.** |                        |

| **4. The site, including working cuts, to be kept free from standing water. All water from the site to pass through settlement ponds prior to discharge from the site. Details of all lagoons and water treatment to be agreed with the MPA and to be well maintained. The discharge of waste, oil or other pollutants not permitted. The MPA to agree any drainage diversion or protection works that might affect drainage onto or from adjoining land.** |                        |

| **5. All coal to be transferred within the site to a conveyor system for transport and despatch by rail; these facilities to be operational before coal production could commence. No coal allowed to leave the site by road.** |                        |

<p>| <strong>6. Progressive replacement of overburden and soil to be carried out following mineral extraction. A restoration plan to be agreed with the MPA, showing suitable contours and profiles to ensure the restored land be free from ponding and erosion, and to provide restoration of the original floral and faunal habitats. Environmental and restoration specialists to be appointed to supervise the spreading and seeding of subsoils, peats, and topsoils.</strong> |                        |</p>
<table>
<thead>
<tr>
<th>Activity</th>
<th>Purpose</th>
<th>Investigation method</th>
<th>Design information</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock slopes</td>
<td>Stability of excavated slopes</td>
<td>Prospecting boreholes (90% openhole, 10% cored); geotechnical coring; piezometers</td>
<td>Geological structure; bedding; faulting; joints and weak horizons; shear strengths; groundwater pressures; fracture state</td>
<td>Total prospecting investigation £2M. Prospecting holes used for both £100k. Specific geotechnical investigations £40k</td>
</tr>
<tr>
<td>Soil slopes</td>
<td>Stability of excavated slopes</td>
<td>Cable tool borings; trial pits; piezometers</td>
<td>Soil strengths; groundwater pressures; peat thicknesses; rockhead levels</td>
<td>£30k</td>
</tr>
<tr>
<td>Spoil mounds</td>
<td>Stability; failures of side slopes and through foundation strata</td>
<td>Cable tool borings; trial pits; rotary openhole boreholes; piezometers</td>
<td>Soil strengths; groundwater pressures; peat thicknesses</td>
<td>£10k</td>
</tr>
<tr>
<td>Crusher and screens</td>
<td>Foundations; stability and diggability of excavations; access roads and subgrades</td>
<td>Cable tool borings; trial pits; rotary openhole boreholes; piezometers</td>
<td>Soil strengths; compressibility; CBR; peat thicknesses; groundwater levels; rockhead levels</td>
<td>£10k</td>
</tr>
<tr>
<td>Conveyor</td>
<td>Foundations; restoration on removal of apparatus from grouse moor</td>
<td>Cable tool borings; peat probing; hand augering</td>
<td>Soil strengths; peat thicknesses; rockhead levels</td>
<td>£10k</td>
</tr>
<tr>
<td>Tunnel and shaft</td>
<td>Diggability; groundwater conditions' safety of historic garden wall</td>
<td>Rotary core drilling; portable air winch percussive boring; piezometers</td>
<td>Fracture state; rock strength; rockhead levels; groundwater levels</td>
<td>£15k including temporary access bridge</td>
</tr>
<tr>
<td>Bridge</td>
<td>Foundations; bank stability; scour protection</td>
<td>Cable tool borings from temporary bridge; piezometers; rotary cored boreholes</td>
<td>Rockhead levels; groundwater levels; soil strengths; compressibility</td>
<td>£15k</td>
</tr>
<tr>
<td>Railhead</td>
<td>Foundations; stability and settlement of embankment widening; road subgrades</td>
<td>Cable tool borings; trial pits; rotary cored and openhole boreholes; piezometers</td>
<td>Soil strengths; groundwater levels; rockhead levels; compressibility; CBR; underlying coal seams</td>
<td>£20k</td>
</tr>
<tr>
<td>Lagoons</td>
<td>Stability of side slopes; excavation groundwater conditions; stability and permeability of dam foundations</td>
<td>Cable tool borings; trial pits; piezometers</td>
<td>Soil strengths; groundwater pressures; soil and rock permeabilities</td>
<td>£20k</td>
</tr>
<tr>
<td>C322 highway diversion</td>
<td>Stability of embankments and cuttings; peat excavation; subgrade</td>
<td>Cable tool borings; trial pits; piezometers</td>
<td>Soil strengths; compressibility; CBR; groundwater levels</td>
<td>£20k</td>
</tr>
<tr>
<td>All activities</td>
<td>Effects of existing shafts, adits and underground workings</td>
<td>Walk over surveys; statutory undertakers records; archive searches; all available OS editions; Mining Records Office; aerial photographs</td>
<td>Index and classification tests; chemical tests; densities</td>
<td>Total specific geotechnical investigations £200k</td>
</tr>
<tr>
<td>---------------------------</td>
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<tr>
<td>COAL PROSPECTING</td>
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<tr>
<td>STATUTORY PLANNING</td>
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<tr>
<td>GEOTECHNICAL STUDIES</td>
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<tr>
<td>COALING CONTRACT</td>
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<tr>
<td>COAL PROCESSING AND TRANSPORT WORKS</td>
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<tr>
<td>LAGOONS</td>
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<tr>
<td>C333 HIGHWAY DIVERSION</td>
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<tr>
<td>RESTORATION</td>
<td></td>
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</tbody>
</table>

**TABLE 4. Bar chart of activities**

- **COAL PROSPECTING**: Mainly sythes drilling, some coring
  - **1973**: Coring
- **STATUTORY PLANNING**
  - Planning Applications: 1
  - Inquiry: High Court: 2
- **GEOTECHNICAL STUDIES**
  - Preliminary Site: 1
  - Main GI: 1
  - Bridgehead: 1
  - Curing: 1
  - Stability: 1
  - Design review: 1
  - Inspections and advice: 1
- **COALING CONTRACT**
  - Environmental, ecological and engineering investigations and design: 1
  - Contract documents: 1
  - Tenders: 1
  - MAIN COALING CONTRACT WORKS: 1
- **COAL PROCESSING AND TRANSPORT WORKS**
  - Preliminary design: 1
  - Tenders: 1
  - Construction: 1
- **LAGOONS**
  - Design: 1
  - Tenders: 1
  - Construction: 1
- **C333 HIGHWAY DIVERSION**
  - Design: 1
  - Tenders: 1
  - Construction: 1
- **RESTORATION**
  - Investigations and trial pits: 1
  - Actual restoration: 1
Fig. 5. Simplified geological structure.
100 boreholes sunk by cable-percussion techniques and 13 boreholes cored. The majority of the investigations were carried out in 1982/1983, but these were extended in 1989 to meet the requirements of a later Code of Practice (Anon 1989).

A further 45 cable percussion boreholes and ten rotary cored boreholes were put down for the coal processing, transportation and loading facilities.PEAT-probing, hand-augering and trial pitting were also carried out. The initial phase of these investigations was carried out in 1979/1980 at the rail loading bunker when rotary drilling was carried out to check for the presence of old underground workings. In 1982, the main phase of these ground investigations took place along the whole length of the conveyor route, from the loading facilities to the crushing and screening plant. The investigation involved construction of a temporary access bridge across the River South Tyne to allow boreholes at the pier positions and on the otherwise inaccessible south bank for the conveyor bridge and tunnel portal.

Extensive conventional field and laboratory testing was carried out to determine the relevant properties of the soils at the site; the range of testing included classification and index testing, strength and compressibility determinations. The material geotechnical properties of the bedrock were assessed from core samples obtained from fully cored boreholes of various diameters from 76 mm to 112 mm. Transparent plastic liners were used and high quality samples of weak zones such as joints and seathears were also obtained. These were tested using the Golder Richards apparatus (Hencher & Richards 1989); the more plastic horizons such as joints and seathears were also obtained. All monitoring installations recorded high water levels. Piezometers installed to the south.

The results of testing the weak zones indicated peak strengths ranging from about 20° up to about 40°, but with a typical average of about 30°; residual strengths were measured either at high strains in the laboratory or on samples that had already suffered displacements before sampling and gave results in the range of 10° to 20°.

Groundwater monitoring involved the installation of Casagrande type piezometers; thirteen piezometers were provided in the superficial deposits or at rockhead, and ten were placed into bedrock. All monitoring installations recorded high water levels. Piezometers installed on either side of the Stublick Fault recorded similar water levels, suggesting that the fault does not act as an aquiclude to the groundwater stored in the barren strata to the south.

**Geological succession and structure**

The succession is shown on Fig. 8. The majority of the site is covered by a layer of peat which varies in thickness from less than 0.5 m up to about 8 m, the thickest deposits occurring in the area to the east of the road crossing the site. In the deeper deposits the structure of the peat changes from a tough coarse brown fibrous crust near the surface to a very soft dark brown or black amorphous paste at the base of the deposit. Under the improved pasture land in some western parts of the site it comprises a black peaty topsoil.

Glacial deposits (usually between 1 m and 5 m thick) blanket virtually the whole of the site area beneath the peat. The glacial deposits are 10 m to 15 m thick in the northern part of the site and a buried glacial channel starts in the centre and extends to the eastern boundary of the site where the glacial materials are over 40 m thick. Very steep rockhead gradients occur as a result of this buried channel. The upper layer of glacial material under the deeper peat deposits is a soft or very soft blue grey clay, but elsewhere the top 3 m or so comprises a firm to stiff mottled clay with sandstone gravel or sandy pockets (possibly a hill-wash material). The glacial materials are mainly very stiff dark grey and dark brown sandy gravelly clays which frequently contain cobbles and boulders (Lodgement Till). Extensive bands or lenses of sandy gravels and cobbles also occur, and are especially prevalent in the buried channel infill.

In general the bedrock strata are Lower Coal Measures, comprising sandstones, siltstones, mudstones, coal seams and occasional seathears. The succession to be worked ranges from the Unnamed seam down to the base of the Low Main seam and includes twelve contractual seams. The Plenneller coalfield is an isolated faulted outlier bounded to the south by the Stublick Fault, which downthrows northwards by approximately 250 m, and associated splinter faults beyond which are the Millstone Grit series. The base of the Coal Measures is in the western, northern and eastern parts of the site, beyond which the Millstone Grits crop out again. The structure, generally steeply dipping with gradients rarely less than 1 in 5, divides the site into three separate excavation areas, referred to as Areas A (west and east) and B, as shown in Fig. 5.

Area A (west) is broadly half-basin shaped, complexly faulted and truncated by the Stublick Fault. A dominant NNW–SSE fault (Fault No 2) separates this area from Area A (east) in which the strata dip steeply, but uniformly, with a constant east–west strike into the Stublick Fault. Strata in Area B are folded into an east–west trending syncline closed at both ends by the inwardly plunging axis. Both ends are characterized by fan-shaped dip faulting, and the southern limb is restricted in its width by truncation against the Stublick Fault. The intensity of the faulting is such as to affect plant selection and slope stability as discussed in the section 'Site mining operations' below.

**Previous mining and groundwater**

Inspection of the Mining Records Office plans and documents together with prospecting drilling revealed...
The infrastructure investigations carried out have been in Areas A and B where estimated to be 160,000 m$^3$ and backfilled areas. Aquifers will continue to feed water into the excavations.

Glacial soils and bedrock are generally accessible and described; the design was generally simple in that the strata beyond. The approximate volumes of water stored removed as the opencasting operations progress, but the ground drainage system which collects water from the surrounding water bearing strata, provides some balancing storage and then feeds into the burns. The aquifers which feed into the site are generally located to the south and associated with the Stubick Fault and the upthrown strata beyond. The approximate volumes of water stored in Areas A and B were estimated to be 160,000 m$^3$ and 130,000 m$^3$ respectively. These old workings will be removed as the opencasting operations progress, but the aquifers will continue to feed water into the excavations and backfilled areas.

**Infrastructure works**

The infrastructure investigations carried out have been described; the design was generally simple in that the glacial soils and bedrock are generally accessible and comprised adequately competent materials for engineering. The organic soils were either removed from beneath heavy loadings or left in place for very light loads, as required under the planning conditions. The construction of these works proceeded according to schedule, at an overall cost of about £8 million. In addition to the works described, items not specifically mentioned include permanent site offices with associated provision of services, access roads, resurfacing and minor upgrading of local highways. The infrastructure works are summarized in Table 5; a more detailed description is given in Hughes & Norbury (1994).

The overland conveyor required 3 km of construction which, as a result of the planning constraints, had to be demountable at the end of the works. The structure was therefore anchored on 2 m long wooden piles, with the adjacent maintenance access road being of softwood logs and wire mesh. The conveyor also had to cross a minor road, an historic garden wall and the River South Tyne before reaching the railhead. The garden wall, now almost derelict, is of historical interest since it has an in-built central heating system to enable exotic fruits to be grown despite the harsh climate. Crossing this involved a 9 m deep vertical shaft with a rubber lined cascade chute, and a 42 m long by 2.59 m internal diameter tunnel. The tunnel was driven northwards from the shaft to an outlet portal on the south bank of the river beneath the garden wall with a clearance of only 3 m between softfill and foundations. Excavation in the sandstone was mainly by pneumatic tools to minimize vibration, but some drill and blast was permitted when the tunnel drive was distant from the wall foundations.

The final section of the conveyor is from the tunnel shaft, south of the unclassified Unthank Road, to the

<table>
<thead>
<tr>
<th>TABLE 5. Summary of infrastructure works</th>
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<tr>
<td><strong>Road diversion.</strong> The Haltwhistle to Bearsbridge road originally crossed the western part of the site but has been permanently diverted over a length of 2 km onto a new alignment, so that coal can be mined from beneath the original route. Construction on embankments up to 2 m high required excavation of the peat and underlying organic clay to a maximum depth of 4 m. The fill used was Coal Measures bedrock taken from the initial cuts.</td>
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<td><strong>Water treatment areas.</strong> There are six water treatment areas (WTA) around the perimeter of the site, with between one and three lagoons at each WTA, giving 15 lagoons in total (see Fig. 3). The majority were formed by excavating into the glacial deposits, but five lagoons were formed by impounding embankments constructed from glacial clays.</td>
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<td><strong>Coal transportation and loading facilities.</strong> A principal requirement of the planning permission was that no coal should leave the site by road and so all coal is transferred off site by conveyor. Coal is brought to the crushing and screening plant on the north western boundary of the site; the structures at this location include a weighbridge, 70 tonne reception hopper, 250 tonne per hour screening and crushing plant, workshop and amenity buildings. From here the coal is loaded onto a conveyor system which crosses moorland, woodland and grazing land. Obstacles to be crossed required a shaft, a tunnel and a twin-span bridge. The final section of conveyor rises steeply to the 20 m high connection into the 2000 tonne rapid loading bunker with now sidings equipped to load the trains automatically. These sections of the works are described more fully in the text. In the area of the crushing and screening plant the boreholes proved peat thicknesses up to 4 m. This peat was all removed from beneath the heavy structures and spread foundations constructed on the underlying glacial clays. The reception hopper was constructed some 7 m below original ground level, which involved excavating up to 2 m into mudstone. All excavations were battered rather than close supported, and only sump pumping was necessary to control ground and surface water. The ground conditions underlying the moorland section of the conveyor include 0.2 m to 0.7 m of peat or peaty topsoil overlying soft mottled clay and stiff glacial clay with bedrock (mudstone, siltstone or limestone) at depths varying from 3 m to at least 12 m. The majority of the conveyor route is at ground level, but elevated sections are supported on piers.</td>
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<tr>
<td><strong>Infrastructure works</strong></td>
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<td><strong>The old underground workings act as a large underground drainage system which collects water from the surrounding water bearing strata, provides some balancing storage and then feeds into the burns. The aquifers which feed into the site are generally located to the south and associated with the Stubick Fault and the upthrown strata beyond. The approximate volumes of water stored in Areas A and B were estimated to be 160,000 m$^3$ and 130,000 m$^3$ respectively. These old workings will be removed as the opencasting operations progress, but the aquifers will continue to feed water into the excavations and backfilled areas.</strong></td>
</tr>
<tr>
<td><strong>Records showed that a relatively small strip of Slag seam had been taken between 1860 and 1942 in six of the seams (see Fig. 8 later) to be mined here:</strong></td>
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<tr>
<td>- Upper Craig Nook</td>
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<td>- Lower Craig Nook</td>
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<td>- Threequarter</td>
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<td>- Welisyke</td>
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<td>- Slag</td>
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<td>- Low Main</td>
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| **The final section of the conveyor is from the tunnel shaft, south of the unclassified Unthank Road, to the**
rail loading bunker. The ground investigations for the tunnel and river bridge took place when the south bank of the River South Tyne supported dense commercial woodland and access was severely restricted. A temporary bridge had to be built to allow boreholes to be sunk at the locations of the proposed pier and abutment, and access to a single borehole position in the woodland with a lightweight portable air-winch percussion rig.

The south abutment of the bridge was founded on sandstone. The central pier foundations in the middle of the watercourse involved excavation within permanent steel sheet piling driven through some 3 m of river bed gravels and 3.5 m into the weathered sandstone and then in-filling with mass concrete. Under the north bank the rockhead level was such that the abutment foundation could only sensibly be constructed on the overlying dense river terrace gravels. The remainder of the elevated conveyor leading to the rail loading facilities was supported on piers founded on shallow spread footings. Figure 6 is a general view of the river bridge and railhead.

The ground conditions underlying the rapid loading bunker and the new railway siding are river terrace gravels overlying bedrock of the Upper Limestone group. The exposed excavation faces at a nearby sand and gravel quarry showed the terrace deposits to consist of clayey silty sand and gravel, with pockets and bands of laminated clay. Thicker deposits of clay occurred in the deeper parts of the excavation (up to 6 m deep), and some steeply inclined bands of clay were observed. Boulders up to 1.5 m diameter were also exposed.

Boreholes at the site of the bunker confirmed the similar nature of the ground conditions, and the Standard Penetration Test values indicated the terrace deposits to be at least dense. Rotary boreholes proved rockhead and the bedrock was recorded as sandstone, siltstones and mudstones with occasional limestones. Two coal seams, the Upper Little Limestone (0.15 m thickness) and the Lower Little Limestone (0.73 m thickness) were recorded within 45 in to 55 in of ground surface, but no cavities or old workings were encountered. Although this depth is greater than strictly necessary, it was preferred to actually prove the depth of the seams, which were known to have been worked. The bunker is supported on nine pairs of steel stanchions, each with different cross sectional areas.

Fig. 6. The bridge taking the conveyor across the River Tyne to the railhead loading bunker in the background.
and vertical loadings. Each stanchion base was sized to provide applied pressures that, in theory, eliminated differential settlements. Total settlements were also required to be small to avoid deflection of the rails passing beneath the bunker and close beside the bases.

Similar ground conditions were proved to underlie the whole length of the new rail siding. The construction of the siding necessitated the widening by 5 m of the existing 5 m high embankment over a distance of 1100 m. A particular British Rail requirement was that quarry material had to be imported (by rail from Shap, Cumbria) to create an inert firebreak between the existing embankment and the fill for the new siding. Minestone (colliery spoil material) from Seaham Colliery, Co Durham, was then trained in and compacted in layers to complete the embankment.

Site mining operations

Bulk excavation and coaling

The first bulk excavation and earthmoving operations were the removal and storage of seed rich topsoil, peat and subsoil in 1991. The storage mounds are mostly sited along the northern sides of the coaling areas with subsoil mounds also sited on the southwest side of Area B. The two main overburden storage mounds are both sited on the south side of their respective excavation areas, and limited to a maximum vertical height of 30 m by the planning conditions. The main peat storage area is located on the north side of Area A, where a network of 8 m high embankments (rock bunds) was constructed to retain this semi-liquid material.

Excavation in the initial cuts in Areas A and B (see Fig. 3) began simultaneously and progressed in the direction shown by the arrows. Overburden removal is performed by two Demag 185S hydraulic excavators, normally both working as backhoes, but the machine in Area B was initially deployed as a face shovel. These machines are equipped with 13 m³ buckets and are used to load a fleet of seven Cat 785 dumptrucks of 150 tonne capacity. Between about 30 and 40% of the rock overburden is blasted prior to excavation. The average overburden to coal ratio for the site is around 20 to 1, whilst the maximum depth of working in Area A is 97 m, and in Area B is 47 m. Dewatering is effected by pumping from sumps located at the lowest point of the current cut, and the water is pumped to the water treatment areas (lagoons) prior to discharge into the existing watercourses.

The size of the excavation plant is affected by the nature of the rock; faults with throws of several metres occur at close spacings and so the individual panels of recoverable coal are small. This is the norm for this site, and the disturbance increases even more near the Stublick Fault. In addition, the effects of a harsh and rapidly fluctuating climate in trying to work such an exposed site should not be underestimated; for instance keeping haul roads passable is difficult, not least during the winter months.

The coal is lifted by up to five smaller hydraulic shovels and loaded into articulated dump trucks which deliver the coal to the screening and crushing plant located in the north western part of the site.

Slope stability

Geotechnical Codes of Practice for spoil mound stability (Anon 1982) and excavated slope stability (Anon 1989) were introduced into the UK opencast coal mining industry in 1982 and 1989 respectively. The Geotechnical Stability Report with all its appendices (Hughes 1991) confirms compliance with these Codes of Practice by British Coal Opencast.

The overall works require substantial fill slopes, in spoil mounds, and cut slopes in superficial materials and bedrock. The properties of spoil from opencast coal sites are generally well known, as are the properties of materials such as the glacial tills. It is reasonably straightforward to investigate the superficial materials and carry out laboratory testing to determine appropriate cut face angles and suitability as a foundation material for high spoil mounds. This aspect of the investigation was carried out in accordance with the Codes of Practice. The expectation was that spoil mounds would be constructed with 1 vertical to 2 horizontal (1V:2H) side slopes, any underlying peat having first been removed, with the same slope being adopted for cuts in glacial till. Appropriate safety zones were to be left between such slopes. Although this was the expectation, the coaling contractor is responsible for slope stability and so is free to review the data and adjust the slopes actually built. As conditions were much as expected, these slopes have been formed at the anticipated inclinations. Nevertheless, occasional small failures occurred including one in which soils were pushed over the lip of the quarry, giving a significant requirement for clean up and an element of disruption.

It is, however, much more difficult to investigate a rock mass for cut slope stability assessments, particularly when the bedrock at the site is not accessible for inspection in advance of the works. Conventional rotary cored boreholes can give some idea of the overall rock mass quality but, without special investigation techniques, no detailed information on, say, joint orientation or roughness. Sophisticated investigation techniques are rarely used; although such methods could be appropriate and beneficial, it would be expensive and time consuming to carry out sufficient testing confidently to design all the important rock slopes. This would not fit comfortably in a commercial mining environment. Use of the observational approach to slope design is much more
more appropriate here, but initial design assumptions may be found to be inappropriate; this could give rise to substantial changes being necessary after the works have started.

An alternative and probably more appropriate approach would be to use probabilistic risk analysis. This approach is particularly appropriate in the early stages of pit design when relatively little site specific information is available. The input of expert judgement to analysis, based on experience elsewhere, and rigorous sensitivity studies allows identification of key parameters. The effect of these parameters can be investigated further, and the design refined, so as to reduce perceived risks to an acceptable level. This type of analysis starts off being a straightforward geomechanical analysis, but its particular value lies in its suitability for extension into expected cost analysis for design (Whittlestone & Johnson 1994; Whittlestone et al. 1994; Johnson et al. 1994). This allows the cost of constructing a particular design to be assessed, together with the cost of a failure (including such factors as loss of reserve, disruption and clean up) to be input, factored by the probability of the failure event occurring.

Another reason for the generally low technology of input to slope design is that there exists a long tradition of appropriate slope angles. However, this tradition sits uncomfortably with the increasing pressure on costs and margins, the pace of change in plant and its capabilities and, most importantly, the exploitation of coal in areas of more complex geological conditions.

The Plenmeller site is a good example of one with complex geological conditions not least because of the presence and effects of the Stublick Fault along the southern boundary, which was to form the highwall. It is always difficult to determine, in advance of exposure, the magnitude of the zone of influence of a fault. An indication of strata dips increasing into the fault, and the presence of frequent faulting, was given in the geological prospecting report. The Stublick Fault was identified on geological sections as a finite and well defined zone, with the excavation limits (both contractual and practical) being parallel to and closely abutting the fault zone.

A common traditional practice, at least in the northeast of England, is to cut rock slopes overall at about 1.5V:1H, with individual benches being about 10 m high and cut at 4V:1H. The contractor proposed such an
approach here for all slopes. For temporary in pit slopes, this generally proved satisfactory for two reasons. Firstly, such slopes tend to be of limited height and, secondly, failures tend to be of modest volume so having relatively minor cost implications although, as always, taking cognisance of the Health and Safety implications. Neither of these reasons can be said to apply to a 90m highwall.

As bedrock first became exposed in the area of the fault, inspections were carried out by an engineering geologist. It became apparent that the effects of the Stublick Fault were even more widespread than anticipated. Smaller-scale faulting was also widespread. In addition to a markedly greater than expected strata distortion and frequency of faulting and fracturing for considerable distances, the character of the fault zone itself was important. In the 10 m or so below rockhead, the combined effects of tectonism and weathering had so fractured and weakened the rock mass as to render it soil like in character; in other words there was a substantial difference in the level between geological and engineering rockheads.

In addition, it was found that the fault zone, over a central width of some tens of metres, included zones of sheared fault gouge. This gouge comprised a melange of rock fragments (generally mudstone) and clay. Although apparently competent when freshly exposed, this material rapidly softened under the combined effects of stress
relief and moisture content increase. The extent of this zone of faulting, and of individual fault gouges was found to be substantial (see Fig. 7). These zones dipped towards the excavation at about 3V:1H overall, thus paralleling the anticipated highwall profile. It was thus not possible to cut even the benches at the anticipated gradients. Also, a view had to be taken as to the attitude of the fault and shear zones towards the base of the slope in view of the possibility of buckling failure involving the whole slope; attention is drawn to the overall slope geometry shown on Fig. 8.

An analysis of the stability of the highwall indicates a condition of marginal stability. However, the results are sensitively dependent on the input material parameters and pore water pressures used, such that a wide range of conclusions could be drawn. It is therefore necessary to adopt a cautious view, also bearing in mind the importance of the highwall, and it became necessary both to step the slope profile away from the core of the fault zone, and to flatten the bench and overall angles so as to provide adequate safety to individual benches and at depth. These measures are shown on Fig. 8 and clearly affect the recoverable coal quantity. Because of this sensible application of the observational approach in the initial cut, subsequent sections of the highwall should be planned and executed at the final profile first time, giving improved efficiency. It is likely that even very extensive and detailed investigations would not have fully identified the conditions that were actually encountered; they might, however, have provided some advance warning of the problems.

Restoration

Once coaling and backfilling have been completed it is anticipated that the same groundwater recharge sources and surface water run-off areas will operate as before the opencast mining took place. The site will be restored to an agreed profile, and to something like its former state of wetland moorland and upland grazing. Trials are being carried out on various plots to combine as many different options of lime, fertilizer and seed sources as possible, and to determine which works best for the specific site conditions and terrain profile. Within a year of work starting on restoration trials, heather was growing. In addition, advice has been obtained on the most appropriate methods of soil stripping and storage; topsoil is stored in large low-level mounds to create extensive areas of live soil for the restoration works.

Conclusions

In order to extract the approximately two million tonnes of coal from this remote upland site, the extensive ancillary geotechnical studies, investigations and construction works that were necessary have been described. Some of these were required by the planning authorities, some by the location of the site, and some arise as a normal outcome of any opencast mining operation. The planning of mining works and associated infrastructure needs to take account of the substantial scale of such works that are likely to be necessary, particularly as requirements for the protection of the environment become ever more stringent.

Acknowledgements. The authors wish to thank the Directors of British Coal Opencast, Mowlem Mining Limited and Soil Mechanics Limited for permission to publish this paper. However, the views expressed herein are entirely those of the authors.

References


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PAPER A2  ENGINEER'S VIEW

Hughes, D.B. 1996.

The glacial deposits of Northern England: an engineer's view.

THE GLACIAL DEPOSITS OF NORTHERN ENGLAND: AN ENGINEER'S VIEW

A lecture given by David B Hughes of Newcastle University (formerly with British Coal Opencast) on 25th September 1996, at Castlegate School, Cockermouth. The lecture was illustrated by slides showing exposures of glacial deposits and examples of civil and mining engineering projects.

Introduction

On 20th September 1996 (i.e. just five days prior to this lecture) both the local and national news media released details of a proposed canal to be constructed across Northern England, at an estimated cost of around £6 billion. The purpose of the canal is to link the Irish Sea at Port Carlisle with the North Sea at Tynemouth, and to allow the passage of ships of up to 15,000 tonnes displacement. If this gargantuan project ever goes ahead it will involve massive excavation and construction works along a 70 mile (110 km) route across countryside which is mostly underlain by glacial deposits. As part of the detailed planning and design work for this project it will be necessary to carry out extensive ground investigations to establish the thickness and geotechnical properties of the underlying strata, including the widespread glacial deposits. However, for preliminary feasibility study purposes much use is likely to be made of existing ground investigation data from the region. Although in no way connected with the canal project, the Geotechnical Group at Newcastle University is currently carrying out research into the geotechnical properties of glacial tills, and a particular aspect of this work is a study of the glacial succession in Northern England. The purpose of this lecture is to illustrate the extremely variable nature of the glacial deposits in our region and to show how this affects civil and mining engineering projects.

Most of the landscape of the northern counties of England (Cumbria, Northumberland, Tyne and Wear, County Durham and Cleveland) has been formed by glacial activity during the Quaternary period. The last major glaciation to fully cover Northern England was the Late Devensian or Dimlington Stadial ice sheet which existed from about 26,000 years to about 13,000 years before present. The Late Devensian ice sheet laid down virtually the whole of the glacial deposits found in Northern England today, although some of these deposits are likely to be reworked materials from earlier glaciations. This resulted in considerable
thicknesses of glacial till materials being deposited in the lower lying coastal and valley areas, and it is in these areas where townships, industrial developments and most infrastructure works exist or are planned. In many of these areas the glacial deposits overlie Coal Measures strata; hence opencast coal mining is also present. (The Scottish term "till" is used nowadays in preference to the older expression "boulder clay", and is briefly defined as a poorly sorted mixture of clay, silt, sand, gravel, cobble and boulder sized material deposited directly from glacier ice. Many engineers, however, still prefer to use the term boulder clay as this accurately describes the maximum range of particle sizes contained within this deposit.)

Opportunities to study exposures of the lowland glacial deposits have been provided over the past fifty years by opencast mining in this region. During the last twenty years or so, extensive geotechnical investigations into the glacial deposits have been carried out in connection with opencast mining and have provided more detailed information than that available to earlier researchers.

**Ground Investigations**

The topic of geotechnical investigations for mining and construction works is very extensive, and only the briefest account of explorations for opencast coal projects can be attempted here. Firstly, openhole rotary drilling (with core sampling) takes place for mineral prospecting purposes, and during this stage the overall thickness of the glacial succession is proved. Then, for the glacial deposits, direct investigation usually involves both cable-tool percussion borings and trial-pitting by backhoe. In cohesive strata (tills and laminated clays) tube samples are taken at very close intervals, and in granular horizons (sands and gravels) in-situ penetration tests are carried out. Piezometers are frequently installed in the boreholes, especially in the more permeable (granular) strata in order to estimate the groundwater conditions and to predict possible inflows into excavations. A wide range of tests is performed in the soil mechanics laboratory, but particularly important are the shear strength and consolidation tests, the results of which are used by engineers in the design and analysis of structures such as spoil mounds, embankments, excavated slopes, piled foundations etc.
Glacial Deposits

In the coalfield areas the overall thickness of the glacial deposits is commonly 5 m to 20 m, ranging from as little as 1 m where bedrock is close to the surface, and up to 60 m or more in the pre-glacial buried channels which dissect the underlying rockhead. Frequently, where the total thickness of glacial drift exceeds about 5 to 8 m, a tripartite succession occurs in the form of a lower till, overlain by a middle sand (and gravel) on laminated clay, or both; which in turn are often overlain by an upper till. The base of the upper till can vary from less than 1 m to over 20 m below the ground surface. In some locations a more complex succession with additional layers of sand and gravel and/or laminated clay is evident.

The colour of the tills forming the Cumbrian coastal deposits has resulted from the colour of the source rocks which were excavated and redeposited by the ice sheet(s). Initially grey tills were deposited by advancing Lake District valley and piedmont glaciers, but then these local glaciers were incorporated into a combined Scottish - North Lake District ice sheet which deposited red till over the local grey till. The red tills predominate nearer the coast, the grey till tending to become more evident further inland. There is much controversy over the occurrence and mode of deposition of the upper tills in Cumbria with the Scottish Readvance and/or local readvances in the Late Devensian, and glaciomarine models each having their supporters. At many of the now restored Cumbrian opencast coal sites often only the lower till was recognised, which was usually grey in the eastern part of the coalfield and red in the western part.

