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British Tunnelling Society

Sprayed Concrete Linings in Soft Ground

A best practice design guide

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A best practice design guide

The British Tunnelling Society

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Foreword

The idea for this guide was sparked over 13 years ago, when Ross Dimmock (Normet) met with Dr Keith Bowers (Cowi, formally Transport for London) and Bob Ibell (then Chair of the British Tunnelling Society) for a quick beverage after a meeting. The Crossrail Project was in full flow, and knowledge of sprayed concrete linings (SCL) in soft ground was advancing in leaps and bounds. It was decided that this knowledge should be captured in a guide to all things SCL: covering design, construction, materials, equipment, safety and much more. Support was gathered at a subsequent meeting of the British Tunnelling Society Committee and a technical working group established. As everyone was so busy it was feared that it might take a couple of years to complete, but enthusiasm was high.

The task was split into different chapters, with a lead assigned to each. It was at this point that I signed up to contribute, requesting to join the design team, led by Brian Lyons. The team quickly established a list of topics to be included within the design chapter, complete with bullet point lists to be expanded under each heading. These were submitted for review, with the hope that the different chapters would be aligned to avoid repetition and overlap.

Time passed. Everyone was indeed very busy, and the other chapters of the book appeared to be lagging behind. It was also noted that there were quite a few topics under the design heading, and that when combined with the other chapters, it might be a very long book indeed. The *Sprayed Concrete Linings in Soft Ground: a best practice design guide* was born. Much was completed by 2019, but sadly the pandemic diverted resources from the final review and publication. That the final reviews were completed during my tenure as chair of the BTS Technical Sub-committee feels fitting, and I am very pleased to have ushered it over the line and share it with you all.

This guide gathers knowledge from the Crossrail Project, where SCL was employed to create the five awe-inspiring central stations (Bond Street, Tottenham Court Road, Farringdon, Liverpool Street and Whitehchapel) as well as crossovers and cross passages under the streets of central London. This was supplemented by concurrent and subsequent projects, including upgrades to Transport for London's stations (including the Bond Street Station Upgrade, Tottenham Court Road Station Upgrade, Victoria Station Upgrade, Bank Station Capacity Upgrade and the Northern Line Extension), the Thames Tideway Tunnel and other utility upgrades, right up to the ongoing High Speed 2 works north of Euston Station.

Sprayed concrete linings were used in all these projects due to their ability to adapt to complex requirements. Working among the maze of existing underground infrastructure of London requires tunnel profiles to change and turn in ways that are impractical using tunnel boring machines. The tunnels are equally too large to complete using hand-mining techniques alone. How SCL is used here in London does differ from its roots in hard rock tunnels, and this guide is specifically looking to capture the considerations of SCL tunnelling in soft ground. Where a topic warrants greater depth than we have space for, we have signposted useful references for further reading. We hope that it serves as a useful introduction to engineers, clients and any other interested parties and helps give confidence in the use of this fantastic material for future tunnelling works.

Bethan Haig
BTS Technical Subcommittee Chair 2023–2025

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This best practice design guide was prepared by the SCL Tunnel Design in Soft Ground working group of the British Tunnelling Society Technical subcommittee.

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Chapter 1
Introduction

The objectives of this best practice design guideline are as follows:

- Provide the designer with a list of current industry standards, guidelines and specifications relevant to sprayed concrete lining (SCL) design and construction.
- Provide guidance in the selection of SCL configuration (e.g. double shell, composite, single shell).
- Provide guidance on spaceproofing and tolerances for SCL construction.
- Provide guidance on ground investigation and the selection of ground and water parameters.
- Provide typical details for excavation sequence and face division, together with a narrative describing their relative benefits.
- Provide guidance for the choice of material parameters and methodologies for SCL design, including designing for fire.
- Provide guidance on ground movements and instrumentation and monitoring for SCL.
- Provide guidance on sustainable design approaches for SCL.
- Provide guidance on the design specification and assurance processes.

Health and safety is integral to every part of the design process.

This guideline has been developed for the benefit of designers, project managers, contractors and clients involved in the design and construction of SCL infrastructure.

It is targeted at the design and construction of SCL in soft ground, London Clay in particular. It is not generally applicable to hard rock conditions. It has been influenced by recent developments within the industry, most notably the successful delivery of the Elizabeth Line (Crossrail) in London and capacity upgrades for Transport for London, which involved extensive use of sprayed concrete lined tunnels.

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Chapter 2
Standards and codes of practice

A number of publications have been developed over the years in the UK, Europe and the USA that have been adopted for the use in SCL design.

2.1. Limitations in current standards

There are few standards and codes specifically developed for the use of SCL. The following areas are particularly under-developed:

- Lack of SCL-specific design standards or codes
- Ground structure interaction using numerical modelling (clarity on use of load and material factors)
- Residual flexural tensile capacity and ductility of sprayed fibre reinforced concrete
- Tensile capacity of plain and fibre reinforced concrete
- Composite linings (SCL/membrane/SCL)
- Analysis of radial joints in SCL
- Permanent/temporary nature of SCL
- Advance rates in relation to strength gain.

