

PAS 8810:2016

Tunnel design – Design of concrete segmental tunnel linings – Code of practice



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Foreword

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The PAS process enables a code of practice to be rapidly developed in order to fulfil an immediate need in industry. A PAS can be considered for further development as a British Standard, or constitute part of the UK input into the development of a European or International Standard.

Relationship with other publications

This PAS is expected to be used in conjunction with BS 6164, which makes recommendations for and gives guidance on health and safety practices in tunnel design and construction.

Use of this document

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

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Presentational conventions

The provisions of this PAS are presented in roman (i.e. upright) type. Its recommendations are expressed in sentences in which the principal auxiliary verb is "should". The word "may" is used to express permissibility and the word "can" is used to express possibility, e.g. a consequence of an action or an event.

Commentary, explanation and general informative material is presented in italic type, and does not constitute a normative element.

Spelling conforms to The Shorter Oxford English Dictionary. If a word has more than one spelling, the first spelling in the dictionary is used (e.g. “organization” rather than “organisation”).

Particular attention is drawn to the following specific regulations:

- Construction (Design and Management) Regulations 2015 [1];
- Construction Products Regulations 2013 [2]; and
- Health and Safety at Work etc. Act 1974 [3].

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a PAS cannot confer immunity from legal obligations.



Introduction

HS2 and BSI engaged with a number of construction industry stakeholders to identify areas in which it was felt that the industry could benefit from further standardization.

PAS 8810 was developed specifically to cover the design of segmental tunnel linings, which was identified as an area in which additional standardization was required. Segmental tunnel linings are currently designed with reference to a large number of published general building standards and industry documents, together with several Eurocodes. However, there is no codified or standardized design document that applies specifically to precast concrete segmental tunnel linings, and the volume of relevant standards, guidance and documentation has led to both conflicting guidance and requirements, and the misinterpretation and misapplication of standards. PAS 8810 therefore aims to bring together existing standards and industry documents into a single, usable standardization document while simultaneously reducing unnecessary administration and delay by streamlining, clarifying and standardizing the design process for segmental lining design.

Clauses 4 to 8 cover the more general aspects of tunnel design and do not restrict the designer to a single construction methodology at the conceptual design stage, as a designer would not limit their study only to segmental tunnel lining design. Clauses 9 to 12 provide specific, technical information on precast concrete lining elements for segmental tunnel linings.

At the time of publication, the intention is to standardize further areas of tunnel lining design in the near future including sprayed concrete linings and cast-in-situ linings.

As tunnel construction technology is fast changing, some of the recommendations set out in this PAS might not be fully applicable to a newly-introduced technology that does not exist at the time of this PAS publication.

This PAS is not intended to limit the design flexibility or the adoption of new technology, and, as such, is not intended to be used as a barrier that prevents the adoption of innovative designs.

A number of other areas were identified as benefitting from standardization. A wider programme of work is underway to develop a further three PASs:

- PAS 8811, *Temporary works – Client procedures – Code of practice* (in preparation), which gives recommendations for UK infrastructure client procedures with respect to temporary works construction projects, from planning through to removal.
- PAS 8812, *Temporary works – Application of European Standards in design – Guide*, which gives guidance on the application of European Standards in the design of temporary works in the UK for practitioners in the fields of structural and geotechnical temporary works design.
- PAS 8820, *Construction materials – Alkali-activated cementitious material and concrete – Specification*, which specifies requirements for alkali-activated cementitious binders for suppliers of alkali-activated binders, ready mixed concrete, engineers and architects, contractors, asset owners and end users.

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1 Scope

This PAS makes recommendations for the design of concrete segmental tunnel linings. It covers design considerations from project inception through to the end of the service life of the tunnel. At the early stage of the design (e.g. conceptual design stage), the study of the options for the selection of the tunnel lining is not limited to concrete segmental tunnel linings. Thus Clauses 4 to 8 in the PAS are applicable to tunnels with all types of linings. Clauses 9 to 12 give specific recommendations on the design of concrete segmental tunnel linings.

This PAS is for use by design engineers (usually directly employed by the client but this could sometimes be the contractor's designer, for example, in a design and build project) and clients (usually the owner of the tunnel who is responsible for the design and construction of concrete tunnel linings) and contractors.

The PAS sets out detailed design recommendations by referencing existing national standards (BS, BS EN) or internationally-recognized industry standards. Technical requirements from existing standards are referenced, rather than repeated. Specific design recommendations are included only for the design items that are not available from existing standards.

This PAS covers:

- 1) functional requirements;
- 2) conceptual design;
- 3) characterization of ground;
- 4) materials design and specification;
- 5) material characterization and testing;
- 6) limit state design;
- 7) concrete segmental lining design;
- 8) concrete segment lining modelling;
- 9) instrumentation and monitoring; and
- 10) design management.

This PAS does not cover:

- a) sprayed concrete lined tunnels;
- b) cast-in-situ concrete lined tunnels;
- c) any tunnel lining using material other than concrete, such as spheroidal graphite iron or steel;
- d) cut and cover tunnels;
- e) drill and blast excavations;
- f) hard rock tunnelling;
- g) pipe jacking; and
- h) project planning and management.

NOTE 1 Recommendations for health and safety practices in tunnel construction are given in BS 6164.

NOTE 2 Requirements for handling ground support elements are given in BS EN 16191.

2 Normative references

Standards publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS 4449, *Steel for the reinforcement of concrete – Weldable reinforcing steel – Bar, coil and decoiled product – Specification*

BS 6164, *Code of practice for health and safety in tunnelling in the construction industry*

BS 6744, *Stainless steel bars for the reinforcement of and use in concrete – Requirements and test methods*

BS 7979, *Specification for limestone fines for use with Portland cement*

BS 8500-1, *Concrete – Complementary British Standard to BS EN 206 – Part 1: Method of specifying and guidance for the specifier*

BS 8500-2, *Concrete – Complementary British Standard to BS EN 206 – Specification for constituent materials and concrete*

BS EN 206:2013, *Concrete – Specification, performance, production and conformity*

BS EN 450-1, *Fly ash for concrete – Part 1: Definition, specifications and conformity criteria*

BS EN 934-2, *Admixtures for concrete, mortar and grout – Part 2: Concrete admixtures – Definitions, requirements, conformity, marking and labelling*

BS EN 1008, *Mixing water for concrete – Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete*

BS EN 1990, *Eurocode – Basis of structural design*

BS EN 1992-1-1, *Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings*

BS EN 1997-1, *Eurocode 7: Geotechnical design – Part 1: General rules*

BS EN 12110, *Tunnelling machines – Air locks – Safety requirements*

BS EN 12620, *Aggregates for concrete*

BS EN 13055-1, *Lightweight aggregates – Part 1: Lightweight aggregates for concrete, mortar and grout*

BS EN 13263-1, *Silica fume for concrete – Part 1: Definitions, requirements and conformity criteria*

BS EN 13369, *Common rules for precast concrete products*

BS EN 14651, *Test method for metallic fibre concrete – Measuring the flexural tensile strength (limit of proportionality (LOP), residual)*

BS EN 14889-1, *Fibres for concrete – Part 1: Steel fibres – Definitions, specifications and conformity*

BS EN 14889-2, *Fibres for concrete – Part 2: Polymer fibres – Definitions, specifications and conformity*

BS EN 15167-1, *Ground granulated blastfurnace slag for use in concrete, mortar and grout – Part 1: Definitions, specifications and conformity criteria*

BS EN 16191, *Tunnelling machinery – Safety requirements*

BS EN ISO 14688-1, *Geotechnical investigation and testing – Part 1: Identification and classification of soil – Identification and description*

BS EN ISO 14688-2, *Geotechnical investigation and testing – Part 2: Identification and classification of soil – Principles for a classification*

BS EN ISO 14689-1, *Geotechnical investigation and testing – Part 1: Identification and classification of rock – Identification and description*

BS ISO 13270, *Steel fibres for concrete – Definitions and specifications*

NA to BS EN 1992-1-1, *UK National Annex to Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings*

PAS 1192-2, *Specification for information management for the capital/delivery phase of construction projects using Building Information Modelling*

Other publications

[NR1] BRITISH TUNNELLING SOCIETY. Tunnel Lining Design Guide, Thomas Telford Books, 2004.