In Northumberland and Durham the upper till is usually red or reddish brown and overlies a lower grey till, except where the succession is only a few metres deep, then normally only red till occurs. A popular interpretation is that the whole succession was deposited as a grey lodgement till by a single ice sheet advance, and that the reddish colour of the upper till is solely due to post-glacial weathering. There are, however, some aspects of the composition of the glacial succession which do not seem to be adequately explained by this single deposit and weathering concept. These include the red (upper) till generally having a much lower stone content (gravel, cobbles, boulders) than the grey (lower) till; also the frequency and extent of the sand/gravel and laminated clay layers which in some cases are well over a square kilometre in area.
In the County of Tyne and Wear an extensive glaciolacustrine deposit is often associated with difficult geotechnical engineering problems, and is referred to by D B Smith (1994) in his BGS memoir of the Sunderland area as the "Tyne and Wear Complex". Towards the end of the Late Devensian glaciation eastwards flowing meltwater issuing from retreating western ice was cut off by northern ice, so creating a series of ice-dammed lakes, the largest of which was the Glacial Lake Wear. The resulting Tyne and Wear Complex deposits are generally interbedded laminated silty clays and clayey silts, plus occasional fine grained sands, stony clays and gravels. The thickness of this formation is commonly between 5 m and 15 m, but can be up to 55 m. These deposits are highly compressible and of low shear strength.

Civil and Mining Engineering Aspects

As stated earlier, glacial deposits generally overlie the shallow coalfields in northern England, and these are frequently associated with earthworks and slope instability problems at opencast coal mining sites. The upper and lower tills as engineering materials are themselves usually adequately strong in relation to the heights of spoil mounds and excavated slope faces that are normally required at opencast sites. However, it is the presence of more permeable sand/gravel layers and lower strength laminated clays which result in earthworks and slope failures. The granular materials can be a source of seepage, which may be short-lived if the material is a lens of limited extent, or may cause long-term problems of ingress of water and sloughing if of large extent or subject to recharge. Experience also shows that the presence of a laminated clay layer, even if only a few millimetres thickness, can have a very significant effect on stability due to its relatively low shear strength.

Similar seepage and stability problems are encountered throughout the region in cuttings and embankments for highways, railways, tunnels, dams and reservoirs. Natural slopes, particularly those adjacent to water courses, are also susceptible to failure.

The laminated clay deposits of the Tyne and Wear Complex have been quarried at a number of sites for brick making, and some quite spectacular slope failures have occurred. Where large buildings or bridges are constructed over these laminated clays (e.g. Team Valley
Industrial Estate and the Metro Centre at Gateshead) then deep piled foundations are usually required.

Conclusion

From carrying out a large number of geotechnical investigations involving thousands of boreholes and trial pits sunk through the glacial materials, and from extensive serial exposures at opencast coal sites, it has been found that there is considerable lateral variability in the depth and succession of the glacial deposits of Northern England. This, together with their wide range of geotechnical properties, often leads to significant problems on civil and mining engineering projects.

The glacial tills of Northern England in relation to the stability of screening and spoil mounds at opencast coal sites.

The glacial tills of Northern England in relation to the stability of screening and spoil mounds at opencast coal mines

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ABSTRACT In order to reduce visual impact, and nuisance from noise and dust, U.K. opencast coal mines are usually surrounded by environmental screening mounds. In Northern England the shallow coal reserves are overlain by extensive glacial deposits which support the screening mounds built of the same glacial deposits. There have been several instances of mound instability, often due to the occurrence of weak horizons within the glacial succession. This paper describes the complex nature of the glacial deposits and goes on to discuss geotechnical investigations and design criteria. Case studies from opencast mines in Northern England are used to illustrate some of the stability problems and their solutions.

1 INTRODUCTION

In the United Kingdom opencast coal mining has been carried out for well over 50 years. Between 1990 and 1995, the annual opencast coal production from the whole of the UK was generally between 14 to 17 million tonnes. There were about 50 to 60 mines operating in the coalfields of the Central Lowlands of Scotland, Northern England, the Midlands and South Wales at any one time.

Before coal extraction can take place it is necessary to obtain planning permission. Originally applications for authorisation to mine for coal were made to the Department of Energy, but from 1985 opencast coal mining became subject to the Town and Country Planning Act of 1971. Applications for planning permission to mine for coal now have to be made to the Mineral Planning Authority (MPA) which is normally the County (Region in Scotland) or District Council that administers the area where mining is proposed.

Whenever planning permission is granted for a particular mining project, the MPA will usually impose a number of "planning conditions". These conditions will normally include the provision of screening mounds, the purpose of which is to reduce visual impact, and to reduce the effects of noise and dust within the area adjacent to the opencast mine.

The majority of the shallow coal reserves in the UK are overlain by glacial soils, and this is particularly so in Northern England where the glacial deposits are very thick and extensive. These deposits, together with the bedrock, are used to form the screening and spoil mounds which are themselves often founded on the glacial strata. The construction of the mounds and the properties of the glacial deposits have a significant effect on the overall stability of the mounds throughout the working life of a mine (typically 3 to 12 years). It is the weaker layers in the glacial deposits, however, that cause instability as demonstrated in the examples given in this paper.

2 MINING OPERATIONS AND MOUND CONSTRUCTION

A simplified sequence of operations for single-seam working is illustrated in Figure 1 (a-h). This sequence is typical of opencast coal mines in the U.K. and particularly Northern England. Coal is won from one or more seams after excavating through glacial deposits and Coal Measures strata. Figure 1 shows that topsoil and subsoil are firstly removed and placed near the site perimeter for storage and to act as screening mounds. Excavation to the coal seam(s) then takes place in a series of cuts with the overburden taken from the initial cut going into a large storage mound, which may also serve as a screening mound. When all the coal has been
removed the stored overburden spoil is placed in the remaining void (final cut), and then subsoil and topsoil are replaced as shown.

The outer perimeter mounds being closest to the site boundary fence are usually formed from organic and fibrous topsoil, and are typically up to 6 m high. The inner perimeter mounds are then formed from subsoil, which in Northern England is normally weathered (upper) glacial till, and these are generally between 8 m and 15 m high. The overburden spoil mounds are usually between 20 m and 30 m high, but on the largest projects have been up to 55 m high, and are constructed to store both glacial materials and bedrock spoils.

The storage/screening mounds are constructed by tractor-scrappers or dump trucks or both which deposit the spoils in deep layers (>1 m) compacted only by the passage of the haulage plant itself. This means that the mounds are not built to a specification intended to produce an inherently internally stable structure, they are built solely for storage and as rapidly as possible. The side slopes of the mounds, however, are designed to ensure stability during their working life by analysing the mounds and the founding strata, the underlying ubiquitous glacial drift.

The many and varied theories about the depositional history of the lowland tills of Northern England are discussed in some detail by Hughes et al (1996). In the west of Cumbria it is generally agreed that the ice flowed into the area from two different sources and the colours of the tills (red and grey) are, due to the rock types traversed by the different ice streams. In Northumberland and Durham, red till usually overlies grey till where the overall succession is deep, but only red till occurs where the succession is relatively thin. It is possible that this eastern succession was deposited as a grey lodgement till by a single ice sheet advance, and that the reddish colour of the upper till is solely due to post-glacial weathering (Eyles and Sladen, 1981). Typical engineering lithostratigraphical details for the Cumbrian and Northumbrian glacial successions are given in Figures 2 and 3 respectively.
England much geotechnical investigation work was carried out for the glacial tills prior to the introduction of these Codes (Hughes and Blythe, 1987). Firstly, openhole rotary drilling takes place for mineral prospecting purposes, and during this stage the overall thickness of the glacial succession is proved. Then, for the glacial deposits, direct investigation usually involves both cable-tool percussion borings and trial-pitting by backhoe. Disturbed and undisturbed samples are taken at very close intervals of depth to enable stratigraphic and property profiles to be produced. In situ tests are usually limited to standard penetration tests in granular deposits. Piezometers are frequently installed in the boreholes, especially in the more permeable horizons in order to estimate the ground water profile and possible inflow into excavations.

Unconsolidated, undrained triaxial tests on 100 mm diameter specimens are routinely conducted to obtain profiles of density and undrained shear strength, the principle parameters used to assess the stability of the mounds. Classification tests to determine profiles of water content and Atterberg limit are carried out so that the principle strata can be identified and the mechanical properties of those strata compared with published data. Whilst design is predominantly based on undrained strength there is an increasing tendency towards effective stress analysis; thus consolidated, undrained triaxial tests with pore pressure measurements are also carried out.

5 DESIGN

The screening mounds are not designed to support a load and settlement is therefore relatively unimportant. The mounds, however, have to be stable during their working life. The gradients of the side slopes of the mounds were usually specified using evidence of slopes in similar materials as the basis for design. This has proved to be unacceptable because of the variation in the properties of the glacial deposits, the presence of weaker layers within the mound and underlying foundation soils, and the softening of the till within the mound with time due
to stress relief. Failures have occurred which led to the need to design the slopes.

The glacial tills are insensitive such that the strength does not change significantly after excavation and placing (provided there is no increase in water content due to precipitation). Therefore, the stability of the slopes is estimated using total stress limit equilibrium analysis based on the triaxial undrained shear strength. It is usual to consider circular failure surfaces, but non circular mechanisms are also analysed especially if weaker strata, such as layers of laminated clay, are identified.

Total stress analyses are valid during and immediately after construction of the mounds. With time, however, the strength of the till forming the mounds can reduce due to stress relief, dissipation of pore pressure and possible softening due to ingress of rain water. In order to estimate the variation in Factor of Safety during the working life of the mine effective stress analyses can be undertaken. Effective stress analyses using fully drained conditions tend to over predict the Factor of Safety of the mounds since the excess pore pressures generated in the foundation soils do not dissipate within the working life because, primarily, of the low permeability of the till.

Therefore, effective stress analyses should be based on partially drained conditions. A number of methods could be used to predict the pore pressure regime but there is very little field evidence of actual pore pressure regimes and the rate of dissipation to support the estimates. For that reason, total stress analyses with an adequate Factor of Safety (FoS) is usually the preferred method, though Blythe et al (1993) do suggest an alternative hybrid solution which has been used to back analyse failed mounds.

Total stress analyses have proved to be adequate for mounds formed of heterogeneous till founded on heterogeneous strata. In practice, however, the stability of the mounds are a function of weak horizons such as laminated clays and water bearing sands and gravels, rather than the strength of the major component of the clay matrix dominant till, which is mostly firm to very stiff. This is demonstrated in the following case studies, the geometries of which are summarised in Table 1.

### 6 EFFECTS OF STRATA ON STABILITY

#### 6.1 Water bearing layer of sand

A subsoil storage mound, shown in Figure 4, located immediately adjacent to a major opencast excavation started to fail towards the open void, i.e. outward displacement in the toe area had developed together with extensive tension cracks at the crest.

The subsoil material placed in the mound consisted mainly of upper weathered till which had contained many sandy pockets and lenses. The natural strata below the base of the mound and above rockhead consisted of upper weathered till overlying clayey sand. Perched groundwater occurred within the clayey sand layer resulting in extensive seepage and sloughing in the upper part of the face of the adjacent opencast excavation.

Two measures were taken to improve the stability of the mound. Rockfill buttresses were constructed into the glacial deposits along the crest of the excavation and below the toe of the mound, and the

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**Figure 4 Failure of a subsoil mound due to a water bearing layer of sand**
overall slope was reduced to lv-3h, as shown in Figure 4. The buttresses were 15m wide and at 30m centres, i.e. a 15m wide unsupported panel was left between each buttress. Only one buttress was excavated at any one time and each was backfilled the same day using selected Coal Measures sandstone from the main excavation. The calculated Factor of Safety at the location of each buttress for a two dimensional slip was 1.6 and that for the unsupported panel 1.0, giving a mean value of 1.3. These were based on non circular analyses. The slopes and mound remained stable for the time required (about six months) to allow the whole of the contractual coal to be won from this area of the site.

6.2 Underlying layer of laminated clay

A topsoil mound and a subsoil mound, shown in Figure 5, were rapidly constructed adjacent to a public highway which was approximately 60 m from the crest of the subsoil mound. About four weeks after the subsoil mound reached full height damage was seen at the edge of the highway, which included ripples in the asphalt surfacing near the drainage channel/kerb edge, cracking and heave in the footway, and the displacement of lighting columns. The topsoil mound had been moved some 2 to 3m horizontally by massive toe heave from the adjacent subsoil mound, the space between the two mounds having been substantially filled by displaced subsoil. Deep tension cracks had formed from the surface of the subsoil mound.

The material stored in the subsoil mound mainly consisted of the uppermost weathered till which had occurred in the top 1 to 2m over most of the opencast site area. The succession in the glacial deposits comprised an upper weathered red/brown till which was described as poorly laminated in places, overlying a lower dark brown/grey till. Within the upper till, and between the two tills, were two laminated clay layers and a sand layer, and these extended under the whole of the storage mound area. Piezometers were installed within and below the mound immediately after the failure, and these recorded pore-water pressure ratios up to 0.5.

Back-analyses of the instability indicated that the base of the subsoil mound failure had been through the higher of the two laminated clay layers. The outward movement of the toe area of the subsoil mound had pushed the topsoil mound towards the site boundary and hence caused damage to the public footway and road. Underneath the topsoil mound the zone of horizontal shear movement was again most probably within the upper laminated clay layer. There was no evidence of failure within the topsoil mound. On the opposite side of the subsoil mound, to that where instability affected the public highway, the main opencast excavation void came close to the toe; but no failure ever took place there.

The height of the subsoil mound was reduced slightly and thereafter no further ground heave or damage to the highway was observed.

6.3 Permeable or weaker layers or both

The boundary of a working opencast coal site, a proposed new highway and an existing main river all ran roughly parallel to each other, and the ground surface sloped quite appreciably down to the river. The opencast excavation adjacent to this boundary was to be around 40m deep, of which the upper 20m or so would be through glacial deposits. No perimeter screening mounds had been planned for this part of the opencast site, as the whole area was agricultural land and there was no public access or rights of way. However, the completion of the new highway would give the general public access to this area. Therefore, it was decided to excavate into the sloping ground surface for the highway and so create a side-long cutting (i.e. to excavate a ledge into the upper glacial deposits). This would then leave a ridge in natural ground which would act as a screen between the highway and the opencast operations as shown in Figure 6. A small topsoil mound (1.5 m high) was placed along the crest to effectively increase the height of the ridge.

An extensive ground investigation in the proposed screening ridge area proved a sand and gravel layer (upper sand) overlying an upper and a lower till, these two tills being separated by a further sand and gravel layer (middle sand). In one part of the area the

![Figure 5](image-url)  
**Figure 5** Failure of adjacent topsoil and subsoil mounds due to layers of laminated clay (after Blythe et al, 1993)
The lower till was divided by a 2m thick lens of laminated clay. Separate groundwater levels were recorded for the middle sand, the laminated clay, and the base of the lower till. The existence of the sand/gravel and laminated clay layers, and their associated groundwater pressures, resulted in low factors of safety for the proposed slopes when using effective stress analyses.

To aid stability for the opencast operations and the screening ridge, the opencast cuts were aligned approximately perpendicular to the site boundary. This ensured that the plan length of the unsupported boundary slope was kept as short as possible so that each coaled-out section could be backfilled as soon as the next section had been fully excavated.

Minor failures were observed in the opencast slopes which appeared to be the result of back-sapping in water-bearing sand layers (middle sand), and slumping in the laminated clay, but the pattern of cuts ensured there was no major failure.

7 CONCLUSIONS

Screening mounds for opencast mines in the North of England can be formed of topsoil, weathered or unweathered glacial till. The clay matrix dominant till is generally insensitive, thus total stress calculation based on undrained shear strength can be used. These give an adequate factor of safety for the stability of a mound during its working life provided any weaker layers are identified and taken into account.

Ground investigation and design calculations are a pre-requisite for 'any' planning applications for opencast mining. When failures do occur, the cause is identified and 'remedial measures' undertaken. Examples include regrading, reducing the height, rockfill buttresses and orientating the slope with respect to the dip of the weaker horizon at a different angle.

Thus, it is possible by careful planning and proper engineering to construct stable screening mounds that reduce visual impact, reduce the effects of noise and dust, and store soils and overburden.

REFERENCES


PAPER A4  GLACIAL SUCCESSION


The glacial succession in lowland Northern England.

The glacial succession in lowland Northern England

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Abstract

The landscape of Northern England has been subjected to glacial activity several times during the Quaternary period. Successive ice sheets may have 'swept clear' the bedrock surface in places, but may also have incorporated materials from previous glaciations into later formations, and eventually into the present cover of glacial till. Hence, almost all the till materials now existing over Northern England were deposited during the last major ice sheet glaciation, which is known as the Late Devensian or Dimlington Stadial. These glacial tills are engineering soils, and the variable and often complex successions in which they occur have frequently led to problems on civil and mining engineering projects. Many theories have been proposed to explain the complex distribution and succession for the Late Devensian tills, which have involved the waxing and waning of the ice sheets, variations in the directions of ice flows, and other changes in the glacial and post-glacial environments. This paper attempts to summarize the published research and compare this with the authors' own experience and observations gained mainly from opencast coal mining operations in the exposed lowland coalfield areas of Cumbria, Northumberland, Tyne & Wear and County Durham. Finally, the implications for ground investigations, plus the design of stable excavations and other earthworks, are briefly discussed in the light of this experience.

Keywords: excavations, site investigations, slope stability, till, weathering

Introduction

Most of the landscape of the northern counties of England (Cumbria, Northumberland, Tyne and Wear and County Durham) has been shaped by glacial activity during the Quaternary period. This activity has resulted in the deposition of considerable thicknesses of glacial till in the lower lying coastal and valley areas, where most of the development (urban, infrastructure, opencast mining, etc.) has taken place and is likely to take place in the future. One consequence of this development is the availability of a considerable amount of information including stratigraphical profiles and properties of the tills, which is an essential part of an ongoing detailed study of the engineering properties of the tills of this region.

Till is defined here as a poorly sorted mixture of clay, silt, sand, gravel, cobble and boulder sized material deposited directly from glacier ice (modified definition based on Hambrey 1994). Often there are some waterlain deposits (glaciofluvial and glaciolacustrine) within the glacial succession. In soil mechanics terms, till is a non-textbook material, in that it is characteristically neither sand nor clay and does not conform to the depositional models upon which much of soil mechanics theory is based. Lack of appreciation of the effects of depositional and post-depositional processes on the properties of tills and the difficulty of sampling and testing tills that can contain apparently random inclusions of sand lenses and gravels, have led to difficulties in engineering on, in or with tills (Blythe et al. 1993; Hughes & Leigh 1985; Hughes 1996; Hughes & Clarke 1997). For these reasons the selection of engineering design parameters must include a study of the geological history, the intrinsic properties and the in situ characteristics of the material (Clarke et al. 1997). In this paper the evidence of the stratigraphical profile of the tills of the northern counties of England is presented.

Studies of the till as a glacial deposit first began in the 1860s. Historically the material was universally known as boulder clay and civil and mining engineers still use this term as it describes the range of particle sizes normally present in this highly variable deposit, even though it may contain neither boulders nor clay. However, present-day geologists generally prefer the term till, a Scottish word for clay. In this paper till is the preferred term but if a reference uses the term boulder clay then that is retained. The term diamict is used for terrigenous sediments in some more recent publications on glacial geology (i.e. diamictite means lithified and diamicton means unconsolidated, as defined by Hambrey 1994); but these terms are little used at present in geotechnical and engineering geology literature and have been avoided in this paper, except where quoting directly from references.

In the last fifty years it has been possible to develop an improved understanding of the nature of tills from site investigations for developments within the coastal and valley areas. In the last twenty years, site investigations carried out in connection with opencast mining of the Coal Measures strata underlying the glacial till have
allowed the interpretation of boreholes to be compared with observations of exposures within working opencast sites. Around 3000 cable percussion boreholes and trial pits were sunk during this period specifically to investigate the glacial deposits (down to rockhead); whilst the number of rotary openhole and cored boreholes sunk in connection with coal prospecting (which usually provided some limited information on the glacial overburden) was probably in the order of 50 000. Also, during this same 20-year period about 15 opencast coal sites have been worked in the Cumbrian Coalfield and about 60 sites worked in the Northumberland and Durham Coalfields, resulting in well in excess of a thousand site visits by the main author of this paper, and many visits by the other authors. Usually, the purpose of these site visits was to assess the stability of excavations and spoil mounds. The advantage of opencast sites is that they provide extensive serial sections of the glacial deposits, enabling a three-dimensional picture to be built up, and this has enabled a comparison to be undertaken with existing published work on the formation and distribution of these tills.

Many geological and geotechnical publications have been researched in order to prepare this paper. In the literature for Cumbrian tills references to observations from opencast sites are very rare; whereas for Northumberland and County Durham tills the existing literature contains much evidence from the opencast coal mining industry, and this is borne out later in the discussions for the two separate coalfield areas.

Quaternary glacial cycles

The main tills of Northern England were deposited during the last glaciation of the Quaternary period. The Quaternary started more than 2 million years before the present (2 Ma BP) and there have been perhaps as many as 20 glacial cycles so far (Fookes 1991). These cycles were controlled by the interaction between the earth’s atmosphere, the oceans and the ice sheets themselves (Boulton et al. 1985) which, in turn, were affected by Milankovitch cycles, i.e. cyclic changes in the earth’s axial tilt, eccentricity of orbit and precession of the equinoxes (Bennett & Glasser 1996).

In the northern hemisphere the glacial cycles involved the growth and decay of two major ice sheets covering North America and Northern Europe. Growth occurred during colder glacial periods, whereas decay occurred during warmer interglacial periods similar to today’s conditions. Within the main glacial and interglacial stages there have been lesser stadials and interstadials, i.e. colder and warmer periods respectively, causing less significant ice cover fluctuations.

Boulton et al. (1985) have used satellite imagery and ground survey data to construct models showing the dynamic behaviour of the two major mid-latitude ice sheets that covered North America and Northern Europe during the last glacial period. They compared these with high-latitude ice sheets that persisted through both glacial and interglacial periods (i.e. Greenland and Antarctica). These high-latitude ice sheets showed a sluggish response to change due to both the relatively stable atmospheric conditions at high latitudes and the widespread occurrence of the resistant rocks over which they moved. In contrast, the mid-latitude ice sheets were intrinsically more active and variable in responding to the climatic changes and to the greater atmospheric circulation energy. Hence these mid-latitude ice sheets showed large fluctuations during glacial periods, and tended to disappear during interglacials leaving a strong imprint of ice sheet decay over large areas.

Mid-latitude ice sheets were active during the Anglian and Late Devensian stages. Ice flowed outwards from the Scottish Highlands, but mainly southwards into and across Northern England as shown in Fig. 1. The Anglian ice sheet covered the Midlands and East Anglia, but not Southern England. The Late Devensian ice sheet extended south of the northern counties of England where it removed virtually all traces of the earlier Anglian deposits. It has been estimated that about three-quarters of all glacial tills found in Britain are of Devensian age (Derbyshire 1975). Table 1 (after Lunn 1995) summarizes the succession in Northern England.

There is some dispute as to how many times the ice sheet advanced during the Devensian period. The Warren House Gill deposits on the Durham coast may be Early Devensian or older (Lunn 1995). Some of the basal deposits in lowland Cumbria have been described as being Early Devensian (Eastwood et al. 1968; Huddart 1971). It has been suggested by Straw & Clayton (1979), from a study of end moraine forms in Holderness and Lincolnshire, that at least three significant ice sheet advances occurred during the Devensian period. However, Worsley (1991) concluded that the occurrence of an Early Devensian glaciation remains unproven.

The Late Devensian glaciation

The Devensian cold stage occurred between the Ipswichian interglacial and the Flandrian, i.e. between about 122 000 and 10 000 years BP. The occurrence of ice sheets over Northern England during the Early to Mid-Devensian period is disputed (see above) but certainly prolonged periods of periglacial conditions would have existed. The last major ice sheet, the Late Devensian Glaciation (also called the Dimlington Stadial by Rose 1985) existed between 25 000 years BP and 13 000 years BP, and reached its maximum extent at around 18 000 years BP (Lunn 1995). Subsequently, during the period
Fig. 1. Limits of Anglian and Late Devensian glaciations in Great Britain (based on Eyles & Dearman 1981; Eyles & McCabe 1989; Boulton et al. 1991; Catt 1991a,b; Stewart 1991).

Table 1. Stratigraphic succession of the Quaternary deposits in Northern England (after Lunn 1995, with minor modifications)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Region</th>
<th>Deposits in Northern England</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flandrian (T)</td>
<td>estuarine and other marine deposits, coastal zones, alluvium, lake deposits, peat, turf</td>
<td></td>
</tr>
<tr>
<td>Loch Lomond Stadial</td>
<td>11,000</td>
<td>alluvium, blockfields, moraines, sand, peat</td>
</tr>
<tr>
<td>Wastwater Interstadial</td>
<td>13,000</td>
<td>peat, lake deposits, alluvium, swamp deposits</td>
</tr>
<tr>
<td>Late Devensian</td>
<td>surface and sub-surface ice-contact and pro-glacial glaciolavina and glaciolacustrine deposits; till; giant erratics</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>Early</td>
<td>?? Inamoean Till</td>
</tr>
<tr>
<td>? “Wessenden” (C)</td>
<td>? Warman House Till</td>
<td></td>
</tr>
<tr>
<td>“Ifford” (T)</td>
<td>ca 200,000</td>
<td>Eastington Raised Beach</td>
</tr>
<tr>
<td>? “Wessenden” (C)</td>
<td>? Warman House Till</td>
<td></td>
</tr>
<tr>
<td>Earlier Angloan (T)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earlier Horican (T)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold Stage (C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earlier Horican (T)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anglian (C)</td>
<td>ice sheet covered North Sea coast, but evidence destroyed subsequently by Late Devensian ice.</td>
<td></td>
</tr>
<tr>
<td>Cromerian (T)</td>
<td>? East Anglia Till; ? Newbiggin beach gravel</td>
<td></td>
</tr>
<tr>
<td>Earlier Stages (C&amp;T)</td>
<td>? East Anglia Till; ? Newbiggin beach gravel</td>
<td></td>
</tr>
<tr>
<td>Tropica (BP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold Stage (B, C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BP before present</td>
<td></td>
<td></td>
</tr>
<tr>
<td>? possibly</td>
<td>? very possibly</td>
<td></td>
</tr>
</tbody>
</table>

NB: Scale 100 km
from about 11,000 to 10,000 years BP, a minor glaciation in the Loch Lomond Stadial, centred in the Scottish Highlands, resulted in cirque and high valley glaciers in the extreme northern and western parts of the region.

Computer modelling studies of the Late Devensian ice sheet (Boulton et al. 1977, 1985, 1991) suggested that the highest part of the ice cap was around 1800 m above corresponding sea level and extended across the Scottish Highlands to the Southern Uplands. From this vast summit area the ice flowed outwards in all directions (Fig. 1). Initially, the ice which moved southwards from Scotland was deflected by ice spreading out from the minor ice domes covering the high ground areas of Northern England as shown in Fig. 2. At maximum glaciation the height of the ice sheet probably sloped down from around 1600 m over the Carlisle plain to less than 600 m over the Tees Lowlands. To the southwest of the region the ice sheet extended over Lancashire, Cheshire, Staffordshire, most of Wales, the Irish Sea and Ireland. The ice sheet also had a lobate margin to the southeast of the region extending on to the east Yorkshire and Lincolnshire coasts, as far south as the Wash (Marsland & Powell 1985; Catt 1991a, b).

Due to the world-wide build-up of ice during the Late Devensian period, the sea level was lowered by some 130 m or more (combined isostatic and eustatic effect). Boulton et al. (1977, 1985, 1991) show two versions of the British ice sheet model; one has it extended across the northern North Sea towards Scandinavia and thus joined to the European ice sheet; whereas the version shown in Fig. 1 has the British and European ice sheets separate from each other. Later publications by Catt (1991a, b) and Stewart (1991) appear to confirm that the British ice sheet was isolated, and that a permafrost desert or tundra extended across the North Sea area into Continental Europe.

The local pre-Quaternary topography probably influenced ice flow directions within the region. It is generally thought that uplift occurred in the early Tertiary period and this was followed by the erosion of many deep valleys. This pre-Quaternary relief or drainage system of the region is thought to have been substantially preserved though modified by glacial and periglacial activity (Lunn 1995). Information from early Quaternary events is minimal and the degree of modification by the last ice sheet is mostly unknown. During the lifespan of the Late Devensian ice sheet it has been suggested that ice flows varied in direction and intensity due to source areas varying in their dominance. Hence the converging ice flows jockeyed in a very complex...
manner, especially in the lowland areas, and quite possibly over-rode one another leading to complex glacial deposits (Lunn 1995). Figure 2 shows the directions of basal ice movements for Northern England based on the occurrence of erratics in the till and a knowledge of the likely sources.

The development of concepts of glacial succession in Northern England

Interest in the glacial deposits of this area goes back at least to the 1860s when mining engineers (e.g. Wood & Boyd 1863) plotted the locations of the deep drift filled valleys which had proved a hindrance to the mining of the upper coal seams in County Durham. Prior to this time boulder clays (glacial till) had been thought of as water-lain deposits, but by then the 'Glacial Theory' was beginning to gain widespread acceptance within the British Isles. Howe (1864) was one of the first people to realize the significance of land-based ice sheets and their erosive power from his work in Northern England. Goodchild (1875), from work on the western side of the Pennines, concluded that at maximum glaciation the ice sheet which filled the Vale of Eden had flowed over both the Tyne Gap and the Stainmore depression (to form one of the till sheets which Howe had described previously).

Mackintosh (1877) proposed a tripartite succession of glacial deposits in northwest England, including Cumbria, that consisted of a lower and an upper clay separated by a middle sand. His model involved deposition of the lower clay by glacial ice from the Lake District, followed by the deposition of the middle sand and the upper clay by floating coast-ice. Also during the 1870s the Geological Survey carried out work in the lower Tees area, from which a series of drift maps were produced. This work also identified two boulder clays separated by sands and gravels, but the lack of a Memoir left the description of these deposits incomplete. Subsequently, Kendall (1902) suggested a tripartite division of the deposits of the Cleveland area into lower boulder clay, middle sands and upper boulder clay. This tripartite division of glacial deposits has been identified in many lowland areas of England which have been covered by the Late Devensian ice sheet. The mode of deposition, however, may not have been the same in each area.

During the period 1896–1921, D. Woolacott (reported by Beaumont 1968) produced many publications on the glacial deposits of County Durham. He recognized a tripartite division of the deposits, the basal layer being a lower stony boulder clay overlain by sand and gravel and, in a number of places, further overlain by an upper clay. The erratic content of the lower boulder clay was considered to have been derived from the north and west. The upper clay, which displayed prismatic jointing and contained far fewer stones, was considered to represent a boulder clay that had been washed and resorted by the sea, after which it had been deposited under relatively calm conditions during or just after the retreat of the ice. Later, Woolacott (1921) suggested that the area had been subjected to four glacial periods, whereas most other workers had identified at least two glacial phases (Beaumont 1968).

The next major development in the study of Northern England glaciation was the expounding of the 'Undermelt Theory' by Carruthers (1939, 1946 and especially 1953). His main proposition was that the whole succession of glacial deposits could be formed by the melting of a single ice sheet, and that this resulted from the process of 'bottom melt' due to the pressure of overlying stagnant ice.

Carruthers suggested that the creation of the characteristic succession of tills, laminated clays, silts and sands resulted from this bottom melt phenomenon. Like most other researchers he regarded the basal till to be a ground moraine or a lodgement till. He considered that the laminated clay found within the till resulted from the shearing of englacial detritus (which he described as banded dirt) within the ice which subsequently was deposited by the process of under-melt. The silt and sand lenses within the till would have to have been deposited by flowing melt-water formed from the basal (lower) tills. The upper tills he initially regarded as sheared lower tills. In 1953, however, Carruthers postulated that an ice sheet from a western source produced the lower grey till, and that this was subsequently overridden by a northern ice flow which deposited the upper till.

