



The risk to third parties from bored tunnelling in soft ground

Prepared by **W S Atkins** for the
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This study has looked at the hazards that are associated with soft ground tunnelling in urban areas. It has considered all of the types of construction methods that are used in soft ground tunnelling. Data on tunnel incidents has been taken from the published literature and from personal data bases and other sources of information. This has been used to understand and describe the range of possible primary and underlying causes of failures. Methodologies for the mitigation of risks are examined and conclusions drawn for the effective management of future urban tunnelling projects.

The authors would like to express their thanks to colleagues in UK and abroad for their assistance in compiling the data used in this report.

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EXECUTIVE SUMMARY

1. Tunnelling is increasingly being used world-wide to provide the infrastructure required for sustainable urban communities. The majority of these works are completed safely and satisfactorily. A number of recent emergency events in urban tunnel construction in UK, and elsewhere, have raised concerns regarding the risk to third parties from future work (Chapter 2).
2. Quantification of this risk cannot easily be undertaken because of a lack of sufficient and reliable data. There is no centralised world-wide data base on tunnelling that can be interrogated to obtain classified factual information on tunnel construction projects, or centralised records of construction failures. Such information that exists is piecemeal and rarely accompanied by documentation and studied analysis. The fragmented and incomplete nature of this data therefore makes formal statistical analysis difficult and potentially unreliable and misleading. (Chapter 3, paragraph 3.1).
3. Data on world-wide tunnel construction projects undertaken within the past six years was obtained from a range of sources including the internet, and was then classified. It indicates that the number of tunnels being constructed in the developed world is increasing year on year, while activity in the rest of the world remains variable and an order of magnitude below the developed countries (Chapter 3, Tables 3.1 and 3.2).
4. Data were also collected on the number of tunnel emergency events “recorded” in the last four decades. The information was obtained from a variety of sources, including the technical literature and the personal contacts of the authors. It indicates that both the total number of emergency events and the proportion of these events taking place in urban areas with soft ground tunnels, increased in the three decades since 1970. In the latter case this trend has continued into this part decade (Chapter 3, Tables 3.4, 3.5 and 3.6).

5. Analysis of the available data by the authors indicates that
- With soft ground urban tunnels, NATM tunnels exhibit different failure characteristics from non-NATM tunnels.
 - The primary cause of failure in NATM tunnels is attributed to unpredicted ground conditions.
 - In non-NATM tunnels, the range of primary causes for incidents is wider than for NATM tunnels.
 - The underlying causes of emergency events are likely to be diverse. These could involve engineering, management, procurement, organisational, competence, resource or communications issues.

In addition, there is evidence that incidents within soft ground urban tunnels result in surface craters forming above the tunnel face in NATM construction and behind the tunnel face in non-NATM construction (Chapter 3, paragraph 3.8)

6. Risks to third parties from underground construction can be classified in physical, economic and societal terms. Control of the physical risk is governed in UK by the health and safety legislation applicable to construction works. The economic risk is managed through the contractual arrangements between the constructor, the insurer and the affected infrastructure owners. Societal risk is more difficult to define and manage as it can include a wide range of issues including wide spread detriment and socio-political issues (Chapter 4).
7. Urban projects introduce additional risks to tunnelling work due to the density of the existing infrastructure and the spread of the population. Construction methodologies may need to be adjusted to suit local environmental restrictions and working space can be difficult to locate and safeguard. The close presence of possibly aging and unfavourably sited infrastructure can introduce hazards that are not met on rural sites (Chapter 5).

8. The statutory methods required to control tunnelling safety risk within the UK construction industry are set out in the health and safety legislation. Detailed guidance is available in British Standard 6164 Code of practice for safety in tunnelling in the construction industry. However one consequence of the recent number of construction incidents in UK and elsewhere has been the setting up of a number of committees to propose measures for better management of tunnelling projects in order to reduce and minimise the number of failures together with their attendant commercial losses. These include
- The International Tunnelling Association. Guidelines for tunnelling risk management. (2004)
 - The Association of British Insurers (ABI) and the British Tunnelling Society (BTS) Joint Code of Practice for the procurement, design and construction of tunnels and associated underground structures in the UK.(2003)

Both of these documents propose that risk based management techniques are embedded into the overall project management system for all stages of a project (Chapter 6, paragraphs 6.3 and 6.4).

- 9 To investigate the specific construction issues arising from closed face tunnel boring machine technology, the British Tunnelling Society has published a document titled “Closed face tunnelling machines and ground stability - A Guideline for best practice” (2005). The Guideline includes the results of targeted confidential research into the number of incidents occurring world-wide associated with this tunnelling methodology, and lists a number of identified hazards together with proposals for their mitigation. (Chapter 3, paragraph 3.6).

10. The manner in which human factors can undermine management systems and result in construction failures has been highlighted. Those elements of a positive safety culture that need to be integrated into effective safety management systems have been identified (Chapter 6, paragraph 6.5)
11. A number of individual risk management systems that have been effectively employed on recent major underground projects have been identified and referenced. Where applicable, these can be adopted as exemplars and developed for future projects by those parties associated with the schemes. (Chapter 6, paragraph 6.6).
12. Six factors have been identified by the authors as having a primary influence on the quality of the overall safety management systems for underground construction projects (Chapter 7). These are:
 1. Project management
 2. Organisational, procurement and contractual arrangements
 3. Engineering systems
 4. Health and safety systems
 5. Human factors
 6. The availability and use of “enforcement” action.

1. BRIEF FROM THE HSE

The authors were commissioned to undertake the following

1. Research and prepare a list of the incidences of internationally occurring “emergency events” in urban soft ground tunnelling construction. The term “emergency event” includes tunnel collapse, tunnel lining failure, fires, floods, excessive surface settlements (such as surface craters) and significant damage to third party surface and subsurface infrastructure.
2. This list should include incidents involving bored tunnel construction methods, but not open cut construction.
3. The focus of the research is third party risks during construction, not employee or worker Health and Safety risks.
4. The report should draw upon the information obtained to draw conclusions and recommendations on generic causes of such emergency events and identify contingency measures that might be adopted in mitigation.

The term “soft ground” means ground that requires a significant level of immediate support upon excavation. The term “bored tunnel construction methods” includes methods of excavation such as hand mining, machine mining and both open face and closed face Tunnel Boring Machine excavation. Lining methods could include sprayed concrete and pre-cast segmental linings.

2. INTRODUCTION

“Tunnelling is a form of civil engineering construction, carried out in an uncertain and often hostile environment, and relying on the application of special knowledge and resources.” The above quotation is taken from the introduction to the 1978 CIRIA Report ¹ on improved contract practices for tunnelling and provides a succinct description of the risks and resources associated with tunnelling that remains as relevant today despite revolutionary changes in methodology and specialist equipment.

The world wide expansion in the development of civil engineering infrastructure over the subsequent three decades has led to a major increase in the numbers and types of tunnels constructed for road, railways and water supply/sewerage schemes. Over this time there has been significant innovation in the development of tunnel linings, tunnelling machines, specialist equipment, ground investigation techniques, methods of procurement and in contractual relationships between parties. These developments have been driven by the knowledge-based experience of engineers and others. Clients now desire cost effective tunnel projects to be built in ground previously considered too difficult. - and all within defined budgets and time scales.

The evolutionary process of developing innovative design and construction often involves balancing the commercial risk of new forms of construction against proven methods while maintaining control over workplace and third party risks during construction. From this experience has evolved the necessity to consider risk-based management systems into the process to ensure that a balance between risk and rewards/benefits is achieved. However a number of identified tunnel failures have led to ground and sub-surface impacts involving loss of life and damage to property resulting in substantial underwriting losses. (For example, insured and uninsured losses following the Heathrow Express tunnel collapse in 1994 are estimated ² to have been as high as £400m.). Consequently, in the UK these events have resulted in an increased awareness of societal risk issues; prosecutions for

Health and Safety offences; and in a requirement for risk based management systems for all independently insured tunnelling projects.

The aims of this study, (see Section 1), were to establish a data base of emergency events that have occurred during recent world wide tunnel soft ground construction projects and to draw out conclusions from this information. Published data was collected for all soft ground tunnel types and construction methodologies, and, where sufficient information was available, the primary and underlying causes of emergency events were pin-pointed. This information was then used to consider what recommendations might usefully be made to the delivery processes of urban soft ground tunnelling projects in order to minimise the risk of third parties being exposed to risks arising from construction work (see Section 5). The scope of the study does not consider commercial risks or other financial risks.

The approach has been to, firstly update and expand existing published data on the numbers of emergency events arising during such tunnel construction that are in the public domain; to examine, where available, the technical and management details of these emergency events; and to assess the possible direct and underlying causes of the events. Secondly, within an understanding of construction methods and societal risk, to look at the technical issues and hazards associated with urban tunnelling and identify possible ways of prevention and mitigation.

Section 3 describes the background to the research into the data on tunnel failures; Section 4 describes the concept of risk as used in this document and the societal health and safety terms used; Section 5 lists the technical issues associated with urban tunnelling; Section 6 discusses the ways in which urban tunnelling risks might be avoided or mitigated; and Section 7 lists conclusions and recommendations about the contingency actions that can be taken to avoid emergency events.

3. BACKGROUND AND RESEARCH

3.1 Size of world and UK markets

There is no centralised international data base on the number of tunnels that are constructed around the world each year. A few countries regularly publish data regarding their own tunnelling statistics, but these are not presented in a common format which would aid the collation of all international data. The UK, for example, does not publish data on its tunnelling output. In order to establish reliable information on the size and rate of growth of the world market, a number of web sites listing current and future tunnel projects were interrogated (see Appendix B). The accuracy and completeness of the available information cannot be fully verified and has to be taken at face value.

From these sources a substantial data set has been abstracted, which lists the numbers of tunnel projects that have been commenced in each of over 100 countries for the last six years, together with the lengths of tunnel constructed per annum in each of these countries (See Appendix A). The data base has also been interrogated and re-classified to include the GNP (Gross National Product, per capita, using the World Bank definition) of the countries listed and the intended usage of the tunnel projects listed (see Tables 3.1, 3.2 and 3.3).

	1999	2000	2001	2002	2003	2004
GNP>\$9386	174	201	241	244	283	363
\$9386>GNP. \$3036	8	33	19	35	11	19
\$3036>GNP>\$766	27	53	51	139	37	17
GNP<\$766	11	13	16	8	11	3
Total	220	300	327	426	342	402

Table 3.1 Number of world-wide tunnel starts between 1999 and 2004 by GNP (US\$ per capita).

	1999	2000	2001	2002	2003	2004
GNP>\$9386	801	840	1039	1080	931	1208
\$9386>GNP>\$3036	34	144	62	89	86	81
\$3036>GNP>\$766	236	408	442	404	225	163
GNP< \$766	97	123	125	47	76	9
Total	1168	1515	1668	1620	1318	1461

Table 3.2 Length of world-wide tunnels starts (km) between 1999 and 2004 by GNP (US\$ per capita).

Both tables show consistent increases in both the number and lengths of world wide tunnel starts over the six year period shown. The figures in the \$3036>GNP>\$766 category are influenced by recent tunnelling projects in China

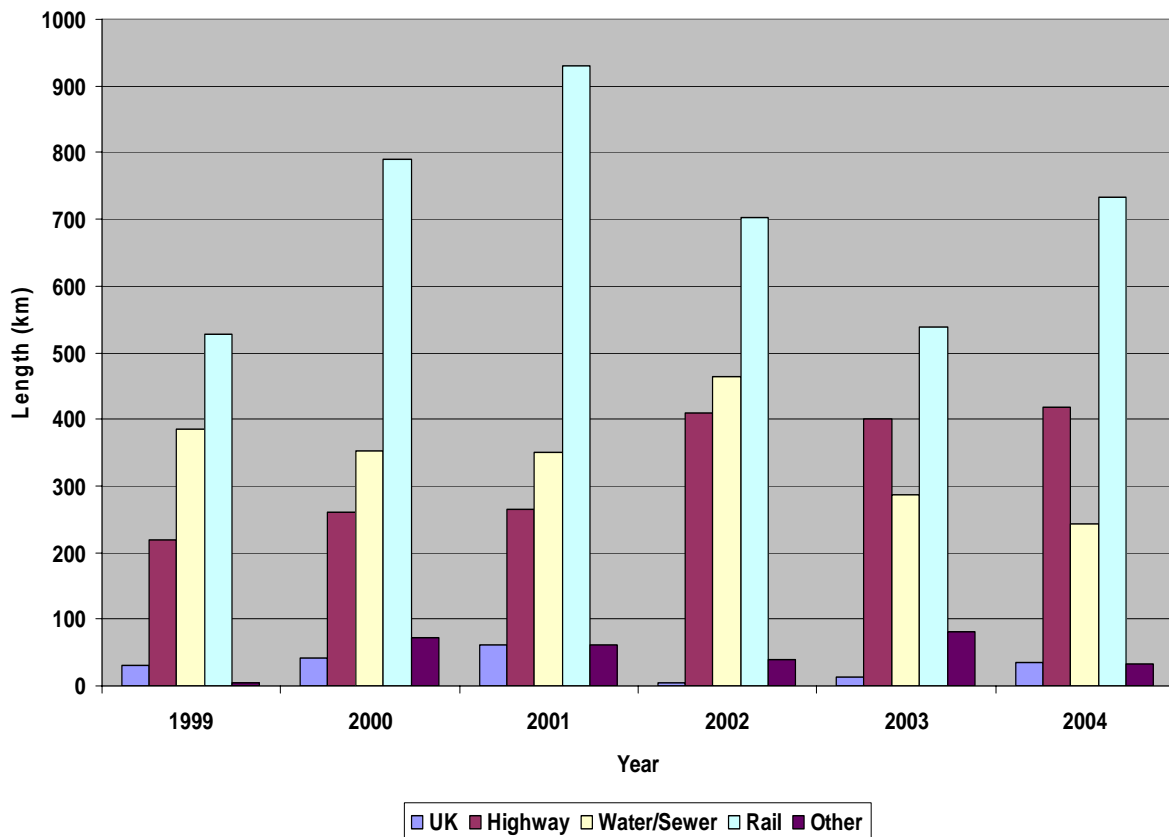


Table 3.3 World and UK tunnel construction 1999-2004. World construction divided by usage.

