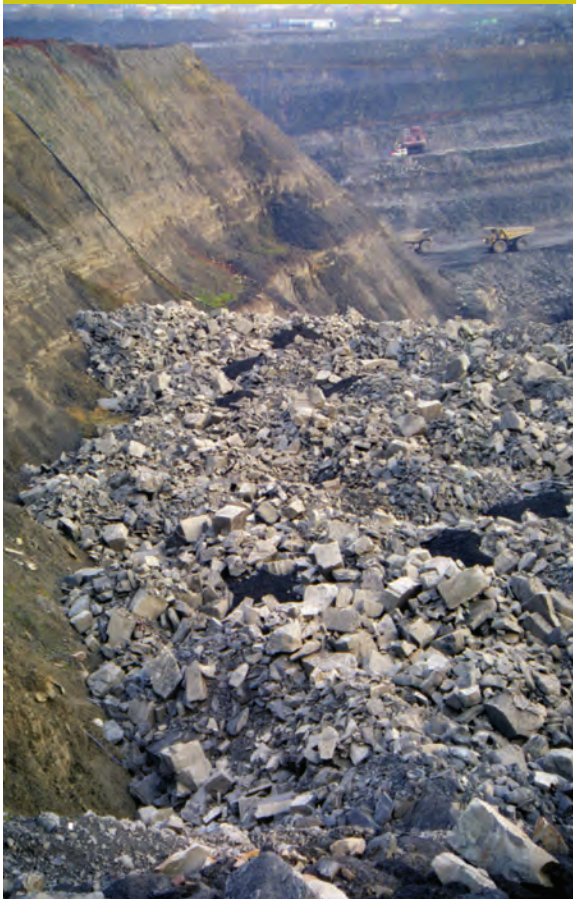
Third edition

Building on fill: geotechnical aspects

Ken Watts and Andrew Charles



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Front cover photographs:

Waverley opencast site, Rotherham, UK

Left, Coal extraction and backfilling

Right top, Large-scale surcharge treatment (courtesy of Harworth Estates)

Right bottom, Development (foreground) on the Advanced Manufacturing Park site (courtesy of Harworth Estates)

Index compiled by Catherine Pritchard.

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Preface to the first edition

One result of the scarcity and cost of good building land is that building development increasingly takes place on sites where there are deep deposits of waste fills. As these fills have considerable economic significance for land values, it may seem surprising that until recently they received relatively little attention from geotechnical engineers. This was not because of an absence of problems; many of the fills are poorly compacted and variable, and their behaviour as foundation materials may be unsatisfactory. However, the heterogeneous nature of many waste fills makes characterisation and analysis difficult, and it is easy to understand why the attention of geotechnical engineers has usually been focused on more promising and better behaved natural soils.

Research at the Building Research Establishment (BRE) has attempted to redress the neglect by:

- monitoring field performance at a large number of filled sites with emphasis on long-term observations of settlement;
- characterising fills on the basis of observed field performance, to assist in the selection of appropriate foundation solutions; and
- assessing the effectiveness of various ground-treatment techniques, by field observations at selected sites.

This report provides a detailed account of BRE research findings and their significance for appropriate and successful building developments on fill. Part A deals with the engineering behaviour of fills, and Part B examines construction on fills. Brief case histories of field performance are presented in Part C; these mostly describe sites where BRE has made measurements of fill behaviour, but some additional case histories, in which monitoring has been carried out by other parties, are included where necessary to give a more complete picture. (Parts A and B make extensive use of these records.) While the report describes experience with fills in the United Kingdom, it has relevance to similar materials found in many other parts of the world.

Field monitoring has shown that in most situations the fill settlement that damages buildings has causes other than the weight of the building. This means that the concept of bearing capacity is not adequate to define the load-carrying characteristics of many fills. Settlements caused by other physical factors, and in some cases by chemical or biological processes, need to be assessed. A particular hazard for poorly compacted partially saturated fills is a reduction in volume which can occur when the fill is first inundated with water.

