

Code of practice for safety in tunnelling in the construction industry

ICS 93.060

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by Technical Committee B/513, Construction equipment and plant, and site safety, to Subcommittee B/513/2, Drilling, piling and tunnelling, upon which the following bodies were represented.

- Association of British Mining Equipment Companies
- British Compressed Air Society
- Construction Health and Safety Group
- British Drilling Association
- British Tunnelling Society
- Chief and Assistant Chief Fire Officers Association
- Civil Engineering Contractors' Association
- Federation of Manufacturers of Construction Equipment and Cranes
- Federation of Piling Specialists
- Health and Safety Executive
- Institute of Sound and Vibration Research
- Institution of Civil Engineers
- Institution of Mining and Metallurgy
- Pipe Jacking Association

This British Standard, having been prepared under the direction of the Sector Policy and Strategy Committee for Building and Civil Engineering, was published under the authority of the Standards Policy and Strategy Committee on 7 December 2001

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First published August 1982
Second edition April 1990
Third edition December 2001

The following BSI references relate to the work on this British Standard
Committee reference B/513/2
Draft for comment 99/102109 DC

ISBN 0 580 38457 8

Amendments issued since publication

Amd. No.	Date	Comments

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Foreword

This British Standard has been prepared by Subcommittee B/513/2, Drilling, piling and tunnelling, under the direction of Technical Committee B/513, Construction equipment and plant, and site safety. It supersedes BS 6164:1990, which is withdrawn.

This revision of BS 6164:1990 takes into account the advances in technology and equipment that are available to the tunnelling industry. It also takes account of new techniques and the effect of new legislation, particularly health and safety and environmental legislation, including The Construction (Design and Management) Regulations 1994 [1], The Construction (Health, Safety and Welfare) Regulations 1996 [2] and The Work in Compressed Air Regulations 1996 [3]. The document is written for all involved in tunnelling projects and addresses the safety of both those engaged in the tunnelling process and those who could be affected by it.

The text follows the pattern established by the previous edition of BS 6164. Clauses contain recommendations for and guidance on health and safety practices in shaft sinking and tunnelling. However, the text has been significantly updated to reflect current and developing best practices.

The International System of Units (SI) (see BS 5555) is followed in this British Standard, with the exception of the unit used for pressure, which is the bar.

NOTE 1 1 bar = $10^5 \text{ N/m}^2 = 10^5 \text{ Pa}$.

It has been assumed in the preparation of this British Standard that the execution of its provisions will be entrusted to appropriately qualified and competent people, for whose use it has been produced.

As a code of practice, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification and particular care should be taken to ensure that claims of compliance are not misleading.

NOTE 2 The word “should” is used to express recommendations of this standard. The word “may” is used in the text to express permissibility, e.g. as an alternative to the primary recommendation of the clause. The word “can” is used to express possibility, e.g. a consequence of an action or an event.

Annex A is informative.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 123 and a back cover.

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1 Scope

This British Standard makes recommendations for and gives guidance on health and safety practices in shaft sinking and tunnelling. Guidance on health and safety in the maintenance, renovation and repair of shafts and tunnels is also included.

The standard includes health and safety recommendations that are also relevant to cut-and-cover tunnelling and immersed tube tunnels. The recommendations are not specifically intended to apply to the construction of shafts or tunnels for the purpose of winning minerals.

NOTE 1 The design, manufacture and use of plant and machinery are referred to only where safety considerations are affected. Various European Standards relating to the design of tunnel boring machines (TBMs) are currently in preparation.

NOTE 2 A list of current legislation relating to tunnel construction is given in Annex A.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this British Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the latest edition of the publication referred to applies.

BS 171, *Specification for power transformers*.

BS 449-2, *Specification for the use of structural steel in building — Part 2: Metric units*.

BS 476-4, *Fire tests on building materials and structures — Part 4: Non-combustibility test for materials*.

BS 476-20, *Fire tests on building materials and structures — Part 20: Method for determination of the fire resistance of elements of construction (general principles)*.

BS 476-21, *Fire tests on building materials and structures — Part 21: Methods for determination of the fire resistance of loadbearing elements of construction*.

BS 476-22, *Fire tests on building materials and structures — Part 22: Methods for determination of the fire resistance of non-loadbearing elements of construction*.

BS 638-4, *Arc welding power sources, equipment and accessories — Part 4: Specification for welding cables*.

BS 638-5, *Arc welding power sources, equipment and accessories — Part 5: Specification for accessories*.

BS 638-7, *Arc welding power sources, equipment and accessories — Part 7: Specification for safety requirements for installation and use*.

BS 1129, *Specification for portable timber ladders, steps, trestles and lightweight stagings*.

BS 4275, *Guide to implementing an effective respiratory protective device programme*.

BS 4293, *Specification for residual current-operated circuit-breakers*.

BS 4363, *Specification for distribution assemblies for reduced low voltage electricity supplies for construction and building sites*.

BS 4592-1, *Industrial type flooring, walkways and stair treads — Part 1: Specification for open bar gratings*.

BS 4592-2, *Industrial type flooring, walkways and stair treads — Part 2: Specification for expanded metal grating panels*.

BS 4592-3, *Industrial type flooring, walkways and stair treads — Part 3: Specification for cold formed planks*.

BS 4592-5, *Industrial type flooring, walkways and stair treads — Part 5: Specification for solid plates in steel, aluminium and glass reinforced plastics*.

BS 4727-1:Group 01:1983, *Glossary of electrotechnical, power, telecommunication, electronics, lighting and colour terms — Part 1: Terms common to power, telecommunications and electronics — Group 01: Fundamental terminology*.

BS 5045 (all parts), *Transportable gas containers*.

BS 5306-1, *Fire extinguishing installations and equipment on premises — Part 1: Hydrant systems, hose reels and foam inlets*.

BS 5306-3, *Fire extinguishing installations and equipment on premises — Part 3: Maintenance of portable fire extinguishers — Code of practice.*

BS 5306-8, *Fire extinguishing installations and equipment on premises — Part 8: Selection and installation of portable fire extinguishers — Code of practice.*

BS 5328 (all parts), *Concrete.*

BS 5395-3, *Stairs, ladders and walkways — Part 3: Code of practice for the design of industrial type stairs, permanent ladders and walkways.*

BS 5607, *Code of practice for the safe use of explosives in the construction industry.*

BS 5911-120, *Precast concrete pipes, fittings and ancillary products — Part 120: Specification for reinforced jacking pipes with flexible joints.*

BS 5930, *Code of practice for site investigations.*

BS 5950 (all parts), *Structural use of steelwork in building.*

BS 6100-2.2.3:1990, *Glossary of building and civil engineering terms — Part 2: Civil engineering — Section 2.2: Substructures — Earthworks — Foundations — Tunnels — Subsection 2.2.3: Tunnels.*

BS 6387:1994, *Specification for performance requirements for cables required to maintain circuit integrity under fire conditions.*

BS 6657, *Guide to prevention of inadvertent initiation of electro-explosive devices by radio-frequency radiation.*

BS 6708:1998, *Flexible cables for use at mines and quarries.*

BS 6724, *Specification for 600/1 000 V and 1 900/3 300 V armoured electric cables having thermosetting insulation and low emission of smoke and corrosive gases when affected by fire.*

BS 7121-1, *Code of practice for safe use of cranes — Part 1: General.*

BS 7375, *Code of practice for distribution of electricity on construction and building sites.*

BS 7430, *Code of practice for earthing.*

BS 7671:2001, *Requirements for electrical installations — IEE Wiring Regulations — Sixteenth edition.*

BS 7704, *Specifications for silicone liquids for electrical purposes.*

BS 7835, *Specification for armoured cables with extruded cross-linked polyethylene or ethylene propylene rubber insulation for rated voltages from 3.8/6.6 kV up to 19/33 kV having low emission of smoke and corrosive gases when affected by fire.*

BS 7863, *Recommendations for colour coding to indicate the extinguishing media contained in portable fire extinguishers.*

BS EN 3-1 (all parts), *Portable fire extinguishers.*

BS EN 344-1, *Safety, protective and occupational footwear for professional use — Part 1: Requirements and test methods.*

BS EN 344-2, *Safety, protective and occupational footwear for professional use — Part 2: Additional requirements and test methods.*

BS EN 345-1, *Safety footwear for professional use — Part 1: Specification.*

BS EN 345-2, *Safety footwear for professional use — Part 2: Additional specifications.*

BS EN 397, *Specification for industrial safety helmets.*

BS EN 418, *Safety of machinery — Emergency stop equipment, functional aspects — Principles for design.*

BS EN 457, *Safety of machinery — Auditory danger signals — General requirements, design and testing.*

BS EN 471, *Specification for high-visibility warning clothing.*

BS EN 559, *Gas welding equipment — Rubber hoses for welding, cutting and allied processes.*

BS EN 730, *Gas welding equipment — Equipment used in gas welding, cutting and allied processes, safety devices for fuel gases and oxygen or compressed air — General specifications, requirements and tests.*

BS EN 791, *Drill rigs — Safety.*

- BS EN 815, *Safety of unshielded tunnel boring machines and rodless shaft boring machines for rock.*
- BS EN 996, *Piling equipment — Safety requirements.*
- BS EN 1679-1, *Reciprocating internal combustion engines — Safety — Part 1: Compression ignition engines.*
- BS EN 1800, *Transportable gas cylinders — Acetylene cylinders — Basic requirements and definitions.*
- BS EN 12862:2000, *Transportable gas cylinders — Specification for the design and construction of refillable transportable welded aluminium alloy gas cylinders.*
- BS EN 50014, *Electrical apparatus for potentially explosive atmospheres — General requirements.*
- BS EN 50018, *Electrical apparatus for potentially explosive atmospheres — Flameproof enclosures “d”.*
- BS EN 50019, *Electrical apparatus for potentially explosive atmospheres — Increased safety “e”.*
- BS EN 50020, *Electrical apparatus for potentially explosive atmospheres — Intrinsic safety “i”.*
- BS EN 50054, *Electrical apparatus for the detection and measurement of combustible gases — General requirements and test methods.*
- BS EN 50055, *Electrical apparatus for the detection and measurement of combustible gases — Performance requirements for Group I apparatus indicating up to 5 % (V/V) methane in air.*
- BS EN 50056, *Electrical apparatus for the detection and measurement of combustible gases — Performance requirements for Group I apparatus indicating up to 100 % (V/V) methane in air.*
- BS EN 50057, *Electrical apparatus for the detection and measurement of combustible gases — Performance requirements for Group II apparatus indicating up to 100 % lower explosive limit.*
- BS EN 50104, *Electrical apparatus for the detection and measurement of oxygen — Performance requirements and test methods.*
- BS EN 50266 (all parts), *Common test methods for cables under fire conditions — Test for vertical flame spread of vertically-mounted bunched wires or cables.*
- BS EN 50281-1-1, *Electrical apparatus for use in the presence of combustible dust — Electrical apparatus protected by enclosures — Part 1-1: Construction and testing.*
- BS EN 50281-1-2, *Electrical apparatus for use in the presence of combustible dust — Electrical apparatus protected by enclosures — Part 1-2: Selection, installation and maintenance.*
- BS EN 60034-5, *Rotating electrical machines — Part 5: Degrees of protection provided by the integral design of rotating electrical machines (IP code) — Classification.*
- BS EN 60076-1, *Power transformers — Part 1: General.*
- BS EN 60079-14:1997, *Electrical apparatus for explosive gas atmospheres — Part 14: Electrical installations in hazardous areas (other than mines).*
- BS EN 60204-1, *Safety of machinery — Electrical equipment of machines — Part 1: General requirements.*
- BS EN 60309-1, *Plugs, socket-outlets and couplers for industrial purposes — Part 1: General requirements.*
- BS EN 60529:1992, *Specification for degrees of protection provided by enclosures (IP code).*
- BS EN 61008-1, *Specification for residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCBs) — Part 1: General rules.*
- BS EN 61008-2-1, *Specification for residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCBs) — Part 2-1: Applicability of the general rules to RCCBs functionally independent of line voltage.*
- BS EN 61099, *Specification for unused synthetic organic esters for electrical purposes.*
- BS EN ISO 2503, *Gas welding equipment — Pressure regulators for gas cylinders used in welding, cutting and allied processes up to 300 bar.*
- BS EN ISO 5172, *Manual blowpipes for welding, cutting and heating — Specification and tests.*
- CP 3010, *Code of practice for safe use of cranes (mobile cranes, tower cranes and derrick cranes).*

3 Terms and definitions

For the purposes of this British Standard, the definitions given in BS 6100-2.2.3:1990 apply, together with those for electrotechnical and related terms given in BS 4727-1:Group 01:1983.

4 The control of risk

4.1 From hazard identification to safe systems of work

4.1.1 General

The achievement of good health and safety performance on site, and the avoidance of any “adverse events”, such as accidents, cases of ill health, incidents and losses, arises from the effective identification and control of risks. Identifying risks, and determining the level of risk and how it is to be controlled, is not a one-off exercise undertaken by the contractor. It is a continuous process that starts at the planning and design stages and continues through to the conclusion of the construction stage of the project.