3.2 Soft ground urban tunnelling

The specific focus of this report is urban tunnelling and, given this objective, further research of the published literature was undertaken to identify and list the numbers of tunnel projects around the world that had experienced emergency events during such construction.

These data sets on historic projects have been divided into two main categories

- The New Austrian Tunnelling Methods (Appendix C),
- Other Tunnelling Methods (Non-NATM). (Appendix D)

Both sets of data were then interrogated to identify projects where emergency events had taken place in urban areas sited in soft ground.

3.3 Listings of recorded tunnel emergency events

The total numbers of incidents for all types of ground conditions, and environments in both NATM and non-NATM tunnels that have been obtained from the published data are shown in Table 3.4. The data has been classified into discrete decades in order to highlight trends.

	1970 - 1979	1980 - 1989	1990 - 1999	2000 – 2005(part)	Total
NATM	2	27	27	10	66
non-NATM	7	7	19	9	42
Total	9	34	46	19	108

Table 3.4 The total numbers of identified * tunnel emergency events per decade identified in this research, divided into NATM and non-NATM tunnels.

(* Note. This research does not purport to have identified all the tunnel emergency events that have actually occurred.)

From these total numbers of incidents it was possible to abstract the numbers of identified incidents relating to tunnels constructed in soft ground in urban areas. These are shown per decade in Table 3.5 and as a percentage of the total number of recorded incidents in Table 3.6.

	1970-1979	1980-1989	1990-1999	2000-2005 (part)	Total
NATM	0	9	12	4	25
non-NATM	2	2	9	6	19
Total	2	11	21	10	44

Table 3.5 The numbers of identified tunnel emergency events per decade identified in this research, occurring in soft ground urban environments, divided into NATM and non-NATM tunnels.

1970 - 1979	1980 - 1989	1990 - 1999	2000 – 2005 (part)
22%	32%	46%	53%

Table 3.6 Percentage of total tunnel emergency events occurring in soft ground urban tunnelling environments

Table 3.6 demonstrates a consistent rise per decade in the proportion of soft ground urban tunnels that have suffered emergency events when compared to the total of all tunnel emergency events world-wide.

3.4 NATM Tunnels

3.4.1 Listings of NATM Incidents

The HSE report on the Safety of NATM tunnels ³, published in 1996 following investigations after the Heathrow Express tunnel collapse, identified over 100 incidents recorded during NATM tunnelling. Table 1 of this document describes 39 significant NATM incidents and collapses throughout the world in both urban and rural environments. That information was obtained from an extensive literature search and was supplemented by other sources including private communication. Table 2 of that document classified the primary cause of each identified collapse. It was emphasised that, for a range of reasons, most incidents that occur are not reported in any “official” way and therefore the data must be considered as incomplete.

In addition to these listed incidents, the HSE report (see Para. 48 page 16) also identified that 71 incidents had been reported in 65 tunnels constructed in Japan between 1978 and 1991 at unspecified locations. These ground collapses ranged from the “quite small” through volumes of between 50 – 500m³ of ground (15 Incidents.) to volumes of over 1000m³ of ground (3 Incidents.).

Additional research undertaken since 1996, and for this study, has extended the HSE 1996 list of NATM incidents from 39 to 66 including two incidents that occurred in early 2005. In 1996 a document was published that uses the term “Sprayed Concrete Linings (SCL)” approach ⁴, but in this document the term NATM is used throughout.

3.4.2 Data from NATM Incidents

A feature of the data obtained for the 66 NATM tunnel incidents was the high number of failures that were recorded in the area between the tunnel face and the first completed ring of the sprayed concrete lining. These types of failure were classified as Type A in the 1996 HSE Report, and this classification has been repeated here.

Of the total number of 66 incidents, 44 have a reported primary cause, and from those 44, 39 are of the Type A.

Of the total number of 25 incidents in soft ground urban tunnelling, 22 have a reported cause of which 20 are of the Type A. Of the total number of 22 with a reported cause, 12 of those incidents also reported the incidence of a surface crater.

Other features of the 66 incidents include

- the overall ratio of urban incidents to rural incidents as was reported in Ref.3 (Para. 47) remains at 2:1, and
- The incidences of craters in urban areas also reported high level of consequences in terms of disruption to the construction work and to third parties.

3.5 non- NATM Tunnels

A list of identified incidents that have taken place since 1970 on Non-NATM tunnels in all types of ground and environments has been researched, and totals 42 emergency events (see Appendix D). As before, this list has been examined to extract details of those urban projects that were constructed in soft ground.

The 42 incidents demonstrate a wider range of primary causation and consequence than the NATM data. This is demonstrated in the following breakdown and analysis of the information from 32 of the most reliable data sets. The list of causes for all cases and for urban soft ground cases are as follows:

Cause	Number of Incidents	
	All	Urban
		Soft ground
Unpredicted Ground	20 (63%)	10 (52%)
Fire	3 (10%)	2 (11%)
Compressed air explosion	2 (6%)	1 (5%)
Methane gas explosion	1 (3%)	1(5%)
Defective Workmanship	2 (6%)	2 (11%)
Temporary works failure	2 (6%)	2 (11%)
Flood	1 (3%)	0
Unknown, (despite investigation)	1 (3%)	1 (5%)
Total	32	19

Table 3.7 Causes of non-NATM incidents and numbers in soft ground.

Half of the above incidents have been recorded as being caused by unpredicted ground conditions. In general terms, unpredicted ground conditions may arise from poor or inadequate site or ground investigations. (See also Reference 3 Para. 57).

In these non-NATM emergency events there are few recorded instances of collapses at the tunnel face. Within the 19 incidents listed above there were 8 instances of surface craters.

A further feature of the data set of 32 incidents is that they are randomly distributed in terms of country of location.

3.6 British Tunnelling Society Working Group. Guideline Document (2005)

During construction of the Channel Tunnel Rail Link tunnels by closed face Tunnel Boring Machine in February 2003, an emergency event took place in Lavender Street in East London.⁵ This incident followed two earlier events on UK tunnel projects at Portsmouth⁶ and Hull⁷, and reflected further incidents that had taken place in other countries (Shirlaw et al⁸) while using closed face tunnel boring machines. In some cases these incidents had resulted in craters appearing in the ground surface above the tunnel. In response, the British Tunnelling Society decided to set up a Working Group to research the details of similar incidents that could be identified and draw conclusions. Their final document, "Closed-Faced Tunnelling Machines and Ground Stability - A guideline for best practice",⁹ was prepared and published in April 2005.

This Guideline (see Section 4- Incident data) brought together information on over 100 incidents which have taken place world wide during construction involving closed face tunnel boring machines. Included within their total of 100 incidents were data on 14 incidents associated with Slurry Type Machines, and 47 incidents relating to Earth Pressure Balance Machines. The BTS incidents are not specifically identified, but at least three of the incidents that are included in the BTS document (i.e. Hull, Portsmouth and Lavender Street) have also been included in the non-NATM list summarised in this report.

The Guideline identifies a number of hazards that are associated with the systems and technologies applied within these particular tunnelling methods, and propose ways to mitigate these hazards through additional works and the application of good practice (see Guideline, Section 10 "Conclusions and Recommendations").

3.7 Other relevant data sources

The world-wide Insurance industry has data on the numbers of tunnel projects that are insured and the quantum and causation of claims arising on those projects. This information is not in the public domain. However, two recently published papers (Hecke et al ² and Blücker et al ¹⁰) analysed the causes of tunnel construction claims. Hecke reports on a study by Munich Re of 107 important tunnel claims made between 1993 and 2003 which stated that the losses arose as follows:-

- 10% from fire
- 50 % from “natural events”
- 25% from “construction methods”
- 10% from “design defaults”

(5% were unassigned)

The paper by Blücker et al entitled “Possible Maximum Loss – Assessment of Civil Engineering Projects” provides further information under the headings “Excavation and Lining Sensitivity Factors” (See sections 6.1.6 and 6.1.7 of their paper). These are reproduced as Tables 3.8 and 3.9 below. Their definition of “Possible Maximum Loss” - used by property and fire insurers, is “the largest loss that may be expected from a single fire (or other peril when another peril may be the controlling factor) equal to any given risk when the most unfavourable circumstances are more or less exceptionally combined and when, as a consequence, the fire is unsatisfactorily fought against and therefore is only stopped by impassable obstacles or lack of sustenance.” These factors provide an estimate of the sensitivity of each type of technical risk for the

assumed most unfavourable hazards from which the maximum damage can be assessed. It is assumed that most projects will have enough in common with these Factors for them to taken as a tenable basis for estimates.

Excavation Method	Sensitivity Factors ★					
	Earthquake	Flood (external)	Flood (at face)	Fire	Explosion	Face collapse, inadequacies of method for unforeseen conditions
1. Conventional	3	2	3	2	2	3
2. Manual	3	1	3	2	2	3
3. Drill and Blast	3	1	3	2	1	3
4. Open cut	2	2	2	1	1	2
5. Open face shield	3	2	3	2	2	3
6. Closed face shield	3	2	2	2	2	2
7. Slurry TBM	3	2	1	2	3	2
8. EPBM	3	2	1	2	2	2
9. Full face hard rock TBM- No shield	3	2	3	2	2	3
10. Hybrid TBM	3	2	3	2	2	2
11. Micro Tunnelling	3	2	3	3	3	2
12. Submerged tube.	3	3		2	2	3

★Severity Factors

0 - Excavation method unaffected

1- Minor influence on method-drive method can be maintained once hazard relieved

2- Major failure of face or drive -may require alternative working method

3- Catastrophic failure of face, possible abandonment of drive.

Table 3.8 Excavation Sensitivity Factors (Source, Blücker et al, Reference 10)

Tunnel Support & Lining Systems (fully installed)	Sensitivity Factors ★				
	Earthquake	Flood	Fire	Explosion	Inadequate design or method of execution: lining failure/collapse
1. Pre-cast segmental linings	2	2	1	2	3
2. Jacked concrete pipes	2	2	1	2	3
3. Steel ribs & Lattice arches (NATM)	2	1	1	2	3
4. Rock bolts (NATM)	2	0	0	0	3
5. Shotcrete, also NATM	3	1	2	2	3
6. In-situ concrete linings (inc. NATM)	3	1	1	2	3
7. Compressed air (face support *)	2	2	3	3	3
8. Ribs and lagging	2	2	3	3	3
9. Contiguous piles (open cut)	2	0	0	0	2

★Severity Factors

0- Lining or support method unlikely to suffer damage

1- Minor damage (or localised) to lining or support system -can be repaired.

2- Significant damage to support systems or lining-may require alternative working method for repair

3- Catastrophic failure of tunnel, possible abandonment

* Compressed air only used for face support, in combination with other lining methods.

Table 3.9 Lining Sensitivity Factors (Source, Blúckert et al, Reference 10)

3.8 Analysis of Data

The Authors believe that the following conclusions may be drawn from a broad analysis of the data contained within this document.

