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British Standard Code of practice for

Safety in tunnelling in the construction industry

Code de bonne pratique pour la sécurité des tunnels dans l'industrie de la construction

Leitfaden für die Sicherheit beim Tunnelbau in der Bauindustrie

British Standards Institution

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This code of practice represents a standard of good practice and takes the form of recommendations. Compliance with it does not confer immunity from relevant legal obligations.

Foreword

This code of practice aims to define good practice in the construction of tunnels with the principal objectives of improving safety and harmonizing the precautions to be adopted.

The recommendations have been prepared primarily for the guidance of those responsible for tunnel construction on site but also to assist engineers designing tunnels so that provision can be made in specifications for the elimination of unnecessary hazards.

Emphasis throughout the code has been placed on safety, particularly the safety of those engaged in tunnelling operations and the safety of others who may be in the vicinity of the work.

Tunnels driven through the Coal measures will often be affected by the hazards more commonly associated with mineral workings (see note) and although the code makes reference to such matters as precautions against fire and explosion these references should be regarded as indicative only. In such conditions tunnelling should not be started until a safety routine has been established under the control of an experienced engineer.

NOTE. Workings for minerals may not be started without the approval of HM Senior District Inspector of Mines and Quarries.

The code lists the current legislative requirements appropriate to tunnelling and makes reference to IFA Report 44 'Medical code of practice for work in compressed air'. These should be studied and carefully followed.

British Standard Code of practice for

Safety in tunnelling in the construction industry

Section one. General

1. Scope

This code of practice makes recommendations for safe practices in tunnelling.

The code does not include recommendations for cut and cover tunnelling or immersed tube tunnels, nor does it apply to the construction of tunnels for the purposes of the winning of minerals.

NOTE. The design, manufacture and use of plant and machinery are referred to only where safety considerations are affected.

2. References

The titles of the publications referred to in this code are listed on the inside back cover.

3. Definitions

There are no definitions used in this code that are particular to the code itself. The terms are those in common use in tunnelling operations.

4. Legislation

The principal legislation, current at the date of publication of this code, affecting safety in tunnelling or relating to operations associated with it, is contained in the following:

- the Health and Safety at Work etc. Act, 1974;
- the Factories Act, 1961;
- the Public Health Acts, 1961 and 1969;
- the Control of Pollution Act, 1974;
- the Employment Medical Advisory Service Act, 1973;
- the Coal and Other Mines (Shafts, Outlets and Roads) Regulations, 1960.

Regulations made under these Acts, with any amendments, include:

- the Work in Compressed Air Special Regulations, 1958;
- the Construction (General Provisions) Regulations, 1961 (SI 1961 No. 1580);
- the Construction (Lifting Operations) Regulations, 1961 (SI 1961 No. 1581);
- the Construction (Working Places) Regulations, 1966 (SI 1966 No. 94);
- the Construction (Health and Welfare) Regulations, 1966;
- the Protection of Eyes Regulations, 1974;
- the Highly Flammable Liquids and Liquefied Petroleum Gases Regulations, 1972;
- the Asbestos Regulations, 1969;
- the Electricity (Factories Act) Special Regulations, 1908 and 1944.

If, on any particular site or part of a site, the regulations are are not directly applicable to tunnel work their requirements

should nevertheless be complied with to the greatest practicable extent as if embodied in this code.

Section two. Planning and organization

5. Organization and administration

5.1 General. While this code is primarily directed to safety in the execution of tunnel construction at site, all preparatory planning and design is directly relevant.

The parties normally concerned are as follows:

- (a) the promoter of the project;
- (b) the engineer, responsible for the design and supervision of the work, for ensuring compliance with specifications, and represented on site by the resident engineer;
- (c) the contractor, responsible for the execution of the work, for providing the labour and physical means for construction, and represented on site by the agent;
- (d) public authorities applying statutory and administrative regulations and control through the Factory Inspectorate and otherwise.

5.2 Precontract organization. Before a contract can be let the promoter and engineer will plan the project. If special hazards or abnormal conditions are expected which come within the responsibilities of statutory authorities they should be fully consulted.

When tenders are invited any special responsibility of the contractor for safety aspects of planning or design should be made clear.

Promoters and engineers need to appreciate that safety involves expenditure and that contracts should be so drafted as to ensure that contractors are obliged to make full and proper provision for those costs. In particular, it should be policy to ensure that, as far as is practicable, the extent and adequacy of the safety measures are not the subject of competition in tendering, and also that the contractor's complete responsibility for the safety of the work and men remains clear and unambiguous and is in no way abrogated (see clause 7).

The safety staff required and the organization and provision of medical and other facilities may with advantage be specified in detail in the contract document, with appropriate items to be priced in each tender.

As part of the tender, contractors should be instructed to submit particulars of qualifications and experience of key staff who will be employed on site, since appropriate skills and experience are essential prerequisites of safety. Details of the contractor's training programmes for new employees should also be requested. Similar high standards of skill and experience, together with appropriate qualifications, are also

necessary where a promoter employs direct labour.

5.3 Contract site organization

5.3.1 Contract site management. The Construction (General Provisions) Regulations, 1961 require the appointment of a safety supervisor by contractors working on sites.

On safety matters, it is essential that the person appointed be given adequate authority, with support from the agent and resident engineer.

An interest in safety matters at all levels should be encouraged. Possible methods include incentives and rewards for good site safety records, and the use of large notice boards comparing the number of accidents with days worked.

On a well-run site, there should be no conflict between production targets and safety, providing that preplanning takes account of both and that basic safety standards are regularly observed. Top management should insist on both these aspects and take an active interest in ensuring that their site staff are adequate to cope with both production and safety.

The contractor should be responsible for the recruitment of sufficient suitably experienced labour for the safe execution of the work and for proper supervision at all levels and in all capacities.

The site should be surveyed to anticipate likely hazards as early as is practicable by the contractor, with any necessary investigations and tests carried out, and contingency plans drawn up. At frequent intervals thereafter, the hazards should be monitored and the prevention of accidents reviewed in detail (see 5.4.1).

It is important that a chain of authority and of communication be defined and established from the beginning so that all relevant information is given quickly to those responsible for assessing it and acting on it. This is particularly important in respect of information concerning safety at the tunnel face.

5.3.2 Temporary works. Temporary works of a substantial character are almost invariably necessary in tunnel construction. They may constitute an essential phase of the permanent construction, as in the case of a pilot tunnel, a working shaft, or framing to form an opening, or they may be structurally independent incidental works, such as working gantries, access stairways, access roads, etc. It is essential that all these works are properly designed and that appropriate drawings, calculations and specifications are prepared in advance, subjected to an independent check, and worked to. Changes should be made only after consultation with the designer. The main contractor should appoint an engineer from his site staff as coordinator of temporary works to ensure proper design and checking and compliance with safety requirements. This is particularly relevant to larger contracts where several subcontractors may be employed whose temporary works may not otherwise receive proper scrutiny and attention.

In tunnelling, one aspect of special relevance is that the adequacy of temporary support may be critical to the loading and stresses in the permanent structure.

Procedures for face timbering, for break-ups and for the construction of openings should therefore be properly designed and subjected to the same supervision as the permanent construction and to the same standard of workmanship.

5.3.3 Supervision and inspection. While the contractor

should be fully responsible for the safety of the work under his control, independent experienced site supervision and inspection by the engineer's and/or client's staff can contribute much in establishing safe working.