[NR2] BRITISH TUNNELLING SOCIETY. Specification for Tunnelling, Third edition, Thomas Telford Books, 2010.

[NR3] NICHOLSON, D., TSE, C.M., and PENNY, C. The Observational Method in Ground Engineering—Principles and Applications. Report 185. London: CIRIA, 1999.

[NR4] RILEM TC 162-TDF: Test and design methods for steel fibre reinforced concrete, σ - ε -design method – Final Recommendation. In: *Materials and Structures/Materiaux et Constructions*, 2003, Vol. 36, October, pp. 560-567.

[NR5] FEDERATION INTERNATIONALE DU BETON. fib Model Code for Concrete Structures 2010, Berlin: Ernst & Sohn, 2013.

[NR6] INTERNATIONAL TUNNELLING ASSOCIATION. Guidelines for the Design of Tunnels, WG on General Approaches to the design of tunnels. In: *Tunnelling and Underground Space Technology*, ITA, 1988, Vol. 3, No.3, pp. 237-249.

[NR7] INTERNATIONAL TUNNELLING ASSOCIATION. Seismic design and analysis of underground structures. In: *Tunnelling and Underground Space Technology*, 16, ITA, 2001. pp. 247-293.

[NR8] DIXON, J.D. Analysis of tunnel support structure with consideration of support-rock interaction, U.S. Bureau of Mines Rept., Invest. No. 7526, 1971.

[NR9] INTERNATIONAL TUNNELLING ASSOCIATION. Guidelines for the Design of Shield Tunnel Lining, WG No.2. In: *Tunnelling and Underground Space Technology*, ITA, 2000, Vol. 15, No.3, pp. 303-331.

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this PAS, the following terms and definitions apply. General tunnel lining design terms not defined in this document can be found in the BTS, *Tunnel Lining Design Guide* [NR1].

3.1.1 action

3.1.1.1 accidental action

action, usually of short duration but of significant magnitude, that is unlikely to occur on a given structure during the design working life

[SOURCE: BS EN 1990:2002+A1:2005, 1.5.3.5]

NOTE *An accidental action can be expected in many cases to cause severe consequences unless appropriate measures are taken.*

3.1.1.2 permanent action

action that is likely to act throughout a given reference period and for which the variation in magnitude with time is negligible, or for which the variation is always in the same direction (monotonic) until the action attains a certain limit value

[SOURCE: BS EN 1990:2002+A1:2005, 1.5.3.3]

3.1.1.3 variable action

action for which the variation in magnitude with time is neither negligible nor monotonic

[SOURCE: BS EN 1990:2002+A1:2005, 1.5.3.4]

3.1.2 approval in principle (AIP)

document which records the agreed basis and criteria for the detailed design or assessment of a tunnel lining structure

3.1.3 category (cat)

level of design check required that takes account of the risk and complexity of design

3.1.4 conceptual design

high-level design stage carried out to develop a preferred single design option that complies with the client's functional requirements

NOTE *For the client's functional requirements, see 4.1.*

3.1.5 concrete

material formed by mixing cement, coarse and fine aggregate and water, with or without the incorporation of admixtures and additions, which develops its properties by hydration of the cement

[SOURCE: BS EN 206:2013, 3.1.1.1]

3.1.5.1 addition

finely-divided-inorganic constituent used in concrete in order to improve certain properties or to achieve special properties

[BS EN 206:2013, 3.1.2.1]

3.1.5.2 additional protective measures (APMs)

measures taken to protect concrete where it is considered that the basic provisions of the concrete specification might not provide adequate resistance to chemical attack

[SOURCE: BRE Special Digest 1]

3.1.5.3 combination

restricted range of Portland cements and additions which, having been combined in the concrete mixer, count fully towards the cement content and water/cement ratio in concrete

3.1.5.4 designed concrete

concrete specified by strength class, consistence and any required limitations on composition

NOTE 1 For example, cement or combination type, minimum cement or combination content, maximum water/cement ratio.

NOTE 2 Additional requirements can be specified, e.g. strength development, resistance to water penetration.

3.1.5.5 designated concrete

concrete specified by a designation from a list of possible concretes

NOTE The designation relates to specific limitations on the concrete including strength class, water/cement ratio, cement or combination content and cement or combination type. Further limitations can be specified.

3.1.5.6 prescribed concrete

concrete specified by the exact required composition and constituent materials including cement or combination, aggregates and admixtures

NOTE Performance requirements, e.g. concrete strength, cannot be specified for prescribed concrete.

3.1.5.7 proprietary concrete

concrete specified by reference to a product name for a particular concrete offered by a particular producer to meet specific claimed performance

NOTE The producer is not required to provide information on the composition of the concrete.

3.1.5.8 standardized prescribed concrete

concrete specified by a designation from BS 8500-2:2015, Table 10 relating to a specific composition of concrete

NOTE 1 For example, ST5.

NOTE 2 Performance requirements, e.g. concrete strength, cannot be specified for standardized prescribed concrete.

3.1.6 construction tolerance

permissible deviation from the designed geometry of the lining

NOTE For example, location of lining relative to designed position, variation in lining thickness, deviation of surface.

3.1.7 critical national infrastructure

infrastructure elements, the loss or compromise of which would have a major detrimental impact on the availability or integrity of essential services, leading to severe economic or social consequences or to loss of life

3.1.8 design gate

stage in the design approval and acceptance process that the design has to pass before proceeding to the next stage

3.1.9 design situation

set of physical conditions representing the real conditions occurring during a certain time interval for which the design demonstrates that relevant limit states are not exceeded

3.1.9.1 accidental design situation

design situation involving exceptional conditions of the structure or its exposure, including fire, explosion, impact or local failure

3.1.9.2 persistent design situation

design situation that is relevant during a period of the same order as the design working life of the structure

3.1.9.3 seismic design situation

design situation involving exceptional conditions of the structure when subjected to a seismic event

3.1.9.4 transient design situation

design situation that is relevant during a period much shorter than the design working life of the structure and which has a high probability of occurrence

NOTE A transient design situation refers to temporary conditions of the structure, of use, or exposure, e.g. during construction or repair.