1. The numbers of tunnels being constructed in the developed world is increasing year on year, while activity in the rest of the world remains variable and an order of magnitude below the developed countries.
2. Both the total number of tunnel emergency events, and the proportion of these incidents that took place in urban areas with soft ground tunnels have increased in the three decades since 1970. In the latter case this trend has also continued into this current part decade.
3. The incidents associated with soft ground urban tunnels show that NATM tunnels exhibit different failure characteristics from Non-NATM tunnels.
 - Approximately 90% of the NATM tunnel incidents occurred within the uncompleted structure close to the face. Of these approximately 55% result in a surface crater.
 - Just fewer than 50% of non-NATM incidents reported resulted in a surface crater, the majority being located behind the tunnel face. Of these incidents, approximately 50% took place in shielded/TBM drives and approx. 50% in hand drives.
 - There is evidence that tunnelling with closed face TBM's can result in surface craters above the face of the machine. A direct relationship between face incidents and the occurrence of surface craters is not clear.

- 4 The significant numbers of the identified NATM incidents recorded in Germany/Austria can perhaps be put down to-
 - A desire to release technical information in order to disseminate lessons learned to assist in the development of this particular method.
 - An approach to the design and construction of tunnels ¹¹ that seek to refine the balance between risk and rewards systems¹².
5. The primary cause listed in the emergency events is attributed to unpredicted ground conditions. This matches a finding in the 1996 HSE Report.
6. In the non-NATM tunnels, the range of primary causes for incidents not attributed to ground conditions is wider than for NATM tunnels. This points to a more complex chain of causation.
7. The underlying causes of emergency events are likely to be diverse. They could involve engineering, management, procurement, organisational, competence, resource or communications issues.

4. THIRD PARTY RISK

4.1 General

4.1.1 Societal Risk.

A paper by Hambly and Hambly¹³ asserted that the Fatality Accident Rate, FAR, (defined by them as the risk of death per 100 million hours exposure to the activity) is greater for construction work than for industrial work as a whole, which would confirm why the construction industry has a poor reputation for accidents. Their figures also show however that some other industries (oil and gas, offshore) have higher FAR (See their Table 1), and that the fatality accident rate for construction workers is lower than the rate for all men of working age. These figures apply to workers within industry rather than third parties affected by industry, and they also show that the FAR to third parties from a collapsing building is extremely small.

In addition, it is the view of insurers when evaluating Possible Maximum Loss¹⁰ that “whilst every segment of construction has to contend with particular hazards and associated risks, there is none which compares to the range and exposures plaguing the tunnelling industry”

It is clear that from the point of view of personal accident statistics and commercial liability that some people may consider tunnelling to be “high risk”, albeit to those working in this industry rather than as risk to the general public. There are exceptions however, in particular an incident on 24 April 1995 in Taegu South Korea¹⁴ during which a gas explosion took place within the underground construction works of a new metro station. This one incident resulted in the death of more than one hundred members of the public including 50 children.

When assessing the magnitude and extent of risk it is important to clarify the definition of the terms being used. This is because the terminology used can be interpreted in various ways by different groups. It might be argued that the consequence of tunnelling induced hazards impacting upon third parties is a societal risk, but one that is not necessarily restricted to accidents. The HSE in

“Generic terms and concepts in assessment and regulation of industrial risks” 1995 ¹⁵ defined societal risk as-

“The risk of widespread or large scale detriment from the realisation of a defined hazard, the implication being that the consequence would be on such a scale as to provide a socio/political response, and /or that the risk (i.e. the chance combined with the consequence) provokes public discussion and is effectively regulated by society as a whole through political processes and regulatory mechanisms.”

“Societal Risks” by Ball et al ¹⁶ also characterises societal risks that derive from the public’s normal activities being interrupted by an accident as “societal concerns” with the assessment criteria stated as “political judgement-possibly aided by multi-criteria techniques”. This would imply that quantitative cost benefit analyses based on “value for a life” calculations are not appropriate. An “as low as reasonably practicable” (ALARP) approach allied to judgements on other relevant issues is likely to be the most practicable way of evaluating societal risk.

Within this document the terminology that is used to describe risk and related terms is defined below.

4.1.2 Definitions

Hazard * is something with the potential to causing harm

Risk * is the combination of the likelihood/probability that an identified hazard will occur and the consequence/severity if it did.

* see paragraph. 11(b) of Management of Health and Safety at Work Regulations 1999 Approved Code of Practice.¹⁷

4.2 Risk Evaluation

4.2.1 Risk Assessment.

Risk Assessment is a part of the overall process of Risk Management. Risk Management starts from initial hazard identification through to the effective control of risks during the use phase of the project. Risk assessment is that stage where residual risks are evaluated in terms of their likelihood and consequence for the purpose of setting priorities and in terms of what can be done to devise effective preventative and protective measures. Risk assessment is not an end in itself, but a means to the end objective of a safe and healthy working environment both during construction work and during the phases thereafter.

In order to identify, understand and control the risks to third parties arising from a tunnelling project, risk assessments should be undertaken to aid decision making on protection and preventative measures.

4.2.2 Acceptability criteria

A risk assessment can be undertaken using either qualitative judgements or quantitative values. As discussed above, it is impracticable to assess societal risk for acceptability against quantitative criteria for two reasons (a) because of the lack of reliable data, and (b) because of the diversity of each tunnel's characteristics (i.e. size, purpose, tunnelling mediums, design and construction details etc.), and in particular the excavation and lining techniques employed.

However, qualitative acceptability criteria are suggested in the ITA Guidelines for risk management ¹⁸ and these should be considered. These are as below;

Unacceptable This risk shall be reduced at least to "Unwanted" regardless of the costs of mitigation.

Unwanted Risk mitigation measures shall be identified. The measures shall be implemented as long as the costs of the measures are not disproportionate with the risk reduction obtained (ALARP principle)

Acceptable The *risk** shall be managed throughout the project.
 Consideration of risk mitigation is not required.

Negligible No further consideration of the *risk** is needed.

(* amended from the term “hazard” by the authors of this document).

4.3 Consequence Analysis

For urban tunnel projects, where damage and disruption on a local scale can result in high impacts, the consequences of emergency events can include-

- Death or Injury to third parties
- Damage or economic loss to third party property or services
- Harm to the environment such as release of toxic/inflammable/harmful materials
- Delay and consequent economic loss to third parties
- Loss of public goodwill which might lead to political action

Any significant incidents occurring in urban areas would be politically, economically and environmentally sensitive, and public opinion and actions could be expected to play a significant role. Loss of public goodwill, arising from emergency events affecting third parties, has the potential to result in adverse media coverage.

Third party injuries and damage arising from emergency events will be controlled by factors such as impact, location and chance. For example, craters opening in rural areas are likely to be less damaging than in urban areas. Similarly, time of day will affect the numbers of third parties exposed to an incident. This randomness, or chance, is an important factor in the consequence of any event.

Consequences arising from an emergency event have been quantified and graded in the ITA Guidelines as follows

Class ^o	Consequence				
	Injury to third parties	Damage to third party	Harm to the Environment	Possible Delays	
				Minimum	Other
	Numbers of fatalities/injuries	Loss in Million Euros	Guidelines for proportions of damage	Months per hazard	Months per hazard-
Disastrous	F>1,SI>10	>3	Permanent severe damage	>10	>24
Severe	1F,1<SI<10	0.3-3	Permanent minor damage	1-10	6-24
Serious	1SI,1,MI<10	0.03-0.3	Long-term effects	0.1-1	2-6
Considerable	1MI	0.003-0.03	Temporary severe damage	0.01-0.1	0.5-2
Insignificant	-	<0.003	Temporary minor damage	<0.01	<0.5

Table 4.1 Classification of consequence. Source ITA Guidelines, Ref. 18. Based on an underground project with a value of €1Bn. and duration of 5-7 years. (Where, F = Fatality, SI = Serious Injury, MI = Minor Injury.)

(^o N.B. The data collected in this report is based upon “emergency events”, which are defined as events that required contingency measures to be activated.)

In 1995 there was an incident on Hollywood Boulevard, Los Angeles when re-mining a completed tunnel caused a crater 70 foot wide and 60 foot deep which resulted in the complete closure of the famous Boulevard.¹⁹ No one was hurt in the incident, but a \$1bn.law suit was brought against the contractor.

The consequences of the three tunnel collapse at Heathrow airport in October 1994²⁰ included the temporary closure of the underground Piccadilly Line, disruption to tens of thousands of travellers, road closures, extensive remedial works and the cost of lengthy investigations, redesign cost and legal costs involved in the subsequent prosecutions.

4.4 Frequency Analysis

The ITA has prepared the following classification of frequency from a review of statistics and from pooled expert judgement.

Frequency class	Frequency Interval	Central value*	Descriptive frequency class
5	>0.3	1	Very likely
4	0.03 -0.3	0.1	Likely
3	0.003-0.03	0.01	Occasional
2	0.0003-0.003	0.001	Unlikely
1	<0.0003	0.0001	Very Unlikely

Table 4.2 Frequency of events in the construction period. (Source: Ref 18).

(NB. The central value represents the logarithmic mean value of the given interval)

The five frequency classes presented represent a way of identifying an event frequency which enables the number of emergency events to be described in terms of per year or per kilometre of tunnel construction. However the ITA recommendation is for such frequencies to be related to the number of events per project construction period.

4.5 Risk Matrix

Based on the above ITA definitions and criteria a risk assessment can be undertaken to produce a risk matrix for frequency and consequence.

An example of a risk matrix is given below.

	Frequency				
Consequence	Very Likely	Likely	Occasional	Unlikely	Very unlikely
Disastrous	Unacceptable	Unacceptable	Unacceptable	Unwanted	Unwanted*
Severe	Unacceptable	Unacceptable	Unwanted	Unwanted	Acceptable
Serious	Unacceptable	Unwanted	Unwanted	Acceptable	Acceptable
Considerable	Unwanted	Unwanted	Acceptable	Acceptable	Negligible
Insignificant	Unwanted	Acceptable	Acceptable	Negligible	Negligible

Table 4.3 Risk acceptance matrix (Source ITA Guidelines, Table 8)

* Special attention needs to be given to the case of a potentially low or very low probability events but which could have high consequences. In the above table this is labelled “unwanted”, but, in the authors’ opinion, the correct classification should be “unacceptable”. The report on the collapses at Heathrow ²⁰ and the publicity associated with the events ²¹ illustrates this issue.

5. URBAN TUNNELLING – THIRD PARTY IMPACTS

5.1 General

Modern cities depend on underground infrastructure to provide support for their commercial and domestic needs. The age, extent and nature of these works in a particular location are a function of local geology, economic growth and technological development. London, for example, with its advantage of a widely distributed geological material of good tunnelling properties- London clay-has a long modern tradition of tunnelling and infrastructure provision. Other cities, such as Hong Kong and Singapore, have developed their underground infrastructure more recently by taking advantage of technological advances in tunnelling equipment to overcome less advantageous ground conditions.

Construction and maintenance of such existing urban tunnels have provided a rich source of information, detailing both the problems and the solutions thrown up during the life cycle of these works. The problems arising from a variety of different hazards associated with urban conditions and constraints provide a set of data that must be fully understood by designers and constructors of new urban tunnelling schemes. A recent paper by Kovári and Ramoni ²² provides a useful summary of the tunnelling risks encountered in an urban environment.

Kovári and Romani cite some examples of the range of direct impacts that might affect third parties from urban tunnel construction, including:

- Failure of tunnel support leading to the formation of a surface crater
- Excessive settlement leading to damaged buildings
- Settlement movement damage to above and below utilities

Specific examples each of these types of impacts, and others, are provided in Section 5.4 below.

5.2 Constraints

5.2.1 Geology

The principle engineering determinant in the design and construction of urban tunnels, as in all tunnels, is the ground conditions and the construction methods that are required to realise the works. Tunnels built in sound rock, as in Stockholm, can be formed of large caverns with little or no added support, allowing spacious architectural designs for transportation systems. Cities founded on soft soils with high water tables require tunnels whose form and support are dependent upon excavation methodologies determined by the need for both immediate support and continuing support of the ground. In the latter case, variation of the anticipated ground provides the largest single risk to the tunnelling works together with the potential to affect third parties. The point is well summarised in CIRIA Report 79¹, which states:

“The ground is the principal construction material, supplied by nature and seldom to specifications that engineers would choose. Methods of construction are highly dependent on the ground, and costs are a function of the rate of advance. An encounter with unforeseen ground conditions not only imposes large extra costs but may itself introduce additional hazards. Although similar circumstances may attend other forms of heavy construction, it is unusual for the difficulties to be so severe or the effects so acutely felt as in underground construction, where difficulties are unavoidably compounded by the limited and restricted access to working faces.”

A large amount of international urban tunnelling is carried out in soft ground, which can be characterised as non uniform, infinitely variable, contain variable water levels and perhaps incorporating man-made features of varying age. For new tunnel schemes it is

essential that the prevailing ground conditions including their possible variations are well understood at an early stage of planning, so that subsequent decisions on layout, design and construction methodology can be based on a thorough and detailed understanding of the potential hazards. This requires that early and comprehensive site and ground investigations are expertly planned, carried out and reported.