Risks arise from hazards. Hazards are things that have the potential for harm (such as unstable ground, water, noise, dust, moving machinery and electricity). The risk associated with any one hazard is an expression of whether that hazard is likely to occur, the frequency at which it could occur, and the consequences if it did occur. Some hazards (such as working at height) are encountered in everyday working, and precautions against the risk of falling are well understood and easily implemented. Some tunnelling risks occur infrequently (such as substantial ground collapses, or underground fires), but their consequences for the work force and others can be very severe.

A structured approach includes the following stages.

- a) **Hazard identification.** A careful identification of the possible hazards that are likely to be encountered during construction is fundamental for the control of risk. Generic approaches to hazard identification result in an incomplete picture. Hazard identification should be undertaken on the specific details of each project.
- b) **The risks arising from the identified hazards.** Certain hazards in tunnelling can give rise to several risks. For example, the occurrence of methane can pose the risk of fire, explosion and asphyxiation. The hazard of compressed-air working can result in the risk of a variety of ill health consequences.
- c) **An assessment of the identified risks.** An overall assessment of the risks is needed in order to prioritize the necessary risk-control measures. Risks that are identified as trivial should be discarded from further consideration. Care should be taken to identify and investigate risks which, although very unlikely to occur, would have serious consequences.
- d) **Risk elimination.** The first form of risk control is to eliminate the hazards and risks completely, if this is possible. This can be achieved by making engineering choices early in the project, or perhaps by exercising design choices during the planning and specification stages.
- e) **Risk-control measures for residual risks.** Risk-control strategies are needed for those risks that remain to be addressed during the construction stage. For example, effective risk-control strategies may be needed to control risks arising from noise, dust, atmospheric pollutants, handling and use of dangerous chemicals, moving plant and transport. The detail of these risk-control measures is best devised by those in control of the construction works, but information on hazards and risks known by the client, the planners and the designers should be passed on to those devising risk-control measures at the beginning of the construction stage.
- f) **Specified safe methods of working.** The ultimate aim of this process is to devise project-specific ways of safely undertaking all work activities. Method statements may or may not need to be particularly prescriptive, but, where appropriate, they should allow a degree of flexibility in decision-making.

4.1.2 Risk assessment and method statements

Arriving at a safe system of work is a process that involves work and decisions by the client, the designers, the specifiers of the work, and the contractors, and is not an activity confined to the construction stage alone. Quantified risk assessment, based on statistics, may be used (e.g. in the selection of the excavation and lining method), but care is needed in the choice of relevant statistics and in their handling. The general principle is that the control measures should be proportionate to the risk. If the risk is substantial and the consequence is high, then more time, effort and resources should be expended in carefully identifying and controlling this risk.

Health and safety legislation requires that all parties to a tunnelling project cooperate to achieve and maintain safe places of work. A team approach that harnesses the knowledge and experience of all concerned has many benefits. Input from an experienced contractor and a machinery equipment designer and supplier during the design and planning stages can be beneficial. Input from the public emergency services and utilities should also be sought during these stages.

Prior to commencement of the site work, the principal contractor should prepare a construction-stage health and safety plan, taking into account the information received from the pre-tender health and safety plan. This should not be a one-off exercise: the plan should be regularly reviewed and revised as appropriate, following on-site experience in addressing the actual health and safety risks underground.

4.2 Planning for contingencies and emergencies (see clause 14)

There is a special need to draw up specific plans for both contingencies and emergencies that might be foreseen on the project.

Contingencies are situations influenced by the degree of uncertainty inherent in the construction work. An example of this is the degree of variability of the ground or water conditions. Plans should be made in advance to address such factors. For example, it might be appropriate to have extra pumping capacity underground; or, on a compressed-air tunnelling contract, it might be appropriate to have extra compressor plant or extra ground-support equipment readily available on site.

Emergencies, on the other hand, are events that are not expected to occur, but, from past international experience, cannot be ruled out. The first consideration is to identify the types of potential emergencies in the context of the project. Those attempting to draw up a list of possible emergencies should have as wide a knowledge of the industry as possible and should be prepared to undertake research to supplement knowledge derived from their own experience. Emergencies that are unlikely but not impossible could include:

- a) severe fire underground: for example, involving a TBM;
- b) sudden collapse of an open face of excavation in soft ground, possibly also involving a flow or slide of loose material;
- c) sudden flooding of a tunnel due to unexpected pressure or quantity of water;
- d) sudden underground explosion, perhaps due to the undetected presence of methane;
- e) gross atmospheric pollution, which might be associated with oxygen deficiency;
- f) sudden failure of the tunnel lining, which might cut off persons from their normal means of egress;
- g) unexpected and complete power failure underground, which would result in substantial egress and rescue problems; and
- h) some form of emergency external to the underground works, but which would require immediate evacuation or rescue of persons underground.

The nature of possible emergencies should be discussed with the public emergency authorities. Planning for emergencies should endeavour to harness the skills and experience of those who have had experience in dealing with such situations. Recommendations for managing emergencies involving flooding and inundation are given in clause 10, and for managing fire emergencies, in clause 14.

4.3 Types of accidents

The types of accident that occur in tunnelling are similar to those in the construction industry in general. These types of accident are described in Table 1, together with examples and references to the corresponding clauses that give guidance on preventive measures.

Table 1 — Accidents — Examples of cause and prevention (not in order of priority)

Accident category	Examples	Precautions and/or principal references	Other references
a) Falling from a height	Falling down shaft	Proper barriers	20.6 and 20.7
	Falling from staging at face	Secure decking; barriers where practicable	
b) Falling on the level	Tripping or slipping	Hand rails; even non-slip surface; cleaning of surface; good lighting; dedicated walkway	clause 17, clause 22
c) Materials falling from a height	Tools and small items dropped or kicked off staging or from shaft	Toe boards; proper stacking and storage; hand tools provided with thongs	20.6
	Slung loads dropped	Proper slinging and loading; loading area kept clear; see BS 7121-1 to BS 7121-5, CP 3010 and BS 4898	20.6, 21.2
d) Materials falling from stacks or vehicles	Collapse of stacks, e.g. timber, segments, cement bags	Proper foundation for stacks; systematic building of and maintenance of stacks	8.3.2, 20.6
	Loads falling from vehicle	Loads properly stacked and secured; level road or track well maintained	20.6
e) Burial by fall of material	Collapse of face	See clause 7 and clause 8	
	Rock falls	Barring down loose rock; immediate support	7.8
	Collapse of stacks or stockpiles	See item d)	
f) Flooding or inrush of water	Broken sewer or pipeline, groundwater, etc.	See clause 10	
g) Lifting machinery	Cranes and hoists	See clause 21	
	Hoisting and placing of segments at face	Appropriate equipment properly maintained; safest procedures enforced	8.3.2, 8.3.3
h) Other machinery	Excavating machines	Exclusion of persons from operating zone; safe procedures defined and enforced; see clause 7	
	Grouting operations	Robust equipment properly maintained; operation by trained persons; see 8.3.5	
	Conveyors	See 23.5	
i) Vehicles	Locomotives and rolling stock	See 23.1	
	Rubber-tyred vehicles	See 23.2	
j) Electrical installation	Electrocution	See clause 25	13.3
k) Fire and explosion	Burns; concussion	See clause 12, clause 13 and clause 14	11.5, 25.3.7
l) Atmospheric pollution	Atmospheric contaminants	See clause 12, clause 15 and clause 16	11.3
m) Handling materials	Lining segments; pipes	Manufacturer's guidance	8.3.2, 20.3.2, clause 21

4.4 Occupational health

4.4.1 *Health surveillance*

As part of the overall control of risk, the management of occupational health during construction on site is essential.

Tunnel workers are a peripatetic group, often living away from home and with poor access to publicly available health services. Pre-employment health screening should be carried out on all prospective employees. For example, exposure of underground workers to dust could exacerbate chest complaints. Health surveillance is a legal requirement for those exposed to certain hazards such as compressed air.

Types of occupational health hazard are described in Table 2.

If elimination of the hazard is not possible, measures should be taken to minimize exposure by, for example, mechanization, ventilation, substitution of less hazardous alternatives, reduction of shift length or rotation of work patterns. In some cases, control measures can introduce other risks, which should be controlled.

4.4.2 *Control of residual occupational health risks*

NOTE Attention is drawn to Regulation 6 of The Management of Health and Safety at Work Regulations 1999 [4], which requires a programme of health surveillance. Information is given in HSE publication HSG 61 [5].

Management, technical personnel and operatives should be trained to recognize occupational health hazards and the early symptoms of ill-health. They should also be trained in first aid.

Early reporting of symptoms should be encouraged to enable prompt reference to the employer's occupational health service. Where appropriate, underground workers should be given regular medical examinations by an occupational health specialist.

4.4.3 *Provision of information*

Information on exposure levels and preventive measures should be made available to employees, both directly and through trades-union-appointed safety representatives where these exist.

4.4.4 *Record keeping*

There are requirements for the keeping of records of assessments and exposures in both general health and safety legislation and in hazard-specific legislation such as The Noise at Work Regulations [6].

Where no statutory requirement for record keeping exists, records should be kept for 20 years.

4.4.5 *Washing facilities and potable water*

Good personal hygiene is important, particularly where work involves contact with contaminated ground and with irritant or caustic substances. It is also important where toilet facilities are limited.

Underground workers should have ready access to supplies of cold potable water.

4.4.6 *Mitigation measures*

4.4.6.1 *Noise*

All reasonably practicable steps should be taken to reduce noise exposure, including substitution by less noisy equipment or by placing machinery in noise enclosures.

4.4.6.2 *Manual handling*

Risks involved in manual handling can be reduced by the mechanization of the excavation and lining erection processes, the breaking down of loads into smaller components, the provision of lifting points, and job rotation.

4.4.6.3 *Work-related upper limb disorders*

Mechanization and job rotation can reduce the risk of work-related upper limb disorders.

4.4.6.4 *Hand-arm vibration syndrome*

Mechanization and job rotation can reduce the risk of hand-arm vibration syndrome (HAVS). In addition, there should be a programme of clinical examinations by an occupational health specialist under the supervision of a medical practitioner experienced in HAVS.

Table 2 — Principal occupational health hazards

Hazard	Occurrence	Possible symptoms and/or consequences	Text reference
A Physical			
1 Noise	Prolonged exposure to high noise levels. Pneumatic tools such as clay spades or rock drills. Machinery.	Long-term irreversible hearing loss.	4.4.2, 4.4.3, 4.4.4, 19.1, 19.2
2 Manual handling (lifting, carrying, pushing/pulling)	Hand excavation techniques. Erection of lining by hand. Use of heavy, awkward, slippery, sharp tools.	Pain including low back pain and restricted body movements that can lead to permanent disability. Prolapsed disc. Muscle/tendon damage.	4.4.3, 8.3, clause 21
	Repetitive, frequent or prolonged operations requiring force, gripping, squeezing of hands, rotation of wrists. Awkward posture.	Work-related upper limb disorders. Pain, numbness and restricted body movement which can lead to permanent disability.	4.4.3, 19.3
3 Vibration	Prolonged exposure to high vibration hand-held tools. Concrete/rock breakers. Clay spades. Percussive drills.	Hand–arm vibration syndrome. Tingling or pins and needles in the fingers, and numbness. Whiteness at the fingertips when exposed to the cold. Finger paleness followed by a rapid red hand flush, plus finger throbbing. More frequent attacks causing hand pain and reduced dexterity. Eventually blue–black appearance of the fingers.	4.4.3, 4.4.4, 19.3
4 Heat	Hand excavation in conditions of high temperatures, high humidity, or low rate of air movement. Exacerbated by working in compressed air.	Heat stress and strain. Exhaustion. Increased heart rate and body temperature and sweating and salt imbalance. Fainting.	4.4.5, note to clause 11, 15.3, 15.6
5 Hyperbaric atmosphere	Work in compressed air.	Decompression illness. Signs and symptoms can include: <i>Acute:</i> Limb joint pains, skin rashes, itching, mottling, numbness, tingling, weakness, paralysis, visual disturbance, unconsciousness, convulsions. <i>Chronic:</i> Bone necrosis.	clause 11

Table 2 — Principal occupational health hazards (*continued*)

Hazard	Occurrence	Possible symptoms and/or consequences	Text reference
B Chemical			
1 Cementitious materials, additives, epoxy resins	Prolonged direct skin contamination of hands, forearms, legs from concreting, grouting, slurries, rock bolting. Application of sprayed concrete.	Redness, itching, scaling, blistering, cracking and bleeding of exposed skin causing irritant or allergic dermatitis.	4.4.5, 7.13.2, 7.16, Table 4, 8.3.5
2 Respirable crystalline silica	Machine cutting of rock. Application of sprayed concrete, drilling, breaking, crushing, conveying, cutting, loading of rock.	Increasing breathlessness, heart failure, acute silicosis, accelerated silicosis, lung fibrosis.	4.4.2, 4.4.3, 4.4.4, clause 16
3 Other respirable dusts	Machine cutting of rock. Application of sprayed concrete, drilling and blasting.	Irritation of respiratory tract. Accumulation of dust in the lungs.	7.8, clause 16
4 Solvents	Skin contact, contamination of tunnel atmosphere. Contaminated land.	Principally skin irritation including dermatitis. Nausea and giddiness.	4.4.3, 15.4.3.11
5 Hydrocarbons	Particulates from diesel engine exhaust emissions.	Irritation of eyes and respiratory tract. Might be a link with cancer (cause unclear).	15.4.3, 24.4.1
C Biological			
Contaminated water or soil	Infection through poor hygiene practices, skin cuts and abrasions or rubbing eyes when working in contaminated land or water sewage.	Weil's Disease (Leptospirosis) — a bacterial infection carried in contaminated water and soil. Early symptoms include sudden high temperature, loss of kidney function, influenza-like illness, joint and muscle pains. Conjunctivitis and jaundice can occur.	4.4.3, 4.4.5, clause 26

4.4.6.5 Heat stress and exhaustion

Mechanization, ventilation and job rotation can reduce the risk of heat stress and exhaustion. Adequate supplies of cold potable water should be made available.

