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Introduction

A problem without a solution may interest the student, but can hardly fail to annoy the casual reader.

The rise of the modern tunnelling industry has been made possible by the introduction of a succession of remarkable technical innovations including new machinery and novel methods of working. This book investigates the most significant of such innovations introduced between about 1825 and 1985. It aims to examine the innovations themselves, the problems which made them necessary and their success in overcoming the practical difficulties encountered in driving particular tunnels. In addition, their contributions to growing technical expertise in the tunnelling industry and its ability to meet the demands for tunnels of all kinds during the period covered is considered. Thus, whilst each of the technical innovations treated in this work has been chosen for its contribution to the solution of a particular problem, the choice has been carefully made to illustrate the development of tunnelling techniques and the tunnelling industry in general. In some cases the practical development of the innovation itself caused problems that had to be solved before the device or process could be made to work satisfactorily. Approached from the viewpoint of solving problems, this study throws light on the origins, reasons for and processes of technical innovation both in the tunnelling industry and more generally. Moreover, it exposes many aspects of the rich field that the tunnelling industry offers for study within the history of technology and it also reveals how past innovations may still have relevance to current problems. Indeed, the potential contributions of the history of technology to the solution of current and future technological problems is a recurring theme throughout this work. Although this book is not intended to be a history of tunnelling,[1] a broadly chronological sequence of important technical developments in the industry has been followed and this serves to emphasise the crucial nature of each of the chosen innovations. In Chapters 2–12 the origins and technical details of these innovations are explored, together with the problems they were intended to solve and the difficulties encountered in putting them into practice. Some of the world's most important tunnels feature in this account because important innovations in tunnelling were introduced during their construction, but other equally important tunnels are not mentioned because they involved no important technical innovations of significance for this study.

It has been remarked that although the objective of the historian of technology is to define the nature of the engineering problem as it was faced in the past and to analyse the ideas and techniques that were used to achieve a solution, the method he must use is actually to study the way that machines, structures and processes were designed, fabricated and developed.[2] To this we should add that it is also necessary to study the way they worked and it is for this reason that throughout this book detailed technical descriptions of the machines and methods used have been given. These accounts are as accurate as it has been possible to make them given the lack of clarity of detail in some of the available contemporary (and later) drawings and the sometimes sketchy contemporary descriptions of nineteenth-century machines and processes. It is emphasised that these technical details are regarded as an important aspect of this work. They have been included because a proper understanding of the design and operation of each innovation is essential if it is to be assessed correctly as a solution to a particular problem. A clear understanding of the technical detail is also necessary if the innovations discussed are to be accorded their due significance in the history of tunnelling technology. Moreover, the ways in which the engineers solved their problems need to be judged by contemporary rather than present standards.[3] Thus, for example, when considering how the engineers of the 1850s strove to produce compressed air rock drilling machines (Chapter 2), we must remember they were operating with the understanding of mechanical principles and practices of the 1850s and not as we know them today. Later, in the 1970s, when the hydraulic rock drilling machine (Chapter 5) was developed, mechanical engineering had advanced so considerably that an altogether more sophisticated machine was possible. Each chapter in this book is devoted to a particular type of innovation. During the course of studying these innovations it was observed that they fell into certain well-defined categories depending on their origins (see Chapter 14). Although derived exclusively from tunnelling, it may be that such a system of classification could be applied to technical innovation more generally and it may therefore prove to have a wider value in helping to identify the potential origins of technical innovation in other branches of engineering and industry.

Several books dealing wholly or in part with the history of tunnelling and touching upon some of the technical innovations discussed here have recently appeared. *Tunnelling history and my own involvement*[4] is by the late Sir Harold Harding (1900–1986), formerly the doyen of British tunnelling. The first part of the book is a précis of the history of tunnelling, whilst the second part is an account of Harding's personal involvement in tunnelling, both as a contractor's engineer and as a consultant, extending over the period from 1922 to 1977. The particular interest of the book lies in some of the comments that Harding was able to make from personal experience on particular tunnels and machines with which he was involved and which do not appear elsewhere in the published literature. The two-volume *Tunnels: planning, design, construction*[5] by T.M. Megaw and J.V. Bartlett is a modern textbook of tunnelling, although the first chapter gives an historical introduction and there are other historical notes at the beginnings of some of the other chapters. One interest of the book is that Bartlett was the inventor of one of the innovations discussed here in Chapter 9. Also, Volume 2 contains an extensive bibliography of books, reports and papers on tunnelling which is a valuable reference source. Barbara Stack's comprehensive 700-page *Handbook of mining and tunnelling machinery*[6] is especially noteworthy. The *Handbook* is clearly a monumental work: the collection, listing and orderly presentation of all the information it contains has produced an encyclopaedia which will be an essential reference work for any worker in the field of mining and tunnelling for many years to come. Some of the research for this book was made easier by the appearance of the *Handbook* – for instance Stack's bringing to light the details of Maus' tunnelling machine which is discussed in Chapter 11 here. Lastly, the *Tunnel engineering handbook*[7] edited by J.O. Bickel and T.R. Kuesel is a modern tunnelling textbook with contributions on the constituent subjects by specialists. There are occasional brief historical notes in the introductions to some of the chapters, but the main interest of the book is that it provides a comprehensive outline of present-day practice in tunnel design and construction.