Interpretation of the factual ground investigations should also be undertaken and the findings set out in a separate document. Depending on procurement strategy, this document might, or might not be issued with the construction contract documentation but, in any event all information relevant to health and safety considerations will be gathered together and made available to designers and others. In view of the number and variety of risks associated with urban tunnelling, the authors believe that Interpretative reports should be made available at tender stage as either Ground Reference Conditions¹ or Geological Baseline Reports²³.

The quality of the information and the opinions expressed in these reports is crucial to those whose task is to make informed decisions on design and construction methodology issues. Site investigations should include geological studies, desk studies, historical and archaeological research, examination of aerial photographs to determine the extent of man made obstructions (see BS 5930)²⁴. In addition archived records of wells, ground anchors, basements, records of previous excavations nearby, and even unexploded ordnance need to be researched.

It has been reported¹ that site investigation costs have been found to range between 0.1 to 7.5% of the capital tunnelling costs. Also reported²⁵ are the results of a 1984 study of 89 underground projects in USA that compared the cost input to site investigations and the out-turn costs of the works. The conclusions of the study were

- Overall, contractual claims averaged 29% of the engineer's original cost estimate for the works

- Low site investigation effort (i.e. cost) resulted in an increase in the level of claims
- When ground investigation effort exceeded 0.6metre length of borehole per metre of tunnel length, there was a pronounced reduction in the cost of contractual claims, and the contractual claims continued to reduce in cost as the level of exploration increased.

If the level of claims is equated to the level of unforeseen ground conditions, the relationship between level of ground investigation and level of unforeseen ground risk is identified. The limit of 0.6 metres of borehole length per metre of tunnel is roughly equivalent to an exploration cost of 1% to 1.5% of project cost depending on the relative amounts of cable percussion or rotary drilling included in the investigations. Site investigations and their costs are likely to be particularly project specific.

5.2.2 Structures on the ground surface

All bored soft ground tunnelling causes relaxation in the medium being excavated (described as ground loss) together with associated ground movements around the tunnel. In turn these below ground movements translate themselves into deformations at the ground surface that vary in magnitude with distance from the tunnel centre line. Infrastructure sited close to the line of the tunnel will be distorted by the resultant “settlement trough” and may be damaged (to varying degrees) by the differential movements placed upon it. In London clay for example, the degree of damage will be dependent on a range of factors and can be predicted with a high level of accuracy ²⁶, thus enabling appropriate mitigation and monitoring to be installed in most cases.

Building damage due to settlements arising from remote tunnelling can, in general, also be predicted with some accuracy. As a consequence the effects of settlement can be determined and mitigated through either variation of vertical and horizontal tunnel alignment, or partly by site specific measures such as underpinning, compensation grouting etc.

Tunnelling induced ground movements will also affect other sub-surface structures such as piles, deep basements, other tunnels and underground structures. As with surface buildings the movements and reactions can be calculated and, where necessary, appropriate mitigation measures introduced. It is usual in these circumstances for tunnel project teams to liaise with engineers representing third parties to ensure due process in the analysis and design of mitigation of the applied forces and movements. Where the impacted tunnels are used by the public additional risk assessments are normally required.

There are recent examples of emergency events that have taken place at tunnel level that have led to the formation of surface craters (Barcelona²⁷ and Shanghai²⁸) These resulted in severe damage to buildings and major disruption to surface activities including road closures and evacuation and demolition of buildings.

5.2.3 Shallow tunnels

Where tunnels have ground cover that is less than twice their diameter, particular difficulties can arise from impacts and clearances to physical obstructions such as foundations, basements, deep utilities etc. In addition, a shallow tunnel may result in a greater magnitude of surface settlement than a deep one, albeit over a narrower settlement trough. In urban areas such configurations can cause severe engineering problems in congested zones. An additional issue, that can cause cumulative problems to the above, is the uniformity of the ground cover. Surface layers can include irregular man-made ground and softer deposits that can result in local distortions to the settlement profile and *in extremis* loss of ground into the tunnel. The Athens Metro²⁹ construction provides an example of the many problems that can arise if inappropriate equipment is used. The recent tunnel collapse at Lausanne³⁰ appears also to be a similar case.

5.2.4 Utilities

All buried utilities, whether shallow or at depth, will be affected by settlements arising from tunnel construction. Culverts and large

pipes, such as sewerage, water or gas mains, may be distorted by the ground movements and have additional loadings placed on their joints and barrels. Particular problems can arise at the connections between linear pipelines and fixed structures such as buildings, manholes etc. Careful analysis is required in all cases to ensure that the pipes, taking account of their material and physical condition in the ground, can sustain foreseeable imposed loadings and movements. Fractured gas and water mains have the potential to cause major disruption and serious or significant damage to third party interests. Other utilities such as telecommunications networks can be similarly damaged from settlements which can result in outage to important systems and cause major third party disruption and result in significant commercial claims. It is good practice safely to divert sensitive utilities prior to tunnel construction, as unexpected movements can endanger plant that might previously have been thought to be at low risk.

5.2.5 Working sites

Tunnel construction sites located in urban areas can suffer from restrictions arising from land availability; access limitations and environmental restraints imposed local Authorities. Their uses can include any of the following functions: permanent works construction, temporary works for access to the permanent works, materials handling and staff accommodation and welfare facilities. All of these activities will impact on third parties close to the site and for which environmental protection will be provided by agreed Site Environmental Construction Plans.

Risks to third parties from these uses can arise from instability of the temporary and permanent works, which by their nature, are close to existing infrastructure. Other risks include the staging of traffic management controls including diversions that can be required to release parts of the working site to enable phased construction.

Restricted sites can result in limitations in the provision of plant and materials which could result in an increased construction risk and which should be taken fully into account in the design,

planning, permissioning and construction stages. Satellite or remote working sites such as for the provision of permanent works shafts and temporary works shafts for ground treatment are also likely to suffer from restricted access issues, and hence the possibility of increased third party risks.

5.3 Potential Constraints

The available references on all the incidents that have been identified in this study provide a plethora of hazards leading to the emergency events. In addition to these there are other potential hazards that might arise specifically from urban tunnelling, modern construction methods and materials and other sources that have not been ascribed to third party risks in the literature. Some of these potential hazards have been identified in the British Tunnelling Society Report on Closed Faced Tunnel Boring Machines and listed in that document for review – see Reference 9.

Other processes with the potential to introduce hazards to the construction of urban tunnels in respect of third parties might include the following:

5.3.1 Compensation grouting.

This is a method of injecting grout into the ground above an advancing tunnel face in order to compensate for anticipated associated ground loss and thus reduce settlement. The process requires the development of very high grouting pressures in the ground and has the potential, if improperly designed, controlled and monitored, to damage the excavation/support at tunnel level leading to local loss of ground and possibly significant surface settlements. There is also the potential to cause heave at the ground surface with consequential damage to utilities and buildings.

5.3.2 Ground water lowering.

This is a traditional technique that has been adopted on a number of recent projects to ease the progress of closed face tunnel boring machines by reducing general ground water levels and in particular the water pressure in the ground at the tunnel face. Its application over a wide area of urban landscape is capable of causing secondary effects such as irregular surface settlement and local piping of the ground.

5.3.3 Tunnel induced disturbance.

Incidents of unexpected near-surface settlement were recorded during construction of the Jubilee Line Extension.^{31, 32.} The movements took place in near surface alluvium and affected overlying railway structures. They have been interpreted to be caused by the tunnelling process introducing meta-stability (sensitivity to slight disturbance) of the ground above the tunnel. In similar ground conditions (which are extensive in East London) it is possible that tunnelling could cause settlement damage to buried utilities such as water or gas mains leading to loss of water/ground or explosions. Such a scenario has been accepted in a judgement given in recent Court proceedings^{33.}

5.3.4 Compressed Air.

A form of temporary works that is used to control the ingress of water and ground into the works during open face tunnelling, and also to limit ground movements during construction. Cases in Tokyo³⁴ and London³⁵ demonstrate the risk to third parties from a sudden loss of air pressure resulting in lining failure and the sudden formation of a surface crater. Advice on the design and control of compressed air installations for tunnels is provided in BS 6164³⁶ and the Work in Compressed Air Regulations 1996^{37.}

5.4 Problems/ Lessons from recent incidents

5.4.1 Open face working

NATM tunnel construction incidents in the city centres of Barcelona ²⁷ and Lausanne ³⁰ in early 2005 resulted in the appearance of large surface craters and consequent significant third party disruption. In Barcelona emergency evacuation of a number of buildings was ordered, with some being subsequently demolished. In both instances open face tunnelling methods were being employed when unforeseen ground conditions were met and miners and others were unable to prevent face collapse and the consequent ravelling of ground to the surface. These cases highlight the necessity for a good prior understanding of the ground and for thorough contingency and emergency pre-planning.

It is also possible for ground conditions to change rapidly over short tunnel advances and this can result in sudden unstable open tunnel faces. In the case of shallow tunnels, like Lausanne, this instability can last for a very short time-span and there may not be sufficient time available to install effective emergency ground support systems. With open-face tunnelling methods the safety-critical feature is the ability of the face to remain in a stable condition during the whole construction sequence. This has been the subject of research spanning 25 years (Lunardi 2000) and has led to the development of an engineering approach which is titled "Analysis of controlled deformations of rock and soil"³⁸. In simple terms, analysis of this type of ground behaviour leads to the solution of stability problems by means of confinement of the existing void and/or the pre-confinement of the block of ground ahead of the tunnel face. Professor Lunardi states that this is a fully designed solution based on an engineering characterisation of the ground. It is not an "observational method" of tunnelling. The range of confinement and/or pre-confinement options are so extensive that the method of tunnel construction remains flexible, but the main principle is that the soil ahead of the tunnel face is stabilised before it can move and present a danger.

On the other hand, the Madrid City Authorities have rejected open face methods for tunnelling through soft ground, except under very carefully controlled conditions. (Melis *et al* 2000)³⁹

5.4.2 Closed face working

Recent examples of third party impacts from closed faced working can be found in Singapore ⁴⁰ and Stratford ⁵ in east London. In

both cases surface craters above bored tunnel works resulted at the least in some social disruption, either to domestic householders or to road users. The consequence of these incidents to third parties and to the existing infrastructure was determined in some measure by route planning but also to chance. These cases are included in the data bases researched by the BTS closed face working group and outlined in their Guideline. Both cases demonstrate the need to fully understand the ground conditions both at the closed face and further ahead of the face. The TBM operator has to be guided by both direct and indirect monitoring systems in the quantification of spoil removed per ring advance and the avoidance of over-excavation, as the cutting process is enclosed and therefore unseen. Obstructions or voids in the ground can be driven through unknowingly if waste material is not visible and accurate spoil measurements are not readily available.

The recommendations in the BTS Guideline include:

- A holistic approach to safety issues.
- Wide dissemination of details of the expected ground conditions within the project team.
- Active management of TBM functions to control surface settlements.
- Maintenance of operational face pressures above the hydrostatic head, checked by continuous monitoring.
- The accurate monitoring of excavation quantities.
- Early grouting of the ring annulus and monitoring for pressure and volume.
- Sufficient, controlled and tested spoil conditioning.
- Setting and real time monitoring of the operating parameters of the TBM.
- Adoption of risk management systems for design, procurement and operation of TBMs.

- Extensive site investigations, including geophysical methods where applicable, to be undertaken at design and construction stages.
- Monitoring of surface and sub-surface structures.
- Good record keeping.
- Use of experienced staff.

5.4.3 Temporary Works

The design and detailing of temporary works can be more complex than for the permanent works themselves. The abnormal loading patterns involved, and the temporary nature of the supports, demand a high level of skill and competence in effecting suitable arrangements. The detailing of primary linings in NATM construction is a case in point.

An example of a temporary support failure in an urban environment is provided by the Los Angeles Metro⁴¹ where a serious underground fire led to the destruction of the timber laggings between the steel ribs and resulted in a collapse of the lining.

Another incident, on the Docklands Light Railway, resulted from the application of internal compressed air pressure to a completed section of running tunnel in order to construct a breakout cross passage beneath the river Thames. In this case the tunnel lining failed following the application of a test pressure and loss of ground cover which resulted in an explosion and surface crater adjacent to a nearby school³⁵.