4.4.6.6 Dermatitis etc.

Skin problems can be reduced in a number of ways, including the use of remotely operated equipment, and the use of personal protective equipment (PPE) such as gloves and overalls. When contact has occurred, contaminated skin should be washed immediately with hot water and cuts covered with waterproof dressings. Barrier creams should be used before work, and moisturizer creams to replenish skin oils. Contaminated PPE should be disposed of or, if appropriate, cleaned before reuse.

4.4.6.7 Dust (including crystalline silica)

Exposure to dust (including crystalline silica) should be reduced by local exhaust ventilation and the use of water sprays. Wet-mix shotcrete should be used to reduce the amount of dust generated in sprayed concrete lining applications.

5 Investigation and information gathering

5.1 General

The safety of tunnelling works can depend critically on adequate pre-construction investigation of the ground and site, and proper interpretation of the information obtained. All reasonably accessible information relevant to the construction of a tunnel, and to any maintenance, renovation or repair of it, should be obtained and studied before the work starts. Project-specific studies (see 5.3) are essential before tunnel construction can proceed, and should continue during the construction stage.

There should be the fullest practicable disclosure of all relevant information, or gaps in the information, to those responsible for design, for planning, and for construction. It is important that the ground information is relevant to, and as complete as practicable for, the needs of the design processes. It is therefore desirable that the designer, taking advice from others as appropriate, should establish the requirements for, and have technical control of, data acquisition for the site and ground investigation programme. This may include on-site design involvement during the site investigation contracts.

The recommendations set out in 5.2 and 5.3 should be treated as a basic checklist, and in no sense as a comprehensive specification. BS 5930 deals with site investigations in much greater detail.

NOTE Some further guidance can be obtained from Transport Research Laboratory reports TRL 192 [7], LR 625 [8] and LR 740 [9].

5.2 Preliminary studies

5.2.1 Topography

Ordnance Survey maps and plans normally provide sufficient detail for the preliminary studies and for the basic siting of the works. Up-to-date information not yet embodied in published editions of the maps can be obtained from the regional offices of the Ordnance Survey and from local authorities. Rights of way in England and Wales are shown on recent editions of the 1:25 000 and 1:50 000 maps but further information is recorded in the Maps Library of the appropriate government department. Old editions of maps, particularly the "County" series pre-1939 at scales 1:10 560 and 1:2 500, can be important documentary sources, as they record workings and structures and watercourses now perhaps abandoned and concealed. Aerial photographs are held by the Ordnance Survey, local authorities and air survey companies. Comparison of recent and earlier aerial photographs can give important information on the masking of earlier features.

In tidal waters and coastal areas, Admiralty charts show the topography and nature of the seabed. The date of the information displayed on the charts is important, and local port or harbour authorities should be contacted for the most recent information on local harbours and their environs.

5.2.2 Geology

The published maps, both solid and drift editions, supplemented by much information accessible in the published and unpublished records and documents of The British Geological Survey and of The Geological Society, provide the essential background information to tunnel siting and construction. Other useful material includes soil maps, a grid-references list of available borehole logs, memoirs of the Soil Survey of Great Britain, contaminated-land maps and land utilization maps. Geomorphological studies can also be of benefit, particularly in the vicinity of tunnel portals to be formed in natural slopes.

5.2.3 Hydrology

Records of surface water levels and flooding can usually be obtained from the appropriate government department. In tidal waters, Admiralty charts and other Admiralty publications provide essential information that can be supplemented by the records of local harbour authorities. Tidal predictions embodied in Admiralty tide tables are of great importance for work at or near sea level. Discharge rates for rivers should be ascertained. All appropriate records and predictions should be fully examined for their relevance to particular locations. Advice from those with local knowledge can be invaluable.

5.2.4 Existing structures, services and old workings

Knowledge of all structures, buildings and earthworks within any possible zone of influence of the tunnel construction should be sought and studied. Plans of buildings and other structures should be examined both from the point of view of ground support required within and adjacent to the tunnel and of danger and damage to existing structures from settlement or vibration. Such plans are likely to be in the possession of the owners or deposited with the local authority.

Industrial works, waste tips and waste disposal sites, whether operational, closed or abandoned, can pose a range of hazards to tunnelling works, particularly if hazardous substances have infiltrated the strata to be tunnelled.

A search should be made for records of any wells, culverts, boreholes, borrow pits, and any old mine workings in the area. These records can also provide information on water table levels. Records of previous tunnel construction can also provide valuable information. Publications of learned societies and libraries can also contain evidence of previous land use. In mining areas, the fullest information on existing and abandoned coal and other mines should be consulted, but it should be noted that this might be incomplete in respect of mine working undertaken before 1909. Enquiries should be made as to whether there are any records of the occurrence of methane or other gases. Local knowledge of pits, adits, drifts and other working is sometimes available.

Forms of structural support to existing buildings and structures, such as piles or temporary or permanent ground anchors, should be fully investigated, as they can pose hazards to the tunnelling operations and are themselves liable to be detrimentally affected by tunnelling works.

The fullest practicable information on underground services should be obtained from cable and communications companies, from electricity, gas, water and drainage companies, and from any other organizations owning underground services. The actual location of these services should be verified. Drawings should not be relied upon, as they might be insufficiently accurate. It should be noted that trunk mains and services can be the responsibility of national rather than local or area authorities.

5.2.5 Weather

The influence of local weather conditions on tunnel construction should be taken into account, e.g. patterns of rainfall and barometric pressure changes and the likelihood of electrical storms. Daily rainfall data from the Meteorological Office should be obtained for comparison with periods of observation in groundwater conditions.

5.3 Project-specific studies

5.3.1 General

All site investigations should be carried out in accordance with BS 5930.

NOTE Further guidance can be found in Site Investigation Steering Group publications [10] to [13].

5.3.2 Boreholes

Boreholes (vertical, horizontal and inclined) should be sited to provide information specific to the tunnel to be constructed, renovated or repaired. Data from boreholes supplement the geological and hydrogeological information obtained from maps and other records. The boreholes should be located close to the line of the proposed tunnel, but not so close as to intersect it, unless for some specific reason. A borehole too close to, or intersecting, a tunnel or shaft can constitute a serious hazard if water is present, and particularly when compressed-air tunnelling methods are employed. The siting of a borehole where a shaft is to be sunk makes correlation possible between the borehole data and the actual ground encountered.

If a borehole intersects an aquifer it should be sealed at the appropriate location. All boreholes should be properly filled and capped using concrete plugs.

The number of boreholes undertaken depends on a number of factors including the length of the tunnel and the character and variability of the ground. The original pattern of boreholes normally needs to be supplemented by additional boreholes to check on areas of doubt and concern and resolve special problems appearing at the construction stage. There is a risk in assuming continuity of strata between boreholes.

It is important that some boreholes are taken to a depth well below the intended tunnel invert, and that these boreholes are adequately sampled and recorded to enable geological structures and hazards adjacent to the proposed tunnel excavation to be determined. Samples of rock, subsoil and groundwater should be properly identified, labelled, and photographed where necessary, and stored for further examination if required. Expert supervision of the drilling operations and of sampling is essential to maximize the usefulness and quality of the information recovered.

Consideration should be given to the use of the most appropriate methods for obtaining undisturbed samples of soil by, for example, rotary coring and thin wall sampling tubes, in order to provide the best information on soil structure, stress/strain behaviour and anisotropy.

5.3.3 Information logging

Consideration should be given to the following techniques for information logging:

- a) stratigraphic logging, by an experienced geologist;
- b) borehole logging, using appropriate techniques for the ground conditions;
- c) impression packer tests to determine joint orientation;
- d) permeability tests over specified zones, preferably using a double packer;
- e) standard penetration test or window sampling;
- f) pressure-meter tests (self-boring or dilatometer);
- g) various types of disturbed/undisturbed samples;
- h) installation of piezometers;
- i) down-/up-/cross-hole seismic measurements.

For stratigraphic logging, it may be advantageous to sink a hole with continuous sampling/coring adjacent to holes from which samples/cores have been obtained for testing or where in-situ tests have been performed. Cores should be retained for inspection by tunnel designers and contractors.

Appropriate techniques for borehole logging include natural gamma, gamma back-scatter, sonar, resistivity and calliper methods. Detailed scan line logging and macro- and micro-fossil identification can provide valuable supplementary information.

Valuable additional information can be obtained from local exposures of strata or from large diameter auger boring in which the strata can be examined in situ, or from test pits or shafts. Precautions should be taken against loose ground, water, gases and other hazards when boreholes and pits are being inspected.

An appropriate laboratory testing programme should be followed to aid the determination of safe alternatives in respect of excavation, ground support and spoil disposal.

5.3.4 Geophysical investigation

The geophysical methods most readily applicable to tunnel conditions are seismic, electrical ground resistivity, ground radar and micro-gravity surveys. These methods should not be used on their own, but as an adjunct to borehole and other information. In particular, they can trace well-defined boundaries between underground strata and thereby provide a more comprehensive picture and identify anomalies, which can then be examined further by, for example, additional boreholes.

In urban areas the use of geophysical methods may not be appropriate because of the interference from existing services and structures. Radar and micro-gravity have been used successfully to identify swallow holes and similar features.

For a subaqueous tunnel, a marine seismic survey can be of assistance in charting the seabed or riverbed, determining bedrock surface and discovering buried channels. The survey can help to decide locations for site investigation boreholes.

5.3.5 Topography and surface survey

It is essential that an accurate site survey be made for the purposes of setting out and tunnel construction. This survey should define accurately the relationship of the tunnel to all existing structures and other features that could be affected.

An aerial survey can provide valuable additional information, particularly for a major tunnelling project.

Reference points, related to Ordnance Survey reference points, for the coordinate grid system of the survey should be established and preserved, as should benchmarks for levelling. The stability of all reference points should be checked and referenced.

Existing surface features such as manholes and valve covers should be identified and recorded, as these help to locate existing sewers and other buried services.

5.3.6 *Underground survey*

In addition to the surface topography, any underground structures should be accurately related to the proposed tunnel alignment. The accuracy of the available survey information should be taken into account.

The structures that should be surveyed include:

- existing basements and foundations;
- existing headings, tunnels and underground workings;
- main sewers;
- underground services of any kind.

Any ground or rock anchor cables that can be located should be accurately surveyed. Owners' plans of basements and foundations should, if possible, be verified by actual survey.

If any existing structure or service intersects or is very close to the proposed tunnel, any special hazards that could result should be carefully examined and appropriate precautions should be taken.

5.3.7 *Structural survey*

All buildings and structures that could be affected by the tunnel construction should be surveyed to determine their condition prior to, during, and after the proposed tunnelling operations.

5.3.8 *Groundwater tests*

Where the response of the groundwater regime to pumping or other methods of creating a differential hydraulic head could be important to the stability of the proposed tunnel or shaft, consideration should be given to carrying out pumping tests in boreholes sunk specifically for the purpose.

Where water levels in the area are variable or could be affected by tunnelling operations, observation wells to observe and record any variations of levels are desirable. They may be needed prior to and during tunnelling work. Water levels in boreholes should be recorded, and any perched water tables or artesian supplies should be identified if at all possible.

In water-bearing ground, permeability tests in boreholes can contribute valuable information.

Where tidal variations could be critical, as in the case of compressed-air working, tide gauges should be provided.

In special circumstances, other water tests should be made for salinity, acidity or pollution and/or the presence of chemicals or dissolved gases of natural or artificial origin.

5.3.9 *Gas*

Ground conditions should be considered very carefully to ascertain the risk arising from gas (e.g. methane, radon etc.) and other pollutants being present or entering the ground that is to be opened. Depending on the level of risk, tests should be carried out to ascertain the mode of its occurrence and the risk that it could present during the construction and the use of the works.

This applies in particular to tunnelling work in or adjacent to:

- coal measures;
- landfill sites;
- refuse tips;
- permeable strata where air has been introduced by previous compressed-air workings; and
- areas where the lowering of the water table has caused deoxygenation.

Gas can be dissolved in water and enter a tunnel construction with any water input to the works. Groundwater can travel considerable distances into tunnelling works.

5.3.10 *Blasting trials*

Where a tunnel is to be driven through rock using explosives, and in proximity to a vibration-sensitive structure or building, it may be appropriate to carry out blasting trials to determine the acceptable vibration parameters of the site, and the safe level of charging.