2.2. General guidelines

- *fib Model Code for Concrete Structures 2010* (*fib*, 2013).
- *Sprayed Concrete Linings (NATM) for Tunnels in Soft Ground*. Institution of Civil Engineers design and practice guides (ICE, Thomas Telford, 1996).
- *Tunnel Lining Design Guide* (British Tunnelling Society (BTS), 2004).
- *TR63 Guidance for the Design of Steel-Fibre-Reinforced Concrete* (Concrete Society, 2007).
- *Guideline Shotcrete* (Austrian Concrete Society, 2013). This publication applies to the production of structural components made of plain and reinforced concrete as well as the close-textured reinforced concrete placed by the method of spraying. The document covers the testing and design of sprayed concrete mixes, and does so by investigating the requirements placed on the finished material.
- *Safety of New Austrian Tunnelling Method (NATM) Tunnels* (Health and Safety Executive (HSE), 1996a). In October 1994, tunnels under construction beneath Heathrow Airport collapsed. The HSE considered whether there were any broader health and safety implications concerning both the construction of NATM tunnels in the UK and the safety of the finished tunnel in comparison with traditional methods.
- *Post Construction Audit of Sprayed Concrete Tunnel Linings* (HSE, 1996b). This report researches the practice in the auditing of the finished sprayed concrete tunnel lining structure.

- *Low Carbon Routemap* (Low Carbon Concrete Group/The Green Construction Group, ICE, 2022).
- *Design Guidance for Spray Applied Waterproofing Membranes* (ITAtech, 2013).
- *Guidance for Precast Fibre Reinforced Concrete Segments, Volume 1: Design Aspects* (ITAtech, 2016).
- *Low Carbon Concrete Linings* (ITAtech, 2024).
- *Permanent Sprayed Concrete Linings* (Working Group No. 12, ITA, 2020).
- *How to Calculate Embodied Carbon* (IStructE, 2022).
- ACI 506R-16: Guide to Shotcrete (ACI, 2016).
- ACI 544.4-18: Guide to Design with Fiber-Reinforced Concrete (ACI, 2018).
- ACI 544.5R-10: Report on the Physical Properties and Durability of Fiber-Reinforced Concrete (ACI, 2010).
- *Monitoring Underground Construction: A Best Practice Guide* (BTS, 2011).
- A Code of Practice for Risk Management of Tunnel Works (International Tunnelling and Underground Space Association (ITA-AITES) International Association of Engineering Insurers (IMA), 2023)

2.3. Eurocodes and British standards

- BS EN 1990: Eurocode 0. Basis of structural design.
- BS EN 1991-1: Eurocode 1. Actions on structures.
- BS EN 1992-1: Eurocode 2. Design of concrete structures.
- BS EN 1997-1: Eurocode 7. Geotechnical design. General rules.
- BS EN 1997-2: Eurocode 7. Geotechnical design. Ground investigation and testing.
- BS EN 14487-1:2022: Sprayed concrete. Part 1: Definitions, specifications and conformity.
- BS EN 14487-2:2006: Sprayed concrete. Part 2: Execution.
- BS EN 14488-1:2005: Testing sprayed concrete. Sampling fresh and hardened concrete.
- BS EN 14488-2:2006: Testing sprayed concrete. Compressive strength of young sprayed concrete.
- BS EN 14889-1:2006: Fibres for concrete. Steel fibres. Definitions, specifications and conformity.
- BS EN 14889-2:2006: Fibres for concrete. Polymer fibres. Definitions, specifications and conformity.
- BS EN 14651:2005: Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual).
- BS EN ISO 14688-1: Geotechnical investigation and testing. Identification and classification of soil. Identification and description.
- BS EN ISO 14688-2: Geotechnical investigation and testing. Identification and classification of soil. Principles for a classification.
- BS EN 206-1: Concrete. Specification, performance, production and conformity.
- BS 6164:2019: Health and safety in tunnelling in the construction industry – Code of practice.
- BS 8500-1: Concrete. Complementary British Standard to BS EN 206. 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.
- ISO 44001: Collaborative business relationship management systems. Requirements and framework.

- ISO 834-1: Fire resistance tests.
- The Construction (Design and Management) Regulations 2015 (CDM).

2.4. Flexural strength guidelines

- RILEM TC 162-TDF (2003) Test and design methods for steel fibre reinforced concrete. *Materials and Structures* **36**: 560–567.
- *fib Model Code for Concrete Structures*. Bulletin 65, vol. 1, Section 5.6: Fibres and fibre reinforced concrete (*fib*, 2010).