Judgement of varying ground conditions is necessary at every stage in tunnel construction and it can be vital to safety to anticipate hazards and to decide on the appropriate action without delay.

Frequent inspection (or if ground conditions are bad, continuous inspection) by experienced men employed by the engineer can be of great value in ensuring that safety aspects are not overlooked. It is particularly important that daily inspections by reliable men employed by the contractor should be made when work is not continuous, namely at weekends, holidays or other interruptions. In all cases, the precautions indicated in 16.4 should be observed.

The person responsible for the design should be adequately represented on site. Any modifications necessitated by changes in ground behaviour should be notified as quickly as possible to the responsible engineers.

5.3.4 Statutory controls. Statutory control of works of engineering construction is exercised under the Health and Safety at Work etc. Act, 1974 and the Factories Act, 1961, in particular Section 127. Administration is by the Health and Safety Commission through the Health and Safety Executive (HSE). The Factory Inspectorate should be consulted regarding relevant notices, registers, forms and other notifications.

Unless the work is to be completed within 6 weeks, the undertaker of the work is obliged to notify the Principal Inspector of the District within 7 days of its commencement.

Over and above the minimum requirements the inspector should be given wherever practicable 7 days advance notice of the intention to start:

- (a) tunnelling;
- (b) shaft sinking for tunnelling;
- (c) compressed air working.

Statutory Regulations require certificates, reports and other documents to be made available to the Factory Inspectorate. There are, of course, other statutory obligations not specific to engineering construction.

5.4 Accidents and dangerous occurrences

5.4.1 Accidents. All accidents, whether or not they result in personal injury, are to be reported to the contractor's site management by the individual involved or his immediate superior. Accident records are to be kept and accidents reported in accordance with HSE regulations. These records should be studied and analysed by the contractor and the safety committee at frequent intervals to highlight the frequency and cause of accidents so that steps can be taken to prevent a re-occurrence of similar accidents.

It is important that visitors report to the contractor on arrival and that they have his agreement to the site visit. They should also check whether the contractor's insurance covers them in case of accidents.

The principal causes of personal accidents are categorized in table 1, together with particular examples illustrating their relevance to tunnelling. The major hazards are dealt with more fully elsewhere in the code, but it should be emphasized that minor hazards can be serious to the individual.

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Table 1. Principal causes of accidents

Accident category	Detailed examples	Prevention and principal references	Other references
1. Falling from a height	Fall down shaft Fall from staging at face	Proper barriers Secure decking. Barriers where practicable	21.6
2. Falling on the level	Tripping or slipping on walkway	Handrails, even non-slip surface, cleaning of surface, good lighting	18, 24.3
3. Materials falling from a height	Tools and small items dropped or kicked off staging or from top of shaft	Toe boards. Proper stacking and storage. Hand tools provided with thongs	21.6
	Slung loads dropped	Proper slinging and loading. Loading areas kept clear. See CP 3010 and BS 4898	21.6, 22.2
4. 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	
	Loads falling from vehicles	Loads properly stacked and secured. Level road or track well maintained	
5. Burial by fall of material	Collapse of face	See clauses 8 and 10	
	Rock falls	Barring down of loose rock. Immediate support	8.8
	Collapse of stacks or stockpiles	See item 4	
6. Flooding or inrush of water	Broken sewer or pipeline, ground water, etc.	See clause 12	
7. Lifting machinery	Cranes and hoists	See clause 22	
	Hoisting and placing of segments at face	Appropriate equipment properly maintained. Safe procedures enforced	10.3.3
8. Other machinery	Excavating machines	Exclusion of men from digging zone. Safe procedures defined and enforced. See clause 8	
	Grouting operations	Robust equipment properly maintained. Operation by trained men	
	Conveyors	See 24.2.1	
9. Vehicles	Locomotives and rolling stock	See 24.1	
	Road vehicles	See 24.2.4	
10. Electrical installation		See clause 25	14.3
11. Fire and explosion		See clauses 13, 14, 15	11.3, clause 25
12. Atmospheric pollution		See clauses 13, 16	11.4

5.4.2 Protective wear. Personal protection equipment should be worn by any man exposed to substantial risk on the following basis.

(a) *Head protection.* All persons should wear protective headwear at all times.

(b) *Foot protection.* Strong boots, preferably with steel sole plates and toe guards, should be worn at all times; in wet tunnels, heavy rubber knee boots may be appropriate.

(c) *Hand protection.* Suitable gloves should be worn where a man is particularly exposed to cuts, burns, electric shock, corrosive and irritant substances. Elbow length gloves should be worn when grouting. Barrier creams should be available.

(d) *Eye protection.* The Protection of Eyes Regulations, 1974 (SI 1974 No. 1681) are to be observed. Safety goggles, face shields, and fixed shields are to be provided, as appropriate, for protection against flying particles, hazardous substances or injurious light rays.

Eye protectors should always be worn by operators when sandblasting, shotblasting, air and water cleaning, spraying concrete, grinding or chipping metal, burning and welding, grout mixing and placing. Where there is a foreseeable risk of injury they should always be worn by operators breaking, cutting or drilling concrete or stone or similar material, and by operators injecting liquids under pressure.

(e) *Body protection.* Protective clothing should be waterproof where appropriate. Special clothing may be necessary for those handling injurious substances.

(f) *Ear protection.* See clause 20.

(g) *Lung protection.* Suitable respiratory equipment should be used where there is unavoidable excessive exposure to harmful fumes or dust. Elimination of the hazard should be the primary aim, then ventilation to transfer it elsewhere and dilute it, and lastly the use of suitable respiratory equipment.

5.4.3 First aid organization. Obligatory first aid requirements are prescribed by statutory legislation. Some of these requirements are briefly included in 5.4.4 to 5.4.8 and in some cases supplemented, but direct reference should be made to the legislation for full details. Potential hazards in tunnelling make the availability of trained first aid personnel essential; on each shift during the main period of construction a named person should be available to give first aid assistance when required. Both contractor and engineer should consider sending a proportion of their senior personnel, including foremen and inspectors, on first aid training courses, either full time or during off-duty time with, say, financial incentives.

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

5.4.4 First aid boxes. A sufficient number of first aid boxes clearly marked 'FIRST AID' should be provided; they should be adequately equipped as set out in the Regulations. Boxes should be readily accessible to working areas and should be in the charge of the designated first aider on each shift.

5.4.5 Stretchers. Stretchers (complete with blankets) suitable for hoisting on a crane or winch hook 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, a stretcher should, where practicable, be stored at tunnel level. Means of safely transporting an injured man to the surface should be ensured (see 22.2.5).

In the event of serious injury, a patient should not be moved until qualified medical personnel can reach the area, unless there is an immediate chance of further injury.

5.4.6 Ambulances. The Regulations require that the local ambulance service be notified in writing of sites employing more than 25 persons; that a responsible person (and a nominated deputy who is readily available) be appointed with the duty of summoning an ambulance if required; and that notices be affixed on site naming these persons and giving instructions 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.

On a tunnel site these requirements should apply even if fewer than 25 persons are employed. In particular, care should be taken to ensure ready vehicle access to the top of any working shaft or adit in the event of an emergency.

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

5.4.8 First aid training. The normal minimum qualification is the holding of a certificate in first aid issued within the previous three years by a recognized training organization. Such organizations include the St. John Ambulance Association, the St. Andrew's Ambulance Association, and the British Red Cross Society.