Preface to the second edition

In the eight years since the first edition was published, the term 'brownfield' has come into everyday use and the importance of locating building developments on such sites has been widely accepted. A precise definition of brownfield has yet to find universal agreement, but the basic concept of land adversely affected by previous human activity is clear. The sustainability agenda requires the long-term productive re-use of brownfield land. The problem is that previous usage may have left a wide range of physical, chemical and biological hazards.

Three systems which may be at risk in brownfield developments can be identified: the human population, the natural environment and the built environment. Physical problems may include buried foundations and settlement of filled ground. The range of problems associated with chemical contamination is vast and can present an immediate or long-term threat to human health, to plants, to amenity, to construction operations and to buildings and services. Biodegradation of organic matter may lead to the generation of gas.

The objective is to build safe, durable and economic structures. The site and the building development form an interactive system and it is important to evaluate the risk of adverse interactions during the lifetime of the development. For many years the redevelopment of derelict land and brownfield sites has been dominated by the hazards associated with contamination and the risks posed to human health. The physical problems have received less attention and it is hoped that this book will help to redress the balance.

Although brownfield land is a world-wide phenomenon, the issues are particularly acute for Great Britain, a heavily populated island with a long industrial history. The scale of the problem was illustrated by the size of the £1 billion plus package which was announced in 1996 for the regeneration of major coalfields. Some 910 ha of land were to be reclaimed for residential, commercial and retail uses. Many of these sites will involve building on colliery spoil. This example illustrates how the redevelopment of brownfield sites is closely linked to building on fill, the subject of this book.

This second edition of *Building on fill: geotechnical aspects* updates and expands the first edition which was published in 1993. Three new chapters have been added covering, respectively, collapse compression on wetting, problems associated with a variable depth of fill, and engineered fill. Records of BRE field monitoring have been brought up to date. The book has been reorganised into four parts and five appendices have been added.

Preface to the third edition

The first edition of *Building on fill: geotechnical aspects* was published in 1993. The growing importance of the subject, increasing industry experience and expanding knowledge of key technical issues led to the publication of the second edition in 2001.

In the 14 years since the second edition the political impetus to advance the sustainability agenda, and commercial incentive to support that agenda, has continued to grow. A high proportion of new commercial, industrial and housing developments are now taking place on 'brownfield' land, and a substantial number of these involve building on a range of fill materials. In particular, building on restored opencast sites has increased, with some developments encompassing complete new communities or townships.

While most potential problems associated with building on fill remain essentially the same, the scale and complexity of remediation on many sites has increased, particularly with very deep opencast backfills where there is a substantial depth of unsaturated fill and significant variation in fill depth within the development area. Commercial imperatives demand maximum use of available site area and the selection of remedial techniques and prediction of post-construction performance of buildings are key issues.

There have been some noteworthy technical innovations in ground treatment since the first edition was published and the 22 years that have elapsed since that time have provided the opportunity to study the behaviour of a wider range of fills and in one case history to extend direct observations of behaviour to over 24 years! As a consequence, this third edition has been expanded to 18 chapters.

The additional chapters on ground treatment recognise the importance of this subject and the fundamental difference in approaches adopted and methods applied, particularly in the use of proprietary and non-proprietary techniques.

The second major expansion is the increase in case histories from 28 in the second edition to 35 in this edition. The case histories are now divided into five chapters reflecting the type of fill encountered.
An additional chapter reflects the diverse types of construction located on fill and focuses on recent major building developments in the UK.

I Fills in context

'The industrial revolution and the creation of parks around the country houses have taken us down to the later years of the nineteenth century. Since that time, and especially since the year 1914, every single change in the English landscape has either uglified it or destroyed its meaning, or both. Of all the changes in the last two generations, only the great reservoirs of water for the industrial cities of the North and Midlands have added anything to the scene that one can contemplate without pain.'

Hoskins, 1981

The long industrial history of Great Britain has led to this small, heavily populated island having a large proportion of its land surface affected by human activity. Many would agree with Professor Hoskins' view, expressed so trenchantly in his *The making of the English landscape*, that these human activities have generally had an adverse effect on the environment, and, it might be added, not only in England, but also in Scotland and Wales.