5.4 Ground investigation during construction

5.4.1 General

It is often necessary to continue ground investigation during the construction stage, and this can be part of the probing operation (see 5.4.2). It can be important to check the water pressures (in hard rock) or the porewater pressure (in soft ground). The latter is important where sprayed concrete temporary support is employed.

5.4.2 Probing ahead

Probing ahead of the tunnel face can provide valuable additional information and can improve the overall quality of the data concerning the ground ahead of the tunnel construction. For large or difficult tunnels, a pilot tunnel (usually located within the cross-section of the intended tunnel) may be the appropriate method, and will provide information on the nature and behaviour of the ground in advance of the main tunnel. This will indicate any need for any possible special construction, ground treatment or ground support.

Probing from the face as it is being advanced should be possible in all tunnels. The extent to which it is actually employed depends on the likely hazards. This work is usually programmed to minimize interruptions to progress.

In extremely bad ground conditions, probing ahead in all directions may be necessary, combined with ground treatment. In extensive investigations of this kind, care should be taken, when drilling, to avoid penetrating any suspected aquifers above or below the tunnel construction (see 9.1.3 and 9.2).

5.4.3 Special investigations

Special investigations may be appropriate if any of the following hazards are anticipated:

- geological faults, fissures or discontinuities;
- cavities or artificial obstructions;
- significant changes in the groundwater patterns;
- loss of safe overhead ground cover;
- the occurrence of hazardous gases and/or liquids.

6 Detailed planning for health and safety

6.1 General

The aim of The Construction (Design and Management) Regulations 1994 [1] is to encourage all parties to work together to reduce health and safety risk. At the detailed planning stage, the project risk assessment will highlight areas of risk. These should be addressed by the parties to the process. Throughout the detailed planning process, the risk assessment should be revised to enable the parties to develop a construction-stage health and safety plan tailored to the circumstances of the project.

6.2 Parties to the processes

The following parties to a tunnelling project have statutory duties and responsibilities under The Construction (Design and Management) Regulations 1994 [1]:

- a) the client or their appointed agent;
- b) the planning supervisor who has responsibility for the coordination of health and safety matters during the planning and design stages; the pre-tender health and safety plan; and the health and safety file;
- c) the designer with responsibility for the design and specification of the works, whether temporary or permanent;
- d) the principal contractor responsible for the execution of the construction stage, the coordination of health and safety activities on site and the effective management of risks during all construction work;
- e) contractors who have responsibility for the safe execution of part or parts of the works.

Other parties, depending on the method of procurement, can include:

- 1) plant and equipment manufacturers and suppliers. These bodies have duties under other legislation to supply plant and equipment that is safe;
- 2) the engineer who may, under the contract, have responsibility for the design and supervision of the works and for checking compliance with the terms of the contract.

Some or all of these parties can be contractually linked to one another, but the civil contracts involved in the project, and what they may or may not say about duties and responsibilities for health and safety, do not alter the statutory duties and responsibilities of each party as set out in health and safety legislation.

6.3 Integral nature of design and construction

The interdependence of the design and construction and their appropriateness to the ground and environmental conditions is more safety-critical in the execution of underground work than in any other construction activity. It follows that there should be authoritative engineering continuity through the stages of planning, investigation, design and construction. This is more effectively achieved by the involvement of a single organization throughout. If, however, there is a change in the engineering direction of the works, a way should be devised to ensure that the essential continuity is maintained and that the total planning, design and construction process is not fragmented.

6.4 Pre-construction-stage organization

The Construction (Design and Management) Regulations 1994 [1] require that as soon as practicable during the planning process, a planning supervisor is appointed by the client. The planning supervisor has to ensure that all foreseeable risks likely to arise from shaft sinking or tunnelling work, and which might affect health and safety, are adequately addressed by the designers. At a later stage, when tendering documents are being prepared, the planning supervisor has to ensure that all health and safety information known to the client and/or the designers relating to the project and its location is made available to the potential principal contractors.

Under The Construction (Design and Management) Regulations 1994 [1], no contractor is allowed to carry out any tunnelling work unless they are able to demonstrate competence in the type of tunnelling work that is proposed and shows a willingness and ability to allocate sufficient resources to identify and manage risks effectively and to comply fully with the health and safety legislation.

Clients and those advising them should appreciate that good health and safety performance is in everyone's interest and involves considerable expertise, organization and expenditure. The organization and provision of medical, welfare and other facilities should be specified in detail in the contract documentation, and appropriate items should be priced in each tender.

6.5 Construction stage

6.5.1 Organization

The construction-stage health and safety plan is the fundamental document that ensures safe working throughout the construction of a tunnel. This plan should be based on the information supplied by the client on the residual risks and should be prepared by persons suitably experienced in the tunnelling operations likely to be involved, including the types of plant and equipment to be used.

The client is obliged under The Construction (Design and Management) Regulations 1994 [1] to ensure that the works do not commence until a satisfactory construction-stage health and safety plan has been produced by the principal contractor.

At the same time, contractors should carry out an assessment of the risks posed to their employees, and should use this assessment in devising and implementing safe systems of work.

The health and safety plan should define a clear chain of responsibility and channels of communication on engineering safety matters. This is particularly important in, for example, the choice of ground-support systems and decisions concerning safety at the tunnel face.

The principal contractor is responsible under The Construction (Design and Management) Regulations 1994 [1] for coordinating the activities of all other contractors. The Construction (Health, Safety and Welfare) Regulations 1996 [2] include a requirement for the provision, accessibility and maintenance of welfare facilities. This needs particular consideration in long tunnels, deep shafts and in other remote locations.

Where tunnel size permits, welfare facilities should be located underground, including on TBMs.

6.5.2 Statutory controls

Statutory health and safety duties and responsibilities with respect to “construction work” are set out in The Health and Safety at Work etc. Act 1974 [14], and the “relevant statutory provisions”, which are the various sets of Regulations, that may apply to individual work activities. Administration is by the Health and Safety Commission, and enforcement is undertaken by the Inspectors of the Health and Safety Executive (HSE). Notification of the construction work is required to the HSE, and details of the information required to be sent can be found in The Construction (Design and Management) Regulations 1994 [1] and (if applicable) The Work in Compressed Air Regulations 1996 [3]. The HSE should be consulted regarding the obtaining and completion of all relevant notices, registers, and official forms. In the case of any construction work involving operational railways, HM Railways Inspectorate is the enforcement authority and should be consulted.

Certain accidents, cases of ill health and specific incidents are reportable to the HSE, and these are specified in The Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995 [15]. All accidents and incidents, whether or not they result in personal injury or losses, should be reported to employers by the individual involved or their immediate superior, and then in turn to the principal contractor.

Careful records should be kept, and these records, together with the results of any associated investigation work and details of similar incidents from elsewhere, should be studied and analysed, and appropriate action taken.

Inspection of a shaft or tunnel by a competent person is a statutory requirement of The Construction (Health, Safety and Welfare) Regulations 1996 [2]. The results of these inspections provide a valuable record of conditions at the time. It is particularly important that an appropriate schedule of inspection be drawn up and implemented when the work, for whatever reason, is not continuous, e.g. at weekends and during holiday periods or other interruptions in the tunnelling work. The use of remote monitoring systems, including remotely monitored instrumentation or closed-circuit television (CCTV), can eliminate or reduce the need for persons to enter the tunnel. Where it is necessary to enter the tunnel, the recommendations in 15.5 should be observed.

6.5.3 Supervision and inspection

All tunnelling operations should be subject to appropriate supervision. Understanding, making engineering judgements, and taking action in response to varying ground conditions can be as vital to safe working conditions as the anticipation of hazards and risks.

The client should appoint appropriately qualified and experienced persons to monitor the site activities on their behalf, and to assist in overall promotion of health and safety.

6.5.4 Temporary works

Temporary works of a substantial character are invariably necessary in the construction of shafts and tunnels, and in their maintenance, renovation and repair. They can constitute an essential element of the permanent construction, as in the case of, for example, a pilot tunnel, a working shaft or the framing to form an opening. They can also be structurally independent incidental works, such as working gantries, access systems, thrust pits and walls.

It is essential that health and safety issues relating to these works be taken into account early in the design stage. In tunnelling, the adequacy of temporary support is often critical to the loading on the permanent structure. Appropriate drawings, calculations, specifications and any contributions to the construction-stage health and safety plan should be prepared and followed. Where any failure of these temporary works would have a significant adverse effect on the health and safety of persons or on the environment, they should be the subject of an independent design check. Once checked, changes should only be made after direct consultation with the appropriate designer.

The principal contractor should appoint a person to ensure safety in the design, checking, construction and use of temporary works and should encourage cooperation and coordination between contractors.

6.5.5 Records and reports

The keeping of proper and adequate records of the physical aspects of the work in tunnel construction and repair is of the utmost importance. This is not only for safety during construction, but for safety in any necessary future maintenance and repair work. It is also important for any future tunnelling or other work in the vicinity. Such records should be kept as part of the health and safety file, required under The Construction (Design and Management) Regulations 1994 [1], for the project.

The content of the health and safety file should be the subject of early discussion with the client. It should contain a longitudinal geological section record based on day-to-day records of the strata encountered, correlated with any borehole records or other records, and with any abnormal ground levels, tidal or river levels and rainfall. In addition, settlements and movements of the tunnel lining and supports, and the ground above and adjacent to the tunnel, should be recorded.

6.5.6 Recruitment of project personnel

How health and safety issues are handled in the context of the recruitment of personnel for a tunnelling project should be addressed in employers' company health and safety policies. All persons employed should have a high standard of physical fitness. It is desirable that all persons working underground and all plant operators and banksmen be not less than 18 years old. Any recruit under 18 years of age should be asked to produce a medical certificate of fitness.

Applicants for engineering and management posts should be assessed on their knowledge of and expertise in health and safety issues relevant to the project.

6.5.7 Competence and training

6.5.7.1 Competence

The most vital contribution to health and safety in any tunnelling operation is through competent engineers and managers, and a competent workforce. Competence is gained through a combination of training and experience. All persons underground should be competent for the environment in which they are working and for the work tasks and activities they are required to carry out. Engineers, managers and supervisors should be competent both with respect to the work under construction, and in the techniques of management, communications and supervision. Evidence of competence such as the achievement of recognized qualifications should be sought. This could include, for example, qualifications in project management or health and safety management; or further education qualifications, such as National Vocational Qualifications (NVQs) in tunnelling-related subjects.

6.5.7.2 Training

It is a legal requirement for all persons at work to be given appropriate training in health and safety related to the risks they might encounter at work. Special training requirements apply, e.g. to first-aiders, plant operators, and, in the case of compressed-air tunnelling, to all those exposed to pressurized atmospheres.

Induction training should be given before any person starts work underground, whether as a new employee or as a person new to the project. Persons who are new to the industry are particularly vulnerable, and their induction training and the degree of supervision of their work, particularly initially, should reflect this. Induction training should cover:

- likely hazards and risks;
- the devised safe methods of working;
- site rules and prohibited activities;
- the use of protective equipment;
- communications and responsibilities for health and safety;
- action in the event of any emergency, particularly egress from underground workplaces.

Widely recognized grading and training schemes are available to assist in recruiting appropriately trained electricians, fitters and general plant operators. In the past, personnel records were the only reliable source of information about a person's training and experience. However, formal vocational qualifications are now becoming widely available.

For hand mining it has been traditional to train on the job, with a miner's labourer being supervised and trained by an experienced miner; but training courses leading to the issue of vocational qualifications in tunnelling technology can be valuable.

Whenever possible, persons employed for the maintenance of mechanical plant should have served an appropriate apprenticeship or similar training; however, a reasonable proportion of these persons may be trainees. Reference should be made to a person's registration grading, under the industry registration scheme, for the level of training and experience that has been obtained.

Persons employed in the installation, operation and maintenance of electrical circuits and equipment should be graded in accordance with the current industrial agreement of the Joint Industry Board for the electrical contracting industry, and should be suitably trained for the work. They should have access to professional electrical engineering advice and supervision.

Persons trained in the use of specialized tunnelling plant should also be experienced in general procedures for tunnelling and should be familiar with both health and safety instructions and operating instructions provided by plant manufacturers and suppliers.

NOTE Specialized tunnelling plant includes items such as TBMs, segment erectors (including winches), concrete spraying equipment, grout pans, drilling and coring equipment and pipe jacking pressure systems.

Toolbox talks are now established as a valuable method of on-the-job-training and for imparting and updating health and safety knowledge. Such talks should be held regularly, and should endeavour to cover each major work activity. They should be fairly brief and restricted to essentials, but allow feedback and questions. The use of visual aids is beneficial. The talks should be repeated whenever circumstances in the workplace change significantly or when new hazards are anticipated or become evident.

Visitors to underground projects should be given appropriate advice and training.

6.5.8 Personal protective equipment

6.5.8.1 General

Good health and safety performance is achieved by the effective identification and control of hazards and risks. Risk elimination can only go so far, and residual risks need to be controlled. Reliance solely on personal protective equipment should be regarded as a last resort. However, in tunnel construction works, the wearing of some personal protective equipment is inevitable.