5.5 Labour: recruitment and training

5.5.1 Recruitment. In the recruitment of labour for tunnelling work it is essential that a high standard of physical fitness is ensured. The provisions of the Employment Medical Advisory Service Act, 1973 also apply.

In respect of persons under 18 years of age it is advisable that they produce a medical certificate of fitness. For certain operations such as crane drivers and signallers there is a statutory requirement to employ persons over 18 years of age. In general, it is desirable that all operatives below ground are more than 18 years old.

The principles to be applied to all tunnelling operations include regular inspection by competent and experienced persons, execution of work under the direction and supervision of competent and experienced persons, and execution of work by competent workmen possessing adequate experience. It is accordingly of the utmost importance that suitable men are given responsibility for the functions of:

- (a) inspection;
- (b) supervision;
- (c) direction.

Experience in the work to be done should be considered essential for a substantial proportion of the men recruited. Should the recruitment of experienced and competent men

be difficult, a training course should be set up, with particular emphasis placed on training shift supervisors who are the key men in the day to day safety programme.

5.5.2 Training. A general requirement to provide training as necessary to all employees is required by law as is the training of specific operators such as crane drivers, signallers, compressed air lock attendants, locomotive drivers and first aid men.

Training in tunnelling, outside the mining industry, has in the past been almost entirely a matter of site experience, with no specific training courses available. Skills of more general application, such as timbering of excavations, are the subject of training courses, but tunnelling skills as such have been learned on site. The most vital contribution to safety in any tunnel is a trained and disciplined workforce. If experienced men are in short supply, then on-site training should be given. In any event, new employees should be taught the rudiments of the tasks they have to do, especially with regard to safety. Promoters and engineers should encourage contractors to institute training programmes by requiring details in the tender documents (see 5.2), so that contractors can price accordingly.

It is highly desirable that operators of specialized tunnelling plant such as mechanical excavators (both cutting heads and full face), lining erectors (including winches) and grout pans be experienced in general procedures in tunnelling; they should therefore have spent at least 6 months working below ground under comparable circumstances. Whenever possible, staff employed for the maintenance of mechanical plant should have served an appropriate apprenticeship or similar training; however, a reasonable proportion of this staff may well be trainees. Reference should be made to the operative's registration grading, under the industry registration scheme, for the appropriate level of competence that has been obtained.

Staff employed for 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 and competent for the work.

5.6 Records and reports

5.6.1 Physical aspects of tunnel construction. The keeping of proper and adequate records of the physical aspects of tunnel construction is of the utmost importance. This is not only for safety during construction but for future safety in any necessary maintenance and repair work, and also in any future tunnelling or other works in the vicinity.

The preservation of records for future reference and use should be the responsibility of the promoter, subject to delegation of that responsibility in the event of the establishment of any regional or central registry for the purpose. Any construction contract should provide for such records to be prepared and handed over by the contractor.

The minimum record to be preserved should be a longitudinal section based on day-to-day records of the strata encountered, correlated with any available borehole records and with any abnormal ground water levels, tidal and river levels and rainfall. Settlements and movements of the tunnel supports and the ground above the tunnel are particularly important and should be recorded.

Progress in excavation and lining, with a note of the type of lining used, should be noted at least on a weekly basis, together with areas of overbreak or special difficulty.

Any continuously monitored or frequently measured data, such as surface settlements, dry and wet-bulb temperatures, dust conditions, and methane content of air, should be recorded as fully as practicable.

6. Information and investigation

6.1 General. All reasonably accessible information relevant to the construction of a tunnel should be obtained before construction starts. Special site studies are almost always essential before tunnel construction can proceed, and are a continuing activity during construction.

Safety can depend critically on adequate investigation and proper interpretation of the information obtained. There should be the fullest practicable disclosure of all relevant information, or gaps in information, to those responsible for construction.

The requirements set out in 6.2 and 6.3 should be treated as a check list and in no sense as a comprehensive specification. BS 5930 deals with site investigations in much greater detail. Further guidance may be obtained from TRRL Reports LR 403, LR 625 and LR 740* to which reference should be made.

6.2 Preliminary studies

6.2.1 Topography. Ordnance Survey maps and plans normally provide sufficient detail for the preliminary studies and for the siting of the works. Up-to-date information not yet embodied in published maps can be obtained from the regional offices of the Ordnance Survey and the local authority, to whom enquiries should be directed. Rights of way are shown on recent editions of the 1 : 63 360 (one inch) and 1 : 50 000 maps but further information is recorded in the Maps Library of the Department of the Environment. Old editions of maps may be important where they record workings and structures, and watercourses now abandoned and concealed. Aerial photographs of many areas are held by the Ordnance Survey, local authorities and air survey organizations.

In tidal waters and coastal areas Admiralty charts show the topography of the bottom and its nature.

6.2.2 Geology. The published maps, both solid and drift editions, of the Geological Survey, supplemented by much extra information accessible in the published and unpublished records of the Institute of Geological Sciences, provide the essential background to tunnel siting and construction.

Other material which may be of use includes soil maps and memoirs of the Soil Survey of Great Britain and land utilization maps.

6.2.3 Hydrology. Records of surface water levels and flooding are usually obtainable from the Rivers Division of the appropriate regional Water Authority. In tidal waters Admiralty charts and other Admiralty publications provide essential information, which may 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 are published by HMSO in 'Surface water year book for Great Britain'. All appropriate records and predictions should be fully examined in the case of exposed areas.

* Transport and Road Research Laboratory Reports LR 403 'Preliminary sources of information for site investigation in Britain', LR 625 'Guidance on planning, directing and reporting site investigations'; LR 740 'A guide to site investigation procedures in tunnels'

6.2.4 Existing structures and services, and old workings.

Knowledge of structures and earthworks should be sought within any possible zone of influence of the tunnel excavation. Plans of buildings and other structures in possession of the owners or deposited with the local authority should be examined both from the point of view of ground support required within the tunnel and of danger to the existing structure from settlement.

Industrial works and waste disposal sites, in operation or defunct, can constitute a special hazard to tunnelling particularly if noxious substances have seeped into the strata to be tunnelled. Ground anchors, whether permanent anchors providing support to existing structures or temporary anchors abandoned after temporary use for construction purposes, should be fully investigated as being both a hazard to tunnelling and liable to be detrimentally affected by tunnelling operations. Similar considerations will apply to piles and piling records should be consulted where available.

Enquiries should be made for records of wells and boreholes in the area to minimize the danger of breaking into old wells, and also to provide information on water table levels. Records of previous tunnel construction may provide valuable information. Learned societies and libraries may also give evidence of previous land use.

In mining areas, the fullest information on existing and abandoned coal mines kept by the National Coal Board should be consulted, but this may be incomplete in respect of older workings. Enquiries should be made as to any records of methane gas. Records of other mines and quarries are kept by the Mining Record Office of the Safety and Health Division of the Department of Trade and Industry. Local knowledge of pits, adits and workings may be available, and may be supplemented by aerial survey photographs.

The fullest practicable information on services should be obtained from British Telecom, electricity, gas, water and drainage authorities and any other bodies having underground services. It should be noted that trunk mains and services may be the separate responsibility of national rather than local or area authorities.