Since the early 1970s there has been increasing concern over this situation. In the preface to his book, *Derelict land*, Kenneth Wallwork reports the Secretary of State for the Environment saying in 1971 that:

'The scars left behind by industrial development of the past, the abandoned waste heaps, disused excavations and derelict installations and buildings no longer needed by industry, are an affront to our concept of an acceptable environment in the 1970s.'

The reclamation of derelict land became an important aspect of government policy. More recently there has been an emphasis on siting new building developments on brownfield rather than greenfield sites and many of these brownfield sites are covered in substantial depths of fill. The subject of building on fill has thus acquired considerable prominence in recent years, although it should be remembered that the practice of building on fill can be traced back to antiquity.

The geotechnical problems in achieving safe and economic developments on filled ground are substantial. Before examining these, the two chapters in Part I of this book present the background context of building on fills. The first chapter provides some historical background and defines the scope of the book. The engineering behaviour of a fill is strongly influenced by the method of deposition and subsequent stress history; it is pertinent, therefore, in Chapter 2 to examine the origins of the principal types of fill encountered in the UK.

1 Introduction

> *'All made ground should be treated as suspect because of the likelihood of extreme variability.'*
>
> BS 8004:1986

Although BS 8004:1986 – *Code of practice for foundations* has been superseded and withdrawn, the warning remains valid!

In this book the terms 'fill' or 'made ground' are used to describe ground that has been formed by human activity in which natural soils or sometimes manmade materials are deposited, in contrast to natural soil which has its origin in geological processes. In addition to numerous technical publications on this subject, a number of descriptions and definitions can be found in British Standards. These are presented in section 1.3.

There is a great need for building land at reasonable cost within and adjacent to built-up areas. Shortage of land and a long industrial history ensure that much of the land now being used for building purposes in the UK has been previously affected by human activities which may cause serious problems during redevelopment. Despite the warning from BS 8004:1986 quoted above, many buildings have been and are being founded on fill. The problems occasioned by building on fill have to be evaluated against a background of growing concern over environmental and sustainability issues, which means that the beneficial re-use of brownfield sites and environmental protection to prevent further land being damaged are of increasing importance.

1.1 Historical background

Throughout history mankind has deliberately adjusted the topography of the earth for a variety of purposes by excavating soil and rock and placing the excavated material in other locations. In urban areas the casual disposal of waste materials has also changed landforms.

In urban locations where there has been continuous occupation of the land for centuries, there are likely to be large areas of filled ground. Fills may have arisen inadvertently from the rubble of demolished buildings and the slow accumulation of refuse. Old urban fills of these types may contain soil, rubble and refuse. They can be quite extensive in area but usually are relatively shallow. They may be very old.

Striking examples of the unplanned accumulation of fills in inhabited areas are provided by many towns in the Middle East. The most common building material was mud brick, and walls of mud brick have to be thick. New construction took place on the ruins of the old, and in Syria and Iraq villages stand on mounds of their own making. The ruins of an ancient city may rise 30 m above the surrounding plain.

This gradual rise of debris has been much less common in Great Britain, although in some situations deep fills have accumulated. By the third century AD the Wallbrook in the City of London was already half buried, and mosaic pavements of Roman London lie 8 m to 9 m below the streets of the modern city. Some fills were placed to achieve a particular objective such as reclaiming low-lying marshy land or providing a suitable elevation for defence. A new Flavian city was erected at Chichester, over the remains of the first Roman city, on a 1 m deep platform of rammed gravel (Carver, 1987).

Although fills accumulated in urban locations during both Roman times and the Middle Ages, it was with the coming of the Industrial Revolution that man's capacity to generate waste materials, and to cover significant portions of the earth's surface with them, greatly increased. Large areas of land have been used for the deposition of mining, industrial, chemical, building, dredging, commercial and domestic wastes. In a country with a long industrial history, much of the land used for building development will have a history of previous uses.

In recent years large-scale opencast mining has left great depths of fills. Many of these sites are close to centres of population where building developments may be proposed. This situation is not confined to the UK. Lange (1986) reported that 1200 residential buildings and farms have been established on the deep uncompacted backfills in the Rhenish brown coal area of Germany.

In urban redevelopment programmes, old buildings are demolished and new buildings have to be built over infilled basements and on the rubble of the demolished buildings. Although this type of redevelopment has continued throughout recorded history, in modern urban redevelopment programmes it is carried out at a rate and on a scale not seen before.