6.5.8.2 Head protection

All persons on site should normally wear protective headgear conforming to BS EN 397 at all times. A “bump cap” is adequate only where there is no risk of overhead falling objects, and where limitations of space prevent the use of the recommended headgear.

6.5.8.3 Foot protection

Strong boots, with steel sole plates and toe protection, conforming to BS EN 344-1, BS EN 344-2, BS EN 345-1 and BS EN 345-2, should be worn at all times. In wet tunnels, heavy rubber knee boots with sole plates and toe protection may be appropriate.

6.5.8.4 Hand protection

Gloves of appropriate material should be worn where a person is at risk from cuts, abrasions, burns or contact with corrosive or irritant substances. Elbow-length gloves should be worn when grouting or handling corrosive or irritant substances. Barrier creams should be made available and used by site personnel.

6.5.8.5 Eye protection

Safety goggles, face shields and fixed shields should be provided and used as appropriate for protection against flying particles, hazardous substances or injurious light rays. Eye protection should always be worn by site personnel engaged on sandblasting, shotblasting, pressurized air and water cleaning, spraying concrete, grinding or chipping metal, cutting, burning and welding, grout mixing and placing. It should also be worn where there is a foreseeable risk of injury while breaking, cutting or drilling concrete or stone or similar material, and by persons injecting liquids under pressure.

6.5.8.6 Whole body protection

Protective clothing should be provided and used where appropriate to the risk, e.g. in wet conditions, when burning or welding or when handling hazardous substances.

6.5.8.7 Respiratory protection

Where there is a risk of respiratory damage, ventilation should be employed to extract or dilute any hazardous materials. The use of respiratory protective equipment should be employed as a last resort.

6.5.8.8 High-visibility clothing

Suitable high-visibility clothing conforming to BS EN 471 should be worn by all persons on site.

6.5.8.9 Hearing protection

Guidance on the selection and care of hearing protection is given in HSE publication L 108 [6a], as well as in BS EN 458. See also clause 19.

6.5.8.10 Self-rescuers

All persons underground should have immediate access to a self-rescuer as described in 14.10.

6.5.9 First aid provision and procedures

6.5.9.1 General

NOTE Attention is drawn to The Health and Safety (First Aid) Regulations 1981 [16] and associated guidance document L 74 [17]. These direct and guide employers in the provision of first aid for persons injured at work.

It is essential that persons trained in first aid and capable of responding rapidly to any incident be available on each shift during working hours. All persons should be informed of the first aid arrangements.

All employers should train their on-site supervisory personnel in managing emergencies involving first aid. All personnel should be told that, in the event of serious injury, a casualty should be moved only by a trained first-aider, unless there is the immediate risk of further injury.

Good communications are essential between the working areas and the surface facilities. A clear plan of action should be formulated to speed up the transfer of any injured persons from working areas and to ensure that ambulances can reach shaft tops or other access points quickly. Lifting arrangements in shafts should take this into account. Clear instructions should be given to all persons on the procedures to be adopted for evacuating tunnels in an emergency and for ensuring that injured persons are not left behind or unaccounted for.

6.5.9.2 First aid facilities

Sufficient first aid boxes should be provided. First aid boxes should be made of suitable material, and designed to protect the contents as far as possible from damp and dirt. They should be clearly identified; the recommended marking is a white cross on a green background. Boxes should be readily accessible to working areas and should be in the charge of designated first-aiders on each shift. Appropriate eye wash facilities should also be provided.

NOTE HSE publication L 74 [17] gives guidance on equipping first aid boxes.

6.5.9.3 First aid rooms

A properly constructed and equipped first aid room should be provided to be used for treatment and rest. It should be in the charge of a person trained in first aid and should be available during all working hours.

6.5.9.4 First aid training

The Health and Safety (First Aid) Regulations 1981 [16] require persons with first aid responsibilities to have successfully undergone a course of training, and to be in possession of a current certificate issued by an organization approved by the HSE.

NOTE Details of such organizations are available from offices of the HSE.

First-aiders should be specifically trained to deal with the range of incidents likely to occur in tunnelling operations.

6.5.9.5 Stretchers

Stretchers (complete with blankets) suitable for the confined space of a tunnel should be provided and maintained. They should be readily accessible for use in working areas in an emergency, and should be protected against dirt and damp. In particular, where access to a tunnel is by a shaft, stretchers should, where practicable, be stored at tunnel level. Appropriate means of transporting an injured person to the surface should be provided (see 21.6.4).

6.5.9.6 Ambulances

The local ambulance service should be notified of the location of the site and the nature of the work to be carried out. All employees should be made aware of the procedure for calling an ambulance. Notices should be posted on site naming the first-aiders and giving instruction on the making of emergency calls.

Where such arrangements are not practicable, a vehicle suitable for stretcher cases should be provided on site. A notice giving the address of the hospital dealing with emergencies should be prominently displayed.

6.5.9.7 Transport underground

Consideration should be given to the provision of a rescue skip, train or dedicated vehicle to expedite the rescue of casualties from long tunnels.

6.5.10 Duplication of provisions

Where employees of more than one employer are involved, and the employers concerned wish to avoid duplication of provisions, a joint agreement should be made and agreed in writing, a copy being kept by each employer. Each employer should inform its own employees of the arrangement made for them. The principal contractor should coordinate these provisions.

7 Excavation and ground support

7.1 General

As the excavation and the support of the ground are often one operation, appropriate cross-references are made to clause 8 and other relevant clauses.

7.2 Basic principles

The essence of safe excavation is to maintain the stability of the ground at all times. This is achieved by either:

- maintaining continuous ground support during excavation (e.g. closed-face and closed-mode); or
- opening up only as much ground as is safely self-supporting (e.g. open-face and open-mode) until temporary or permanent support can be provided.

The amount of ground opened up varies from a small excavation in soft clay or running sand, which needs immediate support, to the total excavated surface of a tunnel in sound hard rock, which can safely remain unlined for many weeks or indeed permanently. Following a full risk assessment, a safe system of work should be instituted and maintained at all times.

The time intervals between excavation, immediate support and final lining are critical to the whole construction procedure and its cost. As soon as a volume of ground is excavated, there is a redistribution of stresses in the remaining ground. This can initiate movement in the ground, which can cease quickly in sound rock, or can continue to develop slowly in firm and stiff clays or rapidly in soft to very soft clays, sand or gravel (see 7.3). If the effects are to be localized, immediate support should be provided to prevent progressive deterioration.

The stand-up times of unsupported ground range from seconds to days or weeks. The nature of the necessary ground support varies from mere containment to support for full overburden.

Major factors that should be taken into account when determining the loads to be taken in the ground-support system include:

- a) the size and depth of the tunnel;
- b) the shape of the tunnel;
- c) the method and speed of excavation and lining;
- d) the stiffness and watertightness of the lining system;
- e) the groundwater regime;
- f) the structural geology;
- g) the proximity of other underground structures;
- h) the construction of adjacent tunnels;
- i) vibration.

Depending on the influence of these factors, and in particular groundwater, a small face can sometimes be safe to leave almost indefinitely, whereas extensive and continuous support can be required for a larger face in similar material.

Experience and sound judgement are essential in assessing how much ground can safely be opened up and for how long it can remain unsupported. In some types of closed-face machine operating in open mode, it is not always possible to see the excavation face upon which a decision is to be made. In this case, alternative methods of assessing the face support required are essential. These include inspection of the excavated material, forward probing, ground radar and excavation volume assessment.

Where sudden changes in ground condition are encountered, immediate temporary support and containment can be vital. In loose ground where silt and sand start to run, mechanically closing down the face or alternatively stuffing quickly with bags of straw or similar material can be effective in minimizing ground loss and maintaining the stability of the face.

In methods of tunnelling which involve incremental excavation and support, continuous observation of both the ground and the ground support is necessary.

NOTE Extensive guidance can be found in the HSE report *Safety of the New Austrian Method (NATM) tunnels* [18] and the ICE design and practice guide *Sprayed concrete linings (NATM) for tunnels in soft ground* [19].

7.3 Ground characteristics

7.3.1 General

Soils and rocks are not homogeneous. The following subclauses (7.3.2, 7.3.3, 7.3.4, 7.3.5 and 7.3.6) offer guidance on the general characteristics of various soil types; but ground conditions can change continuously as the tunnel proceeds, and the material being excavated is unlikely to match any single category described below.

7.3.2 Granular soil

7.3.2.1 General

A granular non-cohesive soil has little or no stand-up ability and will only lie at its angle of repose. Failure in granular soils can occur as:

- a) slow or fast ravelling, when material begins to dry out or to loosen due to overstress;
- b) running, in dry granular materials lacking cohesion;
- c) flowing as a viscous mixture, when a granular material becomes fluid.

7.3.2.2 Sand and gravel

In sand and gravel there is no plasticity and little yielding under stress, but a small fall of loose material can quickly destroy any arching action which is carrying the load and result in sudden progressive collapse. It is vital to provide support immediately to prevent initiation of movement. If water is present, restraint is of even greater importance, and further precautions against the washing out of fine material, resulting in loosening of the whole, may be necessary. A closed-face machine with a pressurized heavy slurry, such as bentonite, will not only support the sand and gravel but also negate the effects of the groundwater by equalizing the hydrostatic head.

Open faces should be carefully boxed up or closed down, and all voids grouted, when progress is interrupted.

7.3.3 Cohesive soil

7.3.3.1 General

In soils having some degree of cohesion and plasticity, ranging from silts to clays, failure can occur as:

- a) ravelling, where the ground dries out or is overstressed, but fractures rather than flows;
- b) squeezing, e.g. where a clay is overstressed and slowly extrudes without visible fractures;
- c) flowing, by vibration or liquefaction in moist or saturated silts, and by vibration in clays;
- d) swelling, of a clay absorbing water, possibly from the atmosphere, and increasing in volume.

Some fluvial and marine clays are particularly sensitive. Soft sensitive clays sometimes appear safe, but are subject to loss of strength and progressive collapse. (Sensitivity relates to the rate of loss of strength on disturbance.)

7.3.3.2 Clay

In soft clays, and in stiff clays where discontinuities (i.e. slickensides or “greasy backs”) are present, it may be necessary to provide, as soon as practicable, support that restrains movement. The plastic characteristics of clays can result in a gradual development of ground disturbance. Immediate support keeps disturbance to a minimum. Changes of moisture content in clays due to exposure of the surface and load changes can, over a long period, result in swelling or shrinkage, with a consequent increase in the load on the supports. In hand excavations where timber supports are used, these should be tightly wedged into position with a proper system of timber or steel struts. In open-faced shields, hydraulic struts may be used. These allow the shield to move forward whilst keeping a controlled support on the face by maintaining hydraulic pressure. In soft plastic clays, a closed-face machine may be appropriate.

In a tunnel in clay, or any yielding ground, additional temporary support may be needed to seal the clay surface if a normal cycle of operations is interrupted. All voids should be boxed up and grouted, or the face should be sealed with sprayed concrete.

7.3.3.3 Silt

The cohesion of silt can suddenly be lost due to changes in water content. The face should be fully supported unless cohesion can be relied upon. When a tunnel in silt is below the water table, compressed air, freezing, or other stabilization measures may be used as an alternative to a closed-face TBM.

7.3.4 Chalk

Chalk is a fine-grained limestone. Its nature varies widely, depending on its mineral content and the degree of weathering. It can be soft, and therefore unstable when excavated; or it can be hard, requiring significant break-out effort. Soft chalk can be putty-like.

Fracturing, block size, permeability and the frequency of bedding joints are also variable. Chalk can be relatively homogeneous, or discontinuous and blocky. It can be a significant aquifer containing open and water-bearing fissures, or it can be dense and of low permeability.

These conditions can be encountered in varying combinations, affecting the safety of the excavation, the working conditions within the tunnel and the viability of the chosen methods of excavation and support. Of particular importance is the presence, or otherwise, of flints within the chalk mass. Excavation, particularly mechanized excavation, can be adversely affected by the presence of flints, which can result in rapid and excessive wear of cutters.

7.3.5 Rock

After excavation or blasting in rock, there is normally an arching action across the tunnel in the newly exposed roof, with some support from the undisturbed rock ahead of the face. The value of this support depends greatly on the direction and slope of the planes of weakness in the immediate vicinity. The dip and strike of the bedding planes, the spacing and pattern of joints, and the presence of faults and any consequent fracturing and crushing should therefore be taken into consideration when assessing the stability of the excavation, and in the design of the supports. In particular, the designer should consider the thickness of rock cover beneath superficial deposits as it could be appropriate to increase the depth of the tunnel. The designer should make every effort to minimize tunnelling through a mixed face where possible.

The arching action is accompanied by redistribution of stresses. There can be movement of blocks of rock and ingress of water acting as a lubricant. Continued redistribution of the stresses can result in rock falls and repetition of the process at higher levels. This can lead to formation of a void above the tunnel profile. Slabs of rock present in the crown can fail in bending. Rock tunnels that break with a square crown should always be treated with caution.