From their research based on the Northumberland coastal area, Eyles & Sladen (1981) concluded that the whole tripartite succession is the product of just one glaciation, i.e. the Late Devensian. They proposed that these deposits were formed beneath a wet-based ice sheet as grey lodgement till and that the upper till, which is usually red/brown is the result of post-depositional weathering (see later). The sand, gravel and laminated clay are presumed to have originated from water-borne material which had been deposited in sub-glacial cavities, channels and lakes; and had subsequently been subjected to deformation, shearing and partial erosion by a successive phase of till deposition within the Late Devensian period.

Glacial deposits in the West Cumbrian Coalfield and adjacent areas

The West Cumbrian Coalfield area is located along part of the northwest coast of Cumbria, and is bounded to the north by the valley of the River Ellen, to the south by St Bees and Egremont, to the west by the Irish Sea, and to the east by the Lake District foothills.
Table 2. Correlation of Devensian Glaciations in Cumbria

<table>
<thead>
<tr>
<th>Cumbrian name</th>
<th>General British name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loch Lomond Stadial</td>
<td>Loch Lomond Stadial</td>
</tr>
<tr>
<td>Main (inc. Gosforth Oscillation and Scottish Readvance)</td>
<td>Late Devensian/Dimlington Stadial</td>
</tr>
<tr>
<td>Early Scottish</td>
<td>Early Devensian</td>
</tr>
</tbody>
</table>

Note: the Gosforth Oscillation and the Scottish Readvance are reported ice sheet readvances which took place near the Cumbrian coast at a late stage in the Main/Late Devensian glaciation (see later).

(Carboniferous limestone outcrop). This area is the subject of several Geological Memoirs and reports produced by the British Geological Survey (BGS), including Dixon et al. (1926), Eastwood (1930), Eastwood et al. (1931), Trotter et al. (1937), Eastwood et al. (1968), Taylor et al. (1971) and Barnes et al. (1988). These and several other authors (e.g. Huddart et al. 1977) referred to a tripartite succession of lower boulder clay, middle sands and upper boulder clay. This succession is present in many localities, but sometimes additional layers are observed, particularly an upper sand and, more rarely, a basal gravel.

Much of the literature on the glacial history of Cumbria and the Lake District refers to three glacial stages during the Devensian period. Table 2 correlates the Cumbrian names with the more widely used names in the general British literature. The latter names are used throughout this paper for consistency.

It is generally accepted that almost the whole of the glacial material in the Cumbrian Coalfield was deposited in the Late Devensian. Very little evidence of the Early Devensian exists apart from a few deposits at the very base of the succession, and it is likely that most of the early material has been incorporated into the Late Devensian deposits (Eastwood et al. 1968; Huddart 1971; Dickins 1995).

Eastwood (1930) and Eastwood et al. (1931) suggested that during the Late Devensian (Dimlington Stadial glaciation the first ice to arrive in the area flowed generally westwards from the Lake District in the form of piedmont glaciers which crossed the Carlisle and West Cumberland plains. This Lake District ice was then opposed by southward flowing ice from southern Scotland, which had filled the area of the Irish Sea. The two ice-bodies united and there was intermingling of their burdens of rock debris as their strengths relative to each other varied. Eventually the southward flowing ice from Scotland became the dominant force and the Lake District became completely covered by the Late Devensian ice sheet centred on the Scottish Highlands (Boulton et al. 1977; see also Fig. 2).

The red tills to the north and west of the area were deposited by the southwards flowing ice and are derived mainly from the Permo-Triassic bedrock located farther north. They also contain many clasts of granite (from Criffel and Dalbeattie) plus clasts of metamorphic rocks (from the Scottish Highlands) including greywacke, quartzite, phyllite, mica-shist, and various types of gneiss and granophyre.

Moving farther inland, into the eastern part of the area (i.e. closer to the Lake District fells) the grey tills start to appear and then to predominate. These tills are derived from the local Coal Measures, together with other Carboniferous bedrock, and from the older Lake District rocks. The clasts are mainly sandstone, mudstone, coal, limestone, with some evidence of Skiddaw Slates, Carrock Fell Gabbro and Borrowdale Volcanic rocks.

Eastwood (1930) refers to the grey tills predominating to the south of the River Ellen, except for the coastal tract southwards from Maryport where the red till is present. The red till and the grey till can occur in the same succession, in which case the red usually overlies the grey, although very occasionally a further grey till overlies the upper red till (Eastwood 1930; Eastwood et al. 1931). At the surface both colours of till are associated with drumlins or drumlin-like ridges and are therefore almost certainly lodgement or deformation tills. These drumlin features are mostly aligned NE–SW in the northern part of the area, but veer more towards NNE–SSW in the southern part (Eastwood 1930; Eastwood et al. 1931). Huddart (1994) referred to proglacial gravels deposited from advancing Lake District valley glaciers which then laid down a grey basal till over sandur sediments. These local valley glaciers were then incorporated into a combined Scottish–North Lake District ice sheet which deposited the red till over the local grey till.

No references have been found to any major investigation into the weathering of Cumbrian till similar to the work of Eyles & Sladen (1981) on red and grey (i.e. upper and lower) till of Northumberland. As Eyles & Sladen themselves state, ‘the depth of post depositional weathering of till is greater in eastern Britain as it is related to sulphide-bearing bedrock lithologies over which the Devensian ice cap moved, and to climatic factors’. However, the grey till that occurs in the Cumbrian coastal lowlands is derived substantially from sulphide-bearing bedrock (i.e. Coal Measures). It is also important to note that, in the discussion that follows for West Cumbria, that the colour of the deposit does not generally define whether it is an upper till or a lower till.

As stated previously, the BGS Memoirs for the Cumbrian Coalfield and adjacent areas reported a tripartite succession formed of a lower till, middle sands and upper till as occurring widely, but not everywhere. This succession has infilled former valleys and channels in the bedrock such that there are many locations where the glacial deposits are 20 to 30 m thick, and throughout the area the overall thickness of these deposits can range...
from less than a metre to a general maximum of around 50 m (Eastwood 1930; Eastwood et al. 1931; Barnes et al. 1988). However, one borehole drilled into a deep channel at Foxhouse South opencast coal site was terminated at just over 70 m depth without having penetrated the full thickness of the glacial deposits (see later).

**Lower till.** The lower till can be either red or grey according to whether the source is predominantly either Permian Triassic rocks or Coal Measures. It contains much boulder, cobble and gravel size material in a matrix of sandy silty clay thus forming a clay matrix dominant till. Basal gravels consisting of mainly Scottish rock types, and possibly of Early Devensian age, occur at the base of the lower till in a few localities (Eastwood 1930). In coastal areas the red version of the lower till has been named the Lowca Till (Huddart 1970; Huddart & Tooley 1972) or the Selker Till (Merritt 1997) and identified as a lodgement till.

**Middle sands.** The middle sands, where present, consist of sands, gravels and laminated clays and are regarded as extra-glacial deposits, mainly laid down during the recession of the ice sheet. Eastwood et al. (1968) state that the sands and gravels may be "outwash-deltas, or overflow-deltas, or land stream-deltas"; and that "the laminated clay and brickearth (red stoneless clay) were accumulated as lake-floor deposits".

**Upper till.** The upper till, where present, can also be either red or grey. It differs from the lower till in that it usually contains much less of the coarser granular fraction, although it sometimes consists of gravel and sand in a silty clay matrix.

Dixon et al. (1926) referred to the upper till as a mud drape or a readvance subglacial till derived from ice moving out of the Irish Sea Basin in a late stage of the Late Devensian deglaciation. Eastwood (1930) and Eastwood et al. (1931) attributed its formation to the Scottish Readvance, but Clark (1989) and Huddart (1991) indicated that the Scottish Readvance ice (except that which followed the coastline and came onshore south of St Bees) did not cover this coalfield area. According to Huddart (1991), Scottish Readvance ice reached just north of Aspatria, immediately offshore to the west of Maryport and Workington, and penetrated up to 5 km inland near Gosforth (southeast of St Bees); and therefore only affected the northern, western and southern margins of the Cumbrian Coalfield.

Evans & Arthurton (1973) suggested that the lower till is a lodgement till, and that the upper till represents deglaciation of the same ice sheet that formed the lower till. Also, according to Huddart et al. (1977) the upper tills may not be basal in origin as thought by earlier workers, but could be ablation tills, flow tills or englacial tills (Boulton 1972). The fact that the two till units are separated by middle sands does not necessarily imply that the succession results from a threefold ice advance–retreat–advance sequence. All the units in the succession could have been deposited from the decay of a complex ice sheet, and the presence of an upper till in the Cumberland lowland is not by itself sufficient evidence for an ice readvance. Huddart et al. (1977), however, listed a number of locations where there is evidence that the upper till has the characteristics of a basal till. It seems a possibility that some of these materials were deposited as melt-out tills as the Late Devensian ice receded.

In addition to upper tills associated with ice sheet readvances from the Solway and along the coast, there are several locations which are well inland and well south of the River Ellen, where an upper till occurs. Eastwood (1930) refers to several places along the Derwent Valley where up to 12 m thickness of grey clay or grey boulder clay has been identified. McCormac (in Cumberland Geological Society 1996) also identified a local deposit of upper till overlying a bedded gravel (middle sand) at Beck Farm (NY 076 197) north of Kirkland. This till contained many clasts thought to be derived from Skiddaw slates, and the mottled orange/light brown/grey colouring indicated weathering and possibly some solifluxion effects. Several current opinions (Cumberland Geological Society 1996) indicate that the upper till in this particular area was deposited during local ice readvances from the northwest, and that these were part of the ice sheet fluctuations or oscillations during its overall decay at the end of the Late Devensian.

A further explanation for the Late Devensian glacial history of the Irish Sea basin involving glacio-isostatic and eustatic changes has been put forward by Eyles & McCabe (1989). They suggested that the upper deposits on the West Cumberland plain (up to the 140 m AOD contour) are glaciomarine in origin. They also postulated that rapid decay of the Irish Sea ice resulted in calving of the marine ice margin and surging of ice streams, with large areas of dead ice left stranded in peripheral (coastal) areas. In northwest Cumbria this is linked with the upper red clays (possible mud drapes), deltaic deposits and the formation of drumlins. Huddart (1991, 1994, 1997) and Huddart & Clark (1993) have subsequently restated their belief in the land based ice model, and refuted the evidence for marine deposits in this area.

**NIREX (Sellafield) Quaternary investigations**

During the period 1993 to 1997, the BGS, with others, carried out a detailed study of the Quaternary geology of West Cumbria on behalf of United Kingdom NIREX
Limited, and this has resulted in many publications and reports (e.g. Anon 1997; Browne et al. (eds) 1997). These investigations have particularly concentrated on the coastal zone (both onshore and offshore) between St Bees and Gutterby Spa, which is an area lying immediately to the south of the Cumbrian Coalfield. This work has also focused on the controversy between the glaciomarine model of Eyles & McCabe (1989) and the various readvance models for the formation of the upper till in this locality. It has provided strong evidence that at least two major readvances of ice from the Irish Sea basin occurred near the end of the Late Devensian period. The earlier readvance, named the Gosforth Oscillation, was first reported by Trotter et al. (1937); and recent BGS mapping (reported by Huddart 1997) has shown the deposits from this event to occur up to 5 km inland and up to 100 m AOD elevation. Deposits associated with the subsequent Scottish Readvance were only found up to 2 km inland and up to 60 m AOD elevation. This suggests that Huddart’s (1991) limits for the Scottish Readvance (see earlier) appear to have included the Gosforth Oscillation.

The St Bees Moraine is one of the main features studied by Huddart, Eyles & McCabe and subsequently by BGS. This is a series of low hummocks, exposed in section as a line of coastal cliffs, and located southwest of the southern end of the Whitehaven to St Bees glacial meltwater channel (St Bees sea front and promenade). The succession in the St Bees Moraine is reported by Huddart (1994) and Merritt (1997) and is summarized below:

- Sandy clays, gravels and sands
- Sandy clays above the St Bees Till
- St Bees Till
- St Bees Sands and Gravels
- St Bees Silts and Clays
- Lowca Till
- Sandstone bedrock

Lowca Till is the red (or brown) lodgement till or lower till for the whole of the West Cumbrian coastal area, and corresponds with the grey lower till generally present just a few kilometres inland. This lower till is the main omnipresent deposit from the Late Devensian glaciation in the Cumbrian Lowland, and can be traced from Edenside to West Cumbria by the drumlin belt. These drumlins are absent from just south of St Bees, but recur farther south in the Furness area, and it is this zone without drumlins which is deemed to have been over-ridden by readvance ice (Huddart 1994).

The St Bees Clays, Silts, Sands and Gravels overlying the Lowca Tills were variously described as a proglacially deposited sequence laid down in front of an advancing ice sheet during the Scottish Readvance (Huddart 1994) or outwash fans/deltas associated with meltwaters discharging from the major channel to the north (Merritt & Auton, reported in Merritt 1997). The St Bees Till may be a basal meltout till deposited during the Scottish Readvance (Huddart 1994), or a till formed possibly during the Gosforth Oscillation and then over-ridden by the Scottish Readvance ice causing shearing and compressional deformation (glaciotectonic deformation) (Merritt & Auton (in Merritt 1997); Eaton 1997). Eyles & McCabe (1989) concluded that the St Bees Till is a glaciomarine deposit, but the results of microfossil and palynomorph analyses by BGS do not support this. Huddart concluded that the sandy clays, silts, sands and gravels overlying the St Bees Tills were also formed by subglacial meltout; whereas Merritt and Auton suggest that these materials (and not the St Bees Tills) are the main deposits of the Scottish Readvance. It would seem that the results of this recent BGS research strongly support the readvance model, but with some modification to Huddart’s earlier ideas.

Observations from opencast sites in Cumbria

Oughterside

Figure 3 shows a schematic succession for the Cumbrian Coalfield glacial deposits based on ground investigation data from Oughterside Open cast Coal Site (NY 126 400), which was located just north of the River Ellen, and southwest of Aspatria. Here there appeared to be an upper sand (and gravel) overlying an upper and a lower till, with a middle sand (and gravel, or laminated clay) between the two tills. However, it can be seen that the engineering description (as given in Fig. 3) for both of these tills is virtually identical; which suggests that the upper and lower tills in this vicinity have very similar characteristics, or that there may be only one till (presumably the lower till). This is based on the observation that lenses or pockets of silty sand, sand and gravel, and laminated clay occur at all levels within the succession at this location, and not a specific horizon which can be defined as the middle sand. Nevertheless, the position of this site is within the area identified by Eastwood (1930) where both a lower till and an upper till occur.

Along the southern boundary of Oughterside site both the sand and laminated clay layers were associated with failures in the excavated slopes, and this case history has also been discussed in more detail by Hughes & Clarke (1997).

Low Close, Linefoot and Foxhouse Group

The Low Close/Foxhouse group of open cast coal sites were located in the Broughton Moor/Little Broughton area (NY 070 330) which is midway between Maryport and Cockermouth. At these sites the till was generally very stiff or hard dark brownish grey, very gravelly
Lowca opencast coal site is located close to the Cumbrian coast (NX 986 235) and is midway between the ports of Workington and Whitehaven. Dark grey lower till similar to the till at Low Close/Foxhouse (situated some 12 km northeast of Lowca) overlaid the majority of the site area to a depth generally between 5 m and 10 m, as shown in Fig. 5(a). This suggests that in this locality, the ice from the Lake District travelled some distance westwards before being cut-off and deflected southwards by the Scottish ice travelling from the north. It was only near the western boundary of Lowca site that reddish (lower) till was encountered (as shown in Fig. 5(b)), which was more sandy than the grey till and contained many red sandstone and granite clasts. This site is very close to the cliff section (NX 978 213) where Huddart (1970) informally named the lower till as the Lowca Till. It can be seen in both Fig. 5(a) and Fig. 5(b) that temporary slopes excavated by face shovel would stand steeply at 60° to 80° elevation. Sand pockets...
Fig. 4. Low Close Opencast Coal Site, Cumbria. Steep faces were excavated by face shovel in the lower till.

Fig. 5. Lowca Opencast Coal Site, Cumbria. (a) Grey lower till covered most of the site (the apparent colour change is due to the excavator bucket marks). (b) Red lower till was encountered only in the western (coastal) part of the site.
and lenses within the till were comparatively rare, as were slope failures. There appear to be no records of an upper till at Lowca site.

**Moresby and Keekle Group**

At Moresby, Keekle and Keekle Extension opencast coal sites (NX 000 180) the thickness of till varied between 1 m and 35 m, and was commonly 10 m to 20 m. The till was red, very sandy, and generally fitted the descriptions given by Huddart (1970) and Merritt (1979) for the Lowca/Selker Till, i.e. the lower till. Figure 6(a) shows a slope excavated to about 27° elevation (1 in 2) in the red lower till at Keekle; where the seepage from an extensive sand layer at about mid-height in the slope can also be seen. This sand layer was cross-bedded in places, which may indicate that the overlying deposit was an upper till. Figure 6(b) shows part of the same slope some four months later, where seepage from the sand layer had resulted in large cavities. Figure 6(c) shows a major slip in the glacial till in a slope adjacent to the one shown in Fig. 6(a) and (b), where the excavated face in the till was formed at about 45° elevation, and where the debris from the failure covered the underlying Coal Measures bedrock slope. This failure appeared to be caused by heavy seepage and back-sapping from sand layers at mid-height and at the base of the till, and occurred about eight months after excavation.

**Glacial deposits in the Northumberland and Durham Coalfield and adjacent areas**

Glacial tills form a nearly continuous cover over most of the lowland area from the Tweed to the Tees. The area described here is bounded to the north by the River Coquet, to the east by the sea, to the south by the River Tees, and to the west by higher ground (usually the 300 m AOD contour or thereabouts). This is an area described by Douglas (1991) as overlain by lodgement till over the Northumberland coastal margin and thus replace the earlier western ice mass. Subsequently this western ice began to wane and recede allowing the Cheviot-Tweed (and eastern Scottish) ice to surge southeastwards along the coastal margin and thus replace the earlier western ice mass. According to Taylor et al. (1971) and Smith (1981 and 1994) the western ice stream was responsible for depositing lodgement till over the Northumberland coastal plain and much of County Durham (the Durham lower boulder clay). The later Cheviot-Tweed ice deposited till mainly offshore of the present Northumberland coastline, and in the Tyne estuary and eastern County Durham (the Durham upper boulder clay, see Fig. 2).

The pattern of ice flow was identified from studies of the principal erratics which include the Cheviot lavas and Lake District volcanic rocks and granites from major cold stage a Scandinavian ice sheet reached the Durham coast, and deposited a grey sandy clay which contains crystalline erratics and arctic shells probably from the area of the North Sea (Lunn 1995). There is also one recorded location of Loch Lomond Stadial glacial deposits at the Bizzle on the north side of the Cheviot summit, being classified by Douglas (1991) as a cirque moraine. A simplified glacial stratigraphy for the northeast of England is given in Table 3.

Much evidence of rockhead topography has been obtained from opencast coal prospecting and extraction, and coastal cliffs. A great many buried channels exist in the rockhead surface and, with the exception of most of the River Tyne, are not generally related to the present-day surface features. Glacial till thicknesses are greatest in these buried channels, and the maximum depth recorded is about 92 m near Sedgefield (NZ 390 300; Smith & Francis 1967). Lawrence & Jackson (1990) referred to buried valleys being 60 m deep or more in the Stobhill and Stannington areas. At opencast coal sites worked near the Northumberland coast, and in west and central County Durham, till thicknesses of 30 m to 40 m in buried channels are quite common. In coastal areas, the base of these glacial deposits can be as much as 30 m below Ordnance Datum (Anson & Sharp 1960; Cuming 1977).

It can be seen from Fig. 2 that ice travelled to the Northumberland coast from the Southern Uplands, the Tweed valley, the Cheviot Hills; and from the Lake District via the Tyne Gap. Further south, in County Durham, these ice streams were joined by Pennine ice, and more Lake District ice via the Stainmore Gap. On the northeast coast the ice flow direction was SSE (i.e. parallel with the modern shoreline). This ice probably originated in the Southern Uplands and Highlans of Scotland, travelled eastwards to the Firth of Forth and then turned almost southwards to travel along the coast (Boulton et al. 1977, 1991; Catt 1991a,b). Smith (1981, 1994) referred to Clapperton's (1970) case for an ice cap over the eastern Southern Uplands and the Cheviot Hills, from which Cheviot ice was initially channelled eastwards along the Tweed valley by more powerful western ice. Subsequently this western ice began to wane and recede allowing the Cheviot-Tweed and (eastern Scottish) ice to surge southeastwards along the coastal margin and thus replace the earlier western ice mass.
Fig. 6. Keekle Extension Open-cast Coal Site, Cumbria. (a) Initial exposure of till slope showing seepage from sand layer at mid-height. (b) 4 months later, showing cavities in sand layer due to seepage. (c) Excavation adjacent to location in (a) and (b) showing failure of till slope due to seepage from sand layers.
Table 3. A simplified glacial stratigraphy of northeast England (after Douglas 1991)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Representative deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Devensian</td>
<td>Loch Lomond Stadial, Windermere Interstadial, Late Devensian/Dimlington Stadial</td>
</tr>
<tr>
<td></td>
<td>Bizzle cirque moraine, Tills and related deposits throughout the region, including widespread glaciofluvial and glaciolacustrine deposits</td>
</tr>
<tr>
<td>Pre-Devensian</td>
<td>Temperate Stage(s): Easington Raised Beach Gravel (&gt;38 000 BP);</td>
</tr>
<tr>
<td></td>
<td>Fissure fillings in Magnesian Limestone</td>
</tr>
<tr>
<td></td>
<td>Cold Stage: Warren House Till (Scandinavian Drift)</td>
</tr>
</tbody>
</table>

Criffel, Dalbeattie and Shap (Taylor et al. 1971), and their limits of travel are shown in Fig. 2. In eastern County Durham, Magnesian Limestone material is prominent in the tills southeastwards from the Permian escarpment (Beaumont 1971). Recently abundant clasts of Magnesian Limestone have been observed in the tills at Herrington Colliery Opencast Coal Site (NZ 335 540), this site being located close to the Permian outcrops east of Sunderland. Elsewhere erratics occur in the lee of Whin Sill outcrops. In southeast Northumberland there is evidence of Magnesian Limestone, chalk and flints in the coastal tills, and these probably originate from the floor of the North Sea (Land 1974).

There is also much evidence from the opencast coal mining industry of glacial rafting and giant erratics. Slope stability problems were encountered in glacially rafted Coal Measures strata at Kibblesworth site (NZ 247 562) in Tyne and Wear, and at Deborah site (NZ 175 273) in County Durham (see later). Mills (1976) referred to glacial rafting at Broomhill site (NZ 110 388) at Tow Law, County Durham, where the raft or erratic was some 3 hectares in area by 12 m thickness, encased in about 3 m of glacial tills, and which may have been moved laterally by at least one kilometre and raised by some 45 m along a sloping rockhead. Lawrence & Jackson (1986) referred to an erratic at Tranwell opencast site (southwest of Morpeth) which was over 270 m long. Eyles et al. (1982) referred to sandstone rafts at Sandy Bay on the Northumberland coast (NZ 306 864) having been 'transported to the south over tectonized shale and mudstones that subcrop below lodgement till as part of a Coal Measures cyclothem'. Excavation for the St James’ Park Metro Station in Central Newcastle (NZ 244 645) revealed a raft of crushed coal within the till which had been identified during ground investigation as a seam in situ. Lunn (1995) described rafting at Bullman Hills (NY 706 374) in the North Pennines (at around 615 m AOD) where masses of the Great Limestone, of up to 200 m in principal dimension, have been moved by the ice by a distance of about one kilometre from their original location below the summit of Cross Fell.

The identification of rockhead, especially in routine ground investigations, is often difficult. The character of the junction varies from a very abrupt change from engineering soil to engineering rock, in some places with the bedrock surface striated, through zones of broken or comminuted rock (sometimes several metres thick), to the giant erratics described above. Locally, for example on the coast at Curry’s Point (north of Whitley Bay—NZ 350 752), there is evidence of subglacial shearing and displacement within the in situ rock. Excavations and cliff sections often show that boulder pavements occur within tills, and these can easily be mistaken for rockhead in boreholes. In some cases the boulder mantle may be a deformation till or a comminution till (McGown & Derbyshire 1977; Lawrence & Jackson 1986).

As in Cumbria, virtually all the BGS Memoirs for the northeast of England, particularly north of the River Tyne, refer to a tripartite succession in the glacial drift deposits. This succession consists of a lower grey till and an upper red or brown till, separated in places by a middle sand or sands (glaciofluvial and/or glaciolacustrine deposits).

**Lower till.** The lower grey till generally occurs throughout the region (Smith & Francis 1967; Smith 1994). It may overlie basal sands and gravels (Fowler 1935; Smith 1994), boulder beds or pavements (Robertson et al. 1994) or rockhead, and can be up to 40 m thick. This till is considered to be a lodgement till associated with the Late Devensian ice sheet; although, as explained above, it could in places be a deformation till. The grey till is usually absent when the total till thickness is less than two to three metres.

**Middle sands.** The upper red/brown till is separated in places from the lower till by a granular layer or layers which are often referred to as the middle sand (Fowler 1935; Smith & Francis 1967; Land 1974; Lawrence & Jackson 1990). These granular layers can vary in thickness from a few millimetres to 40 m, but mostly they are less than one metre thick. They can vary from entirely sand to entirely gravel and, in places, include lenses of laminated clay; or they may consist entirely of laminated clay.
Upper till. The upper red/brown till, like the upper till in Cumbria, has been variously described as lodgement till, ablation, melt-out, or flow till; and as a product of post glacial weathering to a depth rarely exceeding 8 m (Eyles & Sladen 1981). It may also have been subjected locally to some periglacial modification.

Robertson et al. (1994) describe a model for the glacial succession (Fig. 7) based on exposures observed during opencast mining at Stobswood site (NZ 215 935) which divides the upper till into a higher orange/brown/grey, possibly mottled till, overlying a reddish brown till. This upper till contains laminated clays which can vary in thickness from a few millimetres to over eighteen metres (Lawrence & Jackson 1990), and can vary in plan area from several square metres to many thousands of square metres. These laminated clays can occur at the base of the upper till, that is on top of the lower grey till or at any depth within the upper till, and are rarely recorded within the lower till. In addition to the laminated clays the upper till contains randomly distributed lenses of sand and gravel (Robertson et al. 1994).

The presence of the sand and gravel layers sometimes forming the boundary between the upper and lower till led Eyles Sladen (1981) to suggest that they formed the lower limit to a zone of weathering. The upper reddened till is interpreted as a weathering product which through a process involving oxidation and leaching of carbonates has resulted in the colour change from grey to red, an increase in the rotten state of stones and boulders, and in prismatic gleyed jointing. They suggested that deep weathering of tills in the UK is peculiar to the eastern side where summer soil moisture deficits and soil cracking result from lower rainfalls. Eyles and Sladen also described the tills as containing intraformational sands, gravels and laminated clays which have been deposited in subglacial meltwater channels and lakes. At two opencast sites they recorded these glaciofluvial horizons as having continuity of up to 1 km in the conjectured direction of ice flow and up to 200 m across the flow. They suggested that these horizons are "akin to buried ribbons" generally concurrent with the direction of ice-flow, and that the under-drainage effect by these glaciofluvial interbeds has mostly limited the reddened weathering to about 8 m depth.

Eyles et al. (1982) subsequently proposed that the complex succession of the till plain in Northumberland resulted from subglacial deposition from a single ice sheet glaciation, by a process of 'unconformable facies superimposition', consisting of 'cross-cutting lodgement till units'. The ice sheet was wet-based and only attained a steady state during a brief period when at its maximum extent. Till deposition was not continuous but was interrupted by erosional episodes, together with
changes in both the ice flow direction and source areas of the subglacial load, which resulted in variations in till lithology between successive phases of deposition. The previously described glaciofluvial channel sediments and postglacial (reddened) weathering (Eyles & Sladen 1981) were then superimposed on this model. Eyles et al. (1982) also referred to the low relief drumlinised till plain north of the River Tyne (inferring lodgement), and cited Anson and Sharp (1960), but these earlier authors described this area as soliflucted (see later).

The weathering theory of Eyles and Sladen at first attracted some strong opposition, notably Smith (1982) who reiterated his views as expressed in earlier BGS Memoirs (Smith & Francis 1967; Taylor et al. 1971) that there had to have been two successive Late Devensian ice sheets to explain the occurrence of the distinctly different pebble suites and clast orientation fabrics as observed in the lower boulder clay and upper boulder clay of central and eastern County Durham. Subsequently Smith (1994) referred to the Durham upper boulder clay which should not be confused with 'the reddened (weathered) upper part of the Durham lower boulder clay reported by Eyles & Sladen (1981) further north on the Northumberland coast'. Lunn (1983) stated that Eyles & Sladen (1981) and Eyles et al. (1982) 'have argued persuasively that upper tills in southeast Northumberland are simply the post-glacially weathered zones of otherwise more or less homogeneous lodgement tills, the lower tills having remained unaltered'.

As stated in the introduction, the main author's involvement in about 60 opencast sites in Northumberland, Tyne and Wear and County Durham, has necessitated the examination of borehole sections and plans of the superficial deposits for each site, (rotary boreholes were normally drilled to a 30 m or 60 m triangular grid pattern: Hughes & Blythe 1987), as well as many hundreds of visits to working sites. This has led to the observation that the pockets or layers of glacio-fluvial soils are of variable shape in plan, from approximately circular or oval to very irregular or elongated, with the orientation of their longest axis possible in virtually any direction, i.e. they do not appear to be preferentially aligned with the published ice-flow directions (see Fig. 2) and there is no obvious pattern to their occurrence. Cut-orientation is a major factor in observing these horizons of sand, gravel and laminated clay, which in turn have a very large influence on the stability of excavated faces.

It has also been suggested that, in places, the upper till is a soliflucted deposit or has undergone some periglacial modification. Anson & Sharp (1960) stated that the upper clay of the Northumberland coastal plain is, for the most part, a solifluxion mantle. Turner & Smith (1995) referred to evidence of solifluxion in the tills exposed at the coast between Tynemouth and Seaton Sluice. Douglas (1991) in referring to the Northumberland uplands stated that 'a strong case can be made that any former glacial landforms have been substantially modified by periglacial processes, notably solifluxion, after the wasting of the Dimlington Stadial ice sheet and during the cold climate of the Loch Lomond Stadial'. Therefore, there is the possibility that the upper till in parts of Northumberland may have been modified, if not originally deposited, by periglacial activity. In southeast Northumberland and North Tyneside there are numerous hills (e.g. Byker, Kenton, Heighley, Earsdon, Helm) where the bedrock (Coal Measures and Millstone Grit) protrudes through the drift, and these could have acted as sources for local debris flows or earthflows. Similarly Taylor et al. (1971) and Smith (1981 and 1994) referred to solifluxion and slopewash from higher ground in the County Durham and Sunderland districts.

Smith (1981 and 1994) refers to several other glacial and post-glacial deposits which occur in the Sunderland and southern Tyne and Wear districts. Some of these deposits are of limited thickness and extent, and are mainly confined to the coastal area. However, inland the Tyne and Wear Complex (as named by Smith) is a glacioluustrine formation which has been encountered in many construction and mining projects. Towards the end of the Dimlington Stadial, eastward flowing meltwater from retreating western ice was cut-off by advancing northern ice (as described earlier), so creating a series of ice-dammed lakes. The largest of which was the Glacial Lake Wear. The resulting Tyne and Wear Complex deposits are generally interbedded laminated silty clays and clayey silts, fine graded sands, stony clays and some gravels. The thickness of this formation varies from 1 m to 4.5 m. Smith's (1994) tentative explanation for the origin of the Pelaw Clay is that it 'might be the product of periglacial modification and redistribution of existing deposits, but especially of the plastic laminated clays, following the draining of Glacial Lake Wear'.

There are several recorded accumulations of laminated clay in the southeastern part of the region which have been identified in ground investigations carried out for major construction projects. In the Tees Estuary area there is an extensive deposit overlying the local upper till. This laminated clay is generally regarded as a pro-glacial lake deposit, and associated sands have been interpreted as shoreline sediments (Agar 1954; Bell & Coulard 1991). Further upstream on the Tees, for example at Yarm, at least two laminated clays occur; one close to Ordnance Datum, and another, which is often accompanied by sands, is at around 20 m AOD. At Hartlepool Docks a sequence of tills (probably 'lower till'), extending to around 30 m below OD, contained four horizons of laminated clay, each more or less
continuous in an area measuring at least 150 m by 350 m. Extensive deposits of laminated clay have also been found within till sequences in other valley deposits, for example in the lower Tyne valley and at the Derwent Reservoir site (Ruffle 1965).