1.1 Innovations in tunnelling technology

For the purposes of this book an important innovation has been taken to be one which enabled something to be done that could not be done before, or one which allowed something to be done so much better than before that it constituted a great technical advance. For example, compressed air tunnelling (Chapter 7) was an innovation that enabled subaqueous tunnels to be constructed, an operation that was not previously possible, whilst the compressed air rock drilling machine (Chapter 2) was an innovation that allowed hard rock tunnelling to be done very much better than the previous method of hand drilling. So both of these are considered to be major innovations in tunnelling in this book. The majority of tunnel engineers would probably agree that most of the technical innovations selected satisfy the given criteria, although some might wish for some other developments to be included. For example, nothing is said about tunnel surveying because it followed the well-established surveying methods used in civil engineering in general and produced no major innovations in its own right. This is not to say that tunnel surveying is not an important subject and that great ingenuity has not been shown in adapting surface surveying techniques to underground application, but there were no significant innovations in this area which meet the criteria outlined above. One exception to this statement is the laser, which has been such a boon to tunnel engineers, and which is discussed in Chapter 13. Similarly, nothing has been said about ground treatment and similar geotechnical processes because these were innovations in civil engineering more generally and not specific to tunnelling. Again, this is not to say that these processes are not important, indeed some of them have probably become more important in tunnelling than in other branches of civil engineering. Nevertheless, they are basically civil engineering innovations and not tunnelling ones. It so happens that the history of ground treatment in civil engineering has been dealt with by R. Glossop.[8] Lastly, except in passing, cut-and-cover tunnelling is not considered here, this method falling within the purview of general civil engineering rather than of tunnelling.

Whilst this work is a synthesis in that it brings together a number of diverse innovations from different parts of the tunnelling industry and from different periods of time, it is also analytical in that each innovation is examined in an effort to identify its origins and the problems associated with it. The work concerns itself with innovations in the tunnelling industry partly because the author's association with this industry[9] allows a well-informed view to be taken on the innovations in it, but also because of the need to confine the subject to a manageable size. Taking a wider view, the classification of technical innovation that has emerged from the work might be applied to other industries and possible uses for this are discussed in Chapter 14. Also, from time to time throughout the book, but particularly in Chapters 2, 6 and 13, the rise of the tunnelling industry has been related to the social and economic factors which gave rise to the need for tunnels and therefore provided the spur for innovation in the tunnelling industry.

Chapter 13 looks at some other developments, but only the perspective of time will show whether these are to be ranked as major innovations in tunnelling. Also included in Chapter 13 is a brief description of the emergence of a vigorous and innovative tunnelling industry in Japan; as we will see, it would seem that the centre of gravity of innovative tunnelling technology has shifted to Japan.

This work does not deal with the economics of innovation, nor except in passing, with the economic factors associated with the rise of the tunnelling industry. Nor are the costs of tunnels, machinery or construction materials discussed. This is not to say that these matters are not important but rather that they are not of central relevance to the themes here being studied. Nevertheless, it seems likely that an examination of the economics of the tunnelling industry would be a fruitful field of study. Similarly, except for the instances referred to earlier, the work does not concern itself with the social causes of the technical innovations discussed, nor does it deal with the social changes that the construction of tunnels made possible by these innovations may have brought about. Again, this is not to say these matters are not important and, as for economics, it would seem that the social causes and effects of the rise of the tunnelling industry would also be worthy of investigation.