The risk of breaking into faults, fissures or cavities should be recognized and assessed. Faults can contain water or gas under high pressure. At faults, changes in the strata can be encountered and there will possibly be zones of extensive fracture, often with slickensides and fissures filled with gouge or pug. In fault and shear zones, rock can be altered so much as to acquire the characteristics of a soil. This alteration, when combined with the presence of groundwater and higher cover or in-situ stresses, results in some of the most difficult tunnelling conditions found. In such fault zones, full-face excavation may be possible if pre-drainage, pre-grouting and forepoling are employed.

Advance exploration (e.g. forward probing or drilling), followed by grouting or other special precautions should be considered, particularly in subaqueous tunnelling.

7.3.6 *Made-ground and contaminated ground*

Made-ground, mostly encountered in shaft sinking, is usually unstable and requires full support.

Contaminated land should be treated before other construction work proceeds.

Removal of the made-ground or contaminated material is a possible solution.

A latent hazard arises if contamination from the surface seeps below ground to the level of a tunnel. The investigation and information gathering process (see clause 5) should establish the likelihood of hydrocarbons, other solvents and bacteria, as well as of gas (see 5.3.9).

7.4 *Indicative methods of tunnelling*

A risk assessment as outlined in 4.1.2 should be carried out to determine the methods of ground support to be considered.

Table 3 sets out the principal methods of tunnelling and ground support that are appropriate for various ground conditions. These methods are indicative only.

The initial support may be the first stage in the ground-support system or, as in some uses of sprayed concrete, may be the only functional lining of the completed tunnel.

7.5 *Methods of excavation and spoil removal*

7.5.1 *General*

Most tunnels are driven using mechanized excavation and lining techniques. However, hand excavation, because of its adaptability, is still an essential part of the overall tunnelling process. It is used typically for short tunnel drives in appropriate ground conditions, break-outs from shafts, short connections and back drives, cutter maintenance chambers and enlargements.

7.5.2 *Tunnelling machines, including machines for pipe jacking and microtunnelling*

An essential aspect of overall tunnelling safety is the safety of the machinery.

Machinery used should conform to BS EN 815 and other relevant standards.

NOTE prEN 12110¹⁾, prEN 12111¹⁾ and prEN 12336¹⁾ also specify requirements for tunnelling machines. The terminology and machine classification system used in these standards varies from that commonly used in the UK.

All machinery should be operated strictly in accordance with the manufacturer's instructions.

7.5.3 *Hand excavation*

Hand excavation uses either conventional picks and shovels or air-powered picks, breakers and clay spades. The main hazards of this type of work include confined space, noise, vibration, manual handling and falls of persons and materials. Short shifts or frequent rotation of persons around different tasks may be necessary to limit exposure to noise and vibration. It is essential that adequate working space and, where necessary, proper working platforms be provided (see 7.6.3). Tools should be regularly checked, as broken or badly maintained tools increase the likelihood of accidents.

Small elevating conveyors are often used in conjunction with hand excavation. The safety precautions taken with respect to such conveyors should be as described in 23.5.

7.5.4 *Mechanical excavator and loaders*

A variety of mechanical excavation and loading equipment is used in tunnels. Tunnelling machines (with the possible exception of cutter booms) have their own excavation and loading equipment. Hand excavation and drill-and-blast tunnelling often needs separate equipment for loading away the spoil. If this equipment is mobile, it poses additional risks. Special care should be taken in the installation and use of conveyors (see 23.5). The system of work should keep persons clear of moving parts. Before any part of the machinery is set in motion, an audible warning device should be sounded; however, the frequency of alarms should not be so great that they become meaningless.

Power is often routed to excavation and loading equipment by means of hoses or electric cables. These hoses and cables should be kept clear of moving plant and should be prevented from being subjected to excessive tension. Safety chains should be fitted to hoses and cables at the point of entry to the machine, and retention devices should be provided at hose and cable connections.

NOTE Attention is drawn to the recommendations for lighting given in clause 17.

¹⁾ In preparation.

Table 3 — Indicative methods of excavations in various ground conditions

Method of excavation	Text reference	Granular soils, sands and gravels			Silt		Cohesive soils			Rock		
		Stable	Unstable	Wet	Dry	Wet	Soft clay	Clay	Stiff clay	Weak	Medium	Strong
Hand excavation — timber heading	7.5.3 and 7.14											
Open excavation	7.7											
Prefabricated linings	8.3											
Shield excavation — open-faced	7.6.1											
Shield excavation — face support	7.6.1											
Shield excavation — backacter	7.6.2											
Shield excavation — roadheader	7.6.2											
Shielded TBM — open-faced (open mode)	7.6.4.1											
Slurry TBM (closed mode)	7.6.4.2											
EPB machine (closed mode)	7.6.4.3											
Compressed-air bulkhead shield	11.2.9.2											
Remote control microtunneller — slurry	7.5.2											
Remote control microtunneller — auger	7.5.2											
Hard-rock TBM	7.6.4.4											
Drill-and-blast	7.8											
Steel arches and packing	7.9											
Rock bolting	7.11											
Sprayed concrete lining systems	7.10.3											
NOTE 1 The shaded areas show suitable excavation methods for the ground conditions indicated.												
NOTE 2 The above excavation methods can be enhanced by the addition of appropriate geotechnical processes, e.g. compressed air, ground freezing and dewatering.												

7.6 Tunnelling machines

NOTE These machines can also be used for excavation in pipe jacking.

7.6.1 *Open-faced shields*

An open-faced shield provides initial support and protection during excavation and lining erection or pipe installation. Its features include a cutting edge that can, in suitable ground, be used for trimming the periphery of the excavation, and a tail skin that provides protection within which the lining can be erected or a lead pipe fitted. In most conditions, it is useful to extend forward the cutting edge of the crown to form a hood. Excavation should not take place beyond the area protected by the shield.

In some shattered rock conditions or where there is a mixed face, e.g. of rock and soft ground, the rock should be excavated clear of the cutting edge. It may then be necessary to provide crown and shoulder support in the form of headboards or hydraulic poling plates that span between the shield cutting edge and the face timbering.

Before “shoving” the shield, excavation should be complete to the stage where excessive shield or pipe jack ram pressures are not required. Unless an expanded lining is to be used, ground movement should be minimized by grouting as soon as possible. In pipe jacking, the shield is designed to produce a small overbreak to the external diameter of the pipeline. Normally a lubricant such as bentonite is introduced into this overbreak to reduce friction and minimize ground movement.

All shields should have provision for face support, which may be needed continuously as tunnelling proceeds or kept for emergency use only. When face support is necessary, it is normally held by hydraulic face jacks, which maintain a given pressure on the face timbering and retract as the shield is jacked forward. When using segmental linings, the face support is likely to be infrequent. In this case, the support can be strutted back through the shield to the completed segmental lining. This allows the shield to be jacked forward without affecting the timbering.

Other means of face support, such as breasting doors or forepoling, may be adopted. When the shield is being jacked off segmental rings, i.e. “shoved”, it is essential that the person designated as shield operator checks that nobody can become trapped between the rams and the lining.

7.6.2 *Cutter boom, backacter or other mechanical excavator shields*

Mechanized open-faced shields (often described as roadheader or backacter shields) are usually employed only in ground where face support is normally unnecessary. Nevertheless, a set of sized and cut timbers should be kept available for emergency use.

Excavated material is normally removed from the face on a belt or chain conveyor running from the bottom of the shield. It is essential that machines be fitted with appropriate guards and emergency stop facilities.

7.6.3 *Large diameter shields*

On a large diameter shield, excavation should be carried out, and ground support provided, from properly constructed and guarded working platforms. For shields of 2.5 m diameter or greater, platforms should span across the shield, giving access to the face whilst allowing muck to fall into a clear invert.

Scaffolding is not sufficiently robust for this purpose, as the uprights are liable to be knocked away by falling debris. Where there is a hood on the shield, working platforms with a sliding facility should be provided in order to get the platforms close to the face. Working platforms can frequently be temporary, being installed only for the initial support and mucking part of the tunnelling cycle and then removed. Responsibility for their correct and safe installation should be given to a designated person.

7.6.4 *Tunnel boring machines (TBMs)*

7.6.4.1 *General*

A TBM has a rotary wheel excavator capable of cutting the whole tunnel face at each revolution of the wheel. It can be shielded or unshielded. Excavated material is normally lifted on to a central conveyor by scoops attached to the cutting wheel. These machines are usually employed in ground where face support is not normally required, although some machines are fitted with hydraulically operated mechanical doors which can close down the face and provide support. Generally, TBMs are fitted within a shield, but see 7.6.4.4.

A safe system of work at the tunnel face, including provision for rescue, and for the inspection, maintenance and changing of cutters, should be put in place before work begins.

7.6.4.2 Slurry machines

Slurry machines are shielded TBMs with a fixed bulkhead separating the excavation chamber from the rest of the machine. Pressurized slurry pumped into the excavation chamber provides support to the excavated face and balances the groundwater pressure.

Slurry and excavated material are pumped out and then piped to the surface for separation; the clean slurry is then pumped back to the face. The high pressures and the large volumes involved can create hazards, including the particular problems of access to and maintenance of the cutter head. There should be appropriate means of clearing slurry and excavated material from the cutter-head chamber before man-entry. On most machines, head access is through an airlock.

7.6.4.3 Earth-pressure balance machines

Earth-pressure balance machines are shielded TBMs with a closing bulkhead separating the excavation chamber from the rest of the machine. They have a balanced screw conveyor to remove excavated spoil, whilst maintaining a pressure in the remoulded soil within the excavation chamber sufficient to support the face throughout the excavation process.

The plug of excavated material within the excavation chamber and/or the screw conveyor forms an impervious barrier to contain groundwater.

Conditioning agents such as bentonite, polymers and foam can be injected at the cutterhead to improve the efficiency of the machine and the effectiveness of groundwater and material control. The hazardous nature, if any, of these chemicals should be assessed.

7.6.4.4 Hard-rock TBMs

Hard-rock TBMs are used for excavating in extremely varied and variable conditions of rock hardness, jointing and water. They can be fully or partially shielded, but are usually unshielded. There is little standardization of equipment. In general, the face is inaccessible while excavation is in progress, and so, provided that persons are excluded from the moving parts, personal danger at the point of excavation is minimized.

Additional hazards can arise where there is a sudden change in rock condition. Emergency action can be difficult because of inaccessibility. Sudden changes in rock conditions should be considered as part of the risk assessment and appropriate control measures devised. Provision should be made for probing ahead of the face to ascertain the presence of fissures, faults and other changes in the ground. Probing routines should be incorporated where necessary in the operating cycle. Where cover is shallow and uncertain, probes should be made to a point above and ahead of the crown of the machine and should be plugged immediately.

In some rock conditions, unless continuous support is erected immediately behind the cutter head, falls of ground are likely. Means of installing appropriate ground support should be immediately available close to the cutter head, e.g. rock bolting equipment. In extreme conditions, the TBM should be fully shielded. In all situations, appropriate protection should be provided to minimize the risk to personnel.

7.6.5 Other tunnelling machines

Other types of tunnelling machine have been developed but have not yet achieved widespread use within the industry. They should be operated in accordance with the principles set out in this standard.

7.6.6 Segment-erection equipment

The area around the segment- and other lining-erection equipment is one of the most dangerous areas of a tunnelling machine. The visibility of the operator is restricted. The moving parts of such equipment cannot be fenced off and persons invariably have to work in confined spaces close to the structural elements being erected (see 8.3). Site personnel on and immediately behind a machine should be given clearly defined responsibilities.

The tunnel lining should be erected using a purpose-designed full circle erector where practicable. Where that is not practicable, the lining may be erected by other means, including, in order of preference:

- a roller path erector;
- a bird's-wing erector; or
- by hand with mechanical assistance such as winches with snatch blocks and roller bolts.

Wire ropes and connection pins used in lining erection should be inspected frequently as they are subject to heavy wear and damage. Figure-of-eight devices cause excessive rope damage and should not normally be used as rope terminations.

7.7 Hand-driven segmental lined tunnel without a shield

Occasionally tunnels are excavated and cast iron or precast concrete segments are built without the use of a shield. Tunnels built in this way vary greatly in size and ground conditions. In general terms, the procedure for excavation of a full tunnel face in soft ground without use of a shield is to excavate from the top downwards, securing the top and face as soon as exposed. The face is taken out in steps or benches. In firmer ground it can be safe to take the face down vertically with little or no timbering.

Particular attention should be paid to any foreseeable safety risks whilst devising and implementing working procedures for handling and erecting the segmental linings.

7.8 Drill-and-blast

Drill-and-blast methods are used for a variety of rock tunnels. Blasting patterns should be designed to reduce the risk of damage to the excavated surface, which can loosen the rock. Consideration should be given to the use of smooth blasting or pre-splitting techniques.

Apart from the hazards associated with the storage, handling and use of explosives, which are comprehensively dealt with in BS 5607, the main hazards associated with drill-and-blast techniques include noise, vibration and dust from the use of drilling equipment; and falls of ground. The risk depends upon the characteristics of the rock and its structure, on the techniques adopted for drilling and blasting, and on the materials used. The system of work should be reviewed and modified, if necessary, as experience in the prevailing ground conditions is gained.