3.1.10 design verification

process of establishing the validity of the design

***NOTE** Design verification confirms design results or parameters that meet standard document requirements and/or the designer's intent.*

3.1.11 design working life

period of time during which the item is expected by its designers to work within its specified parameters

3.1.12 desk study

preliminary investigation and report which collates currently available, relevant information

3.1.13 feasibility options report

report that provides the details and results of feasibility study options

3.1.14 fire**3.1.14.1 design fire load**

maximum fire load to be considered for the design of the tunnel lining

***NOTE** The design fire load is normally given in Watts and is commonly known as a time-temperature curve.*

3.1.14.2 fire curve

change in temperature experienced at the surface of a structure over a given time frame due to a fire event

3.1.15 geotechnical baseline report (GBR)

contractual document that establishes a definitive statement of the contractually defined geotechnical conditions relevant to the tunnel

***NOTE** The report is used as a baseline for contractual reference.*

3.1.16 geotechnical design report (GDR)

report that includes geotechnical assumptions, data, methods of calculation and results of the verification of safety and serviceability

[SOURCE: BS EN 1997-1:2004+A1:2013, 2.8, modified]

3.1.17 ground investigation report (GIR)

report that includes factual geotechnical information and evaluation of the information

[SOURCE: BS EN 1997-1:2004+A1:2013, 3.4, modified]

3.1.18 grouting**3.1.18.1 annulus grouting**

grouting required to fill the planned gap/voids between the excavated profile of ground and the extrados of linings

3.1.18.2 cavity grouting

grouting required to fill the unexpected/unplanned gap/voids between the excavated profile of ground and the extrados of linings

3.1.19 hydraulic failure

ground failure mode induced by pore-water pressure or pore-water seepage

[SOURCE: BS EN 1997-1:2004+A1:2013, 10, modified]

3.1.20 joint**3.1.20.1 birdsmouthing**

opening of radial joint on one side due to deformation of the tunnel lining

3.1.20.2 bursting (failure)

tensile failure of concrete at a joint of the tunnel lining which is induced by excessive compressive contact stress at the joint contact face

3.1.20.3 circumferential joint

joint formed between the two adjoining concrete sections normal to the direction of tunnel alignment

***NOTE** A circumferential joint is sometimes referred to as a circle joint.*

3.1.20.4 groove

small recess formed around the segment edges to accommodate gaskets or caulking materials

3.1.20.5 lip

misalignment between two segments along a radial joint in direction of tunnel radius

3.1.20.6 radial joint

joint formed between precast concrete segments in a ring along the direction of tunnel

NOTE A radial joint is sometimes referred to as a longitudinal joint.

3.1.20.7 step

misalignment between two segments along a circumferential (circle) joint in direction of tunnel radius

3.1.21 limit state

state beyond which the structure no longer fulfils the relevant design criteria

[SOURCE: BS EN 1990:2002+A1:2005, 1.5.2.12]

3.1.21.1 serviceability limit state

state that correspond to conditions beyond which the specified service requirements for a structure or structural member are no longer met

[SOURCE: BS EN 1990:2002+A1:2005, 1.5.2.14]

3.1.21.2 ultimate limit state

state associated with the collapse or with other similar forms of structural failure

[SOURCE: BS EN 1990:2002+A1:2005, 1.5.2.13]

3.1.22 lining

3.1.22.1 primary lining

tunnel lining structure that is designed to take any actions immediately following excavation over a prescribed period of time

NOTE A primary lining is sometimes called a temporary lining when secondary lining is designed to take all design actions and loads over the design target life.

3.1.22.2 secondary lining

tunnel lining structure that is designed to take full or part of design actions and loads over the design working life

NOTE 1 The secondary lining depends on the design principle of the primary lining.

NOTE 2 When the primary lining is designed as a temporary structure, the secondary lining is referred to as the permanent lining.

3.1.23 parties

3.1.23.1 client

organizations or individuals for whom a construction project is carried out

[SOURCE: HSE CDM Regulations 2015]

NOTE The client is generally the same as the organization or group who own, operate and maintain the tunnel structure, but it depends on the type of contract.

3.1.23.2 contractor

any person (including a non-domestic client) who, in the course or furtherance of a business, carries out, manages or controls construction work

[SOURCE: HSE CDM Regulations 2015]

3.1.23.3 designer

those, who as part of a business, prepare or modify designs for a building, product or system relating to construction work

[SOURCE: HSE CDM Regulations 2015]

3.1.23.4 employer

organization or group of people who employs the designer

NOTE This could be the client, the contractor or another designer depending on the type of contract.

3.1.23.5 principal contractor

contractor appointed by the client to co-ordinate the construction phase of a project where it involves more than one contractor

[SOURCE: HSE CDM Regulations 2015]

3.1.23.6 principal designer

designer appointed by the client in projects involving more than one contractor who has the legal duty to plan, manage and co-ordinate health and safety in the pre-construction phase of the project

NOTE The principal designer can be an organization or an individual with sufficient knowledge, experience and ability to carry out the role.

[SOURCE: HSE CDM Regulations 2015]

3.1.24 requirements

3.1.24.1 functional requirements

requirements defined and provided by the client to ensure the tunnel meets its functional objectives over the design working life

NOTE Functional requirements include operational, security, durability requirements.

3.1.24.2 operational requirements

requirements defined and provided by the client to ensure normal operation of the tunnel over its design working life

NOTE For example, the speed of the train, or water flow rate.

3.1.25 segment

3.1.25.1 clocking position

equally spaced bolt/dowel position on the circumferential joint to allow for rotation of each ring relative to the previous ring

3.1.25.2 key draw

clear length needed from the leading edge of the ring to place the key segment

3.1.26 smooth-bore

segment that has smooth internal surface finish

NOTE It can have small recess close to the perimeter of the segment for bolt assembly.

3.1.27 soft ground

ground that requires a lining to maintain stability during and/or after excavation

3.1.28 temporary works

part of the works that allows or enables construction of, protects, supports or provides access to, the permanent works and which might or might not remain in place at the completion of the works

NOTE Examples of temporary works are structures, supports, back-propping, earthworks and accesses.

[SOURCE: BS 5975:2008+A1:2011, 3.40 modified]

3.1.29 trigger levels

measure of a parameter at which a pre-defined action occurs

NOTE That action could be to do nothing, for example, at a green trigger level.

3.1.30 volume loss

volume of the surface settlement trough per linear metre expressed as a percentage of the theoretical excavated volume per linear metre

NOTE This is sometimes referred to as ground loss.

3.2 Abbreviations

For the purposes of this PAS the following abbreviations apply.

ACEC	aggressive chemical environment for concrete
AIP	approval in principle
APM	additional protective measure
BEM	boundary element method
BIM	building information modelling
CCM	convergence-confinement method
CDM	construction (design and management)
CDS	concept design statement
CSTR	Concrete Society technical report
D&C	design and construct
DC	design chemical (class)
DEM	discrete element method
EN	Euronorm
EPDM	ethylene propylene diene monomer
FD	finite difference
FE	finite element
FRC	fibre reinforced concrete
GBR	geotechnical baseline reports
GDR	geotechnical design reports
GIR	ground investigation reports
GIS	geographic information system
hENs	harmonized European product standards
IDR	interdisciplinary review
MSFRC	macro synthetic fibre reinforced concrete
NATM	new Austrian tunnelling method
PFI	private finance initiative
RSES	register of security engineers and specialists
SCL	sprayed concrete lining
SDR	single disciplinary review
SFRC	steel fibre reinforced concrete
SGI	spheroidal graphite iron
SLS	serviceability limit state
TBM	tunnel boring machine
ULS	ultimate limit state
WG	working group

4 Functional requirements

4.1 General

4.1.1 The designer should design and size the tunnel lining to meet the functional requirements of the specific project.

4.1.2 The designer should undertake a project-specific review to assess all of the parameters that affect the size and the design of the tunnel lining in order to meet the functional requirements of the client, as given in 4.3 and to ensure there is adequate working space to construct the tunnel safely. The results of the project-specific review should be documented.

4.1.3 The designer should assess the typical elements set out in Table 1 and, where relevant, document their impact on the tunnel's sizing and lining design.