Anderson (1939a, b) identified sands and gravels in the valleys of four east Northumberland rivers (the Aln, Coquet, Wansbeck and Blyth) as deposits from a lake dammed by North Sea ice with shorelines at about 42 m and 58 m AOD. Sediments from the higher level were encountered in construction work for the Alnwick Bypass, where excavation of fine sands, silts and clays below the water-table caused considerable difficulties.

Observations from opencast coal sites in Northumberland, Tyne and Wear, and County Durham

Butterwell and East Chevington

The so-called tripartite glacial succession is frequently observed at opencast coal sites in Northumberland. Figure 8(a) is from Butterwell site (NZ 210 900) and shows the red (upper) till overlying an extensive sand layer (middle sand), which was then overlying the (grey) lower till, (the Landrover was standing on rockhead and provides scale to the photograph). Figure 8(b) is from East Chevington site (NZ 265 990) and also shows red (upper) till overlying grey (lower) till, these being separated by an undulating layer of laminated clay which is about 500 mm thick. (The left hand of the person in the centre of the photograph is pointing to the laminated clay layer, and also gives scale to the adjacent boulders.)

Acklington Extension

As described earlier, a rather more complex model for the Northumberland glacial succession was put forward by Robertson et al. (1994) and is shown in Fig. 7. This model is especially relevant to the deeper till deposits where several layers or lenses of laminated clay and/or sand and gravel may occur. Figure 9 is a schematic diagram of the succession at Acklington Extension site (NU 240 010) where two thin layers of laminated clay were present beneath the topsoil and subsoil storage mound constructed near the perimeter of the site. These two mounds failed, resulting in very large horizontal displacements, as indicated in Fig. 9. An investigation of the failure showed that the main zone of the shearing had been along the higher of the two laminated clay layers, both of which were of low strength relative to the adjacent upper till and lower till. This mound failure case history has been described in more detail by Blythe et al. (1993), and Hughes & Clarke (1997).

Herrington Colliery

Work started at Herrington Colliery Opencast Coal Site (NZ 335 540) in May 1996. During recent visits brown till has been seen to occur both above and below grey till, along part of the eastern endwall of the excavation, a five-layer succession in the till of brown/grey/brown/grey/brown has been observed. This evidence is clearly at odds with the Eyles & Sladen (1981) weathering model.

Kibblesworth

At Kibblesworth site (NZ 247 562) glaciolacustrine clays and silts of the Tyne and Wear Complex (Smith 1981 and 1994) overlaid the Coal Measures in the north-eastern part of the site to a maximum thickness of 12 m. Figure 10(a) shows the laminated (varved) structure of the glaciolacustrine deposits as they were exposed in an excavation. Figure 10(b) shows a more distant and general view of the same exposure, where it can be seen that the whole of the excavated slope was unstable. Spoil mound failures also occurred at Kibblesworth site where these were constructed over the laminated clay and silt deposits.

Deborah

At Deborah site in southern County Durham (NZ 175 273) small scale glacial rafting of Coal Measures sandstone was associated with instabilities in the excavated slopes. Figure 11(a) shows a 12 m high very steep excavation face. At about 4 m above the floor of the excavation there was a coal seam from which groundwater was seeping. On the extreme left of Fig. 11(a), at about 2 m above this coal seam, rockhead can be traced dipping to the right until it becomes coincident with this coal seam (where the dark shadow then obscures). About 2 m above rockhead, and dipping parallel with it, was a rafted layer of broken sandstone which was also showing some groundwater seepages. The material both above and below the rafted sandstone layer was very stiff glacial till, i.e. the lower till (or Durham lower boulder clay—after Smith & Francis 1967). There was also evidence of a shear plane through the till underlying the rafted material, which can be seen in the centre of the photograph dipping sub-parallel with both the rafted layer and rockhead. Figure 11(b) shows the same location about a week later, after a failure of the excavation face had occurred. Evidence of the rafted sandstone layer can be seen on each side of the failure. The debris
Fig. 8. (a) Butterwell Opencast Coal Site, Northumberland. Red (upper) till overlying grey (lower) till, with an intervening (middle) sand layer. (b) East Chevington Opencast Coal Site, Northumberland. Red (upper) till overlying grey (lower) till, with the person in the centre pointing to an intervening laminated clay layer which was draped over an underlying boulder.
Conclusions and implications

There seems to be fairly general agreement that, with the exception of some basal sands and gravels in Cumbria and the Warren House Gill deposits on the Durham coast, virtually the whole of the till succession which is now present in Northern England was deposited in some way by the last major glaciation, i.e. the Late Devensian; although some of these tills probably include re-worked deposits from earlier glacial phases. Conversely, there is much controversy as to the origins of the successions within the overall mantle of these Late Devensian soils; in particular the upper tills, the middle sands (and gravels) and the laminated clays.

In Cumbria there is general agreement about the mode of occurrence of the omnipresent lower till, there being much evidence of drumlinization which suggests that it was deposited as lodgement till. However, the distribution of the upper or later tills is sporadic and their mode of deposition is disputed. The latest work by BGS on behalf of NIREX (Anon 1997; Browne et al. (eds) 1997) which was concentrated on the St Bees and Gosforth areas, supports the readvance models of Trotter et al. (1937) and Huddart (many references 1970 to 1997) rather than the glaciomarine theory of Eyles & McCabe (1989). The possibilities of local land-based readvances northeast of St Bees and the processes of weathering and solifluction have also been noted (e.g. Beck Farm, Foxhouse South and Linefoot opencast sites), but these processes have not been given much attention in the existing literature for the Cumbrian lowlands. Observations of tills exposed at opencast coal sites in Cumbria have added some further information on the possible occurrence of upper tills, sand and gravel, and laminated clay layers, but have not provided any further evidence relating to the readvances versus glaciomarine dispute.

For Northumberland and County Durham, different views have been presented to explain the formation of the upper red/brown till as distinct from the lower grey till. Several workers (e.g. Carruthers 1953; Smith & Francis 1967; Smith 1981, 1982, 1994; Catt 1991a, b) have supported the idea that an earlier western ice stream deposited the lower till and that a later northern ice stream deposited the upper till (whether or not this was a single tiered ice sheet (Carruthers & Catt) or two separate ice sheets (Smith)); so accounting for the different clay matrix colours and clast suites and orientations found in the two till layers. Eyles & Sladen (1981) and Eyles et al. (1982) presented their ideas of a single but complex till deposit involving "post-glacial weathering" plus "unconformable facies superimposition and cross-cutting lodgement till units"; and these ideas have gained fairly wide (but not total) acceptance. There is also a discrepancy between the views of Eyles et al. (1982) and the observations from opencast sites (as presented in this...
Fig. 10. Kibblesworth Opencast Coal Site, Tyne and Wear. (a) Close-up of exposed laminated (varved) silts and clays of the Tyne and Wear Complex. (b) Failure of slope excavated through laminated silts and clays of the Tyne and Wear Complex.
Fig. 11. Deborah Opencast Coal Site, County Durham. (a) On the extreme left the higher seepage line denotes a glacially rafted broken sandstone layer which is dipping to the right and is contained within the lower till (Durham lower boulder clay). The lower (horizontal) seepage layer is a coal seam; rockhead is just above this, also dipping to the right. (b) The same location as (a) after the slope had failed. Evidence of the rafted material can be seen on each side of the failure.
paper) regarding the shape and distribution of the 'middle sands', and brown till underlying grey till as seen at Herrington. The possible effects of solifluction processes should also be considered with regard to the upper layers in the succession (Anson & Sharp 1960; Taylor et al. 1971; Smith 1981, 1994; Douglas 1991; Turner & Smith 1995).

To the practising civil or mining engineer these arguments may seem somewhat academic, but a proper understanding of the origin, mode of deposition, post-depositional history, and geometry of these materials is required to make sensible interpretative models of the ground conditions from borehole investigations, and to choose appropriate geotechnical parameters for design and analysis. It has long been suggested (Boulton & Paul 1976) that there should be a relationship between mode of deposition and certain geotechnical properties. It would be expected, for example, that lodgement tills should have higher undrained shear strengths and lower compressibilities than tills deposited by melt-out or flow processes. Also, it is suggested that the relatively high shear strength often obtained for the upper till in Northumberland (Robertson et al. 1994) are unlikely to exist in a post-glacial deposit resulting wholly from solifluction processes.

A large proportion of the publications quoted in this paper refer to the 'tripartite' succession for the lowland tills of Northern England, both in the west and in the east. However, this tripartite model does not appear to adequately describe the variability and complexity of the glacial successions. For example, in Cumbria often only the lower till is present (as shown in Figs 4, 5(a) and 5(b)); whereas in parts of Northumberland, where the total thickness of glacial deposits is often only a few metres, only the red/brown (upper) till may be present, (which supports the weathering theory). Also in Northumberland, and in County Durham, the upper red/brown till frequently immediately overlies the lower grey till without the presence of any intervening middle unit (sand, gravel or laminated clay). Figures 6(a), (b), 8(a) and (b) show what appears to be a simple tripartite succession for each of the locations photographed; whilst Figs 3, 7 and 9 are examples of the complex distribution and variable nature of the middle units as often encountered where deeper glacial deposits occur.

The middle units (middle sands etc.) whether granular soils or laminated (varved) clay, play an important role in determining ground behaviour, especially in excavations. The granular materials can be a source of seepage, which may be short-lived if the material is a lens of limited extent, or may cause long-term problems of ingress of water if of large extent or subject to recharge. Experience in opencast and other excavations shows that the presence of a laminated clay layer, even if only a few millimetres thickness, can have a very significant effect on slope stability due to its relatively low shear strength and tendency to soften rapidly when unloaded. In addition these laminated clay layers have often been associated with foundation failures of spoil mounds and embankments (Blythe et al. 1993; Hughes & Leigh 1985; Hughes 1996; Hughes & Clarke 1997). It is therefore vital to determine whether such materials are present in isolated pockets or extend over large areas.

What has been found from carrying out a large number of geotechnical investigations involving thousands of boreholes and trial pits sunk through these glacial deposits, and observations from extensive serial exposures at opencast sites, is the considerable lateral variability in the extent of these various layers and in their geotechnical engineering properties. Further research is needed to try to establish a relationship between the engineering properties of tills and their mode of deposition. Additional observations are also needed on the distribution and extent of sand and gravel, and laminated clay horizons, as these have such an important effect on the engineering aspects of projects. The authors' experience suggests that advances in knowledge in this field are most likely to continue to be made by further systematic observation and sampling (and testing) for surface mining and construction projects, particularly large-scale excavations.

Acknowledgements. Much assistance has been given by Mr D. R. E. Dickins of Cumbria Environmental and Geological Services, particularly with visiting working opencast sites and re-examining records for restored sites in Cumbria. Several members of the Cumberland Geological Society and staff at BGS have been very helpful by describing exposures of the Cumbrian glacial deposits. Mr M. A. E. Browne (also of BGS) as one of the referees for this paper, made numerous corrections to the original text and offered several suggestions to improve the content. All of these contributions are gratefully acknowledged.

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PAPER A5  FAULTING – UK


The effect of faulting in UK opencast coal mining operations.

Proceedings of Fifth British Geotechnical Society Young Geotechnical Engineers Conference, Newcastle upon Tyne.
THE EFFECT OF FAULTING IN UK OPENCAST COAL MINING OPERATIONS
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INTRODUCTION

Faulting and tectonic disturbance of the Coal Measures strata are very commonly encountered in UK opencast coal mining operations and have often been associated with large scale failures of excavated slopes. Such failures are major safety hazards and can put lives at risk or cause damage to property. They can also have major financial implications (Hughes and Leigh, 1985).

THE DISTRIBUTION OF COAL MEASURES FAULTING AND STRATA DISTURBANCE

The many separate UK coalfields have undergone widely different degrees of tectonic deformation. A tentative and somewhat simplistic classification of the coalfields into groups defined by their tectonic complexity is given below (based on Price, Malkin and Knill, 1967; but with some modifications).

<table>
<thead>
<tr>
<th>Coalfields</th>
<th>Tectonic Style</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pembrokeshire</td>
<td>Overthrust; inverted</td>
</tr>
<tr>
<td>Somerset and Gloucestershire, Forest of Dean, South Wales</td>
<td>Moderate to very steep dips, thrusts and general complex faulting</td>
</tr>
<tr>
<td>Cumbria, North Staffordshire, parts of Scotland</td>
<td>Moderate to steep dips, general complex faulting</td>
</tr>
<tr>
<td>Lancashire, North Wales, parts of Scotland; South Staffordshire, South Durham</td>
<td>Moderate dips, general faulting</td>
</tr>
<tr>
<td>Northumberland, North Durham, Warwickshire, Leicestershire, North Yorkshire, parts of Nottinghamshire and Derbyshire</td>
<td>Moderate to low dips, some faulting</td>
</tr>
<tr>
<td>South Yorkshire, parts of Nottinghamshire and Derbyshire</td>
<td>Low dips, occasional faults</td>
</tr>
</tbody>
</table>

THE NATURE OF COAL MEASURES FAULTING

As shown in Table 1, faults are present throughout the British Coal Measures but the frequency of occurrence and magnitude of dislocation (downthrow) vary considerably. The bedded strata adjacent to faults are usually closely fractured and sometimes locally folded. Fault drag is also a common feature, as are multiple shear planes or zones.

Except where thrusting occurs, Coal Measures faults are almost always normal faults with dips typically about 60-70°, but may range between 45° and vertical. The magnitude of the dip can vary with depth, and the strike direction can also vary, especially with major faults. Downthrows range from just a few millimetres for the smallest and most common faults, up to as much as say 300 m for major faults. The majority of faults recognised at UK opencast coal sites have throws of less than 30 m.

Joints tend to become more frequent in the vicinity of faults, and faults may also separate domains or zones where the major joints are orientated differently. However, the major joint sets do tend to be orientated parallel or sub-parallel to the fault planes.
EFFECTS OF FAULTING ON OPENCAST OPERATIONS

The orientation of any major faults will usually influence the method of working and cut orientations at an opencast site. For example, faults usually present less problems if they strike across an opencast cut, rather than striking parallel or sub-parallel with the main axis of the cut. Also, excavation towards a normal fault from the upthrow side is likely to lead to toppling (free-fall) failure which can be very dangerous, especially to site personnel. Approaching the same fault from the downthrow side may result in planar failure, but this tends to progress more slowly, and is therefore generally less dangerous.

CONCLUSION

There are several published case studies which describe fault related slope failures at UK opencast sites, for example Duckhead (Hughes and McLean, 1986) and Plenmeller (Hughes and Norbury, 1996); and there are many more unpublished case studies for which the data exists.

It is suggested that there is the potential for a comprehensive review of fault related failure case studies, which could then become a useful reference and aid to the future planning and design of opencast coal mining operations.

REFERENCES


Herrington Colliery opencast coal site.


Note: In the paper included in Appendix A, the title has been extended by "Late Devensian deposits at –". The Editors of the QRA Field Guide reduced the title, re-numbered the Figures (but omitted to change the text?), omitted Appendix 1 (Table of Simplified Descriptions for Soils) – but still left reference to it in the text, and included the references in a combined list at the end of the book, The abstract given is also additional to the published paper.
Late Devensian deposits at Herrington Colliery opencast coal site

Abstract:

Herrington Colliery closed in 1985, and left as its legacy an unsightly 40m high pit heap containing some 50 million m$^3$ of colliery spoils, together with a derelict colliery yard and buildings. With the objective of restoring the land to a country park and local amenity area, an opencast mining project commenced in 1996, from which almost 1 million tonnes of coal has been won. The main excavation was through Coal Measures bedrock which was overlain by glacial tills. In the south eastern part of the site the tills were overlain by glaciolacustrine (laminated) deposits. The main till is the 'Durham Lower Boulder Clay' which was deposited by Late Devensian ice flowing from the west. Near the end of the Late Devensian glaciation, northern ice flowed southwards along the east coast of Northern England and thus formed onshore lakes by impounding meltwater from the retreating western ice mass. The largest of these lakes was the Glacial Lake Wear which resulted in the deposition of deep glaciolacustrine sediments (locally named the Tyne-Wear Complex). Good exposures of these glaciolacustrine materials have been a feature at Herrington. However, these laminated deposits have caused several slope failures during opencast operations, and records show that instability of the pit heap was a constant problem when the colliery was working. Although the height of the pit heap has now been much reduced, there still remains a large mound which has been grassed and is beginning to resemble the green and rounded hills of the nearby Magnesian Limestone outcrop.
Herrington Colliery was opened in 1874, and by the time it had closed in 1985, a massive pit heap of some 5,000,000 cubic metres had been created. In 1991 British Coal Opencast, in conjunction with Sunderland MBC (later City of Sunderland), put forward a combined opencast coal/land reclamation project, and planning permission was finally granted in 1993. Following the privatisation of the UK coal industry at the end of 1994, RJB Mining (UK) Ltd (also in association with Sunderland City, and with support from English Partnerships) awarded the mining contract to Crouch Mining Ltd, with site work commencing in May 1996. This contract is for the mining of approximately 750,000 tonnes of coal from 10 seams, with associated earthworks involving excavation to 70 m depth. The main site works are expected to be completed by autumn 2000, and the final restoration will mostly be as a country park and amenity area with a substantial lowering (but not total removal) of the former Herrington Colliery pit heap.

The layout of the site is shown in Figure 1. Digging for coal began with the initial cut at the NW end of the excavation area, and has progressed in a SE direction. The majority of the excavation is through Coal Measures bedrock (sandstone, siltstone, mudstone, coal and seat-earth); plus this solid geology is overlain everywhere by glacial till, and additionally by laminated clay in the SE part of the site. There will also be much excavation and redistribution of the colliery spoils from the pit heap to achieve the final landscaping. By the time the Quaternary Research Association visit takes place in April 1999, it is anticipated that coaling operations will be adjacent to Foxcover Bank Plantation (SNCI), i.e. the south-eastern cuts, as shown in Figure 1.
Figure 1. Plan of Herrington Colliery Opencast Coal Site.
LATE DEVENSIAN AND TYNE-WEAR COMPLEX

An account of the glacial history and glacial deposits of North East England is presented elsewhere in this Field Guide by Teasdale and Hughes (1999). The Quaternary geology of the Sunderland District (Sheet 21), which includes the Herrington area, has been described in detail by Smith (1994). With the exception of the mining spoils and organic soils, the Late Devensian glaciation is thought to be responsible in one way or another for all the superficial deposits which occur at Herrington.

Smith (1994) referred to the Durham Lower Boulder Clay as being the main product of the Late Devensian western (Southern Uplands, Lake District, Northern Pennines) ice sources, with the Durham Upper Boulder Clay being deposited mostly along the coast by the later northern (Tweed-Cheviot) ice stream. It is the Durham Lower Boulder Clay (lower till) which occurs above rockhead over the Herrington site area, and was described by Smith as "a tough, overconsolidated, grey or brown, sandy clay, which contains abundant subangular to subrounded pebbles and cobbles, and a few boulders". The Basal Sand and Gravel (i.e. the base of the Quaternary - Smith) was proved by boreholes to be mostly absent from within the site area.

Toward the end of the Late Devensian, eastward flowing meltwater from the retreating western ice was cut-off by advancing northern ice, so creating a series of ice-dammed lakes, the largest of which was the Glacial Lake Wear. Smith (1994) suggested that this lake stood at different levels as outlets opened and closed. Figure 2 shows the shape of the lake for Smith's inferred 43 m AOD stand, but he also referred to a stand at 90 m AOD when the Tunstall Hope overflow channel would have been active; and the highest lake sediments he recorded were at about 132 m AOD. The glaciolacustrine deposits which resulted from Glacial Lake Wear were named by Smith as the Tyne-Wear Complex. These generally comprise interbedded laminated silty clays and clayey silts, with fine-grained sands and stony clays and some gravels. The thickness of this formation is commonly between 5 m and 15 m, but can be up to 55 m (Smith, 1994).
Figure 2. Approximate shape of Glacial Lake Wear (stippled) during inferred 43m stand (after Smith, 1994). Also shown are Herrington opencast excavation area, and present courses of Rivers Tyne and Wear.
BOREHOLE RECORDS AND SITE OBSERVATIONS

As part of the geotechnical investigations for the Herrington project a total of 85 cable-percussion boreholes were sunk through the superficial deposits down to rockhead. Of these, 37 boreholes were located within or adjacent to the excavation area; the remaining boreholes were sited for lagoons, soil and overburden storage mounds, surface restoration and landscaping. The overall thickness of the superficial deposits (excluding colliery spoils) varies from 2 m up to 28 m, as proved by the boreholes.

Figures 3 and 4 show the geotechnical (cable-percussion) borehole details along the section lines given in Figure 1. The UK ground investigation industry normally uses BS5930:1981 for soil and rock descriptions (i.e. for civil/mining engineering, and engineering geological applications). Hence all the geotechnical boreholes at Herrington have been logged to this British Standard system, and the descriptions given in Figures 3 and 4 have been necessarily abbreviated to facilitate their inclusion on small diagrams. Appendix 1 presents a table showing simplified engineering descriptions for soils.

Figure 3 shows the ground succession details from five boreholes which were sunk along the NE side of the excavation area. These boreholes show till (Durham Lower Boulder Clay) overlying rockhead, with laminated clay (Tyne-Wear Complex) overlying the till only in the SE part (Borehole 9144). The till descriptions vary considerably, but an overall engineering representation is soft/firm/very stiff, silty, sandy, CLAY, with a little/some gravel. Much of the gravel (and any cobbles/boulders) consists of Magnesian Limestone, particularly in the NW part of the site. There are also bands of SILT and/or SAND, which may be clayey, silty, sandy or gravelly. The various colour descriptions include orange/yellow/brown mottled, red, red/brown, dark brown, brown/grey, grey/brown, and grey.

At Herrington the boreholes and the opencast excavations taken through the glacial deposits have frequently revealed brown till beneath grey till, which does not conform with the weathering model of Eyles and Sladen (1981). An examination of the cable-percussion borehole records showed this "brown below grey" colour sequence to occur in about half of the boreholes which penetrated down to rockhead. Borehole 9207 (Figure 3) which was located near the mid-point of the NE side of the excavation area recorded a sequence of
Figure 3. Section looking NE towards the northern sidewall of the excavation area at Herrington Colliery Opencast Coal Site, showing abbreviated engineering descriptions (BS 5938:1981) for the Late Devensian deposits as taken from the Geotechnical Borehole Logs.

This sidewall has been exposed sequentially at the NE end of each successive cut as the opencast excavation has progressed SE from the initial cut which was excavated in May/June 1996 (See Figure 1). At the time of the proposed QRA visit in April 1999 it is anticipated that the south-eastern cuts will be exposed (i.e. in the vicinity of Boreholes 9144, 9007 and 9012 - see Figure 4).
Figure 4. Section looking S.E., along the highwall of cut 9 of the excavation area at Herrington Colliery Opencast Coal Site, showing abbreviated engineering descriptions (BS 5930:1981) for Late Devensian deposits as taken from the Geotechnical Borehole Logs. It is anticipated that excavated slopes in the south-eastern cuts (through this section) will be exposed at the time of the proposed QRA visit in April 1999.
brown and grey bands; and this was confirmed by observations on site in February 1998, when a brown/grey/brown/grey/brown succession was recorded (Hughes et al, 1998).

Figure 4 shows that in the SE part of the excavation area there are laminated clays of the Tyne-Wear Complex overlying the Durham Lower Boulder Clay. The maximum thickness of laminated clay recorded in any borehole was 16 m (in Borehole 9125 - not plotted). The overall engineering description for these glaciolacustrine deposits is soft/firm/stiff, grey/brown or brown/grey, thinly laminated silty CLAY, with silty and fine sandy partings.

DISCUSSION AND IMPLICATIONS

As stated previously, Smith (1994) proposed that two sequential ice advances from different sources (western and northern) led to the separate formation of the Durham Lower Boulder Clay (onshore) and the Durham Upper Boulder Clay (mainly near the coast and offshore). Carruthers (1953) and Catt (1991), however, suggested that a single, but tiered, ice sheet was the creator of the till layers in North East England. From their work done on the Northumberland coastal lowlands, Eyles and Sladen (1981) concluded that a single ice sheet deposited the whole of the till, and that weathering alone explained the colour change from grey in the lower part of the succession (lower till) to red or brown in the upper part (upper till). Yet, we know from the borehole records and from site observations that at Herrington brown till frequently underlies grey till. So weathering alone cannot be the explanation for these colour differences.

Smith (1994) referred to the Pelaw Clay formation that is generally found further east than Herrington, which he described as a reddish brown silty clay, with variable amounts of pebbles, and as being up to 4.5 m in thickness. His tentative explanation for the origin of the Pelaw Clay was that it "might be the product of periglacial modification and redistribution of existing deposits, but especially of the plastic laminated clay following the draining of Glacial Lake Wear". Surrounding Herrington are several hills (e.g. Penshaw, Carr, Hastings, Foxcover Bank, Herrington) where the bedrock (Magnesian Limestone and Coal Measures) protrudes through the drift. These could have acted as sources for local debris flows or earthflows when periglacial conditions prevailed at the end of the Dimlington Stadial and during the subsequent Loch Lomond Stadial. Therefore, could some of the upper and
variously coloured drift layers at Herrington, as shown in Figures 3 and 4, be solifluction deposits?

The Tyne-Wear Complex laminated clays only occur in the SE part of the Herrington excavation area, which fits very well with Smith's 43 m AOD stand for the Glacial Lake Wear (Figure 2), assuming that this also represents the limits of the glaciolacustrine deposits in the area. The occurrence of these laminated clays, being of relatively low shear strength and highly compressible, can lead to problems on civil and mining engineering projects (Hughes, 1996; Hughes and Clarke, 1997). Slope failures in excavated faces have been experienced at Herrington opencast site due to the presence of these laminated deposits. Also, the Herrington Colliery pit heap was known to be very prone to foundation failure (massive toe-heave) due to being placed above these weak clays. The Tyne-Wear Complex deposits have been excavated at a number of locations for brick making (e.g. Kibblesworth (NZ 255 566) and Birtley (NZ 262 562)) and some quite spectacular slope failures have occurred at these quarries. Where large buildings or bridges have been constructed over these laminated clays (e.g. Team Valley Industrial Estate and the Metro Centre at Gateshead) then deep piled foundations have usually been necessary.

CONCLUDING REMARKS

As explained by Teasdale and Hughes (1999) and summarised above, there is some confusion about the behaviour of the Late Devensian ice in North East England, and the mode of deposition of the tills. From the civil and mining engineers' point of view building on, or excavating through, glacial deposits can present many problems. Much research is still needed into the physical and geotechnical properties of these materials, especially the weaker horizons such as laminated clay. From the glacial geologists' point of view there is great potential to study the nature and succession of glacial deposits using the information from geotechnical investigations (e.g. borehole logs and soil mechanics test results) which are usually carried out in connection with civil and mining engineering projects.

Geotechnical reports are usually precisely worded documents containing records of boreholes and trial pits which are often available from localities where no sections are accessible. In the case of Herrington Colliery Opencast Site, mining operations will destroy some of the
geological evidence (about a third of the total site area - see Figure 1), but the geotechnical reports from the site will remain a valuable potential resource to Quaternary researchers.

ACKNOWLEDGEMENTS

The authors wish to record their gratitude to RJB Mining (UK) Ltd for facilitating the study of Late Devensian deposits at Herrington, and for many site visits (including the proposed QRA visit in April 1999); also for permission to present this paper. However, the views expressed herein are entirely those of the authors.
# APPENDIX 1

## Table of Simplified Engineering Descriptions for Soils

(based on BS 5930:1981, but with some later modifications)

<table>
<thead>
<tr>
<th>Consistency (cohesive)</th>
<th>Shear strength kPa</th>
<th>Colour</th>
<th>Bedding or structure (if appropriate)</th>
<th>Bedding thickness mm (if appropriate)</th>
<th>Prefixes</th>
<th>SOIL TYPE</th>
<th>Particle size mm (if appropriate)</th>
<th>Suffixes (if appropriate)</th>
<th>Remarks and clarification (if appropriate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very soft</td>
<td>&lt; 20</td>
<td>e.g.</td>
<td>very thickly bedded</td>
<td>&gt; 2000</td>
<td>e.g.</td>
<td>BOULDERS</td>
<td>&gt; 2000</td>
<td>e.g.</td>
<td>plasticity, surface texture, weathering</td>
</tr>
<tr>
<td>Soft</td>
<td>20 - 40</td>
<td>light</td>
<td>thickly bedded</td>
<td>600 - 2000</td>
<td>slightly</td>
<td>BOULDERS</td>
<td>600 - 2000</td>
<td>with a little</td>
<td></td>
</tr>
<tr>
<td>Firm</td>
<td>40 - 75</td>
<td>dark</td>
<td>medium bedded</td>
<td>200 - 600</td>
<td>very</td>
<td>COBBLES</td>
<td>200 - 600</td>
<td>with some</td>
<td></td>
</tr>
<tr>
<td>Stiff</td>
<td>75 - 150</td>
<td>mottled</td>
<td>thinly bedded</td>
<td>60 - 200</td>
<td>clayey</td>
<td>coarse GRAVEL</td>
<td>60 - 200</td>
<td>occasional</td>
<td></td>
</tr>
<tr>
<td>Very stiff</td>
<td>&gt; 150</td>
<td>orange</td>
<td>very thinly bedded</td>
<td>20 - 60</td>
<td>silty</td>
<td>medium GRAVEL</td>
<td>20 - 60</td>
<td>much/many</td>
<td></td>
</tr>
<tr>
<td>Relative Density (granular)</td>
<td>S.P.T.</td>
<td>red</td>
<td>thickly laminated</td>
<td>6 - 20</td>
<td>sandy</td>
<td>fine GRAVEL</td>
<td>6 - 20</td>
<td>etc.</td>
<td>also minor, constituents or partings</td>
</tr>
<tr>
<td>Very loose</td>
<td>&lt; 4</td>
<td>brown</td>
<td>thinly laminated</td>
<td>&lt; 6</td>
<td>gravelly</td>
<td>coarse SAND</td>
<td>2 - 6</td>
<td>(relate to % proportion - see BS 5930 : 1981)</td>
<td>etc.</td>
</tr>
<tr>
<td>Loose</td>
<td>4 - 10</td>
<td>grey</td>
<td>homogenous/</td>
<td>0.6 - 2</td>
<td>proportion - see BS 5930 : 1981</td>
<td>fine SAND</td>
<td>0.2 - 0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium dense</td>
<td>10 - 30</td>
<td>etc.</td>
<td>heterogenous, intact</td>
<td>0.06 - 0.2</td>
<td>coarse SILT</td>
<td>medium SILT</td>
<td>0.02 - 0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dense</td>
<td>30 - 50</td>
<td>etc.</td>
<td>etc.</td>
<td>0.006 - 0.02</td>
<td>fine SILT</td>
<td>fine SILT</td>
<td>0.006 - 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very dense</td>
<td>&gt; 50</td>
<td>etc.</td>
<td>etc.</td>
<td>e.g.</td>
<td>CLAY</td>
<td>PEAT/Organic soils</td>
<td>&lt; 0.002</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**EXAMPLES**

- Very stiff dark brownish grey, slightly sandy, very silty CLAY with occasional cobbles and boulders (GLACIAL TILL).
- Loose, reddish brown, thickly bedded, medium to coarse SAND with some gravel and occasional cobbles.
- Very soft to soft, light grey, thinly laminated, silty CLAY with occasional sandy partings.

(Note: BS 5930 is currently being revised)
REFERENCES


The River Aire slope failure at St. Aidans Extension Opencast Coal Site, West Yorkshire, United Kingdom.

The River Aire slope failure at the St. Aidans Extension Opencast Coal Site, West Yorkshire, United Kingdom

D.B. Hughes and B.G. Clarke

Abstract: The St. Aidans Extension Opencast Coal Site is located in the flood plain of the River Aire 10 km southeast of Leeds, United Kingdom. In March 1988, a massive (600,000 m³) slope failure caused a breach of the riverbanks and flood-protection levee, and so connected the river to the opencast void, resulting in flooding of the site. A lake of about 100 ha and up to 70 m depth was created, and coal winning operations had to be suspended for 10 years. The causes of this slope failure included the effects of previous underground coal mining beneath those seams which were being surface mined, resulting in large tensile strains (up to 10 mm/m) in a heavily faulted zone that lay beneath the river bed and an adjacent navigation canal. The fracturing and opening of existing faults and joints greatly increased the permeability beneath the river, which then acted as a source of continuous recharge as the failed mass moved towards the opencast void. Subsequent remedial and recovery works (costing £20 million) have included the rerouting of the River Aire together with the canal, and pumping the flood water from the void and restarting opencast mining operations (tender sum £36 million) with a new box cut. This paper details the ground conditions and the history of events and discusses the probable mode of failure.