Following blasting, and before re-entry, a check should be made to ensure that the tunnel atmosphere is fit for respiration (see also clause 15).

The risk from rock falls is most acute in the period after the blast and before temporary support, if required, is completed. Following blasting or re-entry to the tunnel face, the walls, sides, face and support systems should be inspected before normal work commences. Where temporary support is required, this should be installed in a safe manner.

Scaling should be done by mechanical means where reasonably practicable. Scaling should be carried out systematically, working towards the face. Apart from checking the area of the ground that has just been fired, areas that have previously been scaled should be rechecked. Scaling should be carried out regularly and should be checked by a supervisor. The persons carrying out manual scaling should stand to one side of the area of rock being worked. Scaling bars of adequate length should be used and appropriate means of safe access provided.

If longer-term support is necessary, it should be provided as soon as practicable after scaling, so as to maintain the overall integrity of the rock mass and to prevent minor roof falls.

Air and hydraulic drills should be mounted on a frame or on an independent self-propelled machine base (drilling jumbo). In larger faces, several drills can be mounted on the same machine base and operated independently. In small faces, air drills and pusher legs may be used.

Flying rock can easily damage tunnel machinery or services. Vulnerable plant and equipment should be checked for damage before use.

Noise and vibration arise from the use of rotary percussive tools, and exposure levels in tunnelling are normally high. See clause 19 for further guidance on noise and vibration.

7.9 Steel arches and packing

7.9.1 General

Where steel arch ribs, in conjunction with timber or steel poling, are used to provide immediate support, they should be fixed, wedged and packed up as soon as practicable after excavation. Arched support varies widely in size and geometry. The type of arch and spacing should be fully specified. Where ground conditions are variable, a supervisor who has the experience and authority to order the specification and use of arched support should always be present on site.

Recommendations relating to typical forms of steel arch and their associated risks are given in 7.9.2, 7.9.3 and 7.9.4.

7.9.2 Two-part arches

An inverted U-shaped arch with one bolted joint at the crown is commonly used in tunnels up to 3.5 m high. Care should be taken to ensure that the arch is founded on rock capable of sustaining the transmitted load, or that footplates are provided. Appropriate support to resist non-vertical loads in the arches should also be provided. If horseshoe-shaped arches are used, the foot of the arch should be effectively restrained from movement. Arches should be securely fixed to each other with ties and struts. It may also be necessary to rock-bolt the arches or to fix steel dowel pins alongside the arch in order to stop movement during subsequent blasting. The packing between arch and rock should be wedged tight and the arches should be securely packed, particularly at springing level, to stop sideways movement at that point. The bolted joint at the crown should be made correctly and all the bolts tightened through the designed fishplates. Arch rib support adjacent to the face should be checked for movement after each round is fired. During its working life each arch rib support should be checked on a regular basis. Arches used to support a top heading should be secured before lower excavation proceeds.

7.9.3 Large arches

All the criteria listed in 7.9.2 for the correct setting of two-part arches apply to large arches, but in addition the following recommendations apply.

- a) The erection procedure for large arches made from several bolted sections should be specified and should clearly provide for their safe handling and for persons to work under the supported ground.
- b) The erection equipment (which can often be mounted on excavating or drilling machinery) should be properly designed for the particular situation.
- c) Access to the bolted joints and for packing should be from properly designed platforms, stagings or mechanical/hydraulic access equipment.

7.9.4 Steel lattice ribs

In tunnels with sprayed concrete support, supplementary support is often provided by steel lattice ribs embedded in the concrete around the complete tunnel circumference. These ribs should be installed in sections corresponding to the excavation stages, with bolted joints at the bench surfaces.

7.10 Sprayed concrete

7.10.1 General

The term “sprayed concrete” is deemed to cover all pneumatically applied mixes of cement, water, additive and aggregate, including “shotcrete” and “gunite”, using wet or dry processes. Additives can include retarders, activators, accelerators, silica fume and other materials used to improve the properties of the concrete mix both during placing and in the medium and long term. Normal cement replacement materials such as pulverized fuel ash (pfa) and ground granulated blast furnace slag (ggbfs) can also be used.

7.10.2 Precautions

Sprayed concrete may be used as a rapid means of temporary support. It stops deterioration of the ground surface, secures any loose material and minimizes changes in the self-supporting characteristics of the ground.

Where reasonably practicable, sprayed concrete work should be carried out by wet-process spraying, using remotely operated spraying equipment, thus reducing the risk to the operator.

Where remote techniques cannot be used, operators should have full protective clothing and use respirators and eye protection. Any skin likely to be exposed to hazardous materials should be protected with a barrier cream. Full facilities for washing and clothes-changing should be provided. Other persons should work at a distance from the placing operations to reduce their exposure to dust and hazardous materials.

NOTE Reference should also be made to clause 16 for recommendations on the control of dust.

Supply pipes for sprayed concrete should be wired or chained at joints to prevent them from flailing about if a joint bursts while they are in use.

The dry process can cause a build-up of electrostatic charge in the nozzle, resulting in an electrical discharge which could initiate an explosion in the presence of methane or other potentially explosive materials. The dry process should not be used when tunnelling through coal measures.

7.10.3 *Sprayed concrete lining (SCL)*

In all open-face tunnelling, the major construction risk is instability of the newly excavated ground. This can be minimized by subdividing the cross-section, e.g. by adopting a top heading (crown), bench and invert construction sequence. For larger tunnels, the cross-section can be further reduced by the use of side drifts or pilot tunnels. The face may be domed and may be given a temporary sprayed concrete lining. In some cases, the stability of the face can be enhanced by the use of dowels.

When installing sprayed concrete linings, particular care should be taken to adhere to the methods agreed by the contracting parties (see also 7.2).

7.11 Rock bolting

Rock bolting, using either mechanically anchored or chemically anchored bolts, is a common method of providing temporary support or can be an element of the permanent support system.

While rock bolts can be used merely to tie back loose slabs which would otherwise be liable to fall, their more fundamental use is in preventing separation across discontinuities such as joints, fissures and bedding planes so that the integrity of the exposed rock structure can be maintained.

The pattern and type of bolting, and the length and diameter of the bolts, should be determined after study of the particular circumstances, which can vary rapidly as tunnelling progresses. The safe installation and functioning of a rock bolting system depends on its suitability for the rock characteristics and the excavation and lining methods. The anchorage should be of sufficient depth and should be designed to resist the full pull-out value of the bolt without slipping in the bore or crushing the rock locally. Load tests in situ should be carried out on representative bolts. Further guidance is available in BS 8081.

7.12 Compressed air

Compressed air (see clause 11) on its own will not always support a tunnel face, and additional face support is often necessary. Compressed air can reduce settlement caused by ground moving to fill the annular space behind the shield before grouting takes place. Very significant reductions in the number of exposures can be achieved by the use of an air-pressurized shield in preference to applying compressed air to the whole tunnel.

7.13 Geotechnical processes for ground improvement

7.13.1 *Freezing*

7.13.1.1 *General*

Water-bearing ground can be strengthened and made impermeable if it can be frozen and kept frozen. Freezing can be a particularly effective technique in silts and in gravels with silty layers that are very difficult to treat by grouting.

Freezing is often achieved by the circulation of brine at temperatures significantly below 0 °C in a closed system of coaxial pipes in boreholes in the ground. Freezing of the groundwater takes place slowly and can be impossible if there is an underground flow of water which brings in heat at a rate faster than the freezing process can extract. The development and maintenance of the freeze should be confirmed by thermocouples located in monitoring boreholes within the ground to be frozen. There is a residual risk that pockets of unfrozen ground remain, and appropriate contingency plans should be put in place.

After installation, all boreholes should be surveyed throughout their length to confirm their exact position. Boreholes that are out of position should be redrilled. Tunnel excavation should not take place within 0.5 m of a live freeze pipe.

Ground heave can result from the expansion of water on freezing and from the build-up of ice layers. This can be a hazard to overlying structures or buried services. Water mains within the freezing zone may need to be insulated.

If a timber heading is driven through frozen ground, there is likely to be a build-up of ice on timber supports. The utmost care should be taken in refilling the heading, to prevent ice from being left to form a void and cause settlement. If the ice cannot be wholly thawed or removed, subsequent pressure grouting may be necessary through pipes left in and leading to the critical areas.

In some situations personnel will have to be protected from the cold. Self-rescuers (see 14.10) appropriate for cold environments should be provided.

7.13.1.2 Liquid nitrogen

Freezing by liquid nitrogen is possible. Because nitrogen is so cold, it acts more quickly. The risks from handling a cryogenic liquid should be assessed.

Liquid nitrogen should be stored on the surface. All surface pipework should be protected from impact damage. Where possible, the freeze pipes should be installed vertically in the ground to be frozen. Where the freeze pipes have to be aligned horizontally within the tunnel or shaft, the pipework in the tunnel or shaft should be tested for leaktightness before use. Liquid nitrogen should be supplied through boreholes from the surface, which are close to the point of distribution, into the freeze pipes, in preference to being piped through the tunnel. Pipework should be sized to minimize the amount of liquid that could be discharged into the tunnel if a freeze pipe leaks or breaks. Appropriate flow control and flow limiting devices should be installed. Atmospheric monitoring equipment should be installed in the vicinity of the freeze, and of any freeze pipes in the tunnel, to detect leaks. Any cold gas that has leaked will tend to collect in sumps, and the monitoring system should take account of this. Additional emergency ventilation may be necessary.

Exhaust nitrogen should be discharged through a chimney on the surface. The prevailing wind direction should be considered when siting the chimney. The chimney should be sited well away from work areas and from site boundaries. Fans may be needed to dissipate the cold nitrogen from around the base of the chimney on calm days.

Bulk storage of liquid nitrogen should be in a secure area protected from site traffic. Because of the large quantities of cryogenic liquid likely to be required, the risks both to the workforce and to the public from its transport to site and storage on site should be carefully assessed.

7.13.2 Ground injection

Cementitious or chemical ground treatment in advance of tunnelling can usefully enhance safety particularly in open-face excavation. It does this directly by improving the characteristics of the ground to be excavated and indirectly by sealing off water, or strengthening the overlying or surrounding ground. The design of a suitable grouting system and pattern for particular circumstances is very specialized and expert advice is essential.

If sand or gravel is expected in the tunnel face, particularly if it is water-bearing, its permeability can be greatly reduced by the injection of suitable grout mixtures; cohesive strength can be added, and if the tunnel is being driven under compressed air, the air requirements can be greatly reduced.

The choice of grout mixture and the spacing and pattern of injection holes will be determined largely by the grain size of each stratum. For example, cement grout will not travel far or prove effective except in very coarse open gravel. Progressively finer grouts of lower viscosity are required in progressively finer soils. Most difficult of all are silts, which can normally be treated only by clauquage. Clays cannot be treated by permeation grouting.

The permeability of the ground is rarely consistent and the possibility of meeting untreated pockets should never be ignored. Groundwater quality should be taken into account when designing the grout.

Where excessive fines content in the ground prevents permeation grouting, or where silts and peat occur, jet grouting is an alternative. Jet grouting should only be considered where ground heave is not a problem.

Excessive pressures can cause ground heave and damage to surface structures.

Where fissured rock is to be treated, it can be difficult to locate and treat all significant fissures, especially if some are filled with gouge or soft clay. Advance ground treatment by grouting should be considered. This can be carried out from the surface, from a pilot tunnel or through the tunnel face during construction.

When compressed air is being used in a tunnel it can result in the grout being blown aside during injection.

The toxic and environmental risks from chemical grouts should be assessed. In all cases, the chemical properties of the grout used should be taken into account and the risks arising from the handling of the materials during and after mixing, including risks from burst pipes and hoses, should be assessed.

The toxicity of some grouts makes stringent precautions necessary, including the provision of protective clothing and full washing facilities. Grouting from within the confined space of the tunnel, particularly in a small pilot tunnel, can increase the risk.

Care should be taken to avoid pollution and damage at the surface from spillage and waste discharge. Arrangements for collection and disposal of waste should be made in advance and should be approved by all relevant authorities. Similar arrangements should be made with authorities responsible for the prevention of pollution of underground water.

Excavation in ground previously impregnated with cementitious or chemical grouts can release toxic gases or vapours.

7.13.3 Dewatering

For shallow tunnels in water-bearing sands and gravels, it may be possible to stabilize the ground by means of well-point dewatering. Care should be taken to prevent loss of fines from the ground. By using deep wells and “down the hole” pumps, greater drawdown of the water table can be achieved.

The main hazards of these systems are settlement at the surface due to lowering of the water table, and failure of the dewatering system whilst the tunnel is being driven. The latter causes the ground to revert to its former unstable condition and rapid and massive ground loss can follow. It is essential that the dewatering system be set up with the best available equipment and plant, that systems be duplicated where possible and that surface pipework be protected from accidental damage.

Settlement due to dewatering can affect third-party property and cause damage and injury. Consideration should be given to the following precautions:

- the use of a piezometer to monitor the groundwater level;
- the construction of recharge wells to maintain groundwater level adjacent to sensitive structures;
- the installation of cut-off walls to protect sensitive foundations.