Table 1 – Typical elements differentiated from the type of tunnel and associated design issues

Tunnel types	Elements differentiated from the type of tunnel	Design issues
Transportation tunnels	• Rail and track form (for rail tunnel), pavement form (for road tunnel)	• Sizing, operational train or vehicle load to lining
	• Structure gauge	• Sizing
	• Overhead power line or third rail (for rail tunnel)	• Sizing
	• Intervention and evacuation walkways	• Sizing, walkway design, cross passage spacing, derailment containment
	• Firefighting equipment	• Sizing
	• Drainage system	• Sizing
	• Service cables/electrical and mechanical equipment	• Sizing
	• Ventilation/smoke control/overhead jet fans/overhead ventilation ducts/lighting/signage and other services	• Sizing
	• Aerodynamics	• Transient pressure criteria for high-speed rail, sizing
	• Cladding and finishes including support system	• Sizing, durability of support system
Water/sewerage tunnels	• Water head loss – surface roughness	• Joint design, secondary lining design (sizing)
	• Internal pressure maintenance	• Joint design, water tightness design – leakage and external water pressures
Cable tunnel	• Number of service cables and pipes, fixing/hanging method	• Sizing
	• Accessibility of people/equipment	• Sizing
	• Electromagnetic clearance and separation	• Sizing
	• Temperature control (ventilation and cooling)	• Sizing
	• Drainage system	• Sizing

4.2 Health and safety requirements

4.2.1 The client should provide the designer with the health and safety requirements for the project. Such requirements should satisfy the safety requirements during construction, operation and maintenance of the tunnels.

NOTE 1 *Attention is drawn to the Construction (Design and Management) Regulations 2015 (CDM) [1] which impose statutory duties on designers to consider health and safety.*

NOTE 2 *The designer of the tunnel lining may be different from the "Principal Designer" and the "Principal Contractor" defined in the CDM Regulations 2015.*

4.2.2 The designer should design and size the tunnels to fulfil the client's health and safety requirements.

4.2.3 The designer should apply health and safety practices relating to tunnel design and construction in accordance with BS 6164.

NOTE *BS 6164:2011, 6.1 highlights the importance of the integral nature of design and construction for tunnelling projects. Recommendations for the design of tunnel lining with consideration of Health and Safety requirements are given in BS 6164:2011, Clause 8.*

4.3 Client's project-specific functional requirements

4.3.1 General

The designer should review the client's project-specific functional requirements and incorporate these into the design and sizing of the tunnel lining.

NOTE *The client's project-specific functional requirements are commonly defined in the client's design standards or the client's project brief, but might also be prepared by the designer employed by the client.*

4.3.2 Operational requirements

4.3.2.1 The client should document the project's operational requirements and provide these to the designer.

4.3.2.2 If there is no available documentation from the client that states the operational requirements of the infrastructure, the designer should request this information from the client as early as possible.

NOTE *Having the client's operational requirement details during the concept design stage can minimize the risk of resizing the tunnel lining in subsequent stages.*

4.3.2.3 As a minimum, the client should include in their operational requirements document, the project's:

- a) operational requirements (see 4.3.2.1 and 4.3.2.2);
- b) security requirements (see 4.3.3);
- c) durability requirements (see 4.3.4);
- d) repair and maintenance requirements (see 4.3.5);
- e) fire safety requirements (see 4.3.6);
- f) water tightness requirements;
- g) contractual requirements (not covered in this PAS); and
- h) legal requirements (not covered in this PAS).

NOTE *The client might also provide information relating to project-specific tolerances, deformation limits, and design-checking specifications.*

4.3.3 Security requirements

4.3.3.1 The client should identify whether the tunnel structure forms part of the UK's critical national infrastructure and inform the designer of their findings.

NOTE *Specific security-related design requirements can be applied either by the client or by the government, particularly for major infrastructure assets which might form part of the UK's critical national infrastructure.*

4.3.3.2 Where the tunnel structure is identified as forming part of the UK's critical national infrastructure, the client should consult a relevant expert on the specific counter-terrorist design requirements.

NOTE 1 *A relevant expert could be a member of the Register of Security Engineers and Specialists (RSES).*

NOTE 2 *Where a counter-terrorism expert is consulted, they then consult with government security advisers from the Centre for the Protection of National Infrastructure ¹⁾ (CPNI).*

NOTE 3 *Similar notification conditions might also apply when designing for international clients.*

4.3.3.3 The client should provide any security-related design requirements to the designer and these should be incorporated into the design of the tunnel lining.

4.3.4 Durability requirements

4.3.4.1 The client should specify a target design working life for the tunnel lining and provide this to the designer.

NOTE *BS EN 1990 does not specifically cite tunnel structures within its scope although it states that it is applicable for the design of structures where other materials or actions outside the scope of EN 1991 to EN 1999 are involved. NA to BS EN 1990:2002 targets 120 years for the design working life.*

¹⁾ www.cpni.gov.uk

4.3.4.2 The designer should design the tunnel lining to meet the target design working life specified by the client.

4.3.4.3 Tunnels need to be designed, where practicable, to minimize the requirement for maintenance interventions other than visual inspections. To support this requirement, the designer should provide a statement of potential degradation modes identified during the design of the tunnel lining and a schedule of the expected interventions during the design working life.

NOTE To prepare the schedule of the expected interventions required under 4.3.4.3, the designer needs to consider all components, including structural elements, gaskets and sealing materials and also the ability of all materials to resist degradation by ground, groundwater and the environment throughout the design working life.

4.3.4.4 The designer should design the durability of tunnel lining in accordance with 7.9; and the BTS, *Tunnel Lining Design Guide*, Section 4 [NR1].

4.3.4.5 The design needs to cover the durability of all materials used in the tunnel lining as permanent components. Where temporary components are left in place, the designer should assess and document their impact on the durability of the permanent components.

NOTE Permanent components include concrete, reinforcement and waterproofing systems and all exposure conditions, both internal and external, and on both primary and secondary linings.

4.3.5 Repair and maintenance requirements

4.3.5.1 The client should develop the project-specific repair and maintenance regime of the tunnel (including internal operational components such as rail, pavement, and cable) and provide the repair and maintenance regime to the designer.

NOTE Attention is drawn to BS EN 1504-3 for further details on structural concrete repairs.

4.3.5.2 The designer should identify repair and maintenance requirements for the tunnel (including internal operational components such as rail, pavement, and cable) with reference to the client's project-specific repair and maintenance regime.

4.3.5.3 The designer should provide adequate space and structural capacity in the tunnel lining design, so as to fulfil the identified repair and maintenance requirements.

NOTE Failing to identify repair and maintenance requirements can lead to changes in the tunnel size and

structural redesign in the later stages of design. This can introduce significant cost and programme impacts to the design and construction stages. For example, for a pressurized water tunnel, the client might require regular inspection of the tunnel by draining the tunnel, which means a critical load case for the tunnel lining structural design might occur when the tunnel is drained for its maintenance period, rather than during normal operating conditions.

4.3.6 Fire safety requirements

NOTE 1 The ITA document Guidelines for structural fire resistance for road tunnels [4] is focused on road tunnels which are exposed to severe hydrocarbon fire scenarios induced by vehicles' fuel. Further fire safety requirements for road tunnels can be found from World Road Association (PIARC) Road Tunnels Manual [5].

NOTE 2 Railway tunnels (freight, passenger or other) can also be exposed to severe fire events such as the Channel Tunnel fires 1996, 2008 and 2015. The fire resistance of railway tunnels captured by the interoperability regulations are described in COMMISSION REGULATION (EU) No 1303/2014 of 18 November 2014 [6], Technical Specification for Interoperability relating to 'safety in railway tunnels' of the rail system of the European Union.

NOTE 3 The extent of the fire damage and the repair required has an impact on the finance of the infrastructure due to the combination of costs for repairing the tunnel and loss of revenue resulting from extended closure of the tunnel.

4.3.6.1 The client should provide a design fire load, fire curve and post-fire criteria in the design requirements, or provide sufficient information to allow the designer to select the appropriate load, curve and post-fire criteria.

NOTE 1 Sufficient information may include a reference to appropriate regulation.