Ground Treatment to aid tunnel construction and reduce settlement has also provided examples of disruption and third party impacts. On the Heathrow Express site at the Central Terminal Area²⁰, jack grouting was employed to rectify building settlements during tunnel construction. In the event the grouting caused a failure in the primary tunnel lining which in turn led to the ultimate collapse of both the lining and the building. In another case, this time in Sweden, albeit in a rural location, grout was injected into the ground ahead of an advancing tunnel face in order to create a low permeability zone around the tunnel and reduce water ingress to the tunnel to an acceptable level. One of

the chemical grouts used and which was most effective in reducing water flow, was subsequently found to be toxic, having initially affected miners and later some cows that drank water pumped out of the tunnel works⁴²

5.5 Future Projects in London

A number of transportation and infrastructure projects are currently at an advanced stage of planning within the London area. These include railway tunnels in the central area and collector sewers beneath the Thames corridor. It is anticipated that a full range of urban engineering and environmental issues will be met by these works and that construction planning will need to be very detailed.

Appropriate construction methodologies within the deposits of the London basin have already been developed and successfully used over a number of past and recent projects. The technology is therefore available to enable safe and economical tunnelling to be undertaken within all the generally anticipated ground conditions. Planning must ensure that sufficient knowledge of local ground conditions and existing infrastructure is available to enable informed decisions to be made during the design and construction of the works.

There is no reason why these projects cannot be safely and successfully completed.

6. RISK REDUCTION FOR URBAN TUNNELLING

6.1 UK Legislation

The UK legislation that covers the general avoidance of risks to third parties arising out of any work activities is contained in Section 3 of the Health and Safety at Work Act 1974.⁴³ There is a general duty on employers and the self-employed to “conduct their undertaking in such a way as to ensure, so far as is reasonably practicable, that persons not in his employment are not exposed to risks to their health and safety”. An “undertaking” includes not only employers undertaking the construction work but also those providing a service such as a design practice. Because the wording of this Section includes the phrase “so far as is reasonably practicable”, the burden of proof is reversed in any court proceedings as a result of the effect of Section 40 of the 1974 Act.

Regulation 3 of the Management of Health and Safety at Work Regulations 1999⁴⁴ requires every employer and every self-employed person to make a “suitable and sufficient assessment of the risks to the health and safety of persons not in his employment arising out of or in connection with the conduct of his undertaking”. These risk assessments are “for the purpose of identifying the measures he needs to take to comply with the requirements and prohibitions imposed on him by or under the relevant statutory provisions”. Regulation 4 adds that “where an employer implements any preventive and protective measures he shall do so on the basis of the principles specified in Schedule 1 to these Regulations” – the Risk Hierarchy.

Regulation 13(2) (a) (i) of the Construction (Design and Management) Regulations 1994⁴⁵ places a duty on “designers” (as defined by these Regulations), to “give adequate regard to the need to avoid foreseeable risks to the health and safety of any person who may be affected by the (construction) work”. At the time of writing the Health and Safety Executive has issued a Consultation Document with the proposed text of the Construction (Design and Management) Regulations 2006⁴⁶. This text significantly alters the 1994 designer’s duties, and the duty to manage risks to third parties is contained in the new proposed Regulation 14(3). In the Consultative Document the text of this Regulation reads (in part) as follows –

Every designer shall in preparing or modifying a design which may be used in construction work in the United Kingdom avoid risks to the health and safety of any person liable to be affected by such construction work.

The Consultative Document includes a new proposed general duty on the Principal Contractor to “plan, manage and monitor the construction phase in a way which ensures that, so far as is reasonably practicable, it is carried out without risks to health and safety”.

Within the Construction (Health, Safety and Welfare) Regulations 1996 ⁴⁷ there are several duties placed on defined parties to construction work to prevent danger or harm to “any person” – which would include persons not party to the construction works. For example, see Regulations 9(1), 12(1), 12(2), 12(3), 28.

6.2 Controlling Tunnelling Risk

The number of prominent tunnel failures that took place in the 1990’s led to pressures on the tunnelling industry from regulatory bodies and project Insurers to address project risk in a formal and uniform manner. Different client authorities developed their own methodologies for incorporating a risk based processes into the decision making systems serving their management teams, but these were ad hoc and did not rely on common methodologies and criteria. The International Tunnelling Association (ITA) therefore set up a working group to report on these systems and make proposals for a unified approach. This was achieved in 2004 with the publication of their “Guidelines for tunnelling risk management”. ¹⁸

At the same time the global insurance industry represented by the Association of British Insurers (ABI) and the British Tunnelling Society (BTS) began working together to prepare a Joint Code of practice ⁴⁸ for risk management for tunnel works in the United Kingdom. Compliance with this code is required to secure project insurance for “Contractors All Risks” and “Third Party” Insurances. This document was issued in the UK in 2003 “for active implementation”. The UK document is the forerunner for an International Code which is currently under preparation.

6.3 ITA Guidelines (2004)

These Guidelines were prepared by Working Group 2 of ITA “to give guidance to all those who have the job of preparing the overall scheme for the identification and management of risks in tunnelling and underground projects. The guidelines provide owners and Consultants with what is modern-day industry practice for risk assessment, and describes the stages of risk management throughout the entire project implementation from concept to start of operation”.

The ITA has provided no statements with regard to compliance with their Guidelines.

The ITA Guidelines set out how tunnelling risk management systems can be used throughout three stages of a project

- Early Design
- Tendering and Contract negotiation
- Construction

The objectives of risk management are defined as the identification of project risks resulting from design and construction and these are to be achieved by establishing a construction risk policy. This policy would include scope, risk objectives and a management strategy.

It is stated that the scope of the risk policy might include the risks and consequences that are set out below

- Risk to the health and safety of workers, including personal injury and, in the extreme, loss of life
- Risk to the health and safety of third parties
- Risk to third party property, specifically existing buildings and structures, cultural heritage buildings and above and below ground infrastructure

- Risks to the environment including possible land, water or air pollution and damage to flora and fauna
- Risk to the owner in delay to the completion
- Risk to the owner in terms of financial losses and additional unplanned costs

Some of these risks and their consequences are set out in Table 4.1 above.

The stated objectives of risk management would be to allow for the identification of hazards, the identification of mitigation measures and the implementation of mitigation on the ALARP principal. The guidelines suggest that the policy might minimise overall risk by reducing the likelihood of hazards with high consequences (linked to political concerns) if it is considered that low probability high consequence events to be of more concern than high probability low consequence events. Policy should also allocate risks to those best able to control them.

It is suggested that the management strategy should include

- Definition of the responsibilities of the parties
- A list of the actions required to meet the objectives
- A live risk register to be cascaded to all parties
- Feed back loops
- Audits

It should also define its risk acceptance criteria which should be provided in either qualitative form (Table 4.3 above), or in quantitative form. Such quantitative limits, as mentioned before, are difficult to define for third party hazards as the data is not available and anchor points (“accident frequency just on the borderline of acceptability”) ¹⁶ have not been established.

The Guidelines also set out the necessary components of a risk management system which are stated as being:

- Hazard identification
- Classifications
 - Frequencies
 - Consequences
 - Risk classification and risk acceptance

A range of the risk management tools that are available are also listed in the Guidelines and these include the following:

- Fault tree analysis
- Event tree analysis
- Decision tree analysis
- Multirisk
- Monte Carlo simulation

6.4 ABI Code of Practice (2003)

Contact Insurers will require compliance with the Code on all projects in UK where the value of the Tunnel Works is £1.0 million or more. Section 2 of the Code also notes in respect of compliance that:

“Compliance with the Code as it applies to construction projects involving tunnel works should minimise the risk of physical loss or damage and associated delays. It follows that Insurance contracts covering Tunnel Works should include provisions enabling Insurers to enforce the requirements of the Code, if necessary on pain of suspension or cancellation of the cover.”

The Code divides the stages of a project into four

- Development Stage (feasibility studies, site investigations, optioneering and design studies)
- Design
- Construction Contract procurement (contract documentation, tendering process and tender assessment)
- Construction

It then requires that hazard identification and risk management is undertaken throughout each of these stages through the use of a formalised Risk Management System (RMS). This system is to be used as a means of formally documenting the identification, evaluation and allocation of risks, which then have to be managed and mitigated on the ALARP principal. Live risk registers are required in order to properly assign risks and also to cascade the risks to parties throughout the project.

A Client's roles and responsibilities are set out, together with a requirement for their technical and management competences to be demonstrated.

Apart from statutory duties, health and safety issues are only defined within the Code in terms of their input to H&S Plans, Method Statements and Management Plans.

The Code also sets out requirements for the scope and quality of input to the ground investigations, including the need for adequate budget and programme time for the task. It also requires that a set of Ground Reference Conditions ¹ or Geotechnical Baseline Conditions ²³ be prepared.

A systematic process of risk assessment and management is described in order to identify consequences associated with “ *third parties and existing facilities including buildings, bridges, tunnels, roads, surface and subsurface railways, pavements, waterways, flood protection works, surface and subsurface utilities and all other structures/infrastructure which shall be affected by the carrying out of the works*”. Design risk assessments are also

required to consider the impact of the design and its implementation (including realistic variations in the design criteria and/or design values adopted) on third parties. Design checks that assess the level of risk and compliance with requirements to third parties are also a requirement.

6.5 Human Factors

Whichever of the above, or other, system is used to manage risks within a tunnel project's planning, design and construction cycle, it has been put forward that there are four fundamental processes that need to be employed. (Anderson and Lance ⁴⁹)

- The design and implementation of engineering systems
- The design and development of health and safety systems
- The adoption of appropriate organisational and management systems
- The consideration of human factors issues.

(These views are further developed in Section 7).

Most engineers are familiar with the first three of these processes through training and experience, but are generally less familiar with the need to take account of human factors issues in project planning and implementation. At all stages of project development, people have to make complex judgements and can make errors. Such unintended errors can be made at senior levels of management as well as at the tunnel face, and they can lead to an increase in the exposure to risk to workers and third parties. In the construction industry particular factors that might lead to such errors include:

- The number of differing organisations that may be closely involved in any one tunnelling project, and whose work activities may overlap
- The sometimes "adversarial" nature of contractual arrangements between the parties

- The pressure of progress, cost and site productivity in displacing safety as the first priority
- Lack of effective communication and coordination
- The over-compartmentalisation of functions within a project

The role of effective proactive monitoring in picking up errors can not be overestimated. This can be achieved by

1. Validating the initial competence of staff at recruitment
2. Self monitoring by all project personnel
3. The application of peer review to the process of data interpretation and decision making.

Risk based management systems should be able to take account of human factors issues by acknowledging the range of the three types of decision maker identified by Rasmussen,⁵⁰ and further explored by Reason⁵¹

- The skill based practitioner who largely relies on his self acquired experience and practice gained on previous projects
- The rule based practitioner who follows the known rules and guidance set out for design and construction, and
- The knowledge based practitioner who relies on both technical expertise and experience and who may go beyond established “rules”

Urban tunnelling provides a wide range of technical, organisational and human factors challenges to project engineers and others, and these need to be met with a flexible approach to problem solving while ensuring health and safety at all times. Whereas rule based systems and practitioners are a necessity for a base culture, care must be taken to avoid a culture of

unquestioning reliance on rules for problem solving. In his 2004 Harding lecture ⁵², Sir Alan Muir Wood stated that “in practice bureaucracy needs to be tempered by professional judgement. Only the experienced tunneller will detect the potential interactions between superficially diverse and unrelated type of risk.” (See also Section 4.2 in 1996 HSE NATM Report)

The common elements of a positive safety culture that need to be integrated into an overall effective project management system in both design/planning and construction include

- Commitment from the top through an effective safety policy; through positive prioritisation of safety; through organising for safety including the allocation of adequate resources, and the setting of well defined individual responsibilities.
- Demonstration of this commitment through day to day management actions and the provision of resources where and when they are needed, including the provision of specialist support and training and education
- Open and effective communication within and between organisations including a continuous dialogue on safety and risk matters. Communications should maintain impartiality and, where appropriate, confidentiality isolated from a culture of blame and mistrust
- Encouragement and enthusiastic support should be given to good performance, innovations and ideas. This can encourage all those involved to feel fully “on board” and working as a team with the aim of continuous improvement.

- Ensuring that particular management positions are filled by people with the appropriate background, experience, competence and leadership skills.
- Building in appropriate and effective monitoring and review arrangements

6.6 Risk Management Systems

Management teams for some large tunnelling projects that have been delivered within the last decade, have developed and prescribed methodologies to integrate risk management systems into each stage of their project implementation process. These projects have been developed independently but the concepts derived have been reviewed and incorporated as necessary within the development of the ITA Guidelines.

Examples of projects that have successfully employed risk management systems (RMS) throughout the planning, design, procurement and construction cycle include

- Hamburg- 4 th. Elbe Tunnel ⁵³
- Copenhagen Metro ^{54, 55, 56, 57}
- Madrid Metro ³⁹; and very recently
- Heathrow Airport, Terminal 5 tunnels ⁵⁸

These projects all used risk assessments as a tool to inform and record each decision making process and to minimise unforeseen events and costs.