6.2.5 Weather. The influence of local weather conditions on tunnel construction should be taken into account.

6.3 Special site studies

6.3.1 Boreholes. Boreholes, vertical and inclined, should be sited to provide information specific to the tunnel under construction and to supplement the geological and hydrological information obtained from maps and records. They should be located close to the tunnel but not so close as to intersect it, unless for some special reason. A borehole too close to or intersecting the tunnel constitutes a serious hazard if water is present and particularly when compressed air is in use. In any case all boreholes need to be properly refilled, including the use of an adequate concrete plug. The siting of a borehole where a shaft is to be sunk makes possible the correlation between the borehole data and the actual ground experienced.

The number of boreholes to be provided depends on the length of tunnel and on the character and variability of the ground. There will normally be a need for the original pattern of boreholes to be supplemented by additional boreholes to check areas of doubt and to resolve special problems appearing at the construction stage. It is never safe to assume continuity of strata between boreholes or to join up apparently similar horizons.

For tunnelling, it is important that some boreholes are taken to a depth well below the anticipated tunnel invert and adequately sampled and recorded. Automatic data recording techniques should be considered. Samples of subsoil and ground water should be properly identified, labelled and photographed where necessary, and stored for further examination if required. Expert supervision of boring operations and of sampling is essential if their full usefulness is to be ensured.

Where practicable, valuable additional information can be obtained from large diameter auger borings in which the strata can be examined in situ, or from test pits or shafts. Precautions against loose ground, water, gases and other hazards are necessary when boreholes and pits are inspected.

6.3.2 Probing ahead. Horizontal probing ahead of the tunnel face can provide valuable additional information. For large or difficult tunnels a pilot tunnel may be the appropriate method, providing both information on the nature and behaviour of the ground in advance of the main tunnel and added facilities for construction, ground support and ground treatment.

Probing from the face as it is advanced should be made possible in all tunnels. The extent to which it is actually utilized depends on the hazards in question and on minimizing interruptions to progress. The hazards which may call for such investigation include faults and fissures, cavities, ground water, loss of safe overhead cover and methane gas. In extremely bad conditions probing ahead in all directions may be necessary, combined with ground treatment, but care should be taken when drilling to ascertain cover to avoid penetrating aquifers above the tunnel. Suitable equipment should be used to prevent the inrush; should an inrush occur, it should be stemmed immediately to prevent equipment being driven back by water pressure.

6.3.3 Geophysical investigation. The methods most readily applicable to tunnel conditions are seismic and electrical ground resistivity surveys. Their usefulness is limited but they can supplement borehole information, principally in tracing well defined underground strata when boundaries between them have been clearly identified in boreholes.

The use of geophysical methods in combination with horizontal probes may be valuable. In urban areas, geophysical methods are not usually applicable, except to a very limited extent, because of interference by existing services and structures.

For a subaqueous tunnel, a marine seismic survey, e.g. sparker survey, may be of assistance in charting the river bed, determining bedrock surface, discovering buried channels and locating site investigation boreholes.

6.3.4 Topography and surface survey. It is essential that an accurate site survey be made for the purposes of setting out and tunnel construction, and this is normally a contract requirement. This survey should define accurately the relationship of the tunnel to all existing structures and other features that might be affected.

An aerial survey can provide valuable additional information particularly for a major scheme.

Reference points, which are related to Ordnance Survey reference points, for the coordinate grid system of the survey should be established and preserved, as should adequate benchmarks for levelling.

Among the existing features that should be identified and recorded are manholes and valve covers, which help in the location of existing sewers, and buried services.

6.3.5 Underground survey. In addition to the surface topography, any underground structures should be accurately related to the proposed tunnel. A detailed survey to a stated order of accuracy may be a contract requirement prior to tunnel construction.

Among the structures to be surveyed are existing basements and foundations (owner's plans should, if possible, be verified by actual survey), existing headings, tunnels and underground workings, main sewers, and underground services generally. Any ground anchor cables which can be located should be accurately surveyed.

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

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

6.3.7 Ground water tests. Where water levels in the area are variable or may be affected by the tunnelling operations, observation wells to observe and record any variation of levels are desirable and may be required preliminary to or during construction. Water levels in boreholes should be recorded, and any perched water tables or artesian supplies should be identified if possible.

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

Where tidal variations can be critical, as in compressed air working, tide gauges should be provided.

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

6.3.8 Gas. Where any reason exists to suspect that natural or other gas may be present in the ground to be opened by the tunnel or shafts, tests should be carried out to ascertain the mode of its occurrence and the hazards it may present at the level to be tunnelled.

6.3.9 Ground investigation during construction. It may be necessary to continue ground investigation during construction and this can be part of the probing operation (see 6.3.2).

7. Contingency planning

7.1 Assessment of hazards. While the incidence of hazards is not predictable, possible hazards should be considered and plans made for either their elimination if they are probable, or the reduction of the severity of their effect if they are unlikely.

At an early stage, the contractor, preferably in conjunction with the supervision of the promoter, should prepare a tunnel hazard analysis considering the following questions.

- (a) What hazards are there?
- (b) How probable is each hazard?
- (c) If the hazard should occur, what is the danger to life?
- (d) What is the extent of possible damage to the tunnel?
- (e) What damage could result outside the tunnel to other interests?
- (f) What are the appropriate precautions and when should they be taken?

Possible, even if very improbable, emergencies should be considered and each should be the subject of contingency

planning so that all concerned are prepared and know how to take the appropriate action.

This analysis should be considered by the employers of persons on site with regard to their responsibilities under the Health and Safety at Work etc. Act, 1974, and by a site safety committee where formed.

7.2 Need for review of methods of working. Conditions in a tunnel may be considered abnormal when a natural hazard occurs unexpectedly. When such conditions are encountered the situation should be quickly assessed and appropriate precautions taken.

One important factor is the likely duration of the abnormal conditions and the risk of recurrence. If the duration is short, temporary measures such as careful hand tunnelling might suffice, but if the abnormal conditions are likely to continue or to recur, a complete review of the methods of tunnelling and plant used may be necessary.

7.3 Types of emergency. Emergencies for which contingency plans should be prepared are not only those arising primarily from natural hazards but also those arising from accidents, and from plant and power failures and stoppages.

- (a) Ground collapse at the face which may be accompanied by an inflow of water (see clause 8).
- (b) Failure of temporary or permanent support some distance behind the face, which may be accompanied by an inflow of water (see clause 8).
- (c) Flooding of the tunnel from the face or from burst water pipes, pump failure or by inundation at a shaft (see clause 12).
- (d) Gas and explosion most commonly arising from methane in strata of organic origin, or in strata near the surface due to leakage from a piped public supply, especially following any subsidence in adjacent workings (see clause 13).
- (e) Oxygen deficiency (see 11.4.2).
- (f) Fires in stored materials, timber supports, electrical installations, fuel or gas (see clauses 14 and 15).
- (g) Accidents from moving plant may, in the confined space of a tunnel, give rise to disproportionate consequences affecting the safety of all persons in the tunnel or the structural safety of the tunnel.
- (h) Plant and power failures, particularly when the tunnel is dependent on a compressed air supply, pumping capacity or ventilation, when standby facilities should be installed.
- (i) Stoppages for whatever reason that can constitute an emergency because of the need for increased support or problems of flooding.

7.4 Chain of authority. Irrespective of the size or scope of the tunnel work involved on any site there should be a clearly defined chain of authority for emergency action.