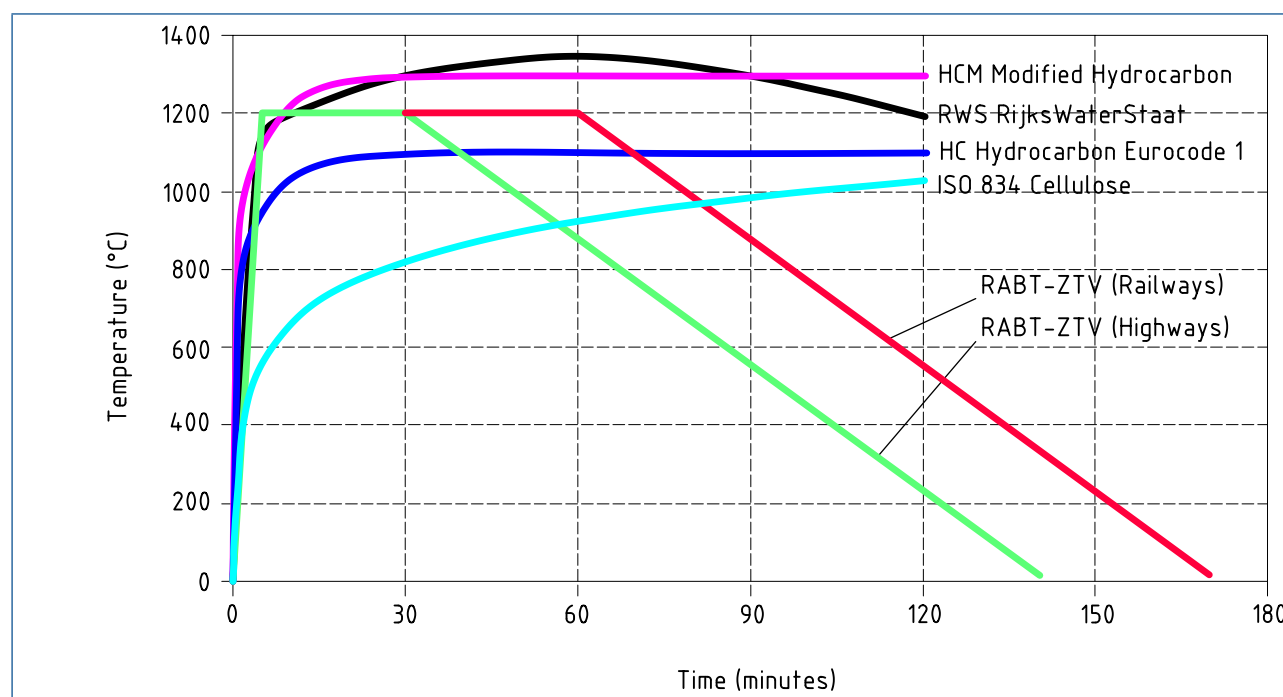
NOTE 2 Different fire loads and curves might be required for the construction and the operational scenarios.

NOTE 3 The fire curve defines the design fire event for the lining design. Further information can be found in EFNARC Specification and guidelines for testing of passive fire protection for concrete tunnels linings [7].

NOTE 4 The selection of the fire curve is dependent on the tunnel use and local conditions. Typical examples are included in Figure 1.

NOTE 5 The tunnel lining may be exposed to a fire during construction. The designer is expected to verify the suitability of the lining for the construction fire case.

Figure 1 – Typical fire curves for tunnel design



4.3.6.2 The client should set out the criteria that the designer should follow for the structural fire design of the tunnel lining under the selected fire load and curve (see 4.3.6.1).

4.3.6.3 The designer should assess and document the properties and performance of the concrete using the appropriate test procedure.

NOTE 1 The required fire resistance can be obtained by the addition of monofilament synthetic fibres to the concrete mix.

NOTE 2 There have been a significant number of tests (e.g. CTRL 2003) undertaken on concrete mixes containing monofilament polypropylene fibres with a diameter of <32 microns. These tests have demonstrated acceptable control of explosive spalling where a suitable quantity of monofilament polypropylene fibres has been added to the concrete mix.

NOTE 3 The quantity of synthetic fibres per cubic metre of concrete can be verified by fire tests as it is a function of the concrete mix.

NOTE 4 An appropriate test method needs to account for the expected in-service loading on the lining as well as the relevant thermal stresses induced by the design fire curve.

NOTE 5 The required fire resistance can also be obtained by the application of protective layers.

4.3.6.4 The designer should design the tunnel lining in accordance with the fire and life safety requirements for the project and assess and document the need for additional active fire-protection measures, including a fire sprinkler system, cross passages, refuges, ventilation and emergency escape.

4.4 Requirements relating to external impacts

NOTE It is important that the tunnel lining is designed to limit any external impacts on the environment around the tunnel.

4.4.1 The designer should carry out a detailed review of the external impacts on the environment around the tunnel that can affect the sizing of the tunnel, selection of tunnel lining type, tunnel construction methodology, construction sequence and/or dimensions of staged excavation details.

NOTE Examples of the external impacts on the environment around the tunnel include impact to existing structures/residences and infrastructures, changes to groundwater level and groundwater pollution.

4.4.2 The client should undertake research into whether there are any existing or proposed plans for developments that might impact the design of the tunnel lining, and should provide this information to the designer.

4.4.3 Where any existing or proposed plans are found, the designer should make an allowance in the tunnel lining design for any potential impact.

4.4.4 The client should provide information to the designer relating to provisions for future loads/unloads, dewatering and proximity to foundations.

NOTE *Tunnels are often constructed in urban areas and, for this reason, it is common to consider a surcharge load at ground level to provide an allowance for future developments (see 9.3.2). Projects often involve dewatering and historical data shows that the groundwater level has been both higher and lower than its current level in many cities.*

4.5 Sustainability

The designer should design the tunnel lining so as to enable the contractor to deliver the most sustainable lining to meet the performance requirements of the project.

NOTE 1 *Further information on the principles of sustainability in construction works is given in BS EN 15804, BS EN 15978, BS ISO 15392, and PAS 2080 (when published).*

NOTE 2 *Guidance relating to responsible sourcing is given in BES 6001.*



5 Conceptual design

5.1 General

5.1.1 The designer should apply design management in accordance with Annex A to manage the deliverables of the tunnel lining design from conceptual design to detailed design.

5.1.2 The designer should carry out the conceptual design of the tunnel lining upon the request from the client in accordance with the accepted schedule of deliverables (see A.5).

***NOTE** It is advisable that this takes place at the Gate 2 stage of the project shown in Annex D or an equivalent stage where a modified process is adopted.*

5.1.3 The designer should identify options for the tunnel construction methodology and document these in the conceptual design output.

5.1.4 The designer and the client should discuss and select a single option from the options identified in 5.1.3, and the option selected should be agreed in writing between the designer and the client in order to proceed to the next design stage.

***NOTE 1** The client can accept multiple options when further study is considered necessary. In this case, the introduction of an intermediate design stage(s) might be required for the selection of a single option.*

***NOTE 2** It is advisable that the client and designer document the reasons for discarding an option to avoid repeating the same option study in the next stage design.*

5.1.5 The designer should carry out conceptual design with consideration given to the following key elements:

- a) space-proofing of the tunnel to meet the client's functional requirements;
- b) review of the tunnel construction methodology and type of lining structure with consideration given to interactions between multiple drifts, adjacent excavations, geotechnical and hydrogeological conditions (including hazardous substances such as gases), third party and environmental impact;
- c) estimation of the tunnel lining structural types and thickness with consideration given to concrete grade and reinforcement type (bar, steel or steel fibres);
- d) feasibility study of the tunnel lining's structural integrity under the expected critical loading conditions (e.g. under high internal pressure for water tunnel);
- e) identified project-specific technical challenges;
- f) tunnel-to-tunnel junctions, such as cross passages;
- g) connections with other underground structures such as portals, station box and shafts; and
- h) development of tunnel lining design concepts.