At Heathrow Terminal 5, for example, the means chosen to minimise risk in the engineering and commercial management organisation was to adopt a non-adversarial contractual approach based on relationships and behaviours rather than transactions tied into a cost reimbursement type contract. This was achieved by reimbursing suppliers' costs with a defined profit plus an

incentivised target payment based on performance. The contract agreement focused on performance and success rather than failure, and on people as individuals in integrated teams not as external suppliers. The contractual risk of cost and programme variations was not shared with the suppliers and was held by the client, British Airports Authority (BAA). As BAA carried the commercial risk, risk management was undertaken by a fully-integrated, co-located team of BAA and its suppliers comprising client, designers, civil constructors and the fitting-out provider.

A separate example of formal hazard assessment procedures that were introduced into an ongoing project management system in order to control tunnelling risk is described in a paper on the Athens Metro ⁵⁹

Other project specific approaches have been described in the tunnelling literature, and include:

- Mala Kapela Tunnel, Croatia. Kolic ⁶⁰
- Hvalfjordur Tunnel, Iceland. Tengborg et al. ⁶¹

One element of any risk management system which must not be overlooked is the quantity of paperwork that can be generated by the processes adopted. At the primary level a risk management system needs to be process driven in order to ensure that a comprehensive study of the issues is carried out. However, modern projects incorporate other processes such as Quality Assurance, Management Manuals, Project Plans, Safety Plans, design submission schedules etc. that provide a substantial demand for form filling and record keeping. Excessive quantities of paperwork can affect delivery of the product and it should be an aim of the risk management system to be effective above and beyond the process driven level.

7. THE STRATEGIC WAY FORWARD

*“Fifty years ago, tunnelling was dominated by empirical methods in design, by traditional craft practices in construction. Today, design and construction of tunnels are based on a set of specialised technologies, with the success of each project dependent on their synthesis, on continuity between design and construction, and on appropriate means of project procurement. The art of tunnelling does not lend itself to inflexible rules or prescriptive codes of practice; engineering judgement remains the key factor.”*⁶²

Incidents and ‘emergency events’ during underground construction are often the failures of the systems devised and put in place to prevent such happenings. It follows that effort should be put into devising, implementing and continuously improving the overall management systems tailored to fit the specific circumstances of any particular underground project. No safety management system, by itself, can eliminate all risk of danger and harm, and some hazards and risks have to be effectively managed on a day-to-day basis by competent persons and organisations. This needs commitment and input from the workforce to the higher management levels of key organisations within the specific project structure.

In underground construction work there is always a level of ‘uncertainty’, but this does not mean that this ‘uncertainty’ need translate itself into danger. The three key parties that have the power to set standards and procedures are the client or owner; the designers, planners and specifiers; and the main and other contractors and their suppliers of plant, equipment and materials.

From the study of the data presented in this report, and from the consideration of other information, it may be seen that the following six factors have an influence on the quality of the overall safety management system required within an underground construction project-

- *Project management*
- *Organisational, procurement and contractual arrangements*
- *Engineering systems*

- *Health and safety systems*
- *The consideration of human factors, and*
- *Availability and use of 'Enforcement' action*

These factors are briefly described in the following paragraphs.

7.1 Project management

Each of the parties needs to project manage effectively his particular input to the development of an integrated safety management system – starting with the client and his initial outline considerations for his project. Often project management needs to begin with the gathering of information; the undertaking of research; the assembly of sufficient and appropriate expertise and the provision of adequate time and other resources before the brainstorming of scenarios and ideas for possible alternative further courses of action. Consideration of the whole-project risk spectrum from the beginning is appropriate and there are advantages to be gained from, for example, integrated management teams, early contractor involvement; early supplier involvement and early operator involvement. Inadequate project management or even mis-management of some or of the whole process is possible at any stage and by any of the key parties.

7.2 Organisational, procurement and contractual arrangements

Organisational, procurement and contractual arrangements such as between the client and his chosen design teams can be crucial to the quality and effectiveness of the overall safety management system. Project organisational systems also need to relate to those third parties who may be affected by the works. The internal contractual arrangements provide an opportunity to emphasise the importance of cooperation, coordination and communication in the effective identification and control of hazards and risks throughout the project by all parties and the responsibility of all parties to expend the necessary competence and resource to ensure 'best practice' approaches. There is no other field of civil engineering where the integration of design and construction is more important or necessary. Poorly drafted procurement and contractual arrangements can conflict with statutory obligations; impose unfair and unreasonable conditions; create ambiguity, misunderstanding and doubt; and cloud areas of responsibility from the very beginning.

7.3 Engineering systems

Much of both design and construction on underground projects relies on the choice and implementation of the engineering systems that are commonly applied to this type of construction work. This could range from the overall design, specification, layout and detailed design of the tunnel lining to the specification and manufacture of complex tunnel boring machines to work effectively in the tunnelling medium of the particular project. The inappropriate choice of, for example, computer analysis software; persons to fill key safety-critical engineering management positions; open or closed face tunnel boring machine; the wrong type of ground stabilising technique; the tunnel lining/surrounding ground monitoring system or the depth of the construction work within the ground in urban situations can compromise the effectiveness of the overall safety management system.

7.4 Health and safety systems

The provision and effective implementation of specific systems for the purposes of health and safety are essential. These range from the provision of specialist advice on health and safety and risk management to those working in both design offices and construction sites and to the provision of persons with special expertise on project expert advisory panels. The prompt, thorough and timely investigation of any accidents, incidents and “near misses”, together with the downloading of the information and conclusions obtained to all who need to know, is of the first importance. Also important is the auditing and review of the elements of the safety management systems with the objective of seeking ways of improvement. Health and safety standards never stand still, and there needs to be the flexibility within the system, coupled with appropriate leadership, to seek to apply higher health and safety standards where this is both practicable and appropriate whether or not required by law.

7.5 The consideration of human factors

In large projects it is almost inevitable that safety management systems will be complicated and diverse, but they will have to be implemented and managed by persons with a range of skills, experience and knowledge. Some persons will also be given the task of exercising judgements in both engineering and in other contexts – in other words aspects of the overall safety management system will be dependent on ‘human factors’. The question then arises, when and where might ‘human errors’ of one

kind or another be made, and, if so, what the possible consequences of these 'errors' might be. It is undoubtedly the case that some 'emergency events' have also been caused by persons intentionally violating work systems and procedures that have been correctly set out, and it is also the case that high level 'errors' can play a major part in creating the circumstances where others might make errors at the workplace. The potential for human failure, error or misjudgement is almost everywhere within the system, and as such merits careful consideration by all parties.

7.6 Availability and use of 'enforcement' action

Where shortcomings in the safety management system have been pinpointed, there needs to be a mechanism by which, if appropriate, effective corrective action can be taken. In some cases it may be necessary to stop the construction work so that the necessary remedial measures can be given priority. This power exists within the statutory enforcement body for health and safety, but should also exist within the contractual arrangements. The sanction of ultimately stopping further construction work on health and safety grounds could be retained by the client – if necessary on being properly advised about the proposed course of action. Alternatively, the client could retain an organisation with the appropriate competence, skills and knowledge to exercise the role of construction supervision on the client's behalf. Such a function would have a clearly defined health and safety monitoring role with a contractual ability to stop further construction work if this was appropriate in the circumstances.

Because of the diversity of underground project work there is no 'one standard system fits all' situation. The authors believe that the factors listed and described above, together with existing published information and guidance, provide a framework of approach that can lead to a satisfactory safety management system for any underground construction project in any location.

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APPENDICES

- A List of world tunnel projects 1999 to 2004.
- B. List of Internet sites used to research world tunnelling market.
- C List of NATM Emergency Events.
- D List of Non-NATM Emergency Events
- E. Glossary of terms.
- F. Authors' background.

Appendix A - List of world tunnel starts 1999-2004

COUNTRY	GNP per capita (\$)	1999		2000		2001		2002		2003		2004		Total	
		No of Tunnels	Length of tunnels (km)	No of Tunnels	Length of tunnels (km)	No of Tunnels	Length of tunnels (km)	No of Tunnels	Length of tunnels (km)	No of Tunnels	Length of tunnels (km)	No of Tunnels	Length of tunnels (km)	No of Tunnels	Length of tunnels (km)
Afghanistan	\$750													0	0.0
Albania	\$1 450											1	5.0	1	5.0
Algeria	\$1 720					1	5.2	1	2.4	9	30.6			11	38.2
Andorra	\$4 046							1	1.2	1	3.0			2	4.2
Argentina	\$4 220			3	26.5	2	16.3					3	24.4	8	67.2
Armenia	\$790							1	3.0					1	3.0
Australia	\$19 530	2	42.4	3	2.2	1	3.2	2	17.0	2	16.4	4	25.1	14	106.3
Austria	\$23 860							2	3.1	5	7.4	9	17.4	16	27.9
Bangladesh	\$380													0	0.0
Belgium	\$22 940	2	12.9	1	2.7	3	9.4	1	12.0	2	4.1	2	9.6	11	50.7
Bhutan	\$71													0	0.0
Bolivia	\$900					1	1.3							1	1.3
Bosnia & Herzegovina	\$1 310							1	0.8					1	0.8
Brazil	\$2 830	1	1.0	4	55.5	1	20.2	1	2.2	2	38.8			9	117.7
Bulgaria	\$1 770					2	11.4	3	18.2					5	29.6
Canada	\$22 390					3	11.4	3	21.9	1	9.4	1	19.0	8	61.7
Chile	\$4 250					2	3.8	3	14.3	2	6.6	2	9.2	9	34.0
China	\$960	7	85.9	16	84.1	17	223.8	115	120.0	8	71.8	7	64.4	170	650.1
Colombia	\$1 820									1	4.1	2	8.8	3	12.9
Costa Rica	\$4 070			12	61.0									12	61.0
Croatia	\$4 540			2	7.8			3	13.6			1	4.1	6	25.5
Cyprus	\$4 795													0	0.0
Czech Republic	\$5 480	1	1.2	3	7.5	2	5.3	14	16.0	4	20.2	5	9.4	29	59.6
Denmark	\$30 260			3	28.3					1	4.0			4	32.3
Dominican Republic	\$900					1	15.4							1	15.4
Ecuador	\$1 490			2	2.1	1	4.1	2	1.4	1	11.1			6	18.7
Egypt	\$1 470					2	5.0	2	16.5	1	4.3			5	25.8
El Salvador	\$2 410													0	0.0
Estonia	\$4 190											1	1.9	1	1.9
Ethiopia	\$100													0	0.0
Finland	\$23 890	1	0.5	1	0.5	1	0.7	1	3.0	2	21.0	13	37.2	19	62.8
France	\$22 240	1	9.5	7	22.7	5	9.7	8	20.1	14	29.4	18	88.2	53	179.6
Georgia	\$650													0	0.0
Germany	\$22 740	31	66.0	6	53.2	19	58.0	9	13.4	28	40.8	11	37.9	104	269.3
Greece	\$11 660	3	24.7	9	40.8	1	1.5	1	4.7	6	10.0	8	12.2	28	93.9
Hungary	\$5 290											1	7.3	1	7.3
Iceland	\$11 252			1	10.2			3	70.9	6	31.2	2	4.6	12	116.9
India	\$470	7	71.7	5	40.4	6	59.1	3	10.3	4	54.6	1	7.1	26	243.2
Indonesia	\$710			1	14.5					1	10.0			2	24.5
Iran	\$1 720	2	36.4			1	25.0	2	8.0	3	15.5	1	63.5	9	148.4
Iraq	\$900							1	6.0					1	6.0
Ireland	\$23 030	2	6.8	4	10.3	1	5.6	1	1.2	2	30.9	2	7.9	12	62.7
Israel	\$16 020	1	1.0	1	1.7	1	6.5	1	6.5	1	9.0	1	7.5	5	25.7
Italy	\$19 080	18	163.7	15	116.2	18	83.4	41	120.8	33	187.5	80	256.6	205	928.2
Japan	\$34 010	18	30.2	4	37.5	1	1.1	1	9.0	3	60.6			27	138.3
Jordan	\$1 760			1	1.0					1	1.2			2	2.2
Kazakhstan	\$1 520													0	0.0
Kenya	\$360					1	6.3							1	6.3
Kuwait	\$16 340													0	0.0
Kyrgyzstan	\$290													0	0.0
Laos	\$310	1	5.5											1	5.5
Latvia	\$3 480													0	0.0
Lebanon	\$3 990													0	0.0
Lesotho	\$550	1	0.2			1	5.6							2	5.8
Liechtenstein	\$23 500													0	0.0
Lithuania	\$3 670													0	0.0
Luxembourg	\$12 110			1	5.9			3	10.2			2	5.9	6	22.1
Macedonia	\$1 710													0	0.0
Malawi	\$160													0	0.0
Malaysia	\$3 540							2	5.0	1	45.0	4	19.2	7	69.2
Malta	\$3 090					1	6.0							1	6.0
Mexico	\$5 820	2	0.7					7	8.4			1	1.6	10	10.7
Monaco	\$16 527													0	0.0
Morocco	\$1 170	1	4.2											1	4.2
Nepal	\$230			5	38.3			1	27.0					6	65.3
Netherlands	\$23 390			5	26.3	8	42.1	1	0.7	1	5.0	3	12.0	18	86.1
New Zealand	\$13 260													0	0.0
Nigeria	\$300													0	0.0
Norway	\$38 790	8	35.8	1	2.6	49	51.3	20	94.2	19	47.3	24	53.2	121	284.5
Pakistan	\$470	2	19.9	2	30.5	2	30.0	1	1.4	6	11.6			13	93.4
Panama	\$4 020			2	2.4									2	2.4
Paraguay	\$1 170			1	3.0									1	3.0
Peru	\$2 020	1	7.5	3	28.3			1	25.0	1	14.0	1	2.6	7	77.4
Philippines	\$1 030			7	55.6	1	10.0	1	3.8			1	4.0	10	73.4
Poland	\$4 570			1	1.6	1	8.5	1	4.7	2	8.4	1	3.8	6	27.0
Portugal	\$10 720	23	36.5	13	22.6	15	49.7	5	22.0	39	35.1	21	36.1	116	202.1
Romania	\$1 870			3	16.4					1	1.4			4	17.8
Russia	\$2 430			4	17.5	2	22.1			2	4.0	1	1.9	9	45.5
Saudi Arabia	\$8 530													0	0.0
Singapore	\$20 690	4	44.4	4	33.9	11	93.2	2	8.8	3	17.0	3	26.7	27	224.0
Slovakia	\$3 970	5	31.7			2	15.1			1	2.9			8	49.6
Slovenia	\$10 370	6	68.6	4	4.0			4	6.3	3	9.0			17	87.9
South Africa	\$2 500							1	80.0					1	80.0
Spain	\$14 580	8	20.6	64	178.3	54	268.5	74	316.8	88	281.3	136	409.7	424	1475.2
Sri Lanka	\$860	1	7.0	1	5.0									2	12.0
Sweden	\$25 970	6	27.4	6	18.6	3	4.9	24	73.5	7	41.3	4	29.2	50	194.8
Switzerland	\$36 170	6	18.0	19	83.4	17	87.6	14	96.2	3	10.2	2	35.1	61	330.5
Syria	\$1 130			1	4.1									1	4.1
Taiwan	\$1 597			5	73.1	9	58.6	1	4.8					15	136.5
Thailand	\$2 000	11	83.7	2	31.0			1	65.0	1	5.3	1	8.7	16	193.7
Tunisia	\$1 990													0	0.0
Turkey	\$2 490	3	10.0	3	31.4	11	31.5	3	32.3	6	23.0	2	3.8	28	132.1
Turkmenistan	\$900							2	15.0					2	15.0
Ukraine	\$780					1	8.8							1	8.8
United Arab Emirates	\$10 000					1	1.2			1	1.5			2	2.7
United Kingdom	\$25 510	10	31.5	8	40.9	4	61.8	3	4.0	8	12.2	8	35.8	41	186.2
United States	\$35 400	24	161.0	21	97.0	25	188.1	21	149.7	5	9.1	9	41.5	105	646.5
Uruguay	\$4 340							4	25.3					4	25.3
Venezuela	\$4 080			10	37.1	9	6.8							19	43.9
Vietnam	\$430					3	9.7	3	8.6			2	2.0	8	20.2
Yemen	\$490					1	1.9							1	1.9
Yugoslavia	\$3 250					1	7.8							0	0.0
Zambia	\$340					1	7.8							1	7.8
Zimbabwe	\$310					1	4.3							1	4.3
Total		220	1168	300	1515	327	1668	426	1620	342	1318	402	1461	2017	8750