There is a duty on all persons to report any abnormal circumstances thought likely to give rise to an emergency. Notices giving details of emergency procedures should be prominently displayed in all locations where concentrations of work are expected to occur, e.g. shaft tops, shaft bottoms, faces, airlocks, control rooms. Such notices should give the names of the responsible persons, the reporting procedure, list emergency telephone numbers and give details of the nearest exit.

The primary responsibility for assessing and taking any immediate action necessary on such reports should be

placed on one person, probably the senior site shift foreman, and this should be made clear to all concerned. The senior site shift foreman should always have a nominated deputy. The ultimate authority for implementing contingency planning and for action in an emergency should rest with the agent or other nominated senior person. The senior site shift foreman should report fully to him as early as possible. The resident engineer or other person responsible for supervision and inspection should be kept fully informed and should be consulted to the greatest practicable extent.

7.5 Priorities. In contingency planning for emergencies, the first consideration should be to minimize risk to persons working in the tunnel, and only then to reducing possible damage to the works and to ensuring that means are available to recover the face and restore damaged structures.

It is important that the number of people in any particular part of the tunnel should be known. The planning should therefore place on someone the responsibility of keeping a record of everyone entering or leaving that part of the tunnel.

In an emergency causing risk to the workforce, evacuation of the tunnel may become advisable, but the plan should be for stages of partial or complete evacuation according to the nature and magnitude of the hazard, so that only persons vital to the safety of the works remain.

Power supply priorities should be clearly defined, circuits being designed, labelled and isolated accordingly for such services as emergency lighting, pumping, compressed air supply and ventilation.

7.6 Emergency access. Access in all possible emergencies should be considered in advance. It is not always possible to ensure alternative access routes, but means of access such as ladders and walkways, independent of hoists or other mechanical equipment, should be provided in all cases.

Safe and well planned routes for access and escape can contribute greatly to the safety of the men and of the tunnel, as emergency work at the point of hazard can then be continued for a much longer period.

In an emergency, teams unfamiliar with the tunnel works may require access for rescue, fire fighting or other reasons. A clear, durable, up-to-date diagram of the underground workings accessible from each shaft should be located at the shaft top.

Escape routes should be marked by signs, and other access routes also indicated. The senior site shift foreman should be responsible for ensuring that such signing is kept up to date.

Where a fire brigade, ambulance team or other outside organization may be called on to enter the tunnel, arrangements should be made for those concerned to visit the site and familiarize themselves in advance with access routes and any special procedures. During such visits, and in an emergency, any such team should be met and accompanied by a responsible man from the site fully familiar with the site conditions. Plans of major works should be made available to such teams for the use of their emergency controllers.

A particular problem arises with compressed air working; unless the outside organization concerned accepts a duty to enter, and prepares their men accordingly, it is the responsibility of the contractor to train and maintain emergency teams for fire fighting and other foreseeable emergencies.

7.7 Standby provision. It is a normal part of construction planning to provide reserve capacity in plant, to consider

standby power supplies (see 25.1) and to ensure the availability of spare parts and equipment for minor emergencies and breakdowns. For tunnelling, a particularly high standard has to be observed; in some cases full duplication of maximum requirements.

Additionally, contingency planning should ensure that essential equipment for major emergencies can be obtained when required. It may be necessary for critical items to be kept on site, but sometimes availability from another site or from a plant yard may be satisfactory; where such an arrangement is made, appropriate up-to-date records of stock should be available to all parties contributing to the arrangements.

8. Excavation and initial support

8.1 General. As the ground support and excavation method are often part of one operation, appropriate cross references are made. Some detailed methods of ground support are given in appendices A, B and C; these include sketches and are for general guidance only.

8.2 Basic principles. The essence of safe excavation is to open up only so much ground as is self-supporting until other support can be provided. This varies over a very wide range from a small hand hole requiring immediate support in soft clay or running sand to the whole area of a tunnel in sound hard rock which may safely remain unlined for many weeks or indeed permanently.

Time is of the essence in tunnelling. The safe 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, the stresses carried by it are relaxed and the load is immediately transferred to another section of the ground. The new loadings then initiate movement in the ground, which may cease quickly in sound rock, or may continue to develop slowly in clay, or rapidly in sand or gravel. If the effects are to be localized, immediate support has to be provided to prevent progressive deterioration.

As safe times of exposure range from seconds to days or weeks, and the loadings range from mere containment to full overburden, the temporary support requirements vary enormously in strength and character,

The size of a tunnel is a major factor when determining the loads to be taken in the ground support system. In a ground where a small face may be safe to leave almost indefinitely, extensive and continuous support may be required when the face is large. In soft ground and sometimes in shattered rock, large faces present a hazard which is usually best reduced by construction of one or more pilot tunnels driven ahead of the main face. Pilot tunnels are preferably lined with a structurally continuous lining such as bolted cast iron (see 8.5.1 and 8.17.2).

Experience and sound judgement are essential in deciding how much ground can safely be opened and for how long. It is not possible to specify any tests of general validity. In all cases, where sudden changes are encountered immediate temporary support and containment may be vital. In loose ground where silt or sand may start to run, stuffing quickly with bags, straw, puddled clay, treated timber packing or other available material can be effective in maintaining the safety of the face. This 'first aid' action has to be followed with more orthodox timbering to a high standard, and when the face is re-opened very great care is necessary.

8.3 Ground characteristics

8.3.1 Characteristics of granular soil. Failure in granular soil may be:

- (a) by slow or fast ravelling, when material begins to dry out due to loosening or overstress;
- (b) by running, in dry granular materials lacking cohesion;
- (c) by flowing as a viscous mixture when a wet granular material becomes waterborne and can fill a long length of tunnel.

8.3.2 Sand and gravel. In sand and gravel there is no plasticity and little yielding under stress, but a small fall of loose material may quickly destroy the arching action which is carrying the load and result in progressively larger collapse. Accordingly, 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 washing out of fine material, resulting in loosening of the whole, may be necessary. Careful boxing up and grouting all voids is necessary when progress is interrupted.

8.3.3 Characteristics of cohesive soil. In soils having some degree of cohesion and plasticity, ranging from silts to clays, failure may be:

- (a) by ravelling, where the ground is overstressed but fractures rather than flows;
- (b) by squeezing, where a plastic clay is overstressed and slowly extrudes without visible fractures;
- (c) by flowing, of a 'sensitive' clay in the presence of water;
- (d) by swelling, of a preconsolidated clay absorbing water possibly from the atmosphere and increasing in volume.

8.3.4 Clay. In soft clays, and in stiff clays where the presence of slickensides or backs causes weakness, it may be necessary to provide, as soon as practicable, support that restrains movement. Such support timbering should fit closely against the excavated ground and should be tightly wedged into position with a proper system of struts accurately cut to length and shaped at the ends. 'Buttering' of poling boards with cement, mortar or puddled clay can be helpful, as can cement grouting behind the boards in a close poled face. The plastic characteristics of clays produce a gradual development of disturbance. Immediate support keeps disturbance to a minimum. Changes of moisture content in clays due to exposure of the surface and load changes may, over a long period, result in swelling or shrinkage, with consequent need for improved support. In a tunnel in clay, or any yielding ground, where a satisfactory cycle of operations is interrupted for any reason, the need for additional temporary support of a high standard should be recognized as should the possible need for sealing the clay surface against changes in moisture content. Boxing up and grouting all voids should be standard practice where there is an interruption such as at weekends and holiday periods.