Key words: opencast mining, slope failure, flooding, mining subsidence, ground strains, faulting.

Introduction

In March 1988, a massive (600,000 m³) slope failure occurred adjacent to the River Aire, in West Yorkshire, United Kingdom, which resulted in the rapid flooding of the working void at St. Aidans Extension Opencast Coal Site. A very large section of the excavated side slope (about 350 m long, 120 m wide, and 50 m high) moved towards the opencast void and was associated with a major breach of the riverbank and flood levee. Over the following 3 days some 17 million m³ of river water flowed into the site, and a lake of about 100 ha and 70 m maximum depth was created (see Fig. 1). This caused the temporary, but quite long term abandonment of around 2 million tonnes of coal.

As well as losses in revenue from the coal and other suspension of work costs, the delay involved expenditure on parliamentary legislation and mineral planning procedures, ground investigations, and the design and construction of new works. This included the construction of a 3.5 km length of new waterway (combined river and canal diversion) and other ancillary works costing a total of around £20 million (Anonymous 1999). Opencast operations did not recommence at St. Aidans until early 1998, i.e., about 10 years


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after this disastrous slope failure. The tender sum for completing the project (involving pumping out the flooded void, excavating a new box cut, and winning 2.8 million tonnes of coal) was around £36 million (Anonymous 1999).

Although slope failures in opencast workings do occur (Hughes and Leigh 1985; Hughes and McLean 1986), it was the flooding of the excavation void that made this case history so unusual and noteworthy. Geotechnically, the failure was exceptional because it appeared to have been triggered by the presence of previous underground workings, which caused a loss in mass strength and an increase in mass permeability.

Major slope failures at opencast coal sites in the United Kingdom involving large mining-induced tensile strains are comparatively rare, but they had been reported previously to 1988. Walton and Taylor (1977) described failures in Yorkshire and Staffordshire where longwall mining caused tensile strains of around 3–4 mm/m, which resulted in shear displacements along weak bedding horizons and surface fissures parallel with the edge of the ribside or mining panel. Scoble (1981) described work done by Walton for Lowther North opencast site (which was adjacent to St. Aidans in West Yorkshire), where the geological succession was very similar, and referred to tensile strains of 3–4 mm/m also causing shearing along weak bedding horizons and fissuring, thus contributing to the instability of excavated slopes. Others have investigated the effects of longwall mining on the stability of colliery spoil heaps (Forrester and Whittaker 1976; Siddle et al. 1985), and they too referred to tensile strains of around 3 mm/m being responsible for surface fissuring and leading to instability. Tensile strains and fissuring which had resulted from much earlier underground mining were also quoted as having contributed to the instability of the spoil heap at Aberfan in South Wales in 1966 where 144 people (mostly children) died when a sudden flow slide in colliery spoils engulfed a school (National Coal Board 1968; Welsh Office 1969). As part of the investigations which immediately followed the River Aire slope failure at St. Aidans, the maximum tensile strains were calculated to be up to 10 mm/m (i.e., two and a half to three times the magnitude of those quoted above), so vertical fissuring (especially in the river bed) and shear displacement along weak bedding horizons must have been major contributory factors to this slope failure.

This paper describes the ground conditions, opencasting operations, and history of events and examines the probable mode of failure including the relationship between the movement of the main mass and the first breach of the river-bank and flood levee. The effects that existing underground workings had upon the stability of surface excavations form an important aspect of this case study. A brief account is given of how the opencast coal site has been recovered, including the recommencement of coal winning operations.
St. Aidans Extension Opencast Coal Site and the River Aire

The St. Aidans Extension Opencast Coal Site is located approximately 10 km southeast of Leeds and 5 km north west of Castleford, as shown in Fig. 2. The site was owned by the National Coal Board (NCB) Opencast Executive, which later became known as British Coal Opencast (BCO), and then, following privatisation of the coal industry in the United Kingdom in December 1994, ownership passed to RJB Mining (UK) Ltd. Figure 3 is a plan of the site and shows some of the main features.

This part of West Yorkshire has been extensively deep-mined for coal since the late 1800s, leaving a legacy of abandoned collieries and spoil tips. Also, there have been several opencast coal mines worked hereabouts since the 1940s. The original intention for the St. Aidans extension scheme was to clear a large area of dereliction. This would then provide land for the construction of visual screening embankments and thus create concealed spoil disposal areas for those collieries still in operation in the 1980s (see Fig. 3). The final restoration was to include a country park with water meadows and shallow lakes to store and control flood water from the River Aire (Morgan 1992).

The first St. Aidans Opencast Site was located farther to the east, and was worked during the middle to late 1970s. The St. Aidans Extension Site was physically a continuation of the earlier St. Aidans Site, but it was a new contract which started in 1981. This extension occupied an area of almost 400 ha and was expected to yield about 6 million tonnes of coal during its programmed 10 year production life.

The River Aire formed the western and southern boundaries of St. Aidans Extension Site (see Fig. 3). In this vicinity the Aire and Calder Navigation Canal ran approximately parallel to the course of the river, but due to the river's several meanders and bends, its location varied between 20 and 500 m farther to the west and south. In 1983 (i.e., during the early stages of the project and as part of the planned programme of work), a diversion of the River Aire was constructed along the western boundary of the site and included a new weir to replace an existing one. This improved the flow of the river and enabled some coal to be recovered from beneath and beyond the former river bed. The new river channel was located near the Fleet oil depot and was known as the Fleet Diversion (Fig. 3), and the new weir became the new Fleet Weir. (The southern (i.e., downstream) end of this diversion coincided with the subsequent River Aire failure zone.) A 4 m high flood levee, constructed with excavated sandstone and colliery spoils taken from within the opencast site, was formed along the eastern side of the Fleet Diversion, and extended for several hundred metres downstream (i.e., south to southwest) of where this new river channel rejoined the previous one. A steel sheet piled cutoff which generally penetrated down to rockhead was driven along the centre line of this flood levee. It had been the intention at a later date to construct a second river diversion (the Astley Diversion, also shown in Fig. 3) farther downstream and adjacent to the southern site boundary, but this later scheme was overtaken by events. The routing of the river diversions and stand-off distances from the river to the excavation limits of the opencast site had all been the subjects of discussion and agreement with the relevant statutory authorities during the planning and design stages of the mining project. It is understood that these agreed stand-off distances were to a large degree based on the previous experience of the BCO of similar situations rather than on detailed geotechnical analyses, as there had been very little drilling or other ground investigations carried out in this vicinity (see the section on Ground investigations immediately following). Davies (1988) did, however, refer to precontract designs.

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Ground investigations

Prospecting for coal by rotary drilling (mainly open hole) began in 1957 and continued intermittently until 1970. The main geological assessment of St. Aidans Extension Site was carried out between 1971 and 1978 using the information provided by rotary open-hole boreholes, cored boreholes, and some geophysical logging techniques. The total number of boreholes drilled was around 1000, and this direct ground investigation exercise was supplemented by information obtained from existing mining and geological records. No boreholes were drilled outside the planned excavation limits, however, and there appeared to be no specific geotechnical ground investigations related to any slope stability studies.

Initially, drilling was permitted by the Yorkshire Mines Drainage Unit (at that time the statutory authority for groundwater matters in this coalfield) to a maximum depth of 1 m below the Dunsil seam (i.e., the basal or pavement seam for opencast mining; see Fig. 4). Subsequently, this was increased to 5 m below to facilitate geophysical logging to the base of the Dunsil. All rotary boreholes sunk prior to the commencement of the main St. Aidans extension coaling contract were sealed with cement grout. This was to prevent groundwater flowing from the higher strata (which could possibly include confined aquifers) into lower strata where underground mining was still considered to be a future possibility.

The spacing of prospecting boreholes was generally at 30-40 m centres on an approximate triangular or diamond pattern in plan. In some central and northern parts of the site, spoil heaps and ponding gave access problems for drilling rigs, and thus resulted in wider borehole spacings and sometimes large gaps in the subsurface information. Of particular relevance was the omission of boreholes in the Swillington Ings area in the southern section of the site (see Fig. 3) which included the ground immediately adjacent to the subsequent River Aire slope failure, and which was covered by up to 2.5 m of water (Ings is a local term for water meadow). Subsequently, in 1986, some rotary boreholes were sunk to prove the geological conditions along the western and southern perimeter of the Swillington Ings (i.e., after opencast operations had commenced), but these boreholes were apparently not sealed with cement grout.

Geophysical logging was only carried out during the final years of prospecting and consisted of downhole (slimline) logging for long spacing density, high resolution density, and natural gamma logs. This information assisted in identifying and correlating coal seams but was of limited geotechnical value (Hughes and Blythe 1987).

Cable percussion boreholes and trial pits were sunk in the vicinity of the River Aire in connection with the construction of the Fleet Diversion of the river. These investigations of the superficial deposits were located to the northwest, i.e., upstream of the subsequent River Aire slope failure.

Geology

The general downwards succession of the strata to the base of the productive coal measures is shown in Fig. 4. This information has been compiled from prospecting drilling and from the shaft section details for the former Methley-Savile Colliery which was located to the south of St. Aidans.

The unconsolidated or superficial deposits of the River Aire flood plain in which the opencast site was situated consisted mostly of fluvioglacial gravels, sands, silts, and clays, the total thickness being generally in the range 5-8 m. There were also some local deposits of made ground associated...
Fig. 4. General geological succession at the St. Aidans Extension Site. OD, Ordnance Datum.

with previous improvements or diversions to this water-course. Elsewhere within the opencast site there existed considerable thicknesses of made ground, being mainly either colliery spoils or older opencast backfills.

The bedrock succession consisted of coal measures from the Kents Thick seam to beneath the Beeston seam. Only the horizon from the Kents Thick seam down to the Dunsil seam has been worked by opencast mining methods, and these strata comprised mainly mudstones which were usually described as silty or sandy. A prominent sandstone band was encountered between the Kents Thick and Barnsley Top Softs seams, and a less persistent sandstone was encountered between the Low Barnsley and the Dunsil seams. Weak seatearths were usually present beneath the coal seams.2 In the vicinity of the River Aire failure the bedding dipped gently at around 2–3° (1 in 110 to 1 in 20 gradient) to the northeast, that is, towards the working void. Also, the Kents Thick seam outcropped just to the north of the main failure zone, and therefore is not shown on any of the failure cross sections (see Figs. 6, 13).

The whole of the St. Aidans Extension Site area lies between two major faults, the Water Haigh Fault to the north and the Methley-Savile Fault to the south (see Figs. 3, 5). Both faults trend west-southwest-east-northeast and down-throw south-southeast, with maximum vertical displacements of around 135 and 25 m, respectively. Records from the underground mining of the sub-Dunsil seams indicated the existence of at least three sets of minor faults within the area bounded by these two major faults (see Fig. 5).

Previous underground mining

Most of the information on past underground mining used in this paper was obtained from records previously kept in the former National Coal Board (NCB) – British Coal (BC) Deep Mines North Yorkshire Area offices. The seams and their method of working are shown in Fig. 6, which also shows a section through the River Aire and western endwall of the working void.3

The seams worked by opencasting adjacent to the failure zone included the Barnsley Top Softs, Low Barnsley, and Dunsil seams. Extensive room and pillar old workings in the Barnsley Top Softs were evident from prospecting drilling and were proved during site working, especially after the site restarted in 1998 when areas of up to 70–80% extraction were encountered to the southeast of the failure zone. A few boreholes recorded old workings in the Low Barnsley seam, but these were probably trial headings from the overlying workings in the Barnsley Top Softs. No previous workings were recorded or encountered in the Dunsil seam.

Beneath the Dunsil pavement at St. Aidans Extension Site, the Haigh Moor, Flockton, Middleton Little, Silkstone, Eleven Yards, and Beeston seams had all been previously worked by underground mining methods. A prominent sandstone band was encountered between the Kents Thick and Barnsley Top Softs seams, and a less persistent sandstone was encountered between the Low Barnsley and the Dunsil seams. Weak seatearths were usually present beneath the coal seams.2 In the vicinity of the River Aire failure the bedding dipped gently at around 2–3° (1 in 110 to 1 in 20 gradient) to the northeast, that is, towards the working void. Also, the Kents Thick seam outcropped just to the north of the main failure zone, and therefore is not shown on any of the failure cross sections (see Figs. 6, 13).

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2 Weak seatearths are sometimes called clay bands, clay mylonites, or intraformational shear zones (Stimpson and Walton 1970; Salehy et al. 1977; Jameson 1995). Seatearths may occur without the presence of such bands or zones but may themselves be weak, or they can have local weaknesses due to the presence of such zones.

3 Note that a site datum of 100 m below Ordnance Datum (United Kingdom) was used so that all levels for the opencast mining project had positive values.
Fig. 5. The pattern of faulting recorded in the sub-Dunsil seams. At least three sets of faulting can be identified: north-south, northwest-southeast, and southwest-northeast.

worked, either by room and pillar or longwall extraction methods. In four of these seams (the Haigh Moor, Flockton, Silkstone, and Beeston) workings from the east terminated adjacent to and subparallel with the end wall in the failure area. In the Middleton Little and Eleven Yards seams, underground workings terminated much farther to the east (see Fig. 6).

The surface subsidence and ground strains due to the known underground mining history were calculated for the centre line of the failure (cut 45) and extended west-southwest to the river and canal. The calculated deformations and strains (obtained from using the empirical methods described in National Coal Board 1975) are presented diagrammatically in Fig. 6, which shows the maximum subsidence to be 3.6 m and the maximum tensile strain at the surface to be 10 mm/m (or 1%). This magnitude of tensile strain is sufficient to cause fault zones to open and to create new discontinuities (National Coal Board 1975; Forrester and Whittaker 1976; Walton and Taylor 1977; Scoble 1981; Siddle et al. 1985).

Faulting aligned subparallel with the course of the river was recorded beneath the main River Aire failure zone in the Haigh Moor, Flockton, and Silkstone seams (Fig. 6). The mining records also indicated subparallel faulting in the other three sub-Dunsil seams, either within or trending towards the area beneath the failure zone (Figs. 5, 6).

**Groundwater**

During prospecting drilling for the St. Aidans Extension Opencast Site, groundwater inflows were recorded in the superficial deposits, in the Barnsley Top Softs seam, and in the sandstone underlying the Dunsil seam, this being the maximum depth of drilling. However, only two piezometers were installed during the entire coal prospecting exercise (see Table 1), one into mudstone overlying Barnsley Top Softs seam old workings (piezometer 1146), and one into made ground (piezometer 1147). Both of these piezometers were located some 750 m north-northeast of the River Aire slope failure and were removed during the early stages of opencast excavation. Several shallow piezometers were also installed within the superficial deposits during the ground investigations for the river diversion works (see previous sections on Ground investigations and Geology), but these were all located well upstream of the failure and generally recorded groundwater at less than 2.0 m depth. Once excavation for coal had begun, a further six rather makeshift piezometers (MM1, MM2, MM3, P1, P2, and NWH) were installed into bedrock on the western side of the site, i.e., near the River Aire. The details and records for these later piezometers are very incomplete and several became blocked (or restricted) soon after installation. A summary of the available data for all piezometers is given in Table 1.

Observations were made of groundwater seepage from excavation faces during the progress of the site works. Persistent seepage was recorded at the base of the superficial deposits, at the base of the Kents Thick seam, at the base of the sandstone underlying the Kents Thick seam (i.e., just above the Barnsley Rider horizon), and from the Barnsley Top Softs old workings. Intermittent seepage was recorded where the Low Barnsley old workings were encountered.

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Fig. 6. A section through the western end wall of the working void (looking north-northwest) showing the underlying seams and their method of extraction, with the magnitudes of surface subsidence and strains shown graphically above the ground profile. The River Aire failure occurred just to the south of the Kents Thick seam outcrop, hence this seam is not shown. Levels shown for seams extracted by underground mining are approximate only.
Table 1. Summary of piezometer details.

<table>
<thead>
<tr>
<th>Piezometer identification</th>
<th>Location</th>
<th>Surface level (m ASD)</th>
<th>Depth to base (m)</th>
<th>Base level (m ASD)</th>
<th>Stratum at base</th>
<th>Depth to standing water (m)</th>
<th>Standing water level (m ASD)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1146</td>
<td>750 m north-northeast of failure</td>
<td>113.73</td>
<td>54.00</td>
<td>59.73</td>
<td>Sandy mudstone overlying Barnsley Top Softs old workings</td>
<td>2.04–2.19</td>
<td>111.69–111.54</td>
<td>Installed during prospecting; removed during early stages of site excavations</td>
</tr>
<tr>
<td>1147</td>
<td>750 m north-northeast of failure</td>
<td>113.73</td>
<td>10.50</td>
<td>103.23</td>
<td>Made ground immediately above rockhead</td>
<td>2.08–3.83</td>
<td>111.65–109.00</td>
<td>Installed during prospecting; removed during early stages of site excavations</td>
</tr>
<tr>
<td>Fleet river piezometers</td>
<td>200–800 m northwest of failure</td>
<td>—</td>
<td>Max. 6.90</td>
<td>—</td>
<td>Superficial deposits</td>
<td>Max. 2.00</td>
<td>—</td>
<td>Part of shallow ground investigations for Fleet river diversion</td>
</tr>
<tr>
<td>MM1, MM2, MM3</td>
<td>500 m north west of failure</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Approx. 102.00</td>
<td>Weak mudstone (?)</td>
<td>Approx. 6.00–7.00</td>
<td>105.36–106.77</td>
<td>Well-pointing pipes; operational May 1986 to January 1988; some blockages (restrictions) occurred (?)</td>
</tr>
<tr>
<td>P1</td>
<td>50 m northwest of section line shown in Figs. 3, 6, 12, and 13; on rockhead bench</td>
<td>100.64</td>
<td>16.18</td>
<td>84.46</td>
<td>Approx. 19 m above base of Barnsley Top Softs</td>
<td>3.53–9.62</td>
<td>97.11–91.02</td>
<td>Became blocked at 81 m ASD immediately after installation; water levels fell gradually during period May 1987 to January 1988</td>
</tr>
<tr>
<td>P2</td>
<td>Same as P1</td>
<td>100.78</td>
<td>35.35</td>
<td>65.43</td>
<td>Approx. 7 m below base of Barnsley Top Softs</td>
<td>11.37–26.83</td>
<td>89.41–73.95</td>
<td>Became blocked at 95 m ASD in September 1987; installed May 1987</td>
</tr>
<tr>
<td>NWH</td>
<td>Same as P1</td>
<td>100.87</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>11.17–12.96</td>
<td>89.70–87.91</td>
<td>Records of installation details for this piezometer could not be found</td>
</tr>
</tbody>
</table>

Note: Seven piezometers provided for the Fleet river diversion were installed in cable-percussion-drilled boreholes. All other devices were installed down rotary-drilled air-flushed boreholes (MM1, MM2, MM3, P1, P2, and NWH were drilled by blast-hole rig) and are thought to have been fairly basic standpipes, which was the normal standard for much of the United Kingdom opencast coal industry at that time.
Table 2. Groundwater horizons.

<table>
<thead>
<tr>
<th>Water table horizon</th>
<th>Possible confining bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial deposits</td>
<td>Mudstone immediately below or very close to rockhead</td>
</tr>
<tr>
<td>Barnsley Top Softs seam</td>
<td>Barnsley Top Softs seatearth</td>
</tr>
<tr>
<td>Sub-Dunsil seam</td>
<td>An aquiclude somewhere below the Haigh Moor seam, but above the Flockton seam (?)</td>
</tr>
<tr>
<td>Sub-Flockton seam</td>
<td>Unknown, but below the Beeston seam (?)</td>
</tr>
</tbody>
</table>

Following the slope failure event, an examination of the “panel layout files” from the NCB – BC Deep Mines records was made which indicated that the Haigh Moor seam (at some 57–60 m below the Dunsil seam) was water-bearing, but indicated that the Flockton seam (below the Haigh Moor) could be worked in relatively dry conditions. These same records also indicated that the underlying Middleton Little, Silkstone, Eleven Yards, and Beeston seams were all water-bearing.

A review of all the groundwater information collected showed that four water-table horizons probably existed before any underground or opencast mining took place, and these are shown in Table 2.

Several of the piezometers which had been installed near the River Aire (following the commencement of coal mining operations) indicated that the groundwater levels in both the superficial deposits and in the Barnsley Top Softs seam were, in fact, the same.

The extraction of coal from the six seams below the site pavement, plus workings in the seams included in the opencast project, had led to large cumulative subsidence displacements and large ground strains (Fig. 6). The creation of the opencast void would also have resulted in further stress relief leading to the opening of many subvertical discontinuities such as joints, cracks, and fault zones (Walton and Taylor 1977; Scoble 1981). This in turn would have created new and improved existing drainage paths, and hence would have greatly increased secondary permeability in the rock mass.

Overall, it can be assumed that there was a fairly high degree of hydraulic continuity through the strata involved in and beneath the River Aire failure. This groundwater system was constantly recharged by the river, together with water from the flooded (Ings) areas and other surface drainage. Thus, the groundwater profile given in Table 2 would have been much altered.

Opencast operations

At St. Aidans the method of winning coal, common on opencast sites in the United Kingdom, used several types of equipment including motor-scrappers, face shovels, dump trucks, backacters, and draglines. The cuts in the northern part of the site were orientated approximately north–south, but in the southern part, including adjacent to the River Aire, failure, they had been changed to a west-southwest–east-northeast alignment, with successive cuts proceeding in a south-southwest direction, as shown in Figs. 3, 7, and 8.

The relatively thin superficial materials were removed by motor-scrappers ahead of the bedrock excavation. Below rockhead the higher benches were excavated by face shovels which loaded into dump trucks to deposit spoils on the upper part of the loose wall. The lower benches were excavated by a Ransome and Rapier W2000 walking dragline which operated alternately from the highwall and the loosewall sides of the cuts. This dragline travelled between the two sides of the excavation void via the “W2000 bench” (see Figs. 7, 8), which was always located on the west-southwest endwall adjacent to the river, and was usually formed well above the Barnsley Top Softs seam. A pilot trench was excavated by backacter on the highwall side to allow the W2000 dragline to commence its operations. A slightly smaller dragline (a Bucyres Eyre BE1150) was also deployed, but only on the loosewall side, to excavate the partings above the Dunsil (pavement) seam and to rehandle W2000 dragline spoils. Fragmentation blasting was required at two sandstone horizons, i.e., in the partings between the Kent Thick and Barnsley Top Softs seams (immediately overlying the Barnsley Rider), and occasionally in the partings between the Low Barnsley and the Dunsil seams. Coal was won from each of the seams using small face shovels or loading shovels, and these loaded the product into lorries to be delivered to the nearby disposal points at Bowers Row for onward transport by rail or road, or to Astley Staithes to be loaded on canal barges. Much of the coal from this site was sold for power generation, and output was generally within the range of 12 000 - 16 500 tonnes per week.

At the time of the River Aire failure, the W2000 dragline was not excavating because of a mechanical breakdown, which resulted in the upper face shovel benches advancing much farther ahead of the dragline benches than was usual. This meant that the zone of excavated ground exposed adjacent to the river was much longer than was normally the case, especially in the upper part of the endwall slope.

Instability of the western endwall

During 1985, after the opencast excavation passed close to the then newly constructed Fleet Weir, surface cracks and vertical displacements began to appear which were aligned nearly parallel with the crest of the western endwall. At the time it was considered that these features were consistent with ground relaxation towards the excavation void. Similar features continued to appear as the western endwall and excavation progressed southwards, and monitoring of these ground movements was carried out. Groundwater seepage was observed all along the western endwall and was recorded at several horizons (as listed earlier in the Groundwater section).

In November 1985 a slope failure occurred in the western endwall of the St. Aidans Extension Site some 400 m south-southeast of the new Fleet Weir (i.e., around 500 m north-northwest of cut 45). The failed mass appeared to have moved outwards on steeply dipping strata including and overlying the Kents Thick seam. This was related to a complex geological feature which was encountered almost continuously in the western endwall batters as far south as cut
and was recorded as an anticlinal structure containing a small reverse fault which dipped into the site (the "western flank feature" (Davies 1988)). Throughout 1986, along the western side of the excavation, tension cracks and minor instabilities were recorded in the endwalls and highwalls and in the W2000 bench, and these were blamed on the presence of the western flank feature. In cut 44 there was evidence of this same geological disturbance approximately perpendicular to the endwall alignment, which was implicated in a slope failure at that location in January 1988. However, at the time of the River Aire slope failure in March 1988 (when the upper seams in cut 45 and projected cuts 46-48 were exposed; Figs. 7, 8), the western flank feature was not seen to be present in the batters of the western endwall. Therefore this geological feature may not have had very much influence on the main River Aire failure, other than at the northern end.  

On Saturday, 19 March 1988, at around 6:10 a.m., abnormal quantities of water were seen to be issuing from the upper parts of the excavated slopes in the southwestern part of the site adjacent to the River Aire and immediately to the south of the then completed and operating Fleet Diversion. By about 11:45 a.m. the river began to break through the flood levee and sheet piling into the opencast workings, and

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4 Note that on the commencement of the St. Aidans Remainder Site in April 1998, this same western flank feature was exposed in the new box cut but on the eastern side, some 300 m away from the river, thus indicating that the axis of the anticline-fault had swung eastwards in this vicinity (see Epilogue and Fig. 16).
the breach quickly widened to around 30 m, and then to 100 m in the next few hours. Instructions had been given for all personnel and plant to be evacuated from the danger zone and this was achieved well in advance of the rising water level (Davies 1988). Figures 1 and 9 show the breach in the riverbank and the opencast void in the process of being inundated. The river flowed from both the upstream and downstream sides into the breach until the river water level was balanced by the flood water level. On the upstream side of the breach the accelerated flow rate caused severe erosion of the riverbanks, and on the downstream side resulted in a reversal of the normal flow direction. Still and video photography carried out while the flooding was in progress showed evidence of a deep-seated failure (Figs. 10, 11). After 3 days a large lake had been created measuring nearly 1.5 km long and up to 70 m deep, and containing about 17 million m$^3$ of river water, with its surface at river level. This disastrous slope failure and inundation brought coal production and virtually all site operations to an abrupt halt, causing the temporary abandonment of in excess of 2 million tonnes of coal which still remained in situ.

Internal investigations were carried out by the BCO into the causes of this major slope failure and flooding, together with appraisals for the safety and recovery of the site, and the financial implications. Other parties also considered the causes of the River Aire failure and published brief post-failure analyses (Davies 1988; Farmer 1996). Some comparisons with these other published analyses are given later in the section on Failure mechanism and analysis.

**Features of the River Aire slope failure**

A plan of the failure area is shown in Fig. 12. The following features are considered to be important.

(1) From the photographic evidence in Figs. 9–11, and as shown in Fig. 12, the failed mass in plan appears to measure some 350 m between its northwest and southeast extremities and about 120 m at the widest part. The overall plan shape of the failure was convex, especially the northern part opposite cuts 43–45. Due to the W2000 dragline breakdown, the excavation of the upper benches was far more advanced than usual (cuts 46 onwards; see also Fig. 8), which resulted in a longer length of western endwall being exposed adjacent to the river. This meant that there was less end restraint to any potential slope failure than was normally the case when the exposed length of endwall was much shorter (i.e., three-dimensional effect). It was in this much advanced reduction zone that the initial breach of the flood levee and riverbank occurred.

(2) The location of the initial breach coincided with the location of former meanders of the River Aire, and these are recorded on an Inland Waterways plan of 1798. Although there is no ground investigation information to verify this, the infilled meanders (whether filled with very recent alluvium or made ground) could have presented a weaker zone which encouraged the initial breach to take place at that particular location.

(3) Two surface survey stations were located on a part of the flood levee which became an “island” (Fig. 12) as the opencast void rapidly flooded. These stations were surveyed both before failure (14 April 1987) and after failure (11

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April 1988). The measured displacements between the two survey dates were 0.31 and 0.47 m vertically downwards and 4.00 and 4.35 m horizontal northeast to east-northeast (i.e., towards the excavation void), that is, the overall gradients that these surface stations had moved down were 1 in 3 and 1 in 10, respectively.

(4) Only a few boreholes had been sunk in the main failure area due to access difficulties (see section on Ground investigations), and the geological structure had to be extrapolated from boreholes sunk to the east. This indicated that the bedding of the coal measures bedrock immediately underlying the river dipped gently towards the excavation void at an estimated gradient of generally less than 1 in 20 (see Fig. 13).

(5) From site records and photographs, weak seatearths or clay bands (intraformational shear zones) were identified in the western endwall. These weak horizons were recorded as underlying all three opencasted coal seams (Barnsley Top Softs, Low Barnsley, and Dunsil) and were also associated with the imperistent and nonproductive Barnsley Rider seam, which (where present) was above the Barnsley Top Softs in the succession. This Barnsley Rider seam, however, was often not recorded in the borehole logs.

(6) Photographs taken during the failure and flooding event showed evidence of the location of the failure surfaces. Figure 9 shows the cracks in the bed of the River Aire which indicates the main back scar of the failure. Figure 10 shows a major series of cracks which define the limit of deep failure at the northern end of the failure area, and these clearly pass below the W2000 dragline bench. Figure 11 shows the lipping (or slight overhang) and seepage in the western endwall at the level of the Barnsley Top Softs in cuts 44 and 45, which probably indicates the basal failure plane. Figure 11 also shows lipping and seepage at the presumed (higher) Barnsley Rider level.

(7) The occurrence of old workings in the Barnsley Top Softs seam in the southwest part of cut 45 and their apparent continuation beyond the endwall produced a zone in which the average strength was less than that of the surrounding intact rock and therefore a very possible horizon in which failure could take place.

(8) Records showed workings in at least four of the sub-Dunsil coal seams terminating just to the east or northeast, and subparallel with the endwall in the failure zone. The cumulative subsidence movements and ground strains calculated to have occurred in the failure zone as a result of this previous underground mining are shown in Fig. 6.

(9) Zones of minor faulting, often closely spaced and subparallel with the river and canal, were shown on underground mining records, especially in the Haigh Moor, Flockton, and Silkstone seams (see Figs. 5, 6). These fault zones were likely to have undergone substantial disruption and displacement due to mining subsidence, most recently when the Flockton seam was mined in this area between 1973 and 1980 (see Fig. 6).

(10) The area adjacent to the river and canal had become a very high permeability zone created by the effects of faulting and mining subsidence. The River Aire provided a constant source of recharge within the opencast endwall once failure had commenced.

(11) The geological structure (the so-named western flank feature) was obviously a factor in the instability of the end wall of cut 44, which had occurred a few weeks earlier. It probably contributed in some way to the main River Aire failure, possibly by providing release surfaces in the northern part. However, the main breach of the riverbank was opposite cuts 45–49 (advance reduction only). It has been recorded that the axis of this geological structure deviated eastwards from around cut 44.

(12) Makeshift piezometers installed in May 1987 on the rockhead bench, adjacent to cuts 42 and 43, became blocked (see Table 1). Figures 7 and 12 show that these installations were in the zone where the western flank geological feature was recorded, and possibly just within the northwest extremity of the main slope failure of March 1988. Piezometer P1 became blocked at 81 m above site datum (ASD) in May 1987 (i.e., at about Barnsley Rider level), and piezometer P2 became blocked at 95 m ASD in September 1987 (i.e., some 14 m above the Barnsley Rider level). These blockages could have been due to nearby blasting operations, or they could have been caused by ground movements resulting from earlier slope failures on the western endwall which possibly later became failure horizons within the main slope failure. The failure mechanism appears to have involved sliding along a planar surface or surfaces which dipped gently

Fig. 9. River Aire failure zone, showing the backscar to the main failure on the fault zone beneath the river bed, and bearing into the excavation void at the northern end; and the buckled and displaced sheet piling where the banks and the flood levee were breached. The ground to the right (east) of the backscar became an island as the water level rose to river level.

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towards the excavated void, these surfaces being weak bedding horizons (seathearts or clay bands) which were recorded at the site. Photographic evidence placed the main basal shear surface somewhere below the W2000 bench and very strongly indicated movement at the Barnsley Top Softs seam, which was exposed only in cuts 44 and 45. The loosewall to the northwest and the unexcavated endwall—highwall to the southeast acted as buttresses outside this central section of the failed mass (see Figs. 7, 8, 11).