5.1.6 The designer should assess and, where relevant, document the following factors to determine the optimal alignment for the project requirements and constraints:

- a) the geology or geological features;
- b) the length of tunnel, necessity of intermediate shafts and access locations;
- c) horizontal and vertical constraints including:
 - 1) availability and desirability of sites for portals, shafts and stations;
 - 2) operational constraints such as gradient and curvature minimum radii;
 - 3) potential obstructions such as existing piles, tunnels, sewers, services and utilities and wells; and
 - 4) connections to existing infrastructure
- d) existing foundations and buildings including listed buildings and heritages; and
- e) the legal, environmental, social and political impact.

5.1.7 The designer should undertake a sufficient level of design detail at the conceptual design stage to allow a robust project cost and programme to be determined.

***NOTE 1** The project cost and programme are determined by either the client or the contractor.*

***NOTE 2** Target tolerances can be set by the client, the planning process or funding requirements.*

***NOTE 3** At the conceptual design stage, it is not advisable to carry out a large amount of detailed structural designs. There might be a project-specific critical design element that requires more design effort to demonstrate an option's feasibility. However, it is not usually possible to carry out a detailed review due to the lack of information at the conceptual design stage, such as ground strength parameters and loading conditions from buildings. In this scenario, the designer can make a feasibility conclusion based on a reasonably conservative assumption, but assumptions need to be registered in the risk register document.*

Table 2 – Tunnel construction methodology and associated typical lining types in soft ground tunnelling

Construction method	Structural lining types	
	Temporary support	Permanent support
Mined tunnel (mechanical)	Sprayed concrete lining (SCL)	SCL Cast-in-situ concrete Spheroidal graphite iron (SGI) ^{A)} Steel Precast concrete segment ^{A)}
	SGI	
	Precast concrete segment ^{A)}	
Hand-mined tunnel ^{B)}	Timber heading	Steel frame and cast-in-situ concrete
	SGI or steel	
Tunnel Boring Machine (TBM)	Precast concrete segment	
	SGI or steel	

NOTE 1 Only precast concrete segment lining design is covered in this PAS.

NOTE 2 This PAS uses the terms “TBM” and “mined” in place of ‘mechanized’ and “conventional” respectively. While “mechanized” and “conventional” are widely used and internationally-recognized terms in the tunnelling industry, this PAS elects to use “TBM” and “mined” which are considered to be more appropriate, given the scope of the PAS.

NOTE 3 TBM tunnelling is one of a number of methods of mechanized tunnelling (for the definition of mechanized tunnelling, see the ITA's website (<https://www.ita-aitec.org/en/>) or BS 6164:2011, 7.1). The term “TBM” is used throughout this PAS to denote that the design of the segment lining is directly linked to the TBM rather than other mechanized tunnelling methods.

NOTE 4 Mined tunnelling is one of a number of methods of conventional tunnelling (for the definition of conventional tunnelling, see ITA Working Group 19 publication “General Report on Conventional Tunnelling Method” or BS 6164:2011, 7.1). As the scope of this PAS is limited to tunnelling in soft ground, the specific term “mined” is considered to be more appropriate than the use of the term “conventional”.

^{A)} Not a common type under the specified construction method.

^{B)} Limited to small diameter tunnels only. Design details not covered in this PAS.

5.2 Selection of tunnel construction methodology

NOTE Selection of tunnel construction methodology in soft ground conditions has a direct link to the selection of tunnel lining types. Table 2 provides the general relationship between the tunnel construction methods and the types of lining structure.

5.2.1 The designer's selection of the tunnel construction methodology should conform to BTS, *Specification for Tunnelling*, Section 301 [NR2].

5.2.2 The designer should take account of the functional requirements of any secondary lining, where required.

5.2.3 The designer should select the junction construction method to conform to *BTS Specification for Tunnelling*, Section 311 [NR2] with consideration given to the:

- a) main tunnel construction methodology and lining type;
- b) branch tunnel construction and lining type;
- c) available access space for construction plant and tunnelling operations;
- d) escape and refuge during construction;
- e) ground and groundwater conditions at the junction;
- f) lining break-out method from the main tunnel; and
- g) water tightness at the junctions.

NOTE 1 Junctions such as sumps, niches, cross passages and intersections require breaking out of the lining which is considered to be a high-risk activity.

NOTE 2 The junction construction method can differ from the main tunnel's construction methodology, for example, a main tunnel constructed using a TBM with precast concrete segment lining, and a cross passage constructed using a mining technique mechanically performed by means of picks or teeth.

5.3 Space proofing

5.3.1 The designer should develop the section profile of the tunnel at the conceptual design stage with consideration given to:

- a) space required to fulfil the functional requirements (see Clause 4);

- b) space requirements for safe construction and maintenance;
- c) construction tolerance based on the assumed tunnel construction methodology;
- d) survey tolerance;
- e) end throw and centre throw when a curved tunnel is constructed using rigid straight sections of lining;
- f) long-term deformation of the tunnel lining (ovalization – see Note to 5.3.2); and
- g) any project-specific space requirements.

NOTE 1 *BTS, Tunnel Lining Design Guide [NR1], Figure 2.1 provides major spatial considerations for tunnel linings for rail, road and utility tunnels.*

NOTE 2 The construction tolerance of a tunnel can be affected by various independent elements. For example in TBM tunnelling, the TBM's driving tolerance links to the lining ring's positional tolerance, and the segment's erection tolerance can be independent from the TBM's driving tolerance.

5.3.2 Where no project-specific tolerance for space proofing is specified by the client, the designer should determine the space-proofing tolerances in accordance with *BTS, Specification for Tunnelling*, Section 328 [NR2].

NOTE The long-term deformation limit of a tunnel lining is sometimes defined in the client's design standard. It is often for the designer to provide guidance on the long-term deformation limit, based on historical deformation or structural/geotechnical limitation, particularly with inexperienced clients. The long-term deformation considers a distortion of the lining that can be caused by unknown future activity around the tunnel.



5.3.3 Where there are no deformation limits specified by the client, the designer should determine the deformation limit in accordance with BTS, *Tunnel Lining Design Guide*, Section 5.8.4 [NR1].

5.3.4 The designer should discuss and agree in writing with the client the overall size of the tunnel, having considered all factors listed in 5.3.1.

NOTE *The sizing of the tunnel section is one of the most critical design input parameters that directly affects the project's construction cost and programme, e.g. tunnel size influences lining thickness, TBM size, excavation volume and ground movement/settlement, ventilation and aerodynamics/hydraulics. Tunnel size determined using unrealistic assumptions and/or uncertain space requirement information is considered to be a critical project risk which could cause significant impact to the project's design programme and cost. The consequences of changing the tunnel size at a subsequent stage in the project increase as the project progresses. It is important to fix the size of the tunnel at the concept stage to minimize programme delay and cost risk.*

5.4 Feasibility options report

5.4.1 The necessity of a feasibility options report should be discussed and agreed between the client and the designer at the beginning of conceptual design stage (see A.5.1 and A.5.3).

5.4.2 Where a feasibility options report is required, the designer should compile a feasibility options report that includes the options development background and associated decision-making history in the tunnel lining design, and reflects the project requirements.

NOTE 1 *The feasibility options report for tunnel lining design can be produced as part of the overall project options report, which provides information on elements such as the alignment options and stations layout options reports.*

NOTE 2 *It is advisable to include the following subjects in the feasibility options report:*

- expected tunnel excavation methods, e.g. mined or TBM;
- suggested tunnel lining types, e.g. SCL, cast-in-situ or precast concrete segment;
- conceptual conclusion about meeting the ultimate and serviceability limit states under critical load conditions of the project;
- feasibility of construction methods; and
- any project-specific challenges that affect the conceptual decisions of the tunnel lining design.