8.3.5 Silt. Silt is particularly dangerous because cohesion can be suddenly lost in the presence of water, or when dried out. Close timbering of all faces becomes essential, unless the time of exposure is brief, the exposed area is small, or cohesion can be ensured. When a tunnel in silt is below the watertable, the use of compressed air, freezing, or other stabilization measures is essential.

8.3.6 Chalk. The upper chalk is usually well fissured and waterbearing and should be regarded as weak rock. Middle chalk contains more marl and is usually more competent. Lower chalk is really a marl and can be regarded as a very stiff clay.

8.3.7 Failure in 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; therefore 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 all need to be taken into consideration. The immediate arching action is followed by redistribution of stresses and movement of blocks of rock with possible penetration of water acting as a lubricant. Progressive disturbance may result in roof falls and repetition of the process at higher levels. In weak rock with frequent horizontal joints, this may lead to a void forming above the tunnel in the shape of a cone several metres in height. Near horizontal slabs of rock present in the crown can fail in bending if they are relatively thin with perhaps a damp layer of soft material above. Rock tunnels that break with a square crown should always be treated with the utmost caution. At all times the hazard of breaking into water-filled faults, fissures or cavities should be recognized. At faults there may be changes in the strata encountered and there will possibly be zones of extensive fracture, often with slickensides and fissures filled with gouge. Advance exploration followed by grouting or other special precautions may be required, particularly in subaqueous tunnelling.

8.4 Methods of initial ground support. Table 2 sets out the main types of tunnelling and ground support systems. The initial support may be the first stage in the ground support system or, for example, as in some uses of sprayed concrete, may be the only functional lining of the completed tunnel.

8.5 Small headings

8.5.1 General. Small headings are generally temporary in character and are driven to explore the ground ahead of the main tunnel, for operations such as pipelaying, or to provide access between two points. No permanent lining is required because the heading will be either refilled or eaten out by the main tunnel; however, temporary support needs to be adequate to last for as long as the heading remains open and to secure the surrounding ground against settlement and collapse.

It should be emphasized that 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 backfilling will ensure safety.

Various types of timbered headings are described in appendix A to illustrate general principles. Senior site management should decide which technique is applicable and ensure that it is carried out safely.

8.5.2 Specific. The size of timber used will depend on the ground type and the size of the heading, but no timber under 38 mm thick should be used. All timbers should be checked for imperfections that reduce strength. Timber that is to be built in should be tanalized or pressure treated.

Table 2. Methods of initial ground support

	Type of tunnelling	Approximate size range	Typical ground	Usual initial support
1	Small heading	1.0 m x 1.3 m to 2.5 m x 2.5 m	All types except sound rock	Timber
2	Small tunnels	Up to 2.0 m diameter	Soft ground	Segmental lining
3	Open shield (a) with face support	1.0 m to 5.0 m diameter	Very soft clay to soft or shattered rock	Segmental lining
	(b) with cutter boom	2.0 m to 6.0 m diameter	Dense sand or gravel with binder. Stiff or firm clay without discontinuities. Soft rock	Segmental lining
4	Pipe jacking	Up to 3.0 m	Soft ground	Concrete pipe
5	Compartmental shield with face support	4.0 m to 10.0 m diameter	Very soft clay to soft or shattered rock	Segmental lining
6	Soft ground tunnel boring machine	1.5 m to 5.0 m diameter	Stiff or firm clay	Segmental lining
7	Hand driven without shield with face support	1.5 m to 10.0 m diameter	As for type 3	Segmental lining
8	Rock tunnelling (a) with steel arches and packing	Up to 12.0 m span	Not used in decomposed rock	
	(b) with sprayed concrete	Over 2.5 m	Not used in decomposed rock	
	(c) with rock bolting	All sizes	Not used in decomposed rock	
9	Hard ground tunnelling machine	2.0 m to 11.0 m diameter	Generally sound rock	
10	Bentonite and slurry shields	Over 2.5 m diameter	Granular soils below watertable	Segmental lining
11	Compressed air	All sizes	Soft ground	Segmental lining
12	Geotechnical processes (a) ground freezing	All sizes	Waterbearing granular soils	
	(b) chemical ground treatment	All sizes	Granular soils	
	(c) ground dewatering	All sizes	Waterbearing sands and gravels	

All materials required for the heading should be readily available as close as is practicable to the face.

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

The primary responsibility for workmanship and safe practice within the technique of the timbered heading chosen rests with the competent person in the face gang, who should be experienced in the type of timbering employed.

The backfilling of small headings with concrete should be done 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 to ensure that all voids are filled.

8.6 Small tunnels

8.6.1 General. Tunnels having a face area of less than 2 m² are included under this code to the extent that men are employed inside them for excavation and construction.

The principles of safety are the same but because of the very restricted space some hazards are intensified. As it is frequently the case that such projects are very limited in space, time and resources it becomes impracticable to apply systems designed for larger projects. It is therefore essential that those working in such tunnels should be responsible and fully experienced men familiar with the actual and potential hazards, and that safety procedures for the particular tunnel should be precisely defined before work commences and faithfully observed.

8.6.2 Specific. In small tunnels, men cannot walk upright and two men can pass one another only with difficulty. It is normal practice for a single man to excavate the face, although a second man should always be present. Arrangements should be defined for the rescue and escape of the face workers in the event of accident, injury or illness. Ventilation may be a problem of particular difficulty because there will be little or no natural circulation and because shallow tunnels through variable ground will frequently pass through or near ground with organic content or with other contamination that may pollute the tunnel atmosphere. A supply of fresh air to the face is therefore essential.

8.7 Tunnelling shields

8.7.1 General. Tunnelling shields are stiffened steel cylinders used to provide initial support and protection during excavation and lining erection in all types of ground except sound rock. Figure 9 shows a 4 m outside diameter shield for use in the worst conditions. Shields are normally used in conjunction with concrete or cast iron segmental rings. Common features include a cutting edge which can, in suitable ground, be used for trimming the periphery of the excavation. In most conditions it is useful to extend forward the cutting edge in the crown to form a hood. The stiffened body of the shield contains rearward acting rams which jack the shield forward off the completed segmental lining.

Before 'shoving' the shield, excavation should be complete to the stage where excessive ram pressures are not required. Unless an expanded lining is to be used, a tail skin is fitted behind the shield. This provides protection within which the grouted segmental lining can be erected. After erection of a ring of such lining the shield is jacked forward and a radial gap of the thickness of the tail skin plus clearances is

left between ground and lining. This gap tends to fill by ground movement and should be minimized by grouting as soon as possible. All shields should have provision for face support, which may be required continuously as tunnelling proceeds or kept for emergency use only. The frequent or continuous use of face support on a shield drive normally means a handmucking operation. When the shield is being jacked off the segmental rings, i.e. 'shoved', it is essential that the person designated as shield operator ensures that nobody can be caught between the rams and the lining.

The operation of clay pocketing is a safety procedure whereby a shield is used in conjunction with compressed air in sands or gravels; this technique is described in appendix C.

8.7.2 Open shield

8.7.2.1 General. Open shields used in conjunction with manual excavation and ground support methods can be employed in a variety of ground conditions. When face support is required it is normally held by hydraulic face jacks which maintain pressure on the face timbering by retracting as the shield is jacked forward. Alternatively, if the requirement for face support is likely to be infrequent the support can be strutted back through the shield to the completed segmental lining. This also allows the shield to be jacked forward without affecting the timbering.