7.14 Small headings and small tunnels

7.14.1 General

For tunnels under construction, the internal size for man-entry should be not less than 1.2 m high by 0.9 m wide, in order to facilitate rescue. Tunnels smaller than this should be constructed by methods that do not involve man-entry. Tunnels having a face area of less than 2 m² are included under this code to the extent that persons are employed inside them for excavation and construction.

Small headings are generally temporary in character and are driven in order to explore the ground ahead of the main tunnel, or for operations such as pipelaying, or to provide access between two points.

No permanent lining is required because the heading will either be refilled or become part of the main tunnel. However, any temporary support should be capable of lasting for as long as the heading remains open and be capable of securing the surrounding ground against settlement and collapse.

The risk of collapse or excessive settlement is greater with small timbered headings than with other forms of tunnel construction. Only the highest standards of workmanship in initial timbering and subsequent back filling should be used.

Because of the very confined space in small tunnels, some hazards are intensified. As such projects are often very limited in space, time and resources, it is impracticable to apply systems designed for larger projects. It is therefore essential that those working in such tunnels be familiarized with the hazards, and that a risk assessment be made to establish appropriate methodology before work commences.

7.14.2 Timber headings

The size of timber used should be appropriate for the type of ground and the size of the heading, but no timber less than 38 mm thick should be used for headboards. All timber should be checked for imperfections that could reduce strength. All materials required for the heading should be readily available as close as is practicable to the face.

Special care should be taken with laying track and maintaining clearances between the bogies and skips and the support timber.

The design and supervision of the construction of timber headings requires appropriate competence.

7.14.3 Back filling

The back filling of small headings with concrete should be carried out with the greatest care. The top 600 mm of heading should be pneumatically filled with concrete or hand-stuffed with dry concrete. If the prevention of surface settlement is critical, the heading should be backgrouted in sections, care being taken to fill all voids.

7.14.4 Rescue and escape

In small tunnels, persons cannot walk upright and can pass one another only with difficulty. It is normal practice for a single person to excavate the face, although a second should always be present.

Arrangements should be defined for the rescue and escape of the face workers in the event of accident, injury, illness, collapse of the tunnel face, immobilization of a locomotive, derailment or fire.

7.14.5 Ventilation

Ventilation can be a particularly difficult problem. There will be little or no natural circulation, and shallow tunnels through variable ground will frequently pass through or near ground with organic content or with other contamination that could pollute the tunnel atmosphere. Where contamination could occur, a forced ventilation system should be used to limit the ingress of contaminants, and a supply of fresh air to the face is therefore essential. Low-volume, high-pressure ventilation systems may be appropriate owing to the lack of space.

7.14.6 Pilot tunnels

Pilot tunnels are sometimes built to provide detailed information on ground conditions, including groundwater regimes, in advance of larger tunnels. They should preferably be lined with a structurally continuous lining such as bolted cast iron (see 8.3). The lining should be designed to facilitate its subsequent safe dismantling or excavation.

7.15 Pipe jacking

Pipe jacking is a system in which pipes or similar structures (see 8.3.4) are thrust through the ground and the material from the face is removed through the pipeline, having been excavated mechanically or by hand. The pipes are introduced at the working pit and cumulatively thrust forward by jacks. The leading pipe is preceded by a shield or TBM (see 7.6), which enables the pipeline to be kept on line and level by using jacks for steering.

NOTE Further information on pipe jacking can be found in *An introduction to pipe jacking and microtunnelling design* [20] and *Guide to best practice for the installation of pipe jacks and microtunnels* [21].

The high thrusts necessary to propel the pipe forward should be resisted by a properly designed and constructed abutment or thrust wall at the working pit. Hydraulic rams and any load-spreading rings, spacing blocks or packers should be carefully secured, with all loaded surfaces precisely aligned perpendicular to the thrust. As far as possible, persons should be protected from and withdrawn from the vicinity of highly stressed equipment during thrusting. Hydraulic pipes and, in particular, flexible hoses, should be properly protected from crushing and impact damage.

The use of bentonite grout or other lubricant injected through the pipes on to the sliding surfaces can assist in reducing thrusts. If lubricants are injected at high pressures, eye protection should be provided.

When jacking pipes through loose or water-bearing soils, a slurry machine or an earth-pressure balance machine should preferably be used to contain the face safely. Alternatively, if using an open shield, precautions should be taken against a run of loose material into the face of the shield, which could lead to the collapse of the overlying ground. When jacking pipes into firm or stiff clays, the techniques adopted should take into account any displacement of the soil caused by entry of the pipes, and possible heave of the ground surface. Particular care is necessary when jacking pipes beneath railway tracks, rivers, canals, other water courses and sensitive structures.

Jacking pipes are installed via a working shaft and joined using hydraulic jacks. It is essential that all persons seek shelter or protection within the part-completed pipeline or elsewhere whilst pipes are lowered.

For small-diameter pipe jacks, arrangements should be made for the rescue and escape of face workers in the event of accident, injury or illness. Alternatively, remotely controlled TBMs may be used to carry out the excavation without any persons entering the tunnel. Ventilation can be a problem, as with small headings and tunnels (see 7.14.5).

7.16 Soil conditioners and lubricants

Compounds such as bentonites, polymers and foams are increasingly being used to support the face in unstable ground conditions, to lower pipe jacking forces (see 7.15) and to improve spoil characteristics for transport from the face to the surface. These materials are collectively known as soil conditioners. Many of these materials are hazardous to health in their preparation and/or usage.

Some of the materials present a hazard in their disposal. Consideration should be given to both the physical and the chemical properties of the soil/conditioner mixture in determining the appropriate method of disposal, in order to minimize risks to the environment and to the public.

The risk assessment for the tunnelling process should take account of any health hazards resulting from the use of these compounds.

The manufacturers' safety data sheets, which give recommendations for handling and personal protective equipment, should be complied with.

Materials used as soil conditioners include those given in Table 4. This should not be regarded as a comprehensive list. New materials are continually being introduced and reference should be made to the manufacturer for information relating to their composition, associated hazards and safe use.

Table 4 — Soil conditioners

Material	Principal components	Typical use	Hazard
Bentonite	Sodium, Potassium, Calcium montmorillonite	As a slurry in slurry shields and to modify the soil in EPB machines; as a ground support and lubricating medium round jacked pipes and in TBMs.	Respirable dust in dry state. Slippery when wet. Skin irritant.
Polymers	<i>Artificial:</i> — polyacrylamides — polyacrylates — carboxymethyl cellulose	Additives to bentonite to modify viscosity. Lubricant.	Generally considered to be non-toxic, but refer to safety data sheets for specific hazards and relevant control measures. Slippery when wet.
	<i>Natural:</i> — starch — guar		
Foams and foaming agents	<i>Synthetic foams containing:</i> — synthetic detergents — glycol ether foam booster — fluorocarbon	For modifying soils to improve handling characteristics.	Toxic, irritant. See safety data sheet for hazards and control measures.
	<i>Protein foams containing:</i> — protein foaming agent — glycol based foam booster		
Other materials	Hexylene glycol	Solvent used with foam.	Toxic, irritant. See safety data sheet.
	Ethylene glycol ether	Solvent used with foam.	Toxic, irritant. See safety data sheet.
	Soda ash	Increase pH for use in acidic conditions.	See safety data sheet for specific hazards and control measures.
	Lime	Possible modifier to improve characteristics at disposal state.	
	Cement		
	Lignosulfonates	Dispersants, thinners in bentonite slurries.	
	Complex phosphates		

7.17 Settlement control

For shallow tunnels in urban areas, control of surface and subsurface settlement is important. If use is made of compensation grouting (where grout is injected into the strata overlying a tunnel to compensate for ground loss from tunnelling operations), the load effects of such grouting on the primary and secondary tunnel linings, on the face stability and on adjacent structures and services should be considered during the design and construction of the tunnel

8 Permanent support

8.1 General

The majority of tunnels require some form of permanent ground support. This can include temporary support followed by a permanent lining, or a lining which itself permanently supports the ground. Some tunnels include a non-structural secondary lining to improve the functional performance of the tunnel. The design of the ground-support system, whether temporary or permanent, should be carried out only by engineers with the necessary experience and knowledge of the subject. Rock bolts, rock anchors and dowels may be incorporated in the permanent support.

In designing the tunnel lining, matters taken into account should include the information available and the investigations, as described in clause 5. Alternative vertical and horizontal tunnel alignments may have to be considered. A number of methods of construction may be available. The tunnel design will be based on a particular method that is deemed to be safe and appropriate for the ground conditions, but other methods may be used by the contractor provided that they are equally safe and appropriate.

The support system specified should be designed for ground loadings and hydrostatic pressure and for external and internal special loading arising from such factors as adjacent foundations, piles, water pressures and traffic loads. Temporary loading can arise from the transfer of shield jacking loads or the application of compressed air.

Handling requirements should be considered as part of the design process, so that structural elements can be set in place without damage.

8.2 In-situ linings

In-situ linings generally take the form of a concrete lining that is either placed behind formwork or sprayed on to the internal surface of the tunnel. Adherence to good practice in the production, placing and compaction of concrete will increase its durability and reduce maintenance and the risks associated with such work. Concrete should be specified, produced, transported and tested in accordance with BS 5328-1, BS 5328-2, BS 5328-3 and BS 5328-4.

Formwork is usually constructed so that it can be moved along the tunnel and reused. Accordingly, it should be made as light and as easy to handle as possible, but its strength and rigidity should be adequate for loads imposed both by the wet concrete and by handling procedures. Inadequate formwork can lead to considerable difficulties in the tunnel. Such difficulties could encourage improvisations that result in unplanned and inherently dangerous situations and a poor quality of lining.

The equipment employed for depositing concrete behind formwork can include a concrete pump or placer. Placers often discharge the material at high velocity. The discharge nozzle should therefore be properly secured and guarded, and any joints in the supply pipes secured to prevent the pipes from flailing about if a joint bursts during concreting. No person should be required to work in the immediate vicinity of a high-velocity discharge pipe or hose.

With sprayed concrete, the hazardous area is more extensive, since no formwork is provided. To reduce exposure to hazardous materials, remote spraying techniques should be considered (see 7.10).

Arch ribs with lagging, or other systems, may be employed as part of the permanent in-situ lining. If so, they will generally be built in, possibly with additional ribs or reinforcement, as appropriate. The building in of untreated softwood timber should generally be avoided (see 7.9).

8.3 Prefabricated linings

8.3.1 General

Prefabricated linings are most commonly used for circular tunnels and are sometimes used for oval or other cross-sections.

This type of lining can be considered under three general categories:

- a) bolted or other structurally rigid systems that are self-supporting and outside which grout or other material has to be injected to complete the support system;
- b) expanded systems that are forced against the ground by circumferential thrust, thus applying immediate support to the ground;
- c) jacking pipes (see 8.3.4).

8.3.2 Segments

Segmental linings consist of a number of units (segments) which make up a “ring”. These units are usually of cast iron or precast concrete, but steel or other materials can be used. The segmental nature of units necessitates the adaptation of ordinary equipment and the provision of special devices for their safe and efficient handling and erection. Segments should be provided with sufficient holes or attachments to allow for safe handling at all stages. Quick-release attachments, such as segment lifting “fingers”, should be employed only where their design prevents the accidental displacement of the load. Pneumatic (vacuum) lifting may be considered as an alternative that saves the need to provide holes and concentrated loading points.

Any problems arising from the lifting, transportation, handling and erection of the units should be considered before manufacture.

Segments should be stacked, preferably on level ground, so that they are stable and will not be damaged. Segment stacks on the surface should be arranged so as not to impose additional loading on tunnel excavations or overload the ground on which they rest. Stacks of segments should be designed, located and constructed to facilitate safe handling.

8.3.3 Transportation and erection

A safe slinging method should be used to transfer segments from the surface to the pit bottom. Within the tunnel, segments are normally transported on a bogie. A positive means of attachment or a specially shaped bogie should be provided so that loads cannot shift during transit.

Segment transfer and erection systems should be provided wherever practicable, but the handling arrangements at the face almost inevitably involve some manual handling, at least in guiding the units into position. There are various types of segment erector, which can be mounted either on the shield or on a towed staging (see 7.6.6).

The choice of system should be determined by the design of the lining to be erected and the space available for segment erection. In a small diameter tunnel where segments could need manual handling, pipe jacking should be considered. In all cases, it is essential that the procedure for the handling and erection of segments be carefully planned and that the erection personnel be properly trained to keep clear of danger points, and that others be kept away from the working area. Manual handling aids should be provided for all lifts over 25 kg.

The designated operator of an erector or erection winch should be situated where there is a clear view of the whole operation, so that it can immediately be halted, if necessary. Alternatively, the erector operator may be provided with alternative control points, control panels on wander leads or radio control of the erector. If a clear view is not obtainable, the use of CCTV may be necessary. The erection personnel should be properly equipped with appropriate hand tools for handling segments, and with an adequate supply of timber or steel wedges and packings if required.

Shove ram thrust (nip) should not be relied upon as the sole means of supporting segments, particularly when upper segments are in place but the ring is not complete. All segments should be positively supported.

Where manual assistance is necessary, erection gantries should be constructed to provide a safe place of work and means of access.