Appendix B

List of internet sites used to research world tunnelling market

www.miningandconstruction.com

www.fhwa.dot.gov/bridge/tunnel/index.htm - This website aims to produce data base of projects in the US.

www.tchas.c3/en/ps_sberaco3.htm

www.insituform.com/coperate/cer_affholder.html#

<http://www.ita-aites.org/cms/329.html> - Cairo metro line information

www.aftes.asso.fr/revues_tos/2004/18/res.htm – Biarritz sewer

www.nationmaster.com/encyclopedia/list-of-cities-in-france

www.rinbad.demon.co.uk/opening.htm - list of all opening metro lines

www.alpine.at/content/node2/alpine/de/nl/utb/tusptb/tu/2818.html - tunnel construction information

www.unece.org/trans/doc/2002/ac9/TRANS-AC9-1-info07e.doc - list of tunnels in different countries

<http://home.no.net/lotsberg/data>

www.showcaves.com/english/de/geology.html

www.roadtraffic_technology.com/project/egnatia/ - EGNATIA ODOS

<http://tunnelling.metal.ritua.gr/GTS/projects/egnatia.htm> - 49km tunnel; 4.5% cut & cover; half hard, half soft rock; 74 tunnels; NATM

www.mjconstruct.com/tunnel/archive/2003/jun/nordie%20tun%20%hard%20rock.pdf

www.mjconstruct.com/tunnel/archive/2003/sep/panorama.pdf-india

www.auaonline.org – American Underground Association

www.britishtunnelling.org – British tunnelling society;

<http://home.no.net/lotsberg> - the worlds longest tunnel page

www.tunnel.no – Norwegian rock technology

www.ita-aites.org/cms/357.html - Norway -references to Norway storing statistical data since 1971 – 1998 best year; Germany – Printout; US \$700-800 million dollars

www.library.tudelf.nl/dckc/keep-current - Delft Cluster Tunnelling – knowledge centre

www.geoscience.org.za/sancot/publ.htm# - South African Tunnel Database purchasable through SANCOT

www.cnplus.co.uk – construction news – pay only

www.tunnelcanada.ca

www.auca.org

www.naslt.org

*Searched German and Norwegian search engines

www.ita-aitet.org – international tunnelling association

www.britishtunnelling.org – British tunnelling society; newsletters –N/A; working groups

www.tunnelbuilder.com – comprehensive list

Geological Research

<http://geologyabout.com/library/bl/maps/blecudermap.htm> - geological maps

<http://encarta.msn.com/encart/features/mapcentre/map.aspx> - maps

www.worldatlas.com/atlas/world.htm - geological maps

GDP Research

www.worldbank.org/data/udi2004/table

www.nationmaster.com/country/an/economy

Appendix C - List of NATM Emergency Events

Research No	HSE Report No	Date	Location	Remarks	Reported Cause	Reference	Project	Environment	Ground	Third Party Consequences	With reported cause	A type Cause	A type Cause USG
NATM/1	HSE/1	Oct-73	Near Paris	Collapse	A6 and A8	Muller 1978	Rail	?	Soft		1	1	
NATM/2		1975?	Massenberg,Austria	Crown lining failure	A7	Muller,T & T 1990			Rock		1	1	
NATM/3	HSE/2	18-Dec-81	Sao Paulo	Local Instability	A1	Kochen, 1987	Metro	Urban	Soft	Building Demolition	1	1	1
NATM/4	HSE/3	1983	Santana, Brazil	Cave-in		Private	Rail	Urban	?	6 houses demolished			
NATM/5		16/11/1983	Germany	Lining instability		Xudong Cui, 1991	Rail						
NATM/6		21/06/1984	Germany	Crater		Xudong Cui, 1991	Rail						
NATM/7	HSE/4	13-Nov-84	Landrucken, Germany	Collapse	A8, A10	Nussbergen,1987 Wogin,1987	Rail	Rural	?		1	1	
NATM/8		14/11/1984	Germany			Xudong Cui, 1991	Rail						
NATM/9	HSE/5	1984	Bochum, Germany	Collapse	B1, A7, A9	Sager 1987	Metro	Urban	Soft	Urban disruption	1	1	1
NATM/10	HSE/6	17-Jan-85	Richthof,Germany	Collapse	A1	Engels, 1987	Rail	Rural	Rock		1	1	
NATM/11	HSE/7	1985	Bochum, Germany	Collapse	A1	Laue, 1987	Metro	Urban	Soft?	Urban disruption	1	1	1
NATM/12	HSE/8	Aug-85	Kaiserau, Germany	Collapse	A4, A5	Wallis, 1988, 1990	Rail	Rural			1	1	
NATM/13	HSE/9	07/02/1986	Kreiberg, Germany	Collapses & Crater	A3, A10	Wallis, 1987	Rail	Rural	Soft	Surface damage	1	1	
NATM/14-18		1985-86	Hanover -Wurzburg	Collapses & Craters		T & T Summer 1990	Rail		Rock				
NATM/19	HSE/10	Pre-1987	Munich, Germany	Collapse	C2	Weber, 1987	Metro	Urban	Soft	Urban disruption	1		
NATM/20	HSE/11	Pre-1987	Munich, Germany	Collapse	A1, A12	Weber, 1987	Metro	Urban	Soft	Urban disruption	1	1	1
NATM/21	HSE/12	Pre-1987	Munich, Germany	Collapse	A1	Weber, 1987	Metro	Urban	Soft	Urban disruption	1	1	1
NATM/22	HSE/13	Pre-1987	Munich, Germany	Collapse	A1, A12	Weber, 1987	Metro	Urban	Soft	Urban disruption	1	1	1
NATM/23	HSE/14	Pre-1987	Munich, Germany	Collapse	A1, A12	Weber, 1987	Metro	Urban	Soft	Urban disruption	1	1	1
NATM/24	HSE/15	Pre-1987	Munich, Germany	Blow out	A1	Weber, 1987	Metro	Urban	Soft		1	1	1
NATM/25	HSE/16	Pre-1987	Weltkugel, Germany	Cave in	A3	Schrewe, 1987	Rail		Soft		1	1	
NATM/26	HSE/17	1987	Karawankan, Austria	Large deformations		Martin, 1991	Road	Rural	Hard				
NATM/27	HSE/18	Pre-1988	Kehrenberg,Germany	Large settlements Tunnel props installed	(A3)	Wallis, 1988	Rail		Soft		1	1	
NATM/28	HSE/19	1988	Michaels, Germany	Tunnel collapse	(A10)	Private			Soft?		1	1	
NATM/29	HSE/20	08/01/1989	Karawankan, Austria	Collapse	A1, A11	Maidl, 1993	Road	Rural	Rock		1	1	
NATM/30		1990	Channel Tunnel Crossov	Crown failure	B2	ICE Proc. Jan 93.	Rail	Undersea	Soft		1		
NATM/31	HSE/21	27-Sep-91	Kwachon, Korea	Collapse & crater		Newspaper articles	Metro	Rural	Soft				
NATM/32	HSE/22	17-Nov-91	Seoul, Korea	Collapse & Crater	A1	Park & Lee, 1993	Metro	Urban	Soft	Fractured gas main	1	1	1
NATM/33	HSE/23	27-Nov-91	Seoul, Korea	Collapse & Crater	A1	Park & Lee, 1993	Metro	Urban	Rock	Urban disruption	1	1	
NATM/34		Nov-91	Sao Paulo	Collapse & Flood		Press reports	Road	Urban	Soft				
NATM/35		"1991"	S.Vitale, Italy	Large deformation		Lunardi, Tunnel 8/98	Rail	Rural	Soft				
NATM/36	HSE/24	1992	Funagata, Japan	Collapse	(C1)	Private	Road	Rural?	Soft		1		
NATM/37	HSE/25	12-Feb-92	Seoul Metro	Collapse	A2	Park & Lee, 1993	Metro	Urban	Soft	Utilities broken. Traffic Problem	1	1	1
NATM/38	HSE/26	30-Jun-92	Lambach, Austria	Collapse & Crater	A5	Vavrosky, 1995	Rail				1	1	
NATM/39	HSE/27	07-Jan-93	Seoul, Korea	Collapse & crater	A1	Park & Lee, 1993	Metro	Urban	Soft	Road disruption	1	1	1
NATM/40	HSE/28	02-Feb-93	Seoul, Korea	Collapse & crater	A1	Park & Lee, 1993	Metro	Urban	Soft		1	1	1
NATM/41	HSE/29	Feb/March 93	Seoul, Korea	Collapse & crater	A3	Park & Lee, 1993	Metro	Urban	Soft		1	1	1
NATM/42	HSE/30	Feb/March 93	Seoul, Korea	Collapse & crater	A3	Park & Lee, 1993	Metro	Urban	Soft		1	1	1
NATM/43	HSE/31	Mar-93	Chungho, Taiwan	Collapse	A1	Private	Road	Rural			1	1	
NATM/44	HSE/32	Nov-93	Sao Paulo,Brazil;	Collapse & Sink hole	A1,A3,A7	Private	Metro	Urban	Soft	Massive disruption	1	1	1
NATM/45	HSE/33	1993	Tuscany,Italy	Severe deformations	A3	Pelizza,1994	Road	Rural?	Rock		1	1	
NATM/46	HSE/34	Apr-94	Cardvalho Pinto,Brazil	Remedial repairs	C1	Private	Road			Traffic disruption	1		
NATM/47	HSE/35	30-Jul-94	Montemor,Portugal	Collapse & crater	(A3)	Wallis.1995	Road	Urban	Soft		1	1	1
NATM/48	HSE/36	01-Aug-94	Montemor,Portugal	Collapse & crater	(A1)	Wallis.1995	Road	Urban	Soft		1	1	1
NATM/49	HSE/37	Aug-94	Galgenberg,Austria	Collapse	A1	Schubert, 1995				One Fatality	1	1	
NATM/50	HSE/38	20-Sep-94	Munich,Germany	Collapse & Crater	A1	Tiefbau 4/95	Metro	Urban	Soft	4 Fatalities,27 Injured	1	1	1
NATM/51	HSE/39	21-Oct-94	Heathrow Airport	Collapse & craters	A1,A3, A12	HSE ,2000	Rail	Urban	Soft		1	1	1
NATM/52		Mid 1995	Kiziac,Turkey	Collapse(s)		Clay, Tunnelling 97	Road	Rural	Soft				
NATM/53		Dec. 1995.	Vasto, Italy	Face collapse	A1	Lunardi, Tunnel 8/98		Rural	Soft		1	1	
NATM/54		18/06/1996	Eidsvoll,Norway	Collapse		Beitnes, 1996	Rail						
NATM/55		"1997"	Bolu, Turkey	Partial collapse	A1	Mentki,Mair&Miles Underground Construction 2001	Road	Rural	Soft		1	1	
NATM/56		11/03/1999	Edge, Germany	Crown collapse		Arnold & Fugenschuh	Rail	Rural	Rock				
NATM/57		02/11/2000	Dulles Airport,USA	Collapse	Not known	T & T Dec-2000	Walkway	Urban	Soft				
NATM/58		11/08/2001	Herzogberg,Austria	Collapse	A1	T & TI, Jan 2003	Road	Rural	Rock		1	1	
NATM/59		Late 2001?	Herzogberg,Austria	Roof collapse	A1	T & TI, Jan 2003	Road	Rural	Rock		1	1	
NATM/60		19/09/2001	Istanbul,Turkey	Collapse & Crater	A1	WT Dec 01	Metro	Urban	Soft	5 Fatalities	1	1	1
NATM/61		01/02/2002	Chienberg,CH	Collapse & Crater		Internet		Rural	Rock?				
NATM/62		Aug. 2002	Hukou, Taiwan	Face collapse		T & T I Feb. 2003	Rail		Soft				
NATM/63		31/10/2002	Hukou, Taiwan	Face and lining collapse		T & T I Feb. 2003	Rail		Soft				
NATM/64		07/01/2003	Athens	Collapse	B2	Private	Metro	Urban	Soft		1		
NATM/65		Feb-05	Barcelona	Collapse		Press articles	Rail	Urban	Rock	Massive disruption			
NATM/66		Feb-05	Lausanne	Collapse & Crater		Press articles	Rail	Urban	Soft	Massive disruption			
											44	39	20