In some shattered rock conditions or where there is a mixed face, e.g. of rock and soft ground, the rock will need to be excavated clear of the cutting edge. It may then be necessary to provide crown and shoulder support in the form of headboards which span between the shield cutting edge and the face timbering. This is often one of the most hazardous tunnelling situations.

8.7.2.2 Specific. The work of providing ground support should be carried out from properly designed and installed working platforms. In the 2.5 m to 5.0 m diameter range platforms should span across the shield, giving access to the face whilst allowing muck to fall into a clear invert. Scaffolding, or similar is not suitable for this purpose as the uprights are liable to be knocked away by falling debris. If there is a hood on the shield it will be necessary to provide working platforms with a sliding facility in order to get the platforms close to the face. Working platforms are frequently temporary, being installed only for the initial support and mucking part of the tunnelling cycle and then removed. Their correct and safe installation is the responsibility primarily of the senior site shift foreman who will generally be a leading miner or shift boss.

The erection of the tunnel lining will normally be carried out by hand, with or without the use of air winches. If temporary working platforms are required, their correct installation is the responsibility primarily of the senior site shift foreman. The design and testing of air winches, snatch blocks, roller bolts and their fixing to the tunnel lining is the responsibility of senior site management. Especial care should be taken over the initial design and wire ropes used in erecting lining should be inspected frequently as they are subject to heavy wear and damage. The correct use of air winches, snatch blocks, roller bolts, etc. is the responsibility of the senior site shift foreman.

8.7.2.3 Cutter boom or other mechanical excavator.

A cutter boom is used only in ground where face support is not normally required. Nevertheless, a set of sized and cut timbers should be kept available for emergency use.

8.7.3 Pipe jacking. The pipe jacking process is a system in which pipes or similar structures are thrust through the

ground, material at the face being excavated and removed through the pipeline. The leading pipe is preceded by a jacking shield which enables the pipeline to be kept on line and level by means of steering jacks.

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

The use of bentonite grout or other lubricant injected into the sliding surfaces may assist in reducing thrusts.

When jacking pipes through loose or waterbearing soils, precautions should be taken against a 'run' of loose material from the face of the heading 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 the displacement of the soil caused by entry of the pipes, and the possibility of heave of the ground surface. Particular care is necessary when jacking pipes beneath the running lines of railway tracks.

8.8 Compartmental shield

8.8.1 General. For larger tunnels in soft ground the cylindrical shield is braced horizontally and vertically to form compartments. These compartments or 'boxes' form workplaces for face excavation and timbering.

Face jacks or other arrangements for supporting the face should be incorporated. It should be noted that the face strutting or jacking device should maintain its thrust when the shield as a whole is being jacked forward and yet allow the shield and platform to move independently. Access to the face will be by ladders and gangways which should be protected by handrails and provided with toe boards as for a normal scaffold.

8.8.2 Specific. The shield should be designed to give men working on it protection from falling muck, and easy egress in an emergency. Segment erection on this size of shield will normally be by erector arm and an audible warning device should be provided. During a shove, only men with specific duties relating to the safety of the operation, including the control of the face timbering, should be allowed on the shield.

8.9 Soft ground boring machine. This type of machine is generally installed on long tunnel drives through sound clay where there is a low incidence of ground support hazards. As with all full face tunnelling machines, access to the tunnel face may be required from time to time for inspection, maintenance, repair or other purposes. Strict precautionary rules need to be enforced to ensure that the machine will not be started up while any men remain in the face. A locking device should be provided, or a main fuse removed, and a competent person designated to ensure that movement of the machine is prevented until all who have entered have checked out again.

8.10 Hand driven segmental lined tunnel

8.10.1 General. There are many occasions where 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, and few rules are applicable overall. In the most general terms the procedure for excavation of a full tunnel face in soft ground 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. Appendix B gives a procedure for timbering a 3.5 m diameter face without a shield in soft ground. In better ground it may well be possible to take the face down vertically with little or no timbering and build the ring in a correspondingly shorter time.

8.10.2 Specific. In smaller tunnels, e.g. below 3.5 m diameter, the recommendations and responsibilities for access and segment erection are given in 8.7.2.2.

In larger diameter tunnels where the length of drive warrants it, a permanent access stage should be designed and built which will normally run on roller brackets fixed on the completed lining. This access stage should be independent of any face timbering. If the drive does not warrant a fully mechanized segment erection system, senior site management should design the equipment and lay down a working procedure for the segment erection method.

8.11 Steel arches and packing

8.11.1 General. In rock tunnels that require support, a common form of immediate support is the steel arch rib. If this, in conjunction with timber or steel poling, can be fixed, wedged or packed up sufficiently quickly after excavation safety can be greatly enhanced. Arched support varies widely in size and geometry and only the most common type and some typical hazards are dealt with.

The design and spacing of arches is the responsibility of senior site management. In variable rock conditions there should always be a competent person on site who has the experience and authority to order the use of arched support.

8.11.2 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, and this is shown in figure 8.

After blasting, mucking and scaling the initial objective is to place the arches in position with some packing in order to give protection as soon as possible. Further packing, wedging or fixing as necessary can then take place. Care should be taken to ensure that the arch is founded on rock capable of taking the vertical load. Arches should be securely fixed one to the other with ties and struts. It may also be necessary to rock bolt the arches or 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. If it is thought that the vertical leg part of the arch is liable to take sideways load, the leg should be tied back to the rock with rock bolts, or otherwise secured. Horseshoe-shaped arches should not be used without the foot of the arch being effectively restrained from movement. The bolted joint at the crown should be made correctly with 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.

8.11.3 Large arches. All the criteria for the correct setting of two-part arches apply to large arches, but in addition the following points apply.

The erection procedure for large arches, made from several bolted sections, should be laid down by senior site management and adhered to. The erection should be carried out in a way which can often be monitored on excavation or drilling

machinery, should be properly designed for the particular situation. Access to the bolted joints and for packing should be from properly designed platforms and stagings.

8.12 Concrete spraying. This term is deemed to cover all pneumatically applied mixes of cement, water, additive and aggregate, including 'shotcrete' and 'gunite'. In rocks where there is liable to be a progressive loosening, the rock surface should be sprayed with concrete as soon as possible after blasting. The effect of this is to stop deterioration of the rock surface, secure any loose material and reduce changes in the self-supporting stress pattern in the rock surrounding the tunnel. The precautions to be taken when using concrete spraying equipment are detailed in 10.2.

8.13 Rock bolting. Rock bolting, in which bolts are anchored into holes drilled into the rock, functions primarily as a method of support by preserving the integrity of the rock mass. Rock bolting may be either temporary support or may form an element of the permanent support. There are several systems of rock bolting which can be divided into two types. The first type consists of providing an anchorage, either mechanically or chemically, at the far end of the drill hole and then tensioning the bolt against a face plate at the rock surface. This type of rock bolt can be grouted up after fixing. The second type of rock bolt is anchored along its length using resins or cement mortar in a perforated sleeve. The effect of having a bond along the length of the bolt is to stitch together rock masses which are divided by natural jointing.

While rock bolts may be used merely to tie back loose slabs which would otherwise be liable to fall, their more fundamental use is in maintaining compression across discontinuities such as joints, fissures and bedding planes so that arching action can be sustained by the whole mass of rock.

The pattern and type of bolting, and the length and diameter of bolts, can be decided only after careful study of the particular circumstances, which may vary rapidly as tunnelling progresses.

The safe installation and functioning of a rock bolting system depends on proper design to suit rock characteristics and the excavation and lining methods.