2.5. Specifications

- *European Specification for Sprayed Concrete* (EFNARC, 1996). This specification treats sprayed concrete as an entity and makes no reference to fields of application, such as tunnelling, which is the case in many other publications.
- *European Specification for Sprayed Concrete: Guidelines for Specifiers & Contractors* (EFNARC, 1999). This publication is to be read in conjunction with the EFNARC *Specification for Sprayed Concrete*. These guidelines refer to the specification and all references relate to the clause numbers in the specification. The guidelines contain a number of updates that supersede items in the specification, particularly a list of the latest CEN test methods relevant to sprayed concrete and a revised section on the execution of spraying.
- *Specification for Tunnelling*, 4th edn. (BTS, 2024).
- ACI 506.2-13: Specification for shotcrete (ACI, 2018).

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Chapter 3
Sprayed concrete lining design process and key decisions

3.1. Design process

The SCL design process is a series of steps that develop a number of requirements, through consideration of cost, programme, risk, sustainability and quality, through to a set of outputs, which provide sufficient detail and information to allow tunnel construction to be safely undertaken. Within this process, a number of key decisions should be taken to develop a safe, durable lining system that satisfies the project requirements, and that can be put in place without risk to the workforce, and that complies with the CDM Regulations. This section highlights the sequence of activities involved in the SCL design process and describes the decisions that should be made at each stage.

SCL tunnelling is an open-face method, and the precise nature of ground in which the tunnel is constructed can only be definitely characterised once the face is open. The design process should therefore embody a risk-based approach to decision-making to demonstrate that a robust design has been provided. The design should take sufficient consideration of construction methods, sequences and processes, and make suitable provision for varying site conditions.

The design process should be carried through into the construction phase, because the performance of the lining system needs to be continually verified.

3.2. Key aspects of SCL design

Issues of particular significance to SCL design include the contractual divisions related to design responsibility, the management of risk, and the necessity for integrated construction and buildability input throughout the design. This section details the importance of these aspects to the development of a successful SCL design and provides guidance on best practice.

3.2.1 Progressive design development

The design process involves a series of stages with increasing level of detail (LoD). This guideline considers the typical stages (feasibility/concept, scheme and detailed) through which the design is progressed in a structured manner, adding detail at each stage and ratifying decisions and approaches. Different client organisations and design partners (such as architects using the RIBA workflow) have different titles for each of these stages, but the principles are typically aligned. Through the various stages, the design should be progressively assured, evidencing the verification/validation of the design outputs for each stage.

3.2.2 Single design responsibility

In SCL design, the distinction between permanent and temporary works can be ambiguous. The commentary offered in BS 6164:2019 clause 6.4.1 should be considered and it should be recognised that temporary ground support provided by sprayed concrete can become part of the permanent works at a later stage.

It is recommended that a single designer is responsible for both temporary and permanent works in so far as they affect the performance of the tunnel lining. If separate designers are employed, a significant interface could be created. This split can lead to duplication, significant interface management effort and ambiguity in responsibilities, leading to the requirement for additional site representation due to the multiple stakeholders involved.

It is, therefore, considered best practice to allocate the responsibility for the design of all lining elements, the conception of temporary measures and for excavation stability to a single entity.

3.2.3 Management of risk

The nature of open face tunnelling, particularly in urban settings, means that a rigorous risk-based design approach needs to be implemented. A high level of attention should be paid to critical areas of the design throughout the design stages, including early reference or conceptual design, so that fundamental risks can be eliminated. The aim is that the risks should be eliminated at source or reduced As Low As Reasonably Practical (ALARP). Constant assessment of risk in terms of health, safety, commercial and programme is essential to ensure that ALARP is achievable and ultimately delivered for the final design.

Robustly designed comparative risk assessments can be a useful tool to demonstrate that the safest and lowest risk option has been selected.

The nature of SCL design means that design decisions and validation continue through the design and construction processes, and the designer should therefore be represented on site and be actively involved in the decision-making/review/approval processes.

3.2.4 Construction input to design

The inherent links between the excavation sequence, face division, cycle time, equipment and construction methodology mean that SCL design and construction cannot be separated, and their interaction is fundamental. Input should be obtained from the construction team intending to undertake the works. This engagement and collaboration should lead to the development of an optimised, safe, robust and efficient design.

Procurement of the design within the framework of the construction contract and resulting responsibilities is critical in terms of demonstrable and effective risk management.

3.2.5 Effective use of analysis

The analytical tools available to the SCL designer are becoming ever more sophisticated. With these advances comes the need for careful consideration of when, by whom, and to what level such analysis should be used during the design process. Analysis should escalate in complexity and sophistication to complement the critical areas of design and LoD required at each stage, as well as the reliability of available information such as the description of the ground.

At the feasibility/concept stage, two-dimensional (2D) analysis is usually sufficient to establish conservative estimates of volumes of excavated material, reinforcement requirements and concrete sections for costing and environmental impact purposes. Precedent experience can assist in determining lining thickening at tunnel junctions or where works are adjacent to existing tunnels