In the northwest and southeast parts of the failed mass, the basal failure zone must have been somewhat higher than the Barnsley Top Softs (where this horizon did not daylight due to the loosewall or highwall batters; see Fig. 8) and was possibly within the Barnsley Rider seathearth. Similarly, in the farther extremities of the failed mass, the W2000 bench horizon or even rockhead may have been a plane of sliding (possible evidence of blocked piezometers, see feature 12). Experience of other large failures of this type in coal measures in the United Kingdom is that secondary parallel shear surfaces are often recorded above the main basal failure zone (Hughes and Leigh 1985; Hughes and McLean 1986). A possible explanation is that differential shearing resistances are mobilised over the large basal shear area, so the overlying rock mass divides into sections where the more prominent subvertical discontinuities exist (i.e., jointing and possible minor faulting), and differential strains are transmitted upwards from differential strains at the base. This mechanism, together with an apparent local increase in bedding gradient at a level somewhat higher than the Barnsley Top Softs seam, was probably the cause of the initial breach of the riverbanks in the southeast part of the main failure mass. It must be emphasised that the main failure was in motion first, and that the breach was a consequential secondary feature (see also Figs. 10, 11).

The back scar to the failed block was coincident with a wide and near-vertical fault zone shown on the underground mining records (as shown in Fig. 6). Photographic evidence supported this view (see Fig. 9).

**Failure mechanism and analysis**

When a massive block of rock is involved in sliding failure, subvertical cracking usually appears near normal to the direction of movement, and these cracks increase in width and frequency as the magnitude of the basal shear displacement increases. These cracks have been observed over many years on virtually all large-scale failures on opencast sites in the United Kingdom (Leigh et al. 1980; Hughes and Leigh 1985; Hughes and McLean 1986). A possible explanation is that differential shearing resistances are mobilised over the large basal shear area, so the overlying rock mass divides into sections where the more prominent subvertical discontinuities exist (i.e., jointing and possible minor faulting), and differential strains are transmitted upwards from differential strains at the base. This mechanism, together with a apparent local increase in bedding gradient at a level somewhat higher than the Barnsley Top Softs seam, was probably the cause of the initial breach of the riverbanks in the southeast part of the main failure mass. It must be emphasised that the main failure was in motion first, and that the breach was a consequential secondary feature (see also Figs. 10, 11).

The driving force which caused the continuing outward movement of this massive block of rock was undoubtedly the very high groundwater pressures acting in the faulted-backscar zone. In many failures in opencast mines a small amount of movement is sufficient to reduce water pressures. The constant recharge source of the River Aire and the high vertical permeability would have ensured that the hydrostatic pressure behind the failure block did not reduce as horizontal movement occurred.

Figure 6 shows a possible failure surface and its relationship to underground workings and the River Aire. Figure 13 is a more detailed section through the block that moved. The

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failure surface appeared to be planar with a near-vertical tension crack and the base located in seatearth. There were four potential basal failure surfaces: below the Barnsley Rider, which outcrops below the W2000 bench; below the Barnsley Top Softs; below the Low Barnsley outcropping at the base of cut 45; and at the base of the working void in cut 44 at the Dunsil pavement.

Both Davies (1988) and Farmer (1996), in their post-failure analyses, concluded that the failure was in the seatearth beneath the Barnsley Rider seam. Also, they both assumed that a near-vertical failure surface outcropping in the River Aire bed was so heavily faulted that it had no shear strength. Similarly, Gosden et al. (1998), when assessing the stability of the route for the new combined river and canal watercourse (see later in this paper), also assumed potential failure along the Barnsley Rider seatearth and a near-vertical tension crack – fault zone in the river bed.

Photographic evidence (Figs. 9–11) shows that the back scar of the slip was in the bed of the River Aire (as assumed by Davies 1988; Farmer 1996; and Gosden et al. 1998), but that the basal shear surface outcropped in the seatearth below the Barnsley Top Softs. The actual basal surface could be more complex, involving sliding on both the Barnsley Top Softs and the Barnsley Rider seatearths. At the time of failure, the Barnsley Top Softs was only exposed in cuts 44 and 45. To the northwest and southeast of these cuts, the failure surface would have been above that, possibly in the Barnsley Rider. More than one zone of intraformational shear could exist in the rock, therefore failure in the Barnsley Rider seatearth was also possible.

At the time of the River Aire slope failure, no site-specific shear strength testing data were held by the BCO, nor was any testing carried out for the immediate post-failure investigations. The shear strength of weak seatearths in the coal measures in the United Kingdom has been studied by Stimpson and Walton (1970), Salehy et al. (1977), and Jameson (1995). Of particular relevance to the St. Aidans Extension Site was the work of Rao (1980), who carried out direct shear box tests on samples of Barnsley Top Softs seatearth taken from the earlier St. Aidans and adjacent Lowther sites and obtained peak shear strength values for cohesion ($c'$) and friction angle ($\phi$) of 12 kPa and 14$^\circ$, respectively, and residual shear strength values for cohesion ($c''$) and friction angle ($\phi''$) of 3 kPa and 11$^\circ$, respectively. The peak values suggest that the seatearths had at some time been sheared, possibly as a result of strains from underground mine workings.

Davies (1988) did not give details of any slope stability calculations or parameters used in the Health and Safety Executive post-failure investigations, but for the seatearths
reference was made to a friction angle $\phi'$ of 19° used by the NCB–BCO in their precontract design, and a residual friction angle $\phi_{rc}$ of 11° as used by the operating contractor’s consultant geotechnical engineer.

Farmer’s (1996) analysis approximated the failed mass to a simple planar failure with a water-filled tension crack (wedge and biplanar failure are terms used by Farmer). Farmer also referred to peak and residual friction ($\phi'$ and $\phi_{rc}$) for the Barnsley Rider seatearth of 19° and 11°, respectively, and quoted factor of safety (FoS) values of between 0.83 and 0.98 for failure along the Barnsley Rider horizon based on residual shear strength.

Gosden et al. (1998) gave parameters for their stability calculations for the new watercourse, as shown in Table 3, and these appear to have been chosen either from back-analyses of the 1988 River Aire slope failure or from direct ground investigations carried out in connection with this new construction project.

Gosden et al. (1998) also suggested that measured residual shear strengths on samples (of seatearth) from the site...
Fig. 13. River Aire failure. Section normal to endwall on cuts 44 and 45, looking towards the north-northwest (see section line in Fig. 12).

Table 3. Geotechnical parameters: new construction works.

<table>
<thead>
<tr>
<th>Stratum description</th>
<th>Unit weight $\gamma$ (kN/m$^3$)</th>
<th>Shear strength parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial deposits</td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>Coal Measures</td>
<td>23</td>
<td>100</td>
</tr>
<tr>
<td>Barnsley Rider seatearth</td>
<td>18.5</td>
<td>0</td>
</tr>
</tbody>
</table>

gave a lower bound of $c' = 0$ kPa and $\phi' = 9^\circ$ (i.e., there is a discrepancy with the value of $\phi' = 11^\circ$ given in Table 3). A minimum $FoS$ of 1.5 against slope failure affecting the new watercourse was incorporated into their design.

For the seatearths, the choice between peak and residual shear strength parameters requires a consideration of how much displacement has resulted from the mining-induced strains. The probability is that some value of post-peak shear strength is applicable. The use of peak values will be somewhat optimistic, whereas the use of residual values may seem to be rather pessimistic. However, the seepage of water through and around the seatearths would have had a softening effect. Certainly the peak friction value $\phi'$ of 19° (quoted by Davies 1988; and Farmer 1996) is very unlikely to have existed in this situation because of the mining-induced strains.

Davies (1988) assumed a hydrostatic profile with the groundwater level in the superficial deposits at the level of the River Aire. Farmer (1996) assumed a hydrostatic profile with the groundwater level dropping from the River Aire to the Barnsley Rider seam. This was based on the fact that water was seen to be seeping at this level. Piezometers installed in the superficial deposits and just above the Barnsley Top Soft seam gave similar phreatic levels, suggesting hydraulic continuity. This was most likely, since the permeability of the faulted zone was probably increased following ground movements associated with underground and opencast workings. Piezometers P1, P2, and NWH (see Table 1) installed in the rockhead bench during excavation showed that the standing-water level in the rock above and below the Barnsley Top Softs seam varied between 74 and 97 m ASD, some 15–45 m below the levels recorded prior to excavation, and this suggests that the phreatic surface was depressed due to the excavation. Thus, the phreatic surface probably varied from the level of the River Aire to the Barnsley Rider seam, since that corresponds with the measured water levels.

For this case study the geotechnical data have been derived mainly from prospecting investigations conducted in the 1970s. That information was limited because of the general absence of any site-specific geotechnical testing, which was typical for exploratory investigations in the opencast mining industry in the United Kingdom at that time. An appropriate analytical method that could justify the use of the available data was chosen, and hence a more simplistic limiting equilibrium analysis was used instead of one of the more modern or advanced numerical techniques. A method of slices was adopted because of the stepped face and the variation of the phreatic surface, and this has been applied to the section shown in Fig. 13 for failure at both the Barnsley Top Softs and Barnsley Rider horizons. The Oasys SLOPE computer program, developed by Ove Arup and Partners, was used for this work, and the type of analysis selected was the Janbu method with parallel inclined interslice forces (Oasys Limited 1997).
The results of the authors’ stability analyses are given in Table 4 for basal failure through the Barnsley Top Softs seatearth and the Barnsley Rider seatearth. A vertical tension crack, corresponding to the cracks observed in the river bed (Fig. 9), has been applied to both failure surfaces. Three sets of shear strength parameters were chosen as being realistic based on those given by Rao (1980) and the lowest values given by Gosden et al. (1998). An upper and a lower phreatic surface are shown in Fig. 13 based on a groundwater profile through the superficial deposits (Davies 1988) and a groundwater profile falling from river level to Barnsley Rider level (Farmer 1996). The sheet piling shown in Fig. 13 intercepts both these phreatic lines; however, it is known that when driving the piles difficulty was encountered due to the coarse gravel (and boulders?) overlying rockhead, and achievement of a completely effective seal was unlikely. Also, the disturbed nature of the fault zone and mining effects could have provided seepage paths beneath the sheet piles.

From an inspection of Table 4 it can be seen that (i) for corresponding shear strength parameters, the FoS values for the upper phreatic surface are all less than the FoS values for the lower phreatic surface, which was anticipated; (ii) for all corresponding shear strength parameters and phreatic surface levels, the FoS values for the Barnsley Top Softs seatearth are less than those for the Barnsley Rider seatearth; and (iii) for the Barnsley Rider seatearth, only the lower residual shear strength parameters in combination with the upper phreatic surface (i.e., worst case) resulted in an FoS value less than unity (or failure), whereas for the Barnsley Top Softs seatearth, for either set of residual shear strength parameters or either phreatic surface, the values of FoS obtained were unity or less (i.e., they all represented failure of the slope).

These results suggest that failure through the Barnsley Rider seatearth was only possible with the lowest recorded individual shear strength parameters in combination with the groundwater level remaining at or above rockhead throughout the slope. Since the phreatic surface was probably depressed because of drawdown due to excavation, the results suggest that failure in the Barnsley Rider seatearth was unlikely (using the parameters from Table 4); however, lipping shown in Fig. 11 is proof that displacements did occur at this horizon. Initial basal failure through the Barnsley Top Softs seatearth was much more likely, as subunity FoS values were obtained for either set of residual shear strength parameters in combination with the more realistic initial groundwater (lower phreatic) surface shown as drawn down to the seepages evident at the Barnsley Rider level.

Information gained from site visits after recommencement of coal winning operations in 1998 indicated that, in the area to the south and east of the 1988 River Aire slope failure, previous extraction in the Barnsley Top Softs seam was around 70-80% (see earlier section Previous underground mining). These workings also exhibited much roof collapse but little pillar collapse. It is suggested that the existence of these old room and pillar workings would probably have facilitated copious groundwater (and river water) seepage. As a consequence, softening of the underlying seatearth may have reduced the shear strengths to even less than the values given in Table 4.

**Conclusions**

Tensile ground strains of up to 10 mm/m had resulted from underground mining in the vicinity of the River Aire at the St. Aidans Extension Opencast Site. This zone of ground strains coincided with a wide band of multiple, closely spaced (but small displacement) faulting which lay directly beneath the River Aire and immediately adjacent to the western boundary of the opencast mining project. Excavation of the opencast void probably caused further horizontal ground strains (relaxation) to add to the existing ground strains, which must have resulted in considerably increased vertical permeability, and possibly shearing of the seatearths. Failure occurred initially along the Barnsley Top Softs seatearth, although failure along the higher Barnsley Rider seatearth and the even higher rockhead was necessary to account for the full 350 m length of the failed block at surface level. The River Aire acted as a constant source of recharge to the hydrostatic force that drove this massive block of ground towards the opencast void. The breach of the riverbank and flood levee which led directly to the flooding of the site was a secondary feature of a complex failure mechanism involving shearing on several subhorizontal and subvertical discontinuity features (seatearths, bedding grounds, etc.).
The results of the stability analyses presented in Table 4, the evidence of overlying strata movement (lipping) and seepage in Figs. 10 and 11, and the existence of room and pillar workings in the Barnsley Top Softs coal seam all strongly support the conclusion that the basal failure surface was through the Barnsley Top Softs seatearth, and not the Barnsley Rider seatearth as suggested by Davies (1988) and Farmer (1996).

These investigations have indicated that ground subsidence and strains resulting from underground mining can have a very adverse effect on the stability of overlying slopes, which concurs with the earlier work of Forrester and Whittaker (1976), Walton and Taylor (1977), Scoble (1981), and Siddle et al. (1985).

In relation to any large-scale excavation works planned in coal measures rocks in the United Kingdom, the lessons which must be learned from this event are as follows:

1) The mining history of the area should be fully researched before direct ground investigations commence so that the locations of possible ground strains and likely fault zones can be identified.

2) To establish the detailed geological structure, direct ground investigations by boreholes are absolutely necessary in all areas of the site and for an adequate distance outside the planned excavation boundaries, irrespective of how difficult surface access may be.\(^5\)

3) Adequate groundwater monitoring utilising piezometers must be carried out prior to excavation to establish the groundwater regime and to permit changes to be recorded during the progress of the works.

Epilogue: recovery of the site and changes in quarries safety legislation in the United Kingdom

After the inundation, the site was protected on a care and maintenance basis while a recovery strategy was formulated and designed. The chosen recovery scheme involved the construction of a new single combined watercourse to replace the existing river and canal, this new water channel being located farther west and south (Fig. 14 shows the new combined watercourse, together with the former river and canal courses, the flooded opencast void, and the River Aire failure zone). In the United Kingdom the construction of a

\(^5\) Note that "a plan distance beyond the proposed slope excavation crest of at least twice the proposed excavation depth" was a general guideline adopted within the BCO following the St. Aidans slope failure.
Fig. 15. New Aire and Calder navigation channel (looking east), showing combined watercourse, a new bridge, and new coal loading staithes (Caroline Staithes).

Fig. 16. St. Aidans Remainder Opencast Coal Site box cut (looking northeast), showing “western flank feature” geological structure. Photograph taken from the top of the River Aire flood-protection levee, about 50 m downstream from the southeast edge of the original breach location as shown in Fig. 1.
new navigation channel requires an act of Parliament, so this was the first stage of the statutory planning procedures, which was followed by planning consent from the local minerals planning authority, this being Leeds City Council (Morgan 1992).

The new navigation channel is 3.5 km long, and construction works commenced in July 1993. Other new items included three bridges, a deep-water lock, a coal loading wharf and staithes, moorings, and a marina. Figure 15 shows part of the new watercourse, with one of the new bridges, and the new Caroline Staithes coal disposal facilities beyond. The total cost for these construction works was almost £20 million (Gosden et al. 1998; Anonymous 1999).

Removal of the flood water from the opencast void by pumping commenced on commissioning of the new watercourse and ancillary works in July 1995 and took 2 years to complete. Inclinometers and piezometers were installed in the surrounding ground to enable the stability of the side slopes of the void to be monitored during the pumping-out process. Also during this time, as a way of overcoming some short-term water supply shortages, the regional water company (Yorkshire Water) installed a temporary water treatment plant (at a cost of £7 million) which supplied 3400 million litres of potable water to homes and industry in the nearby area (Anonymous 1999).

The recovered site is now referred to as St. Aidans Remaider Opencast Coal Site, and the tendered price for this revised opencast project was around £36 million in 1997. A new box cut was formed adjacent to the River Aire failure zone, and the successive cuts are being aligned approximately north-northwest-south-southeast (that is, almost at right angles to the previous cuts) with progress generally to the east-northeast (see Fig. 14). Figure 16 shows the new box cut and the location and trend of the “western flank geological feature” away from the river. Coaling operations began again in February 1998, about 10 years after the disastrous River Aire slope failure, and about 2.8 million tonnes of coal are expected to be recovered by late summer 2002. The planned restoration of the site includes the creation of a country park, and this will include several lakes and a nature reserve.

Following this major opencast slope failure and these investigations, the Health and Safety Executive of the Government of the United Kingdom called for a code of practice to be introduced into the opencast coal mining industry to provide guidance on the ground investigation and design for stable excavations. This code of practice, “The stability of excavated slopes at opencast coal sites” (Federation of Civil Engineering Contractors 1989), was produced very quickly and complemented an existing code of practice “The Siting and Construction of Temporary Spoil Mounds at Opencast Coal Sites” (Federation of Civil Engineering Contractors 1982), which had been introduced 7 years earlier (Adams 1991; Hughes 1991). These codes of practice have recently been superseded by new Health and Safety at Quarries Regulations (Health and Safety Commission 1999).

Acknowledgments

The authors wish to record their gratitude to the directors of RJB Mining (UK) Ltd. (as present owners of the site) for information and some figures used herein, for access to the St. Aidans Remainder Project, and for permission to publish this paper. Neither of the authors was in any way associated with the St. Aidans Extension Project prior to the River Aire slope failure. However, the senior author became very much involved in the project immediately after the failure event as the geotechnical specialist member of an internal BCO inquiry panel, and information originating from former BCO colleagues is therefore gratefully acknowledged. Notwithstanding, the opinions expressed in this paper are entirely those of the authors.

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PAPER A8  FAULTING – NORTHERN ENGLAND


Faulting and slope failures in surface coal mining – some examples from North East England.

Faulting and slope failures in surface coal mining—some examples from North East England

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Abstract. The shallow terrestrial Coal Measures strata of North East England have been faulted and tectonised by geological events (orogenies), and are divided by faulting and the River Tyne valley into the Northumberland and Durham coalfields. The type of faulting is almost exclusively normal faulting, with close spacings and complex geometries being prevalent. These coalfields are generally overlain by glacial deposits. Surface coal mining, as a mechanised operation, has been carried out in this region for about the last 60 years. The earliest workings were on a relatively small scale, and faulting and geologically complex ground was avoided as far as possible; but with time, the introduction of progressively larger excavation plant has led to ever larger and deeper surface mines, and working in faulted ground has become commonplace. Detailed ground investigations by drilling and geophysical logging are carried out to prove the geological structure. The gradient of bedding dips usually determines whether the coal should be mined by opencast dip or strike cuts, or by open-pit working, but the choice of excavation face alignments with respect to faulting can be critical. Faces aligned near parallel with faults tend to suffer failures, whereas faces aligned near perpendicular to faults tend to be stable. The types of slope instabilities which are associated with normal faulting comprise planar failures (including bi-planar and multi-planar), toppling failures, tetrahedral wedge failures and complex endwall failures. Endwalls formed against faults are especially likely to become unstable, and can become very problematic if located close to mining area boundaries where important natural or infrastructure features may exist. Several case studies are included to illustrate these points.

Key words: case studies, normal faulting, slope failures, surface coal mining

1. Introduction

In the United Kingdom, opencast coal mining has been carried out as a fully mechanised operation for about 60 years. Following nationalisation of the UK coal industry in 1947 and until the demise of British Coal Opencast at the end of 1994, annual opencast coal production fluctuated between 7 and 17 million tonnes. At the peak of production in the early 1990s, there were between 50 and 60 opencast sites operating in the exposed coalfields of Scotland, England and Wales. With about a quarter of these sites being in North East (NE) England, an annual coal production from this region of 4 to 5 million tonnes was attained. Opencast coal mining still continues as part of the (re-)privatised UK coal industry, but due to environmental
Faulting and tectonic disturbance of the Coal Measures strata are commonly encountered in all coalfields in the UK (Williamson, 1967). In the early days of UK opencast coal extraction relatively small sites were operated, and faulted or geologically difficult ground conditions were generally avoided. However, with the passage of time the size of mine areas and tonnages of coal yielded have increased considerably, as has the size of excavation plant deployed. As a result of this, many of the more recent projects have involved working in very faulted and complex ground.

This paper shows briefly the operational and geotechnical problems presented by faulting in NE England, and summarises some case histories of fault-related instability from the region. Such slope failures are sometimes major safety hazards and can put lives at risk or cause damage to property. They can also have major financial implications resulting from essential remedial works, such as additional excavation, or alterations to the mining programme and disruption to coal production schedules (Hughes and Clarke, 2001).

2. Geological Setting

Figure 1 shows the location of the exposed Coal Measures in NE England, together with an outline of the geography and solid geology of the region. North of the River Tyne the land surface falls generally from the higher ground in the west (North Pennine hills) to the coastal plain in the east, and hence the main rivers generally flow from west to east. To the south of the River Tyne the land surface is more undulating and in particular the course of the River Wear is deflected north north east (NNE) by the relatively high ground of the Permian outcrop which is located along the coast in the south east (SE) part of the region.

Table 1 briefly summarises the geological history of NE England and shows the downward succession of the strata. Figure 1 shows that the oldest strata outcrop is in the west and the youngest strata outcrop in the east, thus indicating that the regional dip is eastwards and that the bedding dip gradient is steeper than the land surface gradient.

The area to the north of the River Tyne is known as the Northumberland Coalfield and south of the river is the Durham Coalfield. The true geological divide is in fact the Ninety Fathom/Stublick Fault system which approximately follows the River Tyne Valley. To the north of this fault system lies the Northumberland Basin which extends northwards beyond the Hauxley Fault to Warkworth. To the south is the Alston Block which extends southwards beyond the Butterknowle Fault. To the west (along the South Tyne Valley) the Stublick Fault also connects with some minor outlier coalfields (e.g. Plenneller), as shown in Figure 1. To the east the Coal Measures are covered by younger Permian strata, and by the North Sea.
Figure 1. Solid geology of North East England
### Table 1. Simplified geological history and strata succession for NE England

<table>
<thead>
<tr>
<th>Period/System</th>
<th>Age Ma bp (million years before present)</th>
<th>Series/Strata</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>3-present</td>
<td>Mainly late Devensian/Weichselian (Glacial deposits comprising tills, sands, gravels and glaciolacustrine silts and clays)</td>
<td>The Great Ice Age (glacials and interglacials)</td>
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<tr>
<td></td>
<td>(Major unconformity)</td>
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<td></td>
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<tr>
<td>Permian</td>
<td>250-300</td>
<td>Magnesian Limestone – Upper and Lower</td>
<td>Tertiary igneous dykes intrude. Alpine Orogeny (uplift of the whole region with folding and much faulting)</td>
</tr>
<tr>
<td></td>
<td>(Unconformity)</td>
<td></td>
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<tr>
<td>Carboniferous</td>
<td>300-360</td>
<td>Coal Measures (Westphalian) – Upper, Middle and Lower (sandstone, siltstone, mudstone, coal, seatearth)</td>
<td>Intrusion of Whin Sill and igneous dykes. Folding and faulting</td>
</tr>
<tr>
<td>Upper-</td>
<td></td>
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<tr>
<td></td>
<td>– Limestone Group</td>
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<td></td>
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<tr>
<td></td>
<td>– Upper (grits)</td>
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<td></td>
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<tr>
<td></td>
<td>– Middle and Lower</td>
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<tr>
<td></td>
<td>Scremerton Coal Group</td>
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<td></td>
<td>Fell Sandstone Group</td>
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<tr>
<td>Lower-</td>
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<tr>
<td></td>
<td>Cementstone Group</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Conglomerates</td>
<td></td>
<td></td>
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<tr>
<td>Devonian</td>
<td>360-400</td>
<td>Old Red Sandstone Cheviots (andesite, granite)</td>
<td>Formation of the Northumberland Trough which later subsided relative to the Alston Block (to the south) along the Ninety Fathom/Stubick Fault system</td>
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Note: for more detailed accounts of the geology of NE England the reader is directed to Taylor et al. (1971), Warn (1975), Johnson (1995) and Scrutton (1995).
The Northumberland Basin and the Alston Block are geological features which came into being at the end of the Caledonian Orogeny (late Devonian Period). Sedimentary deposition continued over the two areas throughout the following Carboniferous Period, including the deposition of the Coal Measures (Westphalian) series, which were formed in the Upper Carboniferous, i.e. around 300 million years before present (Ma. bp). This series is sub-divided into the Upper, Middle and Lower Coal Measures, but in NE England the Upper sequence is mostly absent having been eroded. The Coal Measures strata themselves comprise mainly sandstones, siltstones, mudstones, coals and seatearths which have been laid down in a cyclic sequence. These cycles (called cyclothems) vary in thickness from 1 m up to 30 m and are typically around 15 m thick. The coal seams themselves are mostly less than 1 m thick. Washouts are frequently recorded in the succession, therefore units within the cyclothems (especially coals and seatearths) are sometimes missing, having been replaced by deltaic sandstone units which are often cross-bedded.

Later, the Variscan Orogeny and later still the Alpine Orogeny, resulted in more folding and faulting in the region. Also, igneous dykes and sills were formed at various times, together with further deposition (Permian period upwards). Then followed major erosion of the land surface.

Lastly, in the Quaternary period, glacial sediments were deposited over virtually the whole of the Northumberland and Durham coalfields. These deposits include mostly clayey tills, with frequent gravels and sands, and some glaciolacustrine silts and clays (Hughes et al., 1998).

(Much more detailed accounts of the overall geological history and stratigraphy of NE England are given in the references listed at the foot of Table 1.)

3. Ground Investigations

Extensive and detailed investigations are normally carried out in order to prove the quantity and quality of the coal within the proposed surface mining area; also to assess the geological structure and so estimate the economic and engineering viability of the project. All the UK shallow coalfields have already been extensively mined by underground methods, particularly in the late 19th and early 20th centuries. However, because of the volume of coal left in situ in pillars, it is often still profitable to surface mine in shallow seams of coal that have previously been mined by room and pillar working. Investigations for surface mining usually start with an appraisal of all the available records from past mining and following this, the programme for direct ground investigations is planned (Hughes and Blythe, 1987).

Openhole air-flush rotary drilling is used mainly to prove the overall structure, strata succession and depth of superficial deposits. Boreholes are located (in plan) to a pattern, which is typically a triangular grid with 50 m to 60 m spacing between boreholes. Closer spacing is adopted in areas of structural complication, or where underground workings exist. In a proportion of boreholes, core samples of all
the coal seams plus roof and floor strata are obtained for quality assessment and correlation. A smaller proportion of boreholes are core sampled for their full depth and are then logged in engineering terms. In areas of close or complex faulting borehole spacings may be as close as 10 m or even less, and inclined drilling and coring techniques may be used. Also, in relation to investigations in fault zones, special core drilling techniques (such as "Mazier" or "Triefus" retractor type triple-tube core barrels—Bell, 1987) have been employed to obtain samples of fault gouge material, so that laboratory shear strength testing can be carried out to establish accurate geotechnical parameters for application in stability calculations. Overall, borehole densities usually vary between 3 and 10 per hectare depending upon geological complexity.

Geophysical (down-the-hole or slimline) logging of boreholes is used extensively to facilitate the interpretation of the various lithologies, coal seams, old workings and groundwater levels. More recent developments include the use of down-the-hole video cameras, ultra sonic imaging (televiwer) and various seismic techniques. Groundwater investigations mainly involve the installation of standpipes and piezometers to allow the recording of water levels over long periods (often for several years). Packer tests and pumping tests are used to assess permeability. Geotechnical investigations of the superficial deposits usually require the use of cable percussion boring techniques, and samples are obtained for soil mechanics laboratory testing, particularly in connection with spoil mound design (Hughes and Clarke, 1997). A more detailed description of the methods of ground investigation deployed in UK opencast coal mining has been given by Hughes and Blythe (1987).

All the information gained from the ground investigation is used to produce detailed plans and sections of the geology and structure of the proposed mining project and for sophisticated (3-dimensional) computer modelling. These are then used to design and plan the way in which the mine area will be excavated and operated.

4. Faulting Characteristics

The locations of the major faults in the region are shown in plan in Figure 1. This shows that the majority of fault traces or alignments, although very variable, do approximate overall to a general W–E orientation, and that only a small minority of faults are aligned in a general N–S direction.

In the Northumberland and Durham coalfields almost all the faults are normal faults, and thrusting or reverse faulting are only rarely seen. The dips of these normal faults range between 45° and vertical but are typically around 60°–70°. Downthrows (vertical displacements) range from just a few millimetres for the smallest and most common faults (which are often not recorded in opencast excavation works) up to as much as 300m for some major faults (which usually have a significant effect on the planning and execution of opencast operations).
Particularly with the more major and extensive faults, the angle of dip may vary with depth, and the strike direction may also vary. Figure 2 (after Knight, 1990) shows a simplified representation of blind and daylighting faults, both as normal faults formed after burial and lithification of the sedimentary strata, and as listric normal faults. In NE England several patterns of normal faulting have been observed at opencast sites (Hughes and Leigh, 1985; Hughes and McLean, 1986) and some of these are illustrated in Figure 3.

Except for toppling (see later), failure usually involves shear displacement along the fault plane or fault zone (where there may be several shear or dislocation planes), and may also involve shear displacement along low strength bedding horizons (Salehy et al., 1977). Crushed and brecciated gouge, or clayey gouge, of variable thickness is commonly found within the sheared planes or zones, especially in the more major faults. This gouge material has been sampled at only a few opencast mines in NE England and the results of geotechnical laboratory testing on these samples are given in Table 2.

The testing of low shear strength bedding horizons (seatearths, clay mylonites, intraformational shear zones) for the NE England Coal Measures has been extensively reported in the geotechnical literature, especially by Stimpson and Walton (1970), Salehy et al. (1977) and Jameson (1995). In particular, Salehy et al. (1977) concluded that intraformational shears are often fault controlled, and are mostly developed close to the faults themselves. They also stated that “much of the shear zone material is in fact very similar to the gouge clays in faults”.

Figure 2. Major types of normal faults (after Knight, 1990). (a) Blind planar normal fault formed after burial and lithification of sedimentary strata, (b) daylighting planar normal fault active during deposition of sedimentary strata, (c) daylighting listric normal fault, (d) blind listric normal fault.
Figure 3. Some normal faulting characteristics observed at surface coal mines in N.E. England. (Note: that all the diagrams show only the dip-slip component of displacement, and that strike-slip may also occur along the strike of the fault.)
Table 2. Geotechnical Properties of Fault Gouges from some NE England Opencast Mines

<table>
<thead>
<tr>
<th>Location</th>
<th>Classification</th>
<th>Residual shear strength</th>
<th>Test type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Togston, Hauxley Fault</td>
<td>15 43 21 50</td>
<td>2.5 16</td>
<td>shear-box</td>
</tr>
<tr>
<td>North Northumberland</td>
<td>13 61 46 48</td>
<td>1.5 13</td>
<td>shear-box</td>
</tr>
<tr>
<td>(Spicer, 1981)</td>
<td>nil 57 40 57</td>
<td>nil 15</td>
<td>shear-box</td>
</tr>
<tr>
<td>Togston, Hauxley Fault</td>
<td>14 57 40 57</td>
<td>nil 18</td>
<td>shear-box</td>
</tr>
<tr>
<td>North Northumberland</td>
<td>(Denby, 1983)</td>
<td>nil 14</td>
<td>shear-box</td>
</tr>
<tr>
<td>Plenmeller, Stublick Fault</td>
<td>16 — — —</td>
<td>—</td>
<td>shear-box</td>
</tr>
<tr>
<td>South West Northumberland</td>
<td>(Robertson and Rodger, 1990)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MC—Moisture Content, LL—Liquid Limit, CF—Clay Friction, PL—Plastic Limit

Fault movement leading to the development of impervious clay gouges, coupled with displacement, which may bring high permeability strata into contact with low permeability strata, may then lead to faults acting as barriers to groundwater flow, and to the development of differential water tables and ponding. Some faults act as aquicludes and thus cause different water levels to exist on either side of the fault zone (e.g. Hauxley Fault at Togston site), whereas other fault zones are quite permeable and do not cause water level differences (e.g. Stublick Fault at Plenmeller site). Where a step in the water level is recorded it is not necessarily influenced by the magnitude or direction of the throw of the fault. Several faults encountered in SW County Durham are associated with water level differences which are considerably higher on the downthrow side of the fault zone than on the upthrow side.