Technical innovation is not only the concern of the historian of technology, but is of vital importance to the well-being of present-day industry. Consequently the state of contemporary technical innovation is frequently the subject of enquiry. For example, the economist Kerry Schott has reviewed the process of innovation in present-day industry in the United Kingdom, the United States and Canada with the objective of making recommendations for action by government and business to stimulate more of it.[10] In 1981 in Great Britain the National Research Development Corporation and the magazine *New Civil Engineer* jointly sponsored a Civil Engineering Innovation Competition, with a first prize of £10 000, the aim of which was to stimulate innovation in civil engineering[11] (see Chapter 13). These approaches take it for granted that technical innovation is a process that can be artificially promoted, fostered, stimulated or directed, but it is not at all certain that this is so, and the point will be taken up again in Chapter 14.

1.2 Source materials

R.L. Hills, Curator of the Manchester Museum of Science and Industry, has stated that there are basically three kinds of source material for the history of technology.[12] These are (i) written records, (ii) pictorial sources and (iii) the machines themselves. To this list we might add, for the recent past, a fourth category – personal experience, and in this book use has been made of all four kinds of source material. In the main, written records and pictorial sources in the form of drawings, prints and photographs form the principal sources used here and the nature of these is discussed below. Except in very rare instances such as the Brandt hydraulic drill (see Section 5.1), old tunnelling machinery has not survived, so that nearly all the old machines themselves are no longer available for inspection. However, for the more recent technical innovations considered here, every opportunity has been taken to examine the actual hardware. This includes most of the British tunnelling machinery described here from 1974 to the present, together with many of the tunnels described and the tunnel linings and support systems. Some foreign tunnelling machinery dating from the same period has also been examined at first hand. The virtually complete disappearance of old tunnelling machinery is in striking contrast to the survival of nearly all the old tunnels themselves, most of which have remained in service to the present, and many of which are therefore well maintained. The Victorian

Technology Survey,[13] carried out in Great Britain in 1968–70, commented on this latter fact, but it is noteworthy that the Survey recorded no examples of the machinery with which the tunnels were built.

In the references cited at the end of each Chapter, wherever possible, published material has been cited. However, during the research for this work numerous unpublished sources have been used such as manufacturers' leaflets, brochures, technical specifications, drawings and photographs, but since these are ephemeral they have not been specifically cited unless no published information is available, when they are referred to in the notes. Correspondence and discussion with people in the tunnelling industry, likewise, have not been specifically cited, although important instances where a crucial point is at issue, are referred to in the notes. Contemporary accounts in engineering journals have been the most useful published sources; some details of the most important of these are listed in Table 1.1.

Patent specifications[14] have been a most useful primary source for the work, but they need to be used with circumspection. This is because many patented ideas or machines were never realised in practice, and because sometimes the actual working machine differed from the patent specification. Most of the patents discussed in this book are either of machines that were made and used or they embody ideas that were subsequently used. Some machines were the subject of multiple patents, specifications being filed both in their country of origin and abroad. Since January 1980, the introduction of a single European patent[15] has obviated much of this duplication. Specific patents used are cited in the notes and references.

Among the primary sources consulted special mention should be made of the seventeen long-quarto volumes comprising Marc Isambard Brunel's diaries for the years he was engaged on the construction of the Thames Tunnel which are now in the Library of the Institution of Civil Engineers, London. The diaries for the years 1828–35 inclusive were examined in order to establish Brunel's early ideas on compressed air tunnelling as discussed in Chapter 7. The quotations from the diaries given there are the author's translations of Brunel's entries in French, although most of the other diary entries are in English. Brunel's diaries have been used by several of his biographers and other writers on the Thames Tunnel (see Chapter 6). Other primary sources include Richard

Table 1.1 *Sources of tunnelling information*

Sources	Period	Volumes
Institution of Civil Engineers		
Minutes of Proceedings	1837–1935	1–240
Journal	1935–1951	1–36
Proceedings	1952–1985	1–79
American Society of Civil Engineers		
Transactions	1872–1981	1–146
Proceedings	1894–1955	20–81
Journals	1956–1985	82–111
Others		
Engineering	1866–1985	1–225
The Engineer	1856–1985	1–261
The Illustrated London News	1842–1985	1–287
Tunnels and Tunnelling	1969–1985	1–17
Tunnels et Ouvrages Souterrains	1974–1983	1–72[a]
Underground Space	1977–1985	1–9
Advances in Tunnelling Technology and Subsurface Use	1981–1985	1–5

[a]Numbers

Trevithick's original drawing of the Thames driftway (see Chapter 6), the contemporary model of Brunel's shield and Thames Tunnel (see Frontispiece), Hawkins' report of an immersed tube trial (see Chapter 10), Harding's unpublished report on one of the Oahe Dam tunnelling machines (see Chapter 11), and John Price's manuscript description of his proposed tunnelling machine for the Central London Railway (see Chapter 12).