Among the precautions necessary are the following.

- (a) The length of bolts should be at least twice the thickness of the rock being secured.
- (b) The anchorage should be designed to hold the full strength of the bolt without slipping in the bore or crushing the rock locally. Load tests in situ should be carried out on representative bolts.
- (c) The spacing should be approximately equal in both directions based on estimated loading and bolt diameter and strength.
- (d) The bolting should be completed as quickly as possible after excavation.
- (e) If a rock is at all friable, metal mesh should be secured to span between bolts, the surface being gunited if necessary.

Secure anchorage at sufficient depth is vital. Fixing as quickly as possible is important to prevent the initiation of movement. All such systems should be executed in accordance with plans prepared by a person competent in the principles of rock mechanics and familiar with the local geology. The condition of the rock in the roof should be thoroughly examined and scaled down and personnel should be adequately protected before drilling takes place.

8.14 Hard ground tunnelling machine. Tunnelling machines have to meet extremely varied and variable conditions of rock hardness, jointing, water, etc. and there is little standardization of equipment. In general, the face is inaccessible while excavation is in progress so that, provided men are excluded from the moving parts, personal danger at the point of excavation is minimized.

The precautions required for access to the tunnel face are as detailed in 8.9 for the soft ground boring machine.

Danger to the tunnel may arise where a sudden change in rock conditions at the face is encountered and where emergency action is difficult because of inaccessibility. The probability of such a contingency and consideration of means to overcome it should be examined before such a machine is put to work and, if necessary, provision should be made for borings and probes 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, after a full study of the information likely to be gained and of the risks involved. Where safe 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 after completion.

In some rock conditions, unless continuous support is incorporated immediately behind the cutter head there is a risk of falls of ground from the roof behind the face and ahead of the completed lining; appropriate screening should be provided to avoid risk to men and damage to equipment.

Tunnelling machines may also incorporate lining erection devices behind the face either for erection of immediate support such as ribs, or for permanent prefabricated linings. Moving parts for such operations cannot be fenced off and men will almost invariably be required to handle the structural element being erected. The special hazards particular to tunnelling machines arise from the confined working space and unavoidable noise, and overlap of the operations of excavation, muck disposal, erection of support or permanent lining and grouting.

Men working on and immediately behind a machine should have clearly defined responsibilities and should receive instructions in their duties and on the hazards before commencing work.

8.15 Bentonite and slurry shields. A special type of closed tunnelling machine is the bentonite or slurry shield designed for use in non-cohesive waterbearing ground. Bentonite or other slurry is retained at appropriate pressures ahead of a diaphragm within a cylindrical shield, and a cutter head rotates within the slurry chamber, excavated material being discharged to the rear through a valve system. In normal operation, the face is totally enclosed and permanent prefabricated linings are erected within a tail so that there is no hazard of falls of ground. The full thrust from slurry pressure against the whole area of the excavation is carried back through the shield structure to the finished lining.

To cope with an emergency during construction or a repair at the tunnel face, provision should be made for the use of compressed air in the tunnel, with an air lock giving access to the face.

8.16 Compressed air. Compressed air will support the face and will also reduce settlement caused by ground moving to fill the annular space behind the shield before grouting takes place. The use of compressed air to support the face is not recommended unless alternative measures are also available which can be used if the air pressure falls or is removed.

8.17 Geotechnical processes

8.17.1 Freezing. Waterbearing ground can be made impermeable and given cohesive strength if it can be frozen and so maintained.

Freezing is normally effected by circulation of brine at subfreezing temperatures in a closed system of pipes. Freezing of the ground water takes place slowly and may be impossible if there is an underground flow of water which brings in heat at too fast a rate. This hazard may not be apparent until excavation is in progress when there arises a risk of very rapid erosion; appropriate tests should be made and precautions taken against the development of such an emergency. Freezing by liquid nitrogen is possible and acts more quickly, but its use presents special problems such as reduction in tunnel oxygen.

Freezing can be a particularly effective technique in silts and in gravels with silty layers which are very difficult to treat by grouting.

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

If a heading, such as a pipe heading, is driven through frozen ground there is likely to be a build-up of ice on timber supports. The utmost care needs to be taken in refilling the heading to ensure that ice is not left in 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.

8.17.2 Ground injection. Chemical ground treatment in advance of tunnelling is used to enhance safety in 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 waterbearing, 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 in compressed air the loss of air 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, and progressively finer grouts of lower viscosity are required in fine sands. Most difficult of all are silts which can normally be treated only by clacquage. Clays cannot be treated. The permeability of the ground is rarely consistent and the possibility of meeting untreated pockets should never be ignored. Ground water quality should be taken into account when designing the grout.

If fissured rock is to be treated, it may be difficult to locate and treat all significant fissures, especially if some are filled with gouge or soft clay.

When advance ground treatment by grouting is considered necessary it may be carried out in one of the following ways.

- (a) From the surface by driving down grouting tubes to the level requiring treatment.

NOTE. If this method is used after compressed air has been used in a tunnel it often results in the grouts being blown aside during injection.

- (b) Radially from a pilot tunnel to improve conditions for driving the main tunnel.

- (c) Through a tunnel face during construction.

In all cases the chemical characteristics of the grout used should be ascertained and appropriate precautions taken.

The hazards to be avoided are as follows.

- (1) 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, including those for water supply and sewerage.
- (2) Pollution of underground water by transfer from the stratum treated.
- (3) Risks to men handling the materials during and after mixing, including risks from burst pipes and hoses.
- (4) The toxicity of some special grouts enhances the risks in handling and makes necessary enhanced precautions, including the provision of protective clothing and full washing facilities.
- (5) Where the grouting is done from inside the tunnel, and particularly in a small pilot tunnel, the enclosed space makes it essential to take all necessary precautions, to adopt high standards of cleanliness and to ensure that the ventilation system provides an ample supply of fresh air.
- (6) Interference with adjacent services and property.
- (7) Excessive pressures which may cause ground heave and damage to surface structures.

8.17.3 Dewatering. For shallow tunnels in waterbearing sands and gravels, it may be possible to stabilize the ground by means of wellpoint dewatering. Expert advice is essential but the basic process consists of lowering the ground water along the line of the tunnel by means of a pattern of filtered well points connected to a header pipe which runs to a vacuum pump. The filters on each well point stop fine particles being drawn into the system. By using deep wells and 'down the hole' pumps, ground can be stabilized to greater depths than is possible by wellpointing.

The main hazards of these systems are as follows.

- (a) Settlement at the surface due to the watertable being lowered.
- (b) Failure of the dewatering system whilst the tunnel is being driven. This causes the ground to revert to its former unstable condition and rapid massive ground loss can follow. It is imperative that the system is set up with the best available equipment and plant, that items are duplicated where possible and that the surface pipework is protected from accidental damage.

8.18 Methods of excavation and loading

8.18.1 Hand excavation. Excavation in many types and sizes of tunnel is carried out by hand using either conventional picks and shovels or airpowered picks, breakers and clay spades. The main hazard of this type of work is from falls of men and materials. It is important that proper working platforms be provided, as detailed in 8.7.2.2, 8.8, 8.10.2 and 8.11.3. Broken or badly maintained tools are a hazard not only because they may fail in use but also because of the need for excessive force on the part of the operator.

Small elevating conveyors are often used in conjunction with hand excavation and the safety precautions for these are described in 24.2.2.