One practical reason for adjusting the topography within the confines of a town or city by the deliberate planned placing of fill has been to increase the area of land suitable for building. In hill country this has been achieved by cut and fill earthworks on hillsides. Some 3000 years ago rockfill platform terracing was formed on the eastern slopes of Jerusalem thereby substantially increasing the building area. It was King Solomon who constructed the Millo (I Kings 9:15,24 and 11:27) and 300 years later it was repaired by King Hezekiah (II Chronicles 32:5). The New King James version of the Bible published in 1982 provides an explanatory note that 'the Millo' is literally 'the landfill'.

Low-lying wet areas have been reclaimed by filling. Again, this type of filled ground has been formed throughout history and is found in many parts of the world. Bordering the Baltic Sea, reclamation of the low-lying marshes on which St Petersburg is built, began in 1703. Rutledge (1970) commented that it was instructive to note how much of downtown Manhattan Island was constructed on filled land created before 1900.

In contrast with waste and demolition fills, large quantities of fill materials are placed as part of carefully controlled civil engineering works. For many years these engineered fills have been placed to form embankment dams and highway embankments. With increasing frequency they are now placed specifically as foundation material for new buildings.

Serious problems have occurred when building on fill. Occasionally prestigious buildings are involved and detailed investigations are carried out and described in the technical press. The settlement of the Royal Scottish Academy in Edinburgh provides such a case (Masters, 2000). The building was completed in 1826 on the Mound which had been formed in the late 1700s using clay spoil from the construction of the New Town. The building was founded on square timber piles which in the course of time rotted, leaving large voids under the stone footings. Carefully monitored remedial works involving compensation grouting were carried out in 2000.

Many of the problems which have been reported in the technical press and daily newspapers refer to houses and other small buildings. In these cases, the reports usually have insufficient reliable technical information for a proper judgement to be formed on the cause of the particular problems at that site and just refer to a 'filled-in tip' or 'rubbish dump'. However, they give an indication of how these situations are popularly perceived, as the following examples indicate.

Figure 1: Houses built on deep opencast mining backfill

- 'Based on a sound Victorian foundation' (*Hardware Trade Journal*, 27.2.75)
- 'Rubbish tips root of house problem' (*Construction News*, 28.10.76)
- 'Firm to buy back faulty homes' (*Daily Telegraph*, 11.12.76)
- 'NHBC seeks remedy for "blighted" estate' (*New Civil Engineer*, 25.1.79)
- ' "Egham experiment" sinks to failure' (*Construction News*, 28.6.79)
- 'Rise and fall of a real Reggie Perrin' (*Manchester Evening News*, 22.12.79)
- 'Landslip homes forcing out the old' (*Sheffield Morning Telegraph*, 7.1.83)
- 'Sinking suburb' (*New Civil Engineer*, 31.10.85)
- 'Tortuous tort' (*New Civil Engineer*, 2.8.90)
- '£1m to shore up sinking homes' (*Watford and Rickmansworth Review*, 28.11.91)
- 'Woman homeless two years after subsidence' (*BBC News Kent*, 24.12.2011)

Although such reports appear from time to time and rightly give cause for concern, they should not be allowed to obscure the fact that many buildings have been successfully built on fill. Figure 1 shows low-rise housing built on a deep opencast mining backfill. Problems and failures on filled ground emphasise the importance of developing an adequate understanding of the behaviour of fills, and of identifying potential hazards so that appropriate types of building development can be successfully undertaken on suitable fill sites.

1.2 Brownfield sites

The use of previously developed land for new building developments offers substantial advantages in social, economic and environmental terms. The redevelopment of sites in urban areas is not a new phenomenon, but the scale and speed of building developments on such 'brownfield' sites has greatly increased in recent years. Maximising the re-use of previously developed land minimises the amount of greenfield land being taken for development and also promotes regeneration in parts of the country where declining industries have left large areas of dereliction. The term 'brownfield' is now widely used to describe previously developed land and is commonly understood as signifying the opposite of greenfield in planning terms. An appropriate definition of brownfield is considered further in section 1.3, but it can be regarded as any land that has been previously developed, particularly where it has been occupied by buildings or other types of permanent structure and associated infrastructure.