NOTE 3 *It is advisable to use a decision tree or flow diagram in the feasibility options report for the development of a preferred option.*

NOTE 4 *The feasibility options report can save time and costs when something changes in the next design stage. The designer and/or client can go back to the feasibility options report and find out why one option had been dismissed, minimising the risk of repetition.*

NOTE 5 *It is advisable that the feasibility options report is reviewed and signed off by the client during the conceptual design stage.*

NOTE 6 *Some clients have a combined documentation process in which the feasibility options report forms part of other documents, such as the approval in principle (AIP).*

5.5 Approval In Principle (AIP)

5.5.1 The necessity of an AIP document should be agreed in writing between the client and the designer at the beginning of conceptual design stage (see A.5.1 and A.5.3).

5.5.2 Where an AIP is deemed necessary, the designer should produce an AIP for the selected tunnel options that provides the design concept, basis, criteria and assumptions to be used for the detailed design of the tunnel lining. The AIP should include:

- a) tunnel lining structural design logic and procedure;
- b) design assumptions;
- c) ground model to be used (this might be preliminary depending on the status of the site investigation and testing information available);
- d) tunnel lining structural analysis methods to be used;
- e) design code/standard to be used for the design;
- f) load combinations to be used;
- g) section profile of the tunnel;
- h) tunnel alignment; and
- i) lining materials, grade and type, including reinforcements.

NOTE *The term concept design statement (CDS) is sometimes used instead of AIP. The purpose and contents of CDS are the same as the AIP.*

5.5.3 The AIP should be reviewed and approved in writing by the client.

5.5.4 The designer should use the AIP as a basis of design in the detailed design stage of the tunnel lining.

NOTE *The AIP can be used as part of the information to assist the transfer of design information from one stage to the other (or from one designer to the other at the same design stage). Information on managing the risk associated with the transfer of information between designers is given in BTS, Joint Code of Practice for Risk Management of Tunnel Works in the UK [8].*

6 Characterization of ground

6.1 General

Subclauses 6.2 and 6.3 should be the responsibility of either the designer, the client, or a third-party contractor employed by either, however this responsibility should be discussed by the designer and the client and agreed in writing.

NOTE 1 A definition of the responsibility for the characterization of the ground is given in BS 6164:2011, Clause 5.

NOTE 2 Clause 6 provides guidance on appropriate strategies and approaches to carrying out desk studies and ground investigations for tunnel lining design. In particular, focus is given to the ground and groundwater characteristics that need to be fully understood to design the lining and to appreciate risks relating to construction of the tunnel. Guidance is offered for deriving ground parameters for tunnel lining design. This is set in the context of the design approach given in BS EN 1997-1 and BS EN 1997-2, and the accompanying National Annexes (NA+A1:2014 to BS EN 1997-1:2004+A1:2013 and NA to BS EN 1997-2:2007).

NOTE 3 The BTS, Tunnel Lining Design Guide [NR1] provides a useful source of reference for many of the topics covered in Clause 6.

NOTE 4 Guidance on the design of tunnel linings in hard rock conditions is given in Hoek and Brown, Underground Excavations in Rock [9]; Franklin and Dusseault, Rock Engineering Applications [10]; and Hudson and Harrison, Engineering Rock Mechanics – An introduction to the Principles [11].

NOTE 5 The use of GIS-based technology can be a useful tool to collate this geotechnical information and communicate to other project team members during the planning, design, construction and operational usages of the proposed tunnel.

6.2 Desk study

6.2.1 A desk study collating the topography, geology, geomorphology, hydrology, hydrogeology and historical uses along the proposed tunnel route should be carried out, and the findings used to develop the ground model (see 6.2.3).

NOTE 1 The desk study is used to identify risks and gaps in available information, and identify areas where particular investigation is required over and above the investigations to provide design input values (see 6.3.1).

NOTE 2 The desk study is of particular importance for urban tunnelling, where existing foundations and buried obstructions constitute key risks.

NOTE 3 Perry and West, Sources of Information for Site Investigations in Britain [12], and BS 6164, Clause 5 give detailed advice on sources of existing information.

6.2.2 Issues that are a material consideration as part of a conventional planning application, such as archaeology and contamination, should be investigated and documented as part of a desk study and subsequent work.

6.2.3 A ground model should be produced from the results of the desk study to assist in guiding the objectives of any subsequent ground investigation.

NOTE 1 The arisings and results from each exploratory hole can be compared against and used to update the ground model developed at the desk study stage. Any differences need to be investigated.

NOTE 2 Additional information on the ground model can be found in Muir Wood, Tunnelling: Management by Design [13].

6.2.4 Site reconnaissance of the tunnel alignment should be carried out to provide an appreciation of the nature of the alignment, potential shaft and work-site locations. The findings should be included in a ground model (see 6.2.3).

NOTE 1 This can be supported by the use of recent aerial photography or satellite imagery and web-based applications such as online maps in the public domain.

NOTE 2 Walkover surveys also provide the opportunity to examine any exposure of the ground and to verify other sources of information acquired as part of the desk study.

NOTE 3 The desk study is used to identify the condition and proximity of existing buildings and infrastructure to the proposed alignment.

6.3 In-situ ground investigation

6.3.1 Planning of ground investigations

6.3.1.1 In-situ ground investigations should be carried out in a phased manner to progressively understand and reduce the uncertainties and risks relating to the tunnelling scheme.

NOTE 1 Guidance for planning an in-situ ground investigation is given in BS EN 1997-2:2007, Section 2.

NOTE 2 Guidance is given in 6.3.2 to 6.3.6 for carrying out appropriate investigation to obtain a range of parameters that are particularly important for the tunnel lining design.

6.3.1.2 When determining the spacing of in-situ ground investigations, the following factors should be reviewed:

- a) knowledge of the ground conditions prior to carrying out the initial phase of investigation;
- b) prevalence of surface infrastructure, e.g. whether tunnelling in urban setting;
- c) location of shafts, cross passages, stations and portals;
- d) variation of ground and groundwater conditions over the alignment of the tunnel;
- e) potential presence of anomalous geological features such as scour hollows, solution features, etc.;
- f) presence of man-made features such as landfills or mine workings;
- g) balance between intrusive and geophysical testing methods;
- h) prevalence of particular strata or deposits that present an elevated risk to tunnelling;
- i) location, depth, diameter and spacing of tunnels;
- j) faults, discontinuities, sand lenses or other geological features that might have localized high groundwater pressure; and
- k) type and quality of sampling and in-situ testing proposed.

NOTE Guidance on the spacing of in-situ ground investigations and the frequency of testing is given in BS EN 1997-2.

6.3.1.3 In-situ ground investigations should be planned to reflect the requirements of the individual project.

6.3.2 Method of investigation and sampling

6.3.2.1 The method of investigation and sampling should be selected to suit the ground conditions and the requirements of the individual project.

NOTE 1 Clayton *et al* [14] provide an overview of exploratory techniques commonly used as part of in-situ ground investigations.

NOTE 2 Appropriate guidance on taking samples can be found in BS EN 1997-2:2007, Section 3. This offers guidance on the quality of sampling necessary to perform the typical range of ground testing used to acquire ground parameters.

NOTE 3 An overview of the applicability of in-situ ground investigation methods for investigating different ground conditions and acquiring a range of ground properties can be found in BS EN 1997-2:2007, Table 2.1.

NOTE 4 An overview of the range of laboratory tests that are commonly carried out to measure specific ground properties can be found in BS EN 1997-2:2007, Table 2.3.

6.3.2.2 Soil and rock description should be carried out in accordance with BS EN ISO 14688-1, BS EN ISO 14688-2 and BS EN ISO 14689-1.

NOTE Appropriate classification of soil and rock is of critical importance for appreciating risks relating to the construction and design.