Engineering drawings are an important kind of source material for the history of technology and extensive use of them has been made in this work. They are particularly valuable when, as is the case with tunnelling technology, few of the early machines have survived. Original old engineering drawings are rare but the author was fortunate in acquiring from the firm Markham and Co Ltd dyeline prints of some relating to two historically important tunnelling machines: the Beaumont–English tunnelling machine (Figure 11.4) and the Whitaker tunnelling machine (Figure 11.6). Both these are examples of the form of engineering drawing known as a general assembly, that is they show the whole machine rather than the parts. These are the most useful form of drawing for the historian of technology since they contain internal evidence of how the machine was intended to work and can resolve points that may be ambiguous or missing in a written description. A considerable amount of this kind of historical research was necessary during the compiling of the detailed descriptions given in Chapters 2–12. On one occasion a careful study of the drawing provided corroborative evidence of the origin of the machine (see Section 2.7). The old engineering drawings used in this study have mainly been of historical technical interest, but old engineering drawings can sometimes assume crucial present-day importance for another reason. For example, the safety of old earth embankment dams has become a subject of great concern, both to the civil engineering profession and to the public at large because of the potentially disastrous consequences of failure. Both an historical knowledge of the way these old dams were made and contemporary construction drawings of them and their associated works are vital to an analysis of their current safety,[16] and these records, where they still exist, show the value of preserving historical technical documents and demonstrate that the history of technology can sometimes have a striking relevance to the present. In certain circumstances, such as when tunnels are to be repaired or enlarged, contemporary construction drawings of old tunnels may have the same importance as those of old dams. For the later tunnelling machines, photographs have also been a useful source, and a selection of these illustrate this book. Photographs are valuable because machines were not always manufactured exactly as detailed in the engineering drawings, but photographs, especially if they are taken of the machine actually on the job, show the machine as it was built.

Good use has been made of secondary sources as well as primary ones, and where secondary sources have been used this is made clear in the notes and references. An example of an excellent secondary source is Glossop's paper on the early use of compressed air in civil engineering works (see Chapter 7); this is a scholarly paper showing the history of technology at its best, and with its comprehensive notes and references is an essential starting point for its subject. Another fine secondary source is the monograph on tunnel engineering by R.M. Vogel of the Smithsonian Institution (see Chapter 2); it has only limited references, but does contain good descriptions of early hard rock and soft ground tunnelling methods which were researched by Vogel for the purpose of producing museum reconstructions. It also contains several reproductions of contemporary drawings and prints of the tunnelling machinery and tunnels with which it deals, together with photographs of the museum reconstructions. It is likely that the discipline of making such reconstructions leads to a very complete understanding of the working of the devices being reconstructed, which lends authority to the descriptions given by Vogel. Nineteenth- and early twentieth-century textbooks[17] on tunnelling have also proved to be a useful source; they often contain a wealth of information on certain technical developments of the time that can now be seen as important innovations. They sometimes contain details of machines or of tunnel construction that are not now available anywhere else. Some of the old tunnelling textbooks are well illustrated. Good illustrations of early tunnels and tunnelling machinery, mainly European, are also given in the collection compiled by Louis Figuier.[18] The sources of some of the illustrations used as Figures here are listed at the end of the book. It should be noted that the dates given in the captions to the Figures are the dates of the items depicted and not the dates of the sources of the illustrations which, in some cases, are later.

Throughout this book many personalities are mentioned: scientists, tunnel engineers, inventors, consultants, contractors etc, and for some of these, brief biographies have been given.[19] This has been done partly as a change from what seems to be a dichotomy in the history of technology when some writers give accounts either of the engineers or of the engines but not of both. An exception to this which must be mentioned is the admirable series of biographies of engineers by L.T.C. Rolt.

1.3 Units of dimensions and technical terminology

In this book the dimensions given in descriptions of tunnel construction and machinery dating from before January 1969 are given in Imperial units, whilst those of tunnels constructed after this date are in metric units. This is because in January 1969 the British construction industry adopted the metric system of units in place of the Imperial system. The following approximate conversions are given; they are accurate enough for general mental comparison purposes.[20]