Some, but not all, brownfield sites are derelict, that is the land has been so damaged by industry, mining and urban development that it can no longer be put to beneficial use without treatment. Industrial and mining activities can cause particularly serious physical, chemical and biological damage to the land. For many years there has been concern over dereliction and contamination left by these activities and the reclamation and re-use of such sites has been an important aspect of government policy. In opening the Land Reclamation Conference at Grays, Essex, in October 1976, the Parliamentary Under Secretary of State emphasised that the Department of the Environment had the complementary aims of reclaiming the dereliction inherited from the industrial past and ensuring, by planning control and other means, that fresh areas are not created and left without effective treatment.

The first official survey of derelict land in England and Wales took place in 1954 and recorded 51,274 ha of dereliction (Ministry of Housing and Local Government, 1956). In commenting on this and subsequent surveys, Wallwork (1974) pointed out that at that time derelict land continued to grow more rapidly than reclamation could restore earlier dereliction to beneficial use. Although in the early 1970s an annual reclamation rate of 2200 ha was reached, Barnett (1976) commented that this had not been wholly sustained. In successive surveys of derelict land in England there were found to be:

- 43,000 ha in 1974
- 45,600 ha in 1982
- 40,500 ha in 1988
- 39,600 ha in 1993.

Thus the area of derelict land in England decreased by 8% in the 20 years between 1974 and 1993 (Parliamentary Office of Science and Technology, 1998). However, the difficulties in developing an appropriate definition of derelict land were bound to reduce the value of such reclamation statistics. Of the 14,000 ha of derelict land reclaimed between 1982 and 1988, 27% was for hard end uses, which would include housing, industry, roads and car parking, in contrast to green environmental after-use.

The growing concern over environmental issues means that reclamation of derelict land for beneficial use and environmental protection to prevent further land being damaged are of increasing importance. Some of the issues involved in sustainability and acceptability in infrastructure development have been reviewed by the Institution of Civil Engineers (1996b).

A national target was set that, by 2008, 60% of additional housing should be on previously developed land and through conversions of existing buildings. However, beneficial as this policy is in many respects, it has to be recognised that brownfield sites can contain many additional hazards and risks for building development that are not encountered on greenfield land and it has been questioned whether current approaches to the redevelopment of brownfield sites are always the most appropriate. In some cases hazards may be overlooked or their significance may not be recognised, whereas in other cases solutions may be over-engineered. The way that hazards and the consequent risks are perceived can be of crucial importance.

While filled ground is often found on brownfield sites, fill is not always present on such sites. Conversely fill materials may be present on a site which is not classified as brownfield, for example opencast mining sites restored to agriculture. Nevertheless, there are many cases where fill is found on brownfield sites and since the problems occasioned by its presence are closely related to other features present on such sites it is appropriate for this study of building on fill to begin with a brief survey of the wider issues posed by building development on brownfield sites. A much fuller introduction to these matters is given in BRE Good Building Guide 59, and two BRE Reports, *Brownfield sites: ground-related risks for buildings* (BR 447) and *Brownfield sites: an integrated ground engineering strategy* (BR 485).

While many of the hazards are related to the previous use of the site, there may also be problems associated with the original state of the ground, which can include various types of ground movement and aggressive ground conditions. Problems associated with rising groundwater levels due to reduced abstraction by

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Building on fill: geotechnical aspects

A high proportion of commercial, industrial and housing developments are now built on fills, that is ground that has been deposited by human activity rather than natural geological processes, and the political and commercial impetus to build on 'brownfield' land continues to grow. An adequate understanding of the behaviour of fills and the ways in which they can economically be rendered suitable for building purposes is a critical element in the safe development of such sites.

This third edition encompasses BRE's unique experience over a period of more than 40 years of research and consultancy, and brings the subject up to date.

New material includes:

- research findings and industry experience since publication of the second edition 14 years ago
- additional chapters on ground improvement and treatment using both proprietary and non-proprietary techniques
- six new case histories and updated cases from the second edition
- studies on the behaviour of fills over both a longer time period and a wider range of fills.

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