5. The Effects of Faulting on Surface Mining Operations

The methods and sequence of UK opencast coal mining operations have been described, in varying degrees of detail, in several technical references (e.g. Walton and Atkinson, 1978; Brook and Thornley, 1983; Hughes and Leigh, 1983; Hughes and Clarke, 2001). The operations at any opencast coal mine in NE England typically involve excavating through superficial materials (generally glacial deposits) and then Coal Measures strata in order to win coal from several seams. A clear understanding of the operations and sequence of working is essential in order to recognise the geometry of how faults intersect faces and benches in a progressive excavation, hence a detailed description of surface mining methods commonly used in this region is given below. This description and associated figures are also used to introduce the terminology.
A simplified sequence of operations for single seam working is shown in Figure 4. Topsoil and subsoil are removed by tractor-scraper and placed in storage mounds near the site perimeter. Excavation to the coal seam in the initial cut (box cut) is usually by face shovel and/or backacter (or backhoe) and the spoil is transported by dump truck to the overburden mound for storage. Successive cuts are then excavated by dragline and/or face shovel or backacter with the spoils going into previous cuts. The final void is backfilled using the spoil from the overburden mound (i.e. the initial cut) and subsoil and topsoil are replaced. The use of explosives to aid machine excavation may be necessary at some horizons, particularly where massively bedded sandstones may be present, and this is usually in the form of bulk blasting to create cracks and fragmentation within the in situ rock mass. Most sites are restored to agricultural use, but sometimes they can be restored for other purposes such as forestry, recreation, or for industrial development. Figure 4 shows that there is usually a nett volume increase in the backfill materials (bulkage due to replacing with angular fragments and hence increased void space) and this has to be accommodated in the final restoration contours.

Figure 5 shows a schematic plan and section of a typical multi-seam operation and illustrates some of the terminology used to describe the main features of an opencast coal mine. The geology greatly influences the way in which a site is operated. Where the strata are only very gently dipping (say 1 in 10 or less) the cuts may be aligned parallel with strike, i.e. strike cuts. In more steeply dipping strata cuts parallel to the dip direction, i.e. dip cuts, are usually adopted to prevent the sliding of either loosewall (along the pavement) or highwall (along bedding planes) into the working void. Figure 5 shows the cuts aligned slightly across the dip to help prevent loosewall sliding.

In some situations the bedding dips so steeply that excavation plant and other site vehicles cannot operate on the inclined bedding surfaces. In these circumstances the "open-pit method", which is illustrated in Figure 6, is usually adopted and involves progressively lowering the floor of the pit and winning the coal from the steep seams as the pit descends. This method necessitates storing a larger quantity of overburden spoil in mounds above ground level than in the more usual "opencast strike cut or dip cut methods", as described previously. This open-pit method also precludes the use of draglines, and hence all bedrock excavation (i.e. below superfluents) has to be done by face shovels and/or backacters. With open-pit mining the placement of the backfill is again progressive, the site area being worked in a series of very wide cuts or "panels" (and is sometimes called "panel mining" or "horizon mining", but this method is also included within the aegis or general meaning of opencast mining).

In the Northumberland coalfield (i.e. north of the River Tyne and the Northumberland Basin geology) the bedding of the strata generally dip gently E or ESE, and the surface topography (being the Northumberland coastal plain) is relatively flat. As a result Northumberland opencast coal mines are comparatively large by UK standards and typically yield between 2 and 20 million tonnes of coal.
Figure 4. Opencast coal mining, simplified sequence of working (after Hughes and Leigh, 1985). (Not to scale: vertical scale exaggerated.)
in working lives of between 4 and 20 years. The opencast method of working as shown in Figure 5 is normally adopted with face shovels working on the higher benches and large draglines deployed to uncover the lower seams. All sites involve multi-seam working with the largest mines extracting coal from as many as 20 different coal seams.
In the Durham coalfield (i.e. south of the River Tyne and the Alston Block geology) the bedding of the strata is often fairly steep and the surface topography is quite undulating with hills in the west and east up to 300 m above sea level (above Ordnance Datum). There are also more highways and other surface lineaments than in Northumberland. These topographical features result in Durham opencast operations being mostly on a small scale with few mines yielding over 2 million tonnes of coal. The methods of working can be either the opencast method as shown in Figure 5 but utilising only small draglines, or the open-pit method as shown in Figure 6 utilising face shovels and/or backacters but not draglines. The working lives of Durham opencast projects seldom exceed five years, and in most cases are only two to three years. Generally Durham sites involve coal extraction from
Figure 7. Scenarios for potential slope instability due to normal faulting (not to scale)
far fewer seams than those in Northumberland and the very smallest mines may involve working to a single seam only.

Figure 7 is a schematic representation of Northumberland style opencast operations which has been drawn to illustrate how the disruption of the coal seams is caused by normal faulting. The strata overlying the basal seam A (or seams B and C in the trough fault zone) being the lowest strata are excavated by dragline, whereas the strata overlying the higher seams B and C (and seam D in the trough fault zone) are excavated by face shovel or backacter, with the superficial deposits above rockhead being removed by scrapers.

In Figure 7, locations O, Q, G and @ are all examples of how normal faulting may be encountered during opencast coal mining operations, and what type of instability may result. Locations O, Q and G represent situations which arise as the working faces and benches advance through the mining area, and therefore instabilities tend to affect all the working faces as they pass through the fault zone, but at any particular instant may only affect the horizons between adjacent benches. However, situations such as location @ represent major faults running parallel or sub-parallel with the boundary (endwall) of the mining area, and hence often lead to major slope failures which may be repeated as endwall profiles are excavated in successive cuts.

6. Characteristics of Fault Induced Failures

The descriptions of fault-induced slope failures given below are illustrated in the associated Figures 8, 9, 10 and 11, and relate to Locations O, Q, G and @ as shown in Figure 7.

6.1. LOCATION O—PLANE FAILURES

Face shovel excavation at the seam D bench, followed by dragline excavation successively on the seam C, B and A benches, will progress the excavation faces through this normal fault from the downthrow side into the strata on the upthrow side, and will create the possibility for plane failures to develop. Plane failures (Figure 8(a)) are probably the most common type of rock slope failure encountered in UK opencast coal mining (Stead and Scoble, 1983). Sliding occurs along the fault plane (or planes) inclined towards and daylighting within the excavation face (Figure 8(b)). With a steeply inclined fault, usually only one plane or failure zone is involved, i.e. the failure is along a relatively straight surface from near the toe to behind the crest of the slope. Sometimes sliding may also take place on an inclined secondary plane or planes, such as bedding planes, in which case the failure mode is usually described as bi-planar (Figure 8(c)), or multi-planar (or curvi-planar) (Figure 8(d)) where the bedding has been distorted due to normal fault drag (see also Figure 3(c)).
Figure 8  Plane Failures

Figure 9  Toppling Failures

Figure 10  Wedge Failure (tetrahedral)

Figure 8, 9 and 10. Rock slope failure models for excavated benches and faces. Based on Hook and Bray, 1981; Walton and Atkinson, 1978; Hughes and Leigh, 1985.
This profile usually indicated on drawings to maximise coal recovery, but usually leads to instability.

This profile ensures stability but much coal is left behind in lower strata.

Best batter profile for stability, but involves some barren dig.

Rockhead

Superficial Deposits

Normal drag

Wide fault zone with several planes of displacement/shear

Barren strata on this side of fault(s)

Coal Seams

Fault

Down-throw

Seams

(a) Endwall/Sidewall against downthrow side of normal fault.

Stable batter profile, but much coal sacrificed

Most economic batter profile, but toppling failures likely due to working through or close to fault zone

Stable batter profile, but much barren dig

Figure 11. Endwall and sidewall instabilities due to proximity of Normal Faults (excavation area is on lefthand side of faults)

(b) Endwall/Sidewall against upthrow side of normal fault.

These seams downthrown by the fault are "out of ratio", is not economic to try to recover.

(b) Endwall/Sidewall against upthrow side of normal fault.
6.2. LOCATION D—TOPPLING FAILURES

As shown in Figure 7, seams C, B and A are to be exposed by face shovel and/or dragline as the eastern limb of the trough fault zone is approached from the upthrow side, and thus will lead to a potential toppling failure situation. Toppling failures occur as a result of overturning rather than sliding (Figure 9(a)). The usual case is where blocks are formed by a closely spaced and steeply inclined discontinuity system (most often jointing) dipping into the excavation face. The centre of gravity of each block must fall outside its outer corner for toppling to occur, which may then start the block falling freely. Hence toppling can be a rapid and particularly dangerous type of failure.

The most common toppling failure situation in UK opencast coal mining is where the highwall advances towards and passes through a normal fault from the upthrow side (Figure 9(b)). A well defined jointing system sub-parallel with the fault creates "overhanging" blocks which tend to topple whilst the excavation face is being advanced through the area.

Another common situation leading to toppling failure is given in Figure 9(c). This shows that in the normal fault drag situation, as the fault plane is almost reached from the downthrow side (as Location D), the inclination of the jointing (being sub-parallel to the fault) changes the mode of failure from planar (as Figure 8(d)) to one of toppling.

6.3. LOCATION D—WEDGE FAILURES

Figure 7 shows two minor faults intersecting in the highwall at the back of the bench formed by exposing seam D within the trough fault zone.

A tetrahedral wedge failure may result when two discontinuity planes intersect, and the line of intersection daylights within the excavation face, as shown in Figure 10. Sliding occurs along both the intersecting planes, which may be faults (or joints or bedding planes). Wedge failures as observed in most UK opencast mines are usually fairly small in size, but because they often occur high above the base of the excavated slope, they can (like toppling failures) be very dangerous due to falling freely and suddenly from the face.

6.4. LOCATION D—ENDBLALL OR SIDEWALL FAILURES

At the outside limits or boundaries of any opencast excavation, be it the initial box cut, the final highwall or any excavated endwall section, the overall slope is formed as steeply as (safely) possible in order to minimise the total volume of rock to be excavated or to maximise coal recovery. Usually some surface feature which cannot be easily moved (e.g. major road, railway, river, canal, power line(s), important building(s) or housing etc.) forms one or more such boundary features. Normally a safety stand-off distance to the excavation limit (slope crest) is agreed with the
owner of the utility or structure. Often the economic limit for winning coal in a
particular succession of seams occurs at a major fault. Sometimes the fault and
an important surface feature/structure may be in close proximity to each other.
Figure 7, Section Y-Y, Location © shows schematically an endwall slope against
a fault with a major river just beyond.

This type of setting often leads to large slope failures which can present many
difficulties. Figure 11(a) shows different batter (slope) profiles against the
downthrow side of normal faults. Provided there is sufficient land available beyond
the fault (i.e. the upthrow side) the most stable situation will usually be achieved
by excavating right up to the fault plane/zone, and then just beyond, to form safety
benches and take out any fault drag affected strata on the upthrow side.
Alternatively, the mine operator may decide that digging through the fault would
be uneconomic, or there may not be sufficient land available, but this invariably
leads to instabilities (see later—Case Studies for Buckhead, Plenmeller and
Togston).

Figure 11(b) shows the choices that have to be made when trying to work coal
seams up to the upthrow side of a normal fault. Excavating through the fault (along
its strike or surface alignment), or terminating the excavation well away from the
fault, may be the two safest options, but will lead either to much barren dig or
to much loss of coal, respectively. However, any attempt to excavate and form
batters within or close to the fault zone will almost certainly result in toppling
failures.

7. Case Studies

The following case studies from opencast mines that have been worked in NE
England have been selected to illustrate the types of slope failures described in
the previous sections of this paper. The locations for each of these opencast mines
are shown in Figure 1.

7.1. BUTTERWELL—PLANE FAILURES

Between 1976 and 1993 around 13 million tonnes of coal was extracted at Butterwell,
near Morpeth in Northumberland, from about 20 different seams. The site covered
an area of 826 hectares and restoration continued for several years after coaling
was completed. Figure 12(a) shows an aerial view of the mine, looking westwards,
as it was in 1988. The main overburden storage mound is shown near the top of
the photograph (i.e. the western part of the site). Perimeter soil storage (baffle)
mounds and excavated faces in the overlying thick (10 m to 40 m) glacial deposits
can be seen on the left (south), and progressive restoration of the mine can be seen
to the right (north).

Figure 12(b) shows a plan of the mine area with the coal seams dipping generally
eastwards (at an average gradient of 1 in 7) and three major faults crossing the site
in an E–W direction (i.e. following the regional trend for faulting). These three faults divided the site into four working areas (A, B, C and D in Figure 12(b)), and the faults were identified by the areas which they separated (i.e. Faults A/B, B/C and C/D). In addition, there were several minor faults associated with, and near-parallel to, these major faults. These more minor faults occurred in the form of stepped, ridge, trough and antithetic faulting, all as shown in Figure 3(b), (c), (f) and (g).

The mine was worked in a series of E–W aligned dip cuts, with the excavation faces advancing southwards. This meant that the alignment of the three major faults and most of the minor faults was nearly always parallel or sub-parallel with the excavation faces. This led to slope failures over quite long sections of the advancing faces and benches. Examples of two plane failures which resulted from these operations and fault geometries are shown in Figures 13(a) and (b).

7.2. KNITSLEY—TOPPLING FAILURE

Knitsley was a fairly small opencast mine in (and typical for) County Durham, which was worked in the mid/late 1970s. Once nearly all the coal from the original planned excavation area had been won, a speculative northwards extension to the Threequarters coal seam was attempted in an area where no prospecting boreholes had ever been drilled, neither prior to the main site working nor prior to the start
Figure 12(b). Butterwell opencast coal mine—Geological plan
of this mine extension. At this stage the depth of excavation to the nearly horizontal Threequarters seam was around 17 m.

Once working of the extension was well underway a previously unknown normal fault was encountered from the upthrow side (see Figure 14(a)) which crossed the excavation area almost parallel with the advancing highwall face. The mainly sandstone strata were excavated from the upthrow side and toppling failure (as shown in Figure 14(b)) was experienced along the whole of the advancing face. One set of joint planes in the sandstone was observed to be sub-parallel with the fault plane and blocks as large as 3 m$^3$ toppled from the face in what was a very
(a). Schematic section showing northwards extension of excavation to Threequarters seam and effect of previous unknown fault—i.e. Toppling Failure

(b). Photograph of excavation to Threequarters seam showing location of fault and consequent toppling failure.

Figure 14. Toppling failure at Knitsley
dangerous situation. Working in this area ceased, and drilling which was carried out immediately afterwards proved that the downthrow of this fault was around 10 m. Groundwater was not encountered, and exposure of the fault plane in the endwalls of the cut showed the dip to be about 60°.

The occurrence of this fault led to the abandoning of this northwards extension as the extra 10 m depth of excavation on the downthrow side made it uneconomic to win the coal.

7.3. BUCKHEAD—WEDGE FAILURE AND ENDWALL FAILURE

Buckhead was a larger than normal opencast mine for the Durham Coalfield. It covered an area of 317 ha and yielded about 1.5 million tonnes of coal between 1980 and 1987. The site geology was very complex owing to the presence of the Wigglesworth Fault and the fact that it divided into two main branches, plus several smaller splinter faults, within the site area. A plan of the site is shown in Figure 15.

Due to the frequency of faulting, and the mostly steeply dipping strata, the mine was worked as a series of 15 separate coaling areas. The open-pit mining method was adopted in the majority of these working areas. A public highway (Esperley Lane in Figure 15) divided the site into two approximately equal parts, and this highway had to be maintained as an open thoroughfare at all times.

Figure 15. Buckhead site plan
Wedge failure
In Area E (see Figure 15) the strata dipped at around 1 in 3 NE (i.e. into the Wigglesworth Fault) and therefore this coaling area was excavated as an open-pit (as illustrated in Figure 6). At one point on the northern side of the excavation, two small faults intersected in the vicinity of a major branch of the Wigglesworth Fault. This resulted in the formation of a fairly large wedge failure which is illustrated in Figure 16 (the mechanism for wedge failure is described in Section 6.3).

Endwall failure (after Hughes and McLean, 1986)
In Area J (see Figure 15) the strata dipped at 1 in 4 NE into the main Wigglesworth Fault zone which was aligned near parallel with Esperley Lane in this vicinity. Endwall failure was seen as a possibility here. Therefore, before excavation works commenced, a system for monitoring ground movements and groundwater levels was installed, as shown in Figure 17(a). These installations included surface survey stations, simple slip-indicators and standpipe piezometers (see Figure 18).

At this location the Wigglesworth Fault was a wide fracture zone containing several displacement planes which varied in dip, strike, throw and lateral continuity. In addition there were old underground workings in the coal seams immediately
Figure 17(a). Buckhead Area J—Locations and cross-sections of monitoring stations

Figure 17(b). Buckhead, Section on A–B
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Figure 17(c). Buckhead, Section on C–D

Figure 17(d). Buckhead Section on E–F
Planes of differential movement (slip-surfaces) are identified by raising or lowering metal rods of various lengths (slip-rods) through the plastic tubes. The formation of a restriction to the free passage of the slip-rods identifies a possible slip-surface.

Figure 18. Simple borehole slip-indicator as used at Buckhead opencast mine
adjacent to both sides of the fault zone, including beneath the highway. The existence of Esperley Lane prevented excavation of the fault zone itself, and the endwall slopes were formed on the downthrow side as shown in Figure 17(b), (c) and (d). Excavation for the two coal seams (Main (G000) and Maudlin (H000)) was to a maximum depth of 35 m, involving cuts aligned at right angles to the highway and advancing in a SE direction. In order to maintain the stability of the highway, backfilling followed very closely behind the excavation and coaling operations (as shown in Figure 19) so that the width of endwall slope exposed at any instant was kept to the minimum possible.

Failure was first indicated by the appearance of tension cracks at the slope crest. The slip-indicators gave evidence of a complex deep-seated failure in the bedrock, as well as shallow failures near rockhead and in the overlying glacial deposits. Vertical settlement at the slope crest reached a maximum of almost 1.5 m (at Station 9, Figure 17(a)).

As the excavation progressed towards the SE limit of Area J, a small quantity of contractual coal was abandoned, because increased safety stand-off distances to safeguard the highway were adopted (especially above the Maudlin (H000) seam—see Section E–F, Figure 17(d)). Some very minor cracking was recorded in the carriageway of Esperley Lane which was repaired during routine maintenance works by the local highway authority; otherwise there was no disruption to traffic using this route.

Due to the very complex nature of this fault zone, no attempt at a rigorous stability analysis of the slopes was made during the working life of Buckhead mine. Instead, the results of the ground surveying and slip-indicator monitoring were used to aid judgement of the severity of the instabilities as the excavation progressed.

![Figure 19](image.png) Buckhead opencast coal mine—excavation works and coal winning in Area J (photograph looking along section line C–D). Note the closeness of the backfilling operations to the advancing excavation faces.
Decisions about amendments to safety stand-off distances and the abandonment of coal were made in relation to the magnitude of vertical and horizontal displacements that were recorded for each location along the slope crest adjacent Esperley Lane.

As part of the research for this paper, a retrospective stability analysis exercise (back-analysis) was attempted for each of the cross-sections shown in Figure 17(b), (c) and (d). Trial calculations were carried out for different combinations of failure surfaces (seatearths, fault planes, tension cracks etc.) together with various assumed shear strength and density parameters, and various groundwater levels. An appropriate analysis method that could justify the use of the available and assumed data was chosen, and hence a series of fairly simplistic limiting equilibrium calculations were executed. The Oasys SLOPE computer program was used for this work, and the type of analysis selected was the Janbu method with parallel inclined interslice forces (Oasys, 1997).

The results of this back-analysis exercise showed that the most critical part of the endwall slope was at or near cross-section C-D along the potential failure planes shown in Figure 17(c). This corresponds with the largest recorded vertical and horizontal ground movements, and with the shear displacements recorded in the slip-indicators. A limiting equilibrium factor of safety (FoS) of 0.77 was obtained for the following conditions:

- Groundwater level in borehole (piezometer) 8003 180 m AOD
- Shear strength of seatearth and fault gouge material ($c'$ and $\phi'$) 30 kPa and 15°
- Density of intact, seatearth and fault gouge material 24 kN/m$^3$
- Shear strength of glacial till (tension crack assumed) nil

The above suggests that the slope was in the process of failing, dependent upon the accuracy of the assumed parameters (shear strength and density values taken from Jameson, 1995).

A more detailed account of opencast mining at Buckhead and the results of the stability monitoring at Area J are given by Hughes and McLean (1986).

7.4. PLENMELLER-ENDWALL FAILURE (after Hughes and Norbury, 1996)

The coal deposits at Plenmeller in SW Northumberland owe their existence to the Stublick Fault which created outliers of Coal Measures strata within the Millstone Grit Series (Namurian) of the Upper Limestone Group (see Section 2 Geological Setting, Figure 1 and Table 1). Approximately 2 million tonnes of coal have been won from Plenmeller between 1991 and 1998, with restoration and site monitoring expected to last a further 10 years.

The location of the Stublick Fault within the Plenmeller site area is shown in Figure 20, and the nature of the fault zone adjacent to the endwall of the initial box cut of Area A is shown in cross-section in Figure 21. This endwall (highwall) was dug to a maximum depth of 90 m where it abutted the fault, and the fault itself
Figure 20. Simplified geological structure at Plenneller opencast mine (after Hughes and Norbury, 1996)
downthrows some 250 m northwards (i.e. into the cut). Figure 20 shows that the very steep dips of the coal seams were generally southwards at gradients between 1 in 2 and 1 in 7, and here the open-pit method of working was adopted with the main excavation work carried out by large face shovels and backacters.
In order to maximise the coal yield from the mine, the contractual coaling limits were set very close to the main fault zone as proved by prospecting drilling. In fact, on initial excavation it was found to be quite possible to form stable batters both above and below the geological rockhead, as shown in Figure 21 and Figure 22. However, tectonism and weathering had greatly fractured and weakened the rock mass for some 10 m or so below geological rockhead, and therefore engineering...
rockhead was found to be much lower than anticipated (see Figure 21). Below this level, increased dip and much minor faulting on the north (downthrow) side of the main Stublick Fault had been indicated from the prospecting and geotechnical drilling. As the excavation was deepened, widespread small scale faulting, fracturing, complex dislocation and sheared fault gouge were encountered across a zone which was often 10 metres or more wide, as shown in Figure 23. Slope failures began to occur and the likelihood of more and greater instabilities was obvious. The
solution adopted was to bench outwards from the fault zone and to form batters in the potentially more stable strata to the north. This resulted in some loss of coal. The original and modified highwall profiles are as shown in Figure 21.

As the mine excavation was extended eastwards by the open-pit method, further instabilities were encountered in this very complex and difficult fault zone, and these are illustrated in Figure 24(a) and (b). A more detailed description of the geotechnical aspects of Plenneller opencast mine and the problems caused by the Stublick Fault are given by Hughes and Norbury (1996).

7.5. TOGSTON-ENDWALL FAILURE

Togston opencast mine was located in North Northumberland, near Warksworth, and yielded about 1.6 million tonnes of coal during its working life from 1980 to 1986. A variable thickness of glacial deposits covered the whole area, and overlay Coal Measures bedrock that had a more complicated structure than was usual for this part of Northumberland. A plan of the geology and sequence of cuts is shown as a schematic insert in Figure 25(a). The Hauxley Fault was aligned approximately west to east across the northern side of the site, and the whole of the planned excavation area was located to the south of this fault. The bedding dipped radially inwards towards a centre point on the line of the fault strike, so that the coal seam outcrops (at rockhead) formed a series of concentric semi-circles (like an amphitheatre), i.e. the dip was eastwards in the west, northwards in the south, and westwards in the east. This led to the mine being worked as a series of tapered dip cuts which radiated outwards and up-dip from the hub or centre of the semi-circle (resembling the ribs or spokes of an open fan in plan).

The initial box-cut was located immediately adjacent to the main Hauxley Fault, and a sub-parallel splinter fault, in the western part of the site and is shown in plan in Figure 25(a). Figure 25(b) illustrates Section A–A through the Hauxley Fault and the box-cut, and shows the normal fault drag on the downthrow (excavation) side. The downthrow in this vicinity was around 150 m with the main fault plane dipping at about 60°. The fault zone itself was an aquiclude and groundwater level on the upthrow (north) side was about 25 m higher than the base of the excavation. Dewatering at Togston was by two external deep wells located on the downthrow (south) side of Hauxley Fault, near the former Hauxley Colliery shafts which were situated to the east of the opencast excavation. The contractual coaling lines for the four main coal seams were drawn to include coal right up the fault zone.

Excavation to the basal (Bottom Radcliffe) seam commenced at the western (shallower) end of the box-cut, but the excavation was not taken through the very complex and shattered strata located on the downthrow side of the main fault plane. The first major slope failure occurred against the fault (as shown in plan in Figure 25(a)) in the spring of 1980. Figure 25(a) then shows that as the excavation to the basal seam progressed eastwards, a second and then a third major slope failure formed adjacent to the Hauxley Fault. Figure 25(b) shows the development of the
Figure 25(a). Togston opencast coal mine, plan of initial box-cut and Hauxley Fault
Faulting and slope failures in surface coal mining

Figure 25(b). Section through Hauxley Fault and slope failure, Togston Opencast Mine
third major failure from its initial onset in June 1980 to its final shape in October 1981. During this same period the crest of the slope above the fault had subsided by some 12 m, and the toe of the slope had moved outwards (southwards) by some 20 m, with a further debris pile of about 10 m width slumped in front of the toe. Also during this same period, the whole of the northern side of the box-cut had deteriorated into a massive failure zone of some 400 m overall length, i.e. the earlier three failures (shown in Figure 25(a)) had spread and merged into one. Figures 26(a) and (b) illustrate the development of the failure zone with the elapse of time.
From an inspection of Figure 25(b) the mode of failure appeared to be multi-planar (illustrated in Figure 8(d)) with the most likely failure surface involving sliding down the 60° dipping fault plane and along the normal drag deformed Bottom Radcliffe seatearth (intraformational shear zone). Samples of fault gouge were tested by Spicer (1981) and Denby (1983) and these results are given in Table 2. A back-analysis for this failure mode has been carried out using the Oasys SLOPE computer program (Oasys, 1997) and applying the Janbu method with parallel inclined interslice forces (chosen for the same reasons as given earlier for the Buckhead case study). A limiting equilibrium factor of safety (FoS) value of 0.64 was the lowest obtained when using Spicer's ring shear strength parameters (Table 2) and the groundwater levels shown in Figure 25(b). This result is consistent with the large size and large displacement failure which occurred. Use of the higher shear-box test results given in Table 2 resulted in higher FoS values, but all results were less than (or close to) unity and thus represented failure of the slope.

8. Discussion

When planning mining operations, an accurate and detailed model comprising plans and cross-sections (or a computer based model) of the structural geology of the site is essential, so that the safest method for working the mine can be chosen. The gradient and orientation of the bedding dips usually have the greatest influence in deciding the overall working method (i.e. opencast dip or strike cuts, or open-pit excavations), but careful consideration has to be given to how any faulting that is present will interact with the progress of excavation faces, especially with endwall or sidewall situations.

Figures 7, 8 and 9, and the case studies for Butterwell and Knitsley, each illustrate the problems caused by attempting to excavate through faults when the alignment of the highwalls of the advancing cuts and forward benches is near parallel to the fault strike. This usually leads to either planar or toppling failures each time the fault is crossed by an excavation face. However, if the advancing faces are excavated approximately at right angles to the fault strike, then both the upthrow and downthrow sides of the fault are exposed simultaneously, and both sides are confined so that it is not possible for the fault planes to act as release surfaces, and hence slope failures cannot take place. This can be demonstrated by considering the cut alignments in Figure 7 to be at right angles to that shown, i.e. Section X-X can be seen as representing the elevation of one particular cut, and Locations ⊙ and ⊙ represent the trough fault exposed end-on, whence it can be seen that neither fault plane is able to project rock outwards from the face. Of course, when these re-aligned cuts reach Locations ⊙ and ⊙ (endwall), then planar failures will result from the faults encountered at these locations.

Figure 10 shows the tetrahedral wedge in its simplest form, and this type of failure has been described in detail by others (e.g. Walton and Atkinson, 1978; Hoek and Bray, 1981; Stead and Scoble, 1983). The Buckhead (Area E) case study and
Figure 16 show an example of an unusually large wedge failure which resulted from two intersecting faults.

Major faults often determine the economic limit for surface coal mining operations, and hence are often present in endwall or sidewall situations. Figure 11(a and b) shows the various options, and Section 6.4 describes the problems. It is the authors' experience that mine operators usually elect not to excavate right up to and through the fault zone, and this invariably leads to ongoing instability problems, for example the Plenmeller and Togston case studies. It seems that most mine operators would prefer this, rather than commit themselves to the additional costs of digging through the fault zone and into the potentially more stable ground conditions beyond. However, where there are major faults located close to and approximately aligned with important surface features (such as rivers, railways, highways etc.) then excavating through the fault zone may not be an option, for example the Buckhead (Area J) case study.

9. Conclusions

Normal faulting is commonplace in the shallow terrestrial coalfields of North East England. The main purpose of this paper is to show how this faulting can cause slope failures when encountered in surface mining excavations. These slope failures can have major cost implications for the mining project.

In relation to internal benches and highwalls, the orientation of cuts with respect to fault strikes is the most critical factor. Faults aligned near parallel with slopes will act as release surfaces for failures, which can be either planar or toppling mode depending on whether the fault is excavated from the downthrow or upthrow side respectively. Highwalls orientated at near right angles to fault strikes are far less likely to suffer any instabilities because the faults are prevented from acting as release surfaces. Faults which intersect with each other may result in tetrahedral wedge failures.

Endwall or sidewall situations usually occur at the edges or statutory (planning) limits of opencast or open-pit excavations, where the excavated slope extends from the ground surface down to the basal coal seam in a series of steep faces and narrow benches. These slopes often coincide with major faults and very careful consideration has to be given to the overall stability of the slope, especially if important natural or infrastructure features are in close proximity to the mine boundary.

References


Surface coal mining and the reclamation of tips, landfills and quarries – some geotechnical case studies from Northern England.

Surface Coal Mining and the Reclamation of Tips, Landfills and Quarries - Some Geotechnical Case Studies from Northern England

DAVID B. HUGHES AND BARRY G. CLARKE

ABSTRACT

Underground coal mining has almost disappeared from Northern England as the deeper terrestrial reserves have been exhausted, and only one mine still continues to extract undersea coal. The legacy of this once major industry has been the creation of many tracts of derelict land and abandoned colliery tips. Old tips are associated with potential hazards such as instability, combustion and contamination, and they are often considered to be visually intrusive or an obstruction to re-development. Surface coal mining is also in decline, due to increased public perception that it causes environmental nuisance and damage, which has resulted in the introduction of ever more restrictive planning statutes, even though it provides a cost effective way of restoring old tips and derelict land. A consequence of this has been the identification of a wider relationship between land reclamation works and the extractive industries which includes underground mining and tips, surface mining and quarrying, and landfilling and contaminated land. The design of surface mining projects to incorporate restoration of tips and derelict land often poses difficult geotechnical and geo-environmental engineering problems. Several case studies illustrate how some of these problems have been resolved for specific restoration projects.

Keywords: Colliery tip reclamation, geotechnical case studies, surface coal mining.

1. INTRODUCTION

With Great Britain (United Kingdom) being a relatively small but densely populated island, the statutory (Town and Country) planning procedures and requirements are usually very detailed and onerous, especially with respect to current environmental protection policies. Over the last twenty years or so there has been a steady increase in

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public opinion against the acceptance of surface mining, and there is now a "presumption against surface coal mining" policy operated by many Minerals Planning Authorities (MPAs), i.e., local/county councils that administer Town and Country planning statutes [1]. Problems resulting from these activities are often difficult to resolve and new applications are frequently refused on the grounds of perceived environmental nuisance or damage. However, the benefits of surface mining in providing opportunities for the remediation and landscaping of abandoned tips and derelict land are very real, especially if the financial burden of these works can be absorbed by the usually favourable economics of such activities. This paper includes several geotechnical case studies from Northern England which illustrate some successful projects.

Figure 1 shows the location of Northern England within the UK. It also shows the locations of the main coalfields and the case study projects.