Total Number of incidents with a reported cause
Number with an A type cause

44
39

Total number of urban soft ground incidents with a reported cause
No with an A type cause

22
20

Appendix D - List of non-NATM Emergency Events

No.	Date	Location	Remarks	Crater	Face Collapse	Behind Pile	Method	Revised Cause	Reference	Project	Environment	Ground	Third Party Considerations	Cause Category	Unsafe Gain	URG Data
GEN0			Face collapse(s)				Shield				Underslab?	Soft				
GEN1	1920	Thames Tunnel	Surface crater	1				Ground Condition change	ENR 02 July 1970	Rail	Urban?	Soft				
GEN2	Jul-70	New York	Surface crater					Excess air pressure	ENR 21-Oct 1971	Water	Urban?	Soft				
GEN3	1970	Rome	Collapse					Over excavation	ENR 21-Oct 1971	Metro	Urban?	Soft				
GEN4	Oct-71	Rome	Surface Crater	1			Head Mixed	Unexcavated void	Private	Metro	Urban	Soft	Building damage	Ground Conditions	1	
GEN5	ME 770's	Larve, East Sussex	Excessive settlement				Head	Rock loosening	Private	Road	Urban	Soft	Building damage	Ground Conditions	1	
GEN6	1986-88	Saltash	Crater	1			Head mixed	Unexcavated void	Private	Road	Urban	Soft	2 Failures	Ground Conditions	1	
GEN7	1975-1979	DISPOSALS	Rockfall				Head mixed	Ground conditions	T & T June-1988	Rail	Rural	Rock	Failures	Ground Conditions	1	
GEN8	Dec-83	Hong Kong	Void under road				Shield	Water eruption	T&T April 1984	Hydro	Urban	Soft?	Failures	Ground Conditions	1	
GEN9	"1984"	S. Stefano, Italy	Collapse of face & 30m.	1			Head	Ground conditions	Lunardi, Tunnel 898	Rail	Urban	Soft		Ground Conditions	1	
GEN10	"1985"	S. Elio, Italy	Collapse of face & 20m.	1			Head	Water pressure	Lunardi, Tunnel 898	Road	Rural	Rock		Ground Conditions	1	
GEN11	"1988"	Trase, Italy	Collapse of face & 40m.	1			Head	Ground conditions	Lunardi, Tunnel 898	Rail	Rural	Soft		Ground Conditions	1	
GEN12	Nov-88	Milwaukee					Head	2 Methane Explosions	Trevall, 1988	Water	Rural	Soft		Ground Conditions	1	
GEN13	1989	Paris	Lining collapse	1			TBM	Lack of face to excavation	T & T June-1988	Sewer	Urban?	Soft		Ground Conditions	1	
GEN14	300X1900	Stammatuzenza	Lining collapse	1			Head	Shore failure in ground	T & T July 90	Water	Rural	Soft/rock		Ground Conditions	1	
GEN15	1990	Toledo	Crater	1			Head	Excess air pressure	T & T March/May 1990	Rail	Urban	Soft		Air Explosion	1	
GEN16	Jul-90	Los Angeles	Lining damage				Shield	Fire	Wallis, 1995	Metro	Urban	Soft		Fire	1	
GEN17	1990	Los Angeles	Collapse				TBM	Over excavation	ENR 15-19-90	Rail	Altoost	Soft		Workmanship	1	
GEN18	14/07/1991	Denmark	Flooding of tunnel	1			TBM	Bulldozed door left open	Wallis, 1993	Rail	Underslab	Soft		Flood	1	
GEN19	Jun-92	Grainholz, CH	Surface crater	1			TBM	Water charged soil trough	Wallis, 1993	Rail	Rural	Soft		Ground Conditions	1	
GEN20	1992 et seq	Prodlin, Taiwan	Ground collapses, 10 floods	1			TBM	Squeezing ground	T&T, May 2002, April 2004, April 2005	Road	Rural	Hard		Ground Conditions	1	
GEN21	1993	Grainholz, CH	Collapse above cutting	1			TBM	Lack of adequate face support	T & T Sep-93, and 10/11/93	Rail	Rural	Soft		Ground Conditions	1	
GEN22	1993	S. Rudolfo, Italy	Collapse of face	1			Head	Ground conditions	Lunardi, Tunnel 898	Road	Rural	Soft		Ground Conditions	1	
GEN23	11/02/1994	Denmark	Lining damage				TBM	Fire	Tal & Hodge, 1996	Rail	Underslab	Soft		Fire	1	
GEN24	1994	Los Angeles	Excessive settlement	1			Shield	Poor workmanship	Wallis, 1995	Metro	Urban	Soft	Urban disturbance	Workmanship	1	
GEN25	1994-1997	Athens	Surface Craters	1			TBM	Unsettling ahead of TBM	Lunco, 1999	Metro	Urban	Soft/rock	Urban disturbance	Ground Conditions	1	
GEN26	2004/1995	Taeon, Korea	Underground exhalation	1			TBM	Gas leak under temporary deck	Flaminio, 1995	Metro	Urban	Soft?	Multiple fatalities	Gas Explosion	1	
GEN27	2006/1995	Los Angeles	Surface Crater	1			Head	Unstable remedial works	Wallis, 1995	Metro	Urban	Soft	Urban disturbance	Temporary Works	1	
GEN28	17/02/1995	Thess	Collapse				Head	"major defect"	Internet	Hydro	Rural	Soft			1	
GEN29	18/07/1996	Toulon, France	Lining failure	1			Pierforex	Compressed air explosion	Constantin, 1996	Road?	Urban	Soft?		Air Explosion	1	
GEN30	23/02/1998	BLR, London	Surface Crater	1			Head	Stagnant sands	M Jones, 1998	Metro	Urban	Soft	Buildings demolished	Ground Conditions	1	
GEN31	14/02/1998	Moscow	Surface Crater	1			TBM	Compressed air leaks	Kerzhakov, 1998	Sewer	Urban	Soft		Ground Conditions	1	
GEN32	16/03/1999	Reims, France	Lining failure	1			TBM	Compressed air leaks	Kerzhakov, 1999	Metro	Urban	Soft		Ground Conditions	1	
GEN33	16/02/2000	Italy	Lining failure	1			TBM	Soil leak	Mosca, 2002	Water	Urban	Soft		Ground Conditions	1	
GEN34	2002/2000	Portsmouth	Lining failure	1			TBM	Soil leak	BTS 2003	Water	Rural	Soft		Ground Conditions	1	
GEN35	01/02/2000	London Blue Line	Excessive settlement	1			TBM	Soil and water ingress	tunnelbuilder.com	Metro	Urban	Soft		Ground Conditions	1	
GEN36	Dec 2000	Osoto	Surface crater	1			TBM	Mixed face conditions	T&T Nov & Dec 2002	Metro	Urban	Soft/rock	House collapse, Fatality	Ground Conditions	1	
GEN37	05/02/2002	Paris	Lining damage	1			TBM	Fire	T & T April 2002	Road	Urban	Soft		Fire	1	
GEN38	Feb-00	CTRL, London	Surface Crater	1			TBM	Unknown	Allison 2000	Rail	Urban	Soft	Urban disturbance	Unknown	1	
GEN39	Apr-03	Detroit, USA	Flood	1			TBM	Insufficient pump capacity	T & T Dec 2003	Outfall	Urban	Soft	Buildings demolished	Temporary works	1	
GEN40	Jul-03	Shanghai	Collapse & Crater	1			Head	Ground reaction inadequate	ITA, 2004	Metro	Urban	Soft	Buildings demolished	Ground Conditions	1	
GEN41	Aug-04	Cher, Dam India	Collapse				Head	Floods	Internet	Hydro	Rural	Soft	Buildings demolished	Ground Conditions	1	
GEN42	May-04	Adamsung, Taiwan	Crack-ins (4 No)	1			TBM	Geological problems	T & T, august 04	Metro	Urban	Soft	Buildings demolished	Ground Conditions	1	
TOTAL				33	6	8								TOTALS	33	19

Soft ground Urban

32

CAUSES

19

20
10
2
2
1
1
2
2
1
1
0

Soft ground, Urban
Primary Cause
Unexpected Ground Conditions/lack of data
Air Explosion
Gas Explosion
Workmanship
Temporary Works
Flood
Unknown

19
10
2
2
1
1
2
2
1
1
0

19
10
2
2
1
1
2
2
1
1
0

Appendix E

Glossary of terms

ABI	Association of British Insurers.
BTS	British Tunnelling Society.
CIRIA	Construction Industry Research and Information Association
HSE	Health and Safety Executive
ITA	International Tunnelling Association
NATM	The New Austrian Tunnelling Method
SCL	Sprayed Concrete Linings
TBM	Tunnel Boring Machine

Appendix F

Authors' background

Guy Lance graduated in civil engineering from King's College, London University and is currently a Technical Director at Atkins Tunnelling. He has over 30 years' experience in tunnel design and in the management of major transportation projects in both the UK and overseas. These projects include Jubilee Line, Singapore MRT, Channel Tunnel, Channel Tunnel Rail Link and London Underground PPP. He acted as technical advisor to HSE during the investigations following the Heathrow Express collapse.

John Anderson graduated in civil engineering from Glasgow University. After work in industry he joined the Health and Safety Executive as a Specialist Inspector. For over 10 years of his 26 years service in the HSE he specialised in underground construction occupational health and safety issues. He has contributed to the meetings and the on-going work of the ITA "Health and Safety in Works" Working Group since 1989, and has written international papers on tunnelling health and safety matters since 1991. He left the service of the HSE in 1997 and works as an independent consultant.



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