6.3.3 Ground chemistry considerations with respect to concrete and other material durability

6.3.3.1 As part of the in-situ ground investigation, ground and groundwater testing should be carried out in accordance with BS 8500-1 and BS 8500-2 to characterize the constituents of the ground in order to select a concrete mix for the tunnel lining design.

6.3.3.2 The ground chemistry and potential for oxidization should also be assessed and documented as part of the design process.

NOTE 1 If there is potential for the exposed ground to oxidize, this can result in an oxygen-deficient environment and can present a risk to tunnellers working within confined or unventilated spaces.

NOTE 2 Of particular interest is understanding the requirement for sulfate resistance in the concrete mix and whether other naturally-occurring minerals or historical contaminants in the ground may present a risk to the performance of the tunnel lining.

6.3.4 Coefficient of earth pressure at rest, K_0

The methods used to determine the in-situ pressure prior to tunnelling should be compared with regional stress information from available structural geological mapping.

NOTE An important input parameter to establish is the coefficient of earth pressure at rest. The coefficient of earth pressure prior to tunnelling, K_0 , can be established by a number of laboratory and field techniques. The most commonly used tests are by pressuremeter testing (of which self-boring pressuremeter testing is usually preferred on the basis of minimized disturbance) and carrying out suction measurements of the soil. For soft rocks, hydraulic fracturing is also commonly used. In addition, there are various analytical-based methods by which K_0 can be derived. These include using empirical methods such as those proposed by Mayne and Kulhawy [15] or from soil models such as BRICK proposed by Simpson [16]. The action of constructing the tunnel, however, significantly modifies the in-situ stress in the ground (see 11.7.2.3).

6.3.5 Groundwater pressure and permeability

The selection of the instrumentation to monitor groundwater pressure should be based on the permeability of the ground. Consideration should be given as to whether the groundwater pressures are beneficial or detrimental to the aspect of the tunnel lining design being considered.

NOTE 1 The permeability of the ground influences the rate at which excess pore pressures in the ground dissipate during and following construction and whether short- or long-term parameters govern ground behaviour.

NOTE 2 Some groundwater monitoring installations can also be used to establish the permeability of the ground. Guidance on the range of installations and carrying out groundwater monitoring and permeability testing are given in BS EN 1997-2 and BS EN ISO 22475-1.

6.3.6 Ground stiffness

In-situ ground investigations and laboratory testing should be carried out to measure ground stiffness either directly or indirectly.

NOTE For both direct and indirect methods, the measured stiffness can be influenced by the ground disturbance that has occurred prior to testing. For indirect measures it is important to understand the basis of the correlation being used and to check that it is appropriate for the ground strain level, ground stress and direction of loading likely to be experienced when forming the tunnel. The testing can also be designed to inform strength and stiffness calibration for constitutive models.

6.4 Reporting

6.4.1 General

NOTE 1 Reporting of geotechnical data is described in BS EN 1997-1:2004+A1:2013, Sections 2 and 3. This describes two types of geotechnical reports, namely ground investigation reports (GIRs) and geotechnical design reports (GDRs). Further to this, the use of geotechnical baseline reports (GBRs) can be used as part of contract documents.

NOTE 2 At project inception, it is important that the definitions and content of these reports are defined by the client or client's advisor. For instance, the term GIR has historically been used to refer to the geotechnical interpretative report. The content of these reports traditionally covered some of the scope of the GDR under Eurocode terminology. Historically the terms geotechnical factual report or geotechnical data report have also been used to describe some of the content covered by the GIR under Eurocode terminology.

6.4.2 Ground investigation report (GIR)

6.4.2.1 A GIR should be produced and provided to the client by the designer, or a third-party contractor employed by either the designer or the client. The GIR should include:

- a presentation of all available geotechnical information, including geological features and relevant data; and
- a geotechnical evaluation of the information, stating the assumptions made in the interpretation of the test results.

NOTE A GIR can be produced by either a ground investigation contractor or geotechnical consultant, who might be part of the designer's organization. Consideration needs to be given as to who is responsible for 6.4.2.1 a) and 6.4.2.1 b). It is recommended that the tasks outlined in 6.4.2.1 b) are carried out by the tunnel designer.

6.4.2.2 The designer should base the design of the tunnel lining on the GIR.

6.4.3 Geotechnical design report (GDR)

6.4.3.1 A GDR should be produced and provided to the client by the designer. The GDR should include:

- the assumptions, data, methods of calculation and results of the verification of safety and serviceability;
- a description of the site and surroundings;
- a description of the ground conditions and ground-borne risks;

- d) a description of the proposed construction, including actions;
- e) design values of soil and rock properties, including justification, as appropriate;
- f) statements on the codes and standards applied;
- g) statements on the suitability of the site with respect to the proposed construction and the level of acceptable risk;
- h) design calculations and drawings;
- i) design recommendations; and
- j) a note of items to be checked during construction or requiring maintenance or monitoring.

NOTE 1 Where agreed between the client and the designer, alternative suitable design documentation other than a GDR can be provided.

NOTE 2 The GDR is typically produced by a ground investigation contractor or geotechnical consultant responsible for the design of the tunnel.

6.4.3.2 The designer should make reference to the content of the GIR when designing the tunnel lining.

6.4.3.3 The GDR should make reference to the GIR and any other relevant documentation, such as those that provide the basis for the proposed design parameters.

6.4.4 Geotechnical baseline report (GBR)

NOTE 1 The GBR's primary purpose is to establish a definitive statement of the geotechnical conditions ahead of tunnel construction, as a baseline for contractual reference, if subsequently required. The contractual framework to be adopted for construction needs to reflect the client's approach to and acceptance of risk, the consequences of which are expected to be advised by an experienced tunnelling engineer. Usually, risks associated with conditions consistent with or less adverse than the baseline are allocated to the contractor, and the client accepts responsibility for those risks significantly more adverse than the baseline. Essex [17] discusses the subject of risk allocation in detail.

NOTE 2 The GBR is not to be used as a basis for design and consequently is not to be included in either "works information" or "site information" under NEC contracts. The GBR provides contract information.

6.4.4.1 A GBR should be produced and provided to the client by either the designer, the client themselves, or a third-party contractor employed by either the designer or the client.

6.4.4.2 The designer should not base the design of the tunnel lining on the GBR.

6.5 Digital data

6.5.1 The designer should produce digital data on the in-situ ground investigations and provide this to the client.

NOTE 1 The Association of Geotechnical Specialists (AGS) guidance documentation defines the format for the data transfer protocol. See <http://ags.org.uk>.

NOTE 2 The use of digital data can significantly speed up the transfer of data between project participants and the provision of such data can accelerate the development of ground models and the interpretation of the geotechnical data. This has significant benefits in both supporting the design process and enabling the quick communication of information at all stages of the project between the client, designer and contractor. The use of digital data also reduces the risk of transcript errors propagating into the design process.

NOTE 3 It is recommended that this format is used throughout the in-situ ground investigation design and construction process.

6.5.2 The client and designer should each have procedures and systems in place to manage the volume and type of data.

NOTE It is advisable that where a third-party contractor is used, the client or designer checks that the third-party contractor has procedures and systems in place to manage the volume and type of data.

6.6 Derivation of design parameters

6.6.1 General

NOTE The parameters required for design depend on the analysis proposed to carry out the tunnel lining design. Closed-form analyses require relatively few ground parameters, while numerical analyses incorporating complex constitutive models require many additional ground parameters.

6.6.1.1 The designer should identify and document the construction sequence for derivation of design parameters.

6.6.1.2 The designer should identify and document the ground and drainage conditions along the tunnel alignment.

NOTE These conditions can change over the different phases of construction and therefore multiple design stages might require input parameters and regular analysis.