2. BACKGROUND

Mining and quarrying wastes (or spoils) result from the extraction of fossil fuels (mainly coal), ores, minerals and aggregates. These waste materials, which are often
produced in large volumes, can be solid (soil or rock fill) or liquid, and they can be inert or contain hazardous (contaminated/toxic/explosive/combustible) constituents, although the toxicity levels and other hazard risks are usually quite low. Solid wastes are generally stored in tips (also called spoil mounds, or pit heaps if associated with collieries), whilst liquid wastes are stored in lagoons.

Figure 2 shows, in the form of a flow diagram, some relationships between the UK mining and quarrying industries and the creation of tips, landfills and contaminated land. These relationships are illustrated by the case studies which are described later. In the UK surface mining is commonly referred to as opencast mining or opencast quarrying (especially in legal or statutory documents).

The following brief accounts of certain aspects of British coal mining history, practice and legislation have been included to expand on the theme of this paper and to provide some background information to complement the later case studies.

2.1. A Brief History of Coal Mining in Northern England

Coal mining has taken place in the UK for at least 2,000 years, with the earliest recorded workings dating from Roman times. The coalfields of Northern England (shown in Fig. 1) were mainly worked during the late eighteenth, nineteenth and early twentieth centuries.

In the combined Northumberland and Durham coalfields of North East England, the maximum annual coal output from underground mining of 56.4 million tonnes was achieved in 1911, and production has gradually contracted ever since, especially after nationalisation of the UK coal industry in 1947 [2]. Currently Ellington mine, which is located near the Northumberland coast (and which extracts coal from beneath the North Sea), is the only major colliery still operating in this region. In the Cumbrian coalfield the total number of collieries ever recorded was only fourteen, and the last one of which (Haig Colliery) closed in 1986.

Opencast or surface coal mining, as a fully mechanised operation, began in the 1940s. In the early years only relatively small sites were operated, sometimes yielding as little as 10,000 to 20,000 tonnes of coal per site. With the ever increasing size of draglines and other excavation plant, the size of opencast mining projects has also increased, and nowadays sites rarely yield less than 1 million tonnes and can even produce as much as 15 million tonnes. Annual production for the Northern England region reached a maximum of about 5 million tonnes during the 1980s and early 1990s.

During the last two decades more onerous statutory planning requirements have gradually been introduced for opencast mining proposals, especially with respect to environmental protection matters. Together with the re-privatisation of the UK coal business in 1994, this has led to a further contraction of the industry. For example, in 1992 there were nineteen opencast mines operating in Northern England, but by the end of 2001, this number had been reduced to only six.
2.2. Some Characteristics of Colliery Spoils and Tips

In the 1930s, the extraction of 1 million tonnes of coal by underground mining resulted in about 35,000 tonnes of spoil or discard; but with the steady introduction of mechanised coal cutting methods from the 1950s onwards, this had increased to about...
430,000 tonnes of discard per 1 million tonnes of coal by the 1970s [3]. In County Durham, a large quantity of discard arising from coastal collieries was tipped onto the east coast beaches at or below the high water line, and this has been gradually washed out to sea by the tides. With the closure of most coastal collieries this practice has now almost ceased, although Ellington mine spoil is still tipped onto the Northumberland beaches. A very large quantity of discard, previously produced by inland collieries in Northern England, has been stored on land away from the coast.

Tips or spoil heaps constructed before 1950/1960 were usually formed by loose tipping, e.g. by tipping from wagons, tubs, aerial ropeways, Maclane tipplers, belt-conveyors, lorries or dump-trucks. More recently constructed tips have mostly been formed in layers by tractor-scrapers and dump-trucks, with spreading and compaction resulting from the use of bulldozers and sometimes heavy rollers. In 1970 about 60% of all colliery tips were recorded as less than 30 m high, and about 15% were more than 50 m high [3].

The two principal types of spoil which result from underground coal mining are referred to as coarse discard and fine discard. Coarse discard is predominantly argillaceous and is produced mainly from washery material above 0.5 mm in size, but also includes spoil from the excavation of roadways and drifts, plus table and belt pickings prior to screening of the coal, and therefore may contain some arenaceous material. Fine discard consists of either slurry or tailings, slurry being the fine material (predominantly coal) remaining in suspension after the washing process, whereas tailings is the fine reject material (predominantly argillaceous) from the froth flotation process used for cleaning the coal which is less than 0.5 mm in size.

Fine discard (both slurry and tailings) tends to be disposed of in lagoons, which are usually constructed within colliery tipping areas. These lagoons are mostly sited on or between existing tips and are often covered over by later coarse discard tipping. After burial, the fine discard consolidates due to self weight and the weight of the overlying fill. This process is accelerated by the free draining characteristics of the overlying and underlying coarse discard material. In time, and due to their relatively low permeability, these buried lagoons may become confining layers associated with perched water tables which often form within individual tips or within large tipping complexes.

2.3. Instability of Tips and Geotechnical Legislation

According to Bishop [4] “On 21st October 1966, the problem of the stability of tips and spoil heaps was brought to public attention with dramatic force by the disaster at Aberfan (South Wales), when a slide involving some 110,000 m$^3$ of colliery waste resulted in the loss of 144 lives, 116 of those were children mostly between the ages of 7 and 10.” In this same paper, Bishop gave accounts of colliery tip failures at Aberfan and Cilfyndd (also in South Wales), together with illustrations of tip failures in China.
clay waste, limestone waste, fly ash, and various tailings dams and lagoons. There are many other accounts of spoil heap and lagoon failures in the geotechnical literature [5, 6].

The disaster at Aberfan led to the UK government introducing the Mines and Quarries (Tips) Act in 1969, and the Mines and Quarries (Tips) Regulations plus the Mines and Quarries (Tipping Plans) Rules in 1971, all of which were subsequently published collectively [7]. These three pieces of legislation require that all spoil heaps and lagoons should be regularly inspected and reported on by a suitably experienced (civil) engineer, the reports to include details of ground investigations, design and analyses, construction and maintenance.

After the enactment of the above legislation it was discovered that temporary spoil mounds and lagoons connected with opencast mining were not included, and this led to the parties involved in UK surface coal extraction to introduce two voluntary codes of practice (in 1982 and 1989) [8, 9] which related to both spoil storage and to excavations and backfilling. In 1999 opencast mining and quarrying was the subject of new legislation in the form of new statutory regulations and an approved code of practice which superseded the earlier voluntary codes of practice [10].

2.4. Combustion and Contamination In Colliery Tips

All colliery spoils contain pyrite, but the proportion varies depending upon the nature of the coal seams worked, together with the methods of winning and cleaning that were employed. Pyrite is stable until exposed to air and water, both of which cause oxidation, leading to an exothermic reaction and thus to progressive heat build-up. This can result in spontaneous combustion, which can then lead to continuous burning if sufficient oxygen is available. This is especially the case in older tips which tend to be loosely placed (i.e., have a high percentage of air voids), and which usually contain larger proportions of coal and other combustible matter than newer engineered tips. Hazards that can result from the burning of tips include the collapse of the surface due to the creation of large cavities within the body of the tip, and the release of noxious gases such as carbon monoxide, carbon dioxide, methane, sulphur dioxide and hydrogen sulphide. Some of these gases can ignite or explode when mixed with oxygen or water, although such occurrences are rare in open spaces [11]. Oxidation of pyrite in an aqueous environment also produces sulphuric acid which often results in acid drainage discharges or seepages from colliery tipping complexes.

Many of the older tips in Northern England have undergone some burning, and this has created a material commonly called “burnt colliery discard” (or “burnt shale”). This material is usually pink or red in colour and is generally harder than the original “unburnt colliery discard” (or “unburnt shale”) from which it was formed. Burnt discard has been much used in the recent past in construction works, for example as high quality (engineered) fill and as low-grade sub-base material for new highways.
A disadvantage of using burnt discard is that it usually has a high water-soluble sulphate content, which can be harmful to concrete [14].

In the past underground mines often supplied coal for the manufacture of gas, coke, tar etc. from plants or works usually located within or adjacent to the colliery site, and wastes from these complementary industries were then deposited on the nearby tips. As a result, a large number of pollutants or contaminants may be found within colliery tips and these can include aluminium, ammonium, arsenic, benzene, boron, cadmium, chromium, copper, combined cyanide, total cyanide, cyclohexane extractable matter (CEM), iron, lead, magnesium, manganese, mercury, mineral oils, naphthalene, nickel, pH (high acidity), phenols, polynuclear aromatic hydrocarbons, poly-nuclear aromatic hydrocarbons (PAH), pyrite, acid soluble sulphate, water soluble sulphate, sulphide, elemental sulphur, toluene extractable matter (TEM) and zinc [15].

In the UK ground investigations for contaminated sites are now covered by a Code of Practice – BS 10175 : 2001 [16], which requires the completion of a “risk assessment” prior to the commencement of any direct ground exploration (i.e., boreholes and trial-pits). Guidelines for the safe investigation of landfills and contaminated land are given in the Institution of Civil Engineers Site Investigation Steering Group Report – Part 4 [17]. This includes a section on the assessment of sites which are categorised as green/yellow/red (in ascending order of hazard risk) from the results of a desk study or preliminary investigation. The allocation of a colour category, following the preliminary study, then determines the level of precautions and protection to be used in the main (direct) ground investigation.

2.5. Tipping Space and Surface Mining

The theme of this paper is about the use of surface mining projects to facilitate the restoration of tips and for landfills. However, in the UK, the backfilling of surface mining voids usually presents a “bulkage” problem which is often not fully appreciated by the MPAs (or their “planning professionals”).

A simplified sequence of operations for surface mining for a single near-horizontal coal seam is shown in Figure 3. Topsoil and subsoil are removed (usually by tractor-scraper) and placed in storage mounds near the site perimeter (a, b, and c). Excavation to the initial cut (box-cut) is usually by face shovel and/or backacter (backhoe) and the spoil is transported by dump truck to the overburden mound for storage (d). Successive cuts are then excavated by dragline and/or face shovel or backacter with the spoils going into previous cuts (e). The final void is backfilled using spoil from the overburden mound (i.e., the initial cut spoil) and the subsoil and topsoil are replaced (f, g, and h). Most surface mines are restored to agricultural use, but sometimes they can be restored to other purposes such as recreation, forestry or for industrial development.
Figure 3 (g and h) shows that there is usually a net volume increase in the backfill materials. This is "bulkage" which is due to replacing the Coal Measures bedded strata by "as excavated" angular fragments (although it is the same Coal Measures rock). Hence there is increased void space in the backfilled mass, which results in a raised ground surface on completion that has to be accommodated in the final design restoration contours. A consequence of bulkage is the long-term settlement of the restored surface after opencast mining has taken place. Much site monitoring and research has been carried out in attempting to predict the rates and magnitudes of surface settlement, and has been reported by several authors with respect to investigations carried out specifically in Northern England [18–20]. This research has shown that long-term surface settlement is typically within the range 0.5% to 1.0% of the total backfill depth, but can be up to 3.0% or more where the majority of the backfill has been placed by dragline tipping [19].

Figure 3 (i) shows the usual problems that can be caused by providing a void for accommodating colliery spoils (restoration of tips), or for other landfills, in a situation where bulkage of the run-of-mine backfilling already necessitates raised final ground levels. Imaginative landscaping, involving the creation of hills or other raised areas, is often adopted in order to overcome these problems.
It should be noted that Figure 3 only illustrates the simplest opencast operating situation, and that surface coal mines in Northern England usually involve more complex structural geology including several coal seams, faulting and variable bedding dips [21, 22]. However, the problem of backfill bulkage and shortage of tipping space is always present.

3. CASE STUDIES

The following case studies all relate to surface coal mining, and are all geotechnical projects investigated and designed by, or under the direction of, the principal author of this paper during the period 1979 to 1994. These projects were located within the Northern Region of the former British Coal Opencast (BCO) and their actual locations are shown in Figure 1.

Several of the following case studies refer to the results of slope stability analyses. These analyses mostly involve a consideration of either circular failure (usually Bishop's method [23]) or non-circular failure (usually Janbu's method [24]), both of which are based on the "method of slices" where a Factor of Safety (FoS) of unity represents the boundary between stability and failure, or the "limiting equilibrium." In UK surface mining situations, FoS values higher than 1.2 or 1.3 are frequently considered to be satisfactory, but this often depends on the length of time that the slope may be required to stand, or on confidence in the accuracy of the geotechnical parameters used in the analyses. During the period 1979–1994, several stability analysis software packages had been available at BCO, which were mostly based on the work published by Little and Price [25]. Subsequently, as part of the preparation of this paper, many of the original analyses have been repeated or re-examined using the Oasys software [26] which includes analysis methods similar to those used previously.

3.1. Removal of Walkmill Tips

Walkmill Colliery was located in Cumbria on the west bank of the River Keekle some 4 km east of Whitehaven. The spoil tips which were left when the colliery closed had a relatively high pyrite content and leached an ochreous (acid) discharge into the River Keekle, especially after periods of heavy rainfall. There had also been coke ovens at the former colliery, and this was probably the cause of further pollution. A ground investigation of the tips carried out in 1980 proved the existence of phenols plus traces of cadmium and arsenic (i.e., "red list" contaminants [17]). Both the local MPA and the National Rivers Authority (now the Environment Agency) were keen to have this source of pollution removed, and a scheme was agreed with BCO whereby all the tip material was excavated and transported a distance of about 1 km to be dumped into
the northern void of the nearby Keekle Extension opencast coal site, as shown in Figures 4 and 5.

The base of the northern void in the opencast mine was well below the bed level of the River Keekle and thus below the regional water table. Consequently there was a requirement to prevent this new storage arrangement of the colliery tip material from causing further pollution. The local glacial till which overlies the Coal Measures strata in this part of Cumbria [27] has a relatively low permeability (10^{-6} to 10^{-8} m/s) when well compacted. Therefore it was decided to encapsulate the transported tip material with a 3 m thick layer of this till. Figure 5 shows the site operations with the colliery tip in the top left hand corner of the picture and dump trucks depositing tip material (also in 3 m thick layers) in the opencast void. Against the sides of the opencast void the encapsulation layer was usually constructed 4 or 5 times the specified width or thickness, as this acted as a haul road and thus facilitated its construction and site plant operations.

In order to win the coal, and then to place and encapsulate the Walkmill tip material, the void remained open below rockhead level for about 12 months. The remainder of the backfilling up to finished level (approximately original surface)

Fig. 4. Plan of Walkmill Tips and Keekle Extension Opencast Coal Mine.
then followed and was completed in early 1994. As shown in plan in Figure 4, a public highway formed the northern boundary of the Keekle Extension opencast mine. The upper parts of the excavated slopes (i.e., above the Coal Measures rockhead level) located immediately to the south of this highway (i.e., on the north side of the void) began to show increasing signs of instability during this period. These upper slopes had been excavated through the overlying glacial deposits, which here comprised an upper and a lower till layer separated by a middle horizon of coarse sand and gravel, and groundwater seepage was usually present in this middle granular stratum [27]. As shown in Figure 6, seepage from this middle horizon created cavities and undercutting (back-sapping) leading to instabilities which necessitated regular monitoring of the condition of these slopes. Fortunately, completion of the void backfilling was achieved before the site boundary was breached, and therefore no damage was caused to the highway.

3.2. Landscaping of Stobswood Pit Heap

The disused spoil heap for the former Stobswood Colliery was landscaped as part of the final restoration of Sisters opencast coal mine. This old pit heap was located on the
south-west boundary of the opencast site, immediately adjacent to the London-Edinburgh main line railway, as shown in Figure 7. The overall dimensions of the unrestored pit heap were approximately 400 m long, by 100 m wide, by 25 m maximum height, and contained about 500,000 m$^3$ of material. No ground investigation data or tipping records existed. The landscaping scheme involved no reduction in the overall volume of the heap, but the height was to be reduced and the base width increased to create more gentle slopes which could be planted with a variety of trees.

In the summer of 1981, during the early stages of pit heap earthmoving operations, slurry lagoon deposits were unexpectedly encountered at the base of the heap. At the same time ground heave was observed in the drainage ditch adjacent to the railway embankment, and the movement appeared to be confined to a fairly local area at the toe of the slope near the mid-point of the south-west side of the heap. However, due to the proximity of the main line railway, there was concern about the potential for further ground heave putting railway safety at risk. Slow running on the railway and full time surveillance were immediately introduced, and all earthmoving equipment was directed to reduce the overall height of the heap.

A detailed ground investigation was carried out as an emergency action to facilitate a stability assessment. Twelve shell and auger boreholes were sunk along the toe and

Fig. 6. Keekle Extension Opencast Coal Site in 1993. Looking NNW, showing cavitation and general slope deterioration due to seepage of northern side slopes, which occurred whilst infilling with Walkmill Tip materials was ongoing.
through the crest of the partially reduced pit heap. Figure 8 is a cross-section drawn perpendicular to both the rail tracks and the long axis of the heap and shows the original ground profile, the intermediate stage (when ground heave was first noticed and the investigations commenced) and the final landscaped profile. Boreholes 2, 4, 5, 11, and 12 were located on the cross-section chosen for the stability analyses (Fig. 8) which also shows the strata succession and descriptions, and groundwater levels. In the natural strata underlying the railway and the heap there was a fairly continuous layer of laminated clay. A layer of soft to firm silty, sandy clay also underlaid the railway and the adjacent toe of the heap, but did not extend under the main body of the heap. Within the basal zone of the heap, and extending right up to the south-western toe, was a continuous layer of slurry lagoon material which was formed from coal washery fine discard. This indicated that part of the pit heap had been constructed over a former lagoon site after the slurry had partially drained and solidified. Figure 9 shows boring work in progress on Borehole 2 which encountered the former lagoon material.

From the borehole samples taken during the ground investigation, and the subsequent laboratory tests, density and shear strength parameters were obtained, and these are also shown in Figure 8. A Bishop type [23] slope stability analysis was carried out for failure circles passing through the laminated clay, and through the lagoon material and the silty, sandy clay. These gave minimum FoS values of 2.13 and 2.17 respectively, demonstrating that the landscaped pit heap profile was quite safe.
Fig. 8. Cross-section of SW side of Stobswood Pit Heap showing ground investigations and stability analyses results after ground heave was discovered adjacent to railway embankment.
As stated above, the ground movements in the drainage ditch were very local. This disturbance was probably brought about by earthmoving plant operating near the toe of the heap, and thus causing the lagoon material and the soft silty, sandy clay to be displaced into the ditch. It was concluded that a large scale failure in the spoil mound was not in progress, as had been initially feared.

Figure 10 shows the landscaped pit heap in 1997 with trees having been established. It can also be seen that the main line railway has been electrified at some stage after the photograph in Figure 9 was taken in 1981.

A later feature of Sisters opencast coal site was the incorporation of a landfill site into the final void (see Fig. 7 for location), which led to a surplus of backfilling materials being accommodated by raising the final restoration contours. The restored Stobswood Pit Heap still forms a prominent hill or mound alongside the mainline railway.

3.3. Removal of Tips at Linton Colliery

Surface mining began at Linton Lane opencast coal site in 1990, and the contracted quantity of 1.1 million tonnes was achieved by 1995, with restoration continuing for a
few years thereafter. As part of the planning consent, it had been agreed that the disused tips of the former Linton Colliery should be included within the site area, and would be removed and the land restored to agricultural use on completion of the opencast mining project. The disused tips were unsightly (see Fig. 11) and their removal was seen as a significant land improvement by the MPA (Northumberland County Council).

Prior to the commencement of surface mining, extensive prospecting and geotechnical investigations were carried out, including drilling in the area of the disused tipping complex. These investigations proved that the coal and pyrite content of the tips was fairly low. A few minor instabilities existed in the side slopes of the tips, but these did not present any danger, or affect adjacent land or property. Smoke and steam were observed to be escaping from some of the cracks in parts of the tips and hence gas and temperature monitoring tubes were installed. However, no significant levels of noxious gases were detected, and the maximum recorded temperature was only 60°C. Subsequently, no areas of burnt or burning material were encountered during excavations into the tips, and it was assumed that the smoke and steam seen earlier denoted only the very start of exothermic reactions.

The total volume of the tip material was incorporated into the backfilling of the opencast site and resulted in an overall increased surface level on restoration.
Figure 11 shows the disused tipping complex at Linton Colliery in 1987, with much of the lower lying area flooded, and a drilling rig (installing temperature monitoring tubes) on top of one of the tips (top centre of picture). Figure 12 shows the same area from approximately the same viewpoint in 1993, with the opencast excavation taking place beneath the former tipping complex. Figure 13 again shows the same area from the same viewpoint, in 1997, with fences erected and crops growing on the newly created farmland that was previously the colliery tipping area.

In addition to the restoration of tips, the working of this opencast mine also involved the creation of a conservation area and a nature reserve. A lake was provided to attract bird life, and this has been occupied by a sizable population of waders and wild fowl. The Northumberland Wildlife Trust now owns and manages this nature reserve.

3.4. Surface Mining and Landscaping at Herrington Colliery

Herrington Colliery was closed in 1985 and left its legacy of a 5 million m$^3$ spoil heap, at around 35 m–40 m high, as a major unsightly feature on the landscape (see Fig. 14). The tip together with the abandoned colliery buildings brought the total area of derelict land to about 43 ha. Shallow unworked coal suitable for opencast mining was
Fig. 12. Linton Lane Opencast Coal Site in 1993. Looking E from same viewpoint as Figure 11, showing opencast void where tips had previously been.

Fig. 13. Restored Linton Lane Opencast Coal Site in 1997. Looking E from same viewpoint as Figures 11 and 12, showing restoration to agriculture.
known to exist in this locality, i.e., in the north eastern part of the Durham coal field where the Coal Measures strata dips below the Permian (Magnesian Limestone) outcrop nearer to the coast. A scheme to win coal and to restore and improve the area was devised, which incorporated a further 100 ha of mainly low quality agricultural land. The mining project yielded 950,000 tonnes of coal during the working period from 1996 to 2001. The finished scheme will be a country park and public amenity area, together with a tract of restored agricultural land where improved drainage has been provided (i.e., the most easterly plot in Fig. 15). The pit heap has not been totally removed, and still remains as a mound or high ground feature in the final landscape, but is now beginning to resemble the natural green and rounded hills of the nearby Magnesian Limestone topography.

The layout of the opencast site was as shown in Figure 15. Digging for coal began with the initial cut at the north-west end of the excavation area, and progressed in a south-easterly direction, with the final two cuts shown in the central part of the site. The majority of the excavation was through Coal Measures bedrock (sandstone, siltstone, mudstone, coal and seatearth), and this solid geology was overlain everywhere by glacial till, and additionally by glaciolacustrine deposits (laminated
Fig. 15. Plan of Herrington Colliery Opencast Coal Site, showing location of former pit heap.

...silts and clays) in the south-east part of the site [28]. Excavation and distribution of the colliery spoils from the pit heap were also undertaken to achieve the final landscaping. Apart from the reduced height of the tip itself, this has resulted in an average 5 m increase in final ground level over the majority of the restored site area.

Figure 15 shows that the southern part of the opencast excavation area had to be cut through the northern part of the pit heap, and for this location Figure 16 shows the slope geometries and strata succession above rockhead together with the corresponding geotechnical parameters obtained from ground investigations carried out prior to working the site. Figure 16 also shows the most critical FoS values for several possible circular failure profiles occurring above rockhead, and...
Fig. 16. Cross-section of Herrington Pit Heap slope adjacent to Herrington Burn Diversion and excavation through glacial deposits of opencast void.
for non-circular failures near rockhead and through bedrock. The lowest FoS values, 1.27 and 1.31, were obtained for potential circular failures through the pit heap material, and through the upper parts of the glacial deposits which included the laminated clay layers. These FoS values being adequately in excess of unity indicated that the slopes should remain stable during the period of the excavation works, which proved to be the case. Figure 17 shows the exposed pit heap material at the location of the Figure 16 cross-section, and shows an inclined layer of burnt discard (lighter coloured in the photograph) within the mainly unburnt discard.

Early in 2001 the last coal was removed and the final cuts were backfilled. The transformation of the whole site area into a country park and amenity area, plus some agricultural land, is currently nearing completion.

3.5. Tipping Down Shafts at Marley Hill and Byemoor

An opencast coal mining project was proposed following the closure of Marley Hill and Byemoor Collieries. One objective of the proposal was to facilitate the reclamation and restoration of the derelict land resulting from the past underground mining activity, although much of the land included in the proposed scheme is in agricultural use in a generally attractive rural setting. Coke and tar had been produced
at these collieries, and there was uncorroborated (hearsay) evidence that tipping of waste from these processes had taken place down disused and abandoned shafts. This brief case study has been included to illustrate the past practice of tipping of mining industry wastes, especially toxic or harmful wastes, down old shafts (as shown on the left-hand side in Fig. 2).

Geotechnical drilling was carried out for the proposed Marley Hill opencast mine during the period 1988 to 1993. Figure 18 shows a shell and auger boring rig positioned over an old abandoned shaft during these investigations. Because of the possibility of ground instability due to shaft collapse, and the further possibility of contact by the drilling crews with contaminated or harmful wastes, this was deemed to be a fairly hazardous activity. The boring rig shown in Figure 18 was supported on a substantially constructed platform which was secured via steel ropes to four anchorage points, each located some 30 m from the shaft position. In addition, the drilling crews and technicians all wore protective clothing and safety harnesses (which were also secured by ropes to the platform anchorages); these being the precautions for a “red category” site, as per the ICE Site Investigation Steering Group Guidelines [17].

Figure 19 shows a close-up view of the boring rig with liquid wastes discharging from the bailer tool. It was confirmed that hazardous wastes had indeed been tipped down several abandoned shafts, in particular coke and tar works wastes containing
phenols. To date planning permission for opencast mining at Marley Hill has not been obtained.

3.6. Surface Mining Adjacent to Landfill at Old Eldon Quarry

In the early 1950s, south-west of Eldon village in the south of County Durham, a small quarry was worked near the outcrop in the Magnesian Limestone (Old Eldon Quarry in Figs. 1 and 20). This same quarry (under the name of East Eldon opencast coal site) was then deepened below the base of the limestone to allow opencast working of the underlying Main and Maudlin coal seams, with work terminating in 1953 (see Fig. 21). The maximum depth of excavation was 42 m.

The quarry (or opencast) void was not lined when landfill tipping began some years later (the precise date that tipping commenced was not recorded). The first landfill licence was issued in 1977, and this was renewed in 1989. Cessation of landfilling and partial covering with a sandy clay and crushed rock layer occurred in August 1992. The list of materials known to have been tipped included construction waste, asbestos (slurry and sheeting), "non-hazardous" industrial waste (slag, foundry sand, concrete, scrap metal, ceramics, glass, timber, fibreboard, paper, plastics, cloth, garage waste, rubber), inert coal recovery plant fine discard, sewage sludge, transfer station waste, and possibly other unrecorded wastes (especially in the early pre-licence years).
The potential for a small opencast coal project at Eldon Deep (which would be located to the north and west of Old Eldon Quarry Tip – as shown in Fig. 20) was identified by BCO, and geotechnical investigations for this proposed surface mine were carried out during the late 1980s and early 1990s. When the engineering and operational aspects of the proposed Eldon Deep opencast coal site were investigated, it became apparent that overburden tipping space would be very limited, and the planning application to the MPA included a proposal to store overburden top of the landfill at the Old Eldon Quarry Tip (see Figs. 20 and 21). The maximum permissible height of the overburden mound was fixed by the MPA at 168 m above Ordnance Datum (AOD) (presumably for aesthetic/landscape reasons?). Landfill tipping was originally supposed to cease in March 1990, but continued until August 1992. As a result, it was difficult to assess the volume of storage that would be available before tipping actually stopped and the final landfill surface level was known.

Geotechnical boreholes sunk into the tip encountered many of the waste materials listed above, and identified the main potential hazards as methane gas...
Fig. 21. Eldon Deep Opencast Coal Mine – section through SE endwall and Old Eldon Quarry Tip. (Looking NE – see section location in Fig. 20).
(with concentrations up to 35%) and carbon dioxide gas, plus leachate containing asbestos and traces of cadmium ("red list" substances [17]) and phenols. Geotechnical drilling operations, with personnel wearing full protective and disposable clothing and equipment, are shown in Figure 22. The geotechnical investigations involved both shell and auger, and rotary drilling, and included the installation of standpipes and piezometers so that both gas and leachate/groundwater levels could be monitored. It was recommended that a clay blanket should be placed over the completed landfilling to reduce further ingress of surface water.

Based on the approximate finished landfill surface level, in August 1992, of 158 m AOD (including an allowance for the clay blanket), then the height available for opencast overburden storage would be 10 m (i.e., up to the 168 m AOD maximum prescribed by the MPA). It was estimated that the surcharge weight of this height of overburden on top of the landfill would cause at least 1 m of surface subsidence of the landfill itself. This in turn would tend to expel gas out of the landfill and into the fissured bedrock sidewalls of the Old Eldon Quarry (see Fig. 21). As a result, a gas drainage scheme, consisting of vertical wells and perimeter collection mains, was designed to intercept as much gas as possible. Also, the flow of leachate down dip through the old pillar and stall coal workings (see Fig. 21) could result in seepage into the proposed opencast void, and countermeasures were recommended which
included the installation of a pumping well to the lowest part of the landfill, plus sealing the old coal workings with clay as soon as they were exposed.

Figure 21 shows that the excavation for the Eldon Deep opencast project results in a rock barrier being formed on the north-west side of the Old Eldon Quarry landfill which acts as a retaining wall to support both the landfill and the overlying opencast overburden mound. The approximate dimensions of the rock barrier are 37 m high, 75 m wide (at base), and 400 m long, measured along the opencast south-east sidewall/boundary. Using a range of geotechnical parameters, a series of slope stability analyses, as well as conventional retaining wall calculations, were carried out to check the competence of the rock barrier to support the existing landfill and proposed overburden mound.

The most critical parameters were the strengths of the seatearths associated with the Main and Maudlin coal seams at the base of the rock barrier. The values of shear strengths used in these analyses were based on laboratory testing and research work in progress at that time at Newcastle University [29]. Due to the provision of the clay blanket over the completed landfilling, and the installation of a pumping well, it has been assumed that leachate/groundwater level in the landfill will not exceed 125 m AOD. Based on the above dimensions, and a wide range of seatearth shear strength parameters, calculated FoS values against the rock barrier sliding down dip vary between 0.75 and 2.25. The lower FoS value corresponds with the lowest residual shear strength measured in County Durham seatearths, and is probably unrealistically low. In addition, it is anticipated that the long axes of the opencast cuts will be aligned near perpendicular to the face of the rock barrier, and hence the length of opencast endwall/rock barrier face exposed at any one time is unlikely to exceed 50 m. Therefore extra support should also result from the end restraint (3 dimensional effect) provided by the closeness of the opencast highwalls and sidewalls [21, 22, 30, 31].

One way to reduce the surcharge effect of the opencast overburden mound on the landfill, and hence on the rock barrier, is to reduce the side slope gradients of the mound from 1 in 1 1/2 to 1 in 3 (shown in Fig. 21), but this also reduces the available storage volume of the mound.

Opencast mining operations began at Eldon Deep in 1998 and are still ongoing. Neither author has had any involvement in this project after re-privatisation of the UK coal industry in 1994. However, it is understood that the post-privatisation owner/operating company has adopted similar designs and working practices to those outlined above.

4. CONCLUSIONS

Over the last two decades there has been a swing in public opinion against allowing surface coal mining in the UK, which has been taken up by successive elected
governments and passed down to the MPAs in the form of more restrictive statutory planning conditions. However, surface mining can be an appropriate and economical way of carrying out the remediation or reclamation of old tips and derelict land or landfill sites.

This paper has highlighted some of the issues associated with restoring land that had become derelict or unproductive due to past mining activity. The man-made hazards associated with this derelict land included combustible and toxic materials, gas and leachate, instability due to weak horizons within spoil mounds, and shaft collapse. Natural hazards included weak horizons within the underlying soils and groundwater movement. The absence of records of both the mining activity and the construction of spoil mounds often associated with industrial waste highlight the need to undertake a thorough investigation, and at the same time expect the unexpected.

The engineered solutions, as described in the case studies, have returned land to its former (mainly) agricultural use, and has also created areas for wildlife and for leisure use. The land will continue to settle by as much as 3% of the depth of fill, but this is acceptable given the land use.

The cost of these projects has been, in some cases, absorbed within other projects such as surface mines but the benefits, in the long-term, far outweigh the costs of maintaining derelict sites with all the potential hazards due to uncontrolled tipping. There is a limit to the number of sites to be treated, but the legacy of past underground mining activity is such that it will be many years before that limit is reached. For that reason, these case studies provide an insight into the issues and how they can be overcome for future clean-up and restoration operations.

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