CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Civil Engineering
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The use of spray-applied waterproofing membrane in underground construction

DOCTORAL THESIS

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DECLARATION

Ph.D. student's name: Barbora Píšová, MSc.

Title of the doctoral thesis: The use of spray-applied waterproofing membrane in underground construction

I hereby declare that this doctoral thesis is my own work and effort written under the guidance of the tutor prof. Ing. Matouš Hilar MSc., Ph.D., CEng.
All sources and other materials used have been quoted in the list of references.

The doctoral thesis was written in connection with research on the project: SGS15/043/OHK1/1T/11.

In Prague on 31.01.2020 ……………………………………

signature

To the memory of my father

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Prague, in January 2020 Barbora Píšová

Abstract (Czech)

Jednou z aktuálně diskutovaných technologií v podzemním stavitelství je použití stříkaných hydroizolačních membrán. Tradičně se k zajištění vodotěsnosti podzemních staveb používají prefabrikované hydroizolační fólie, nicméně existuje možnost použití stříkaných hydroizolačních membrán vyrobených přímo na stavbě. O stříkaných hydroizolačních membránách se často hovoří jako o inovaci posledních let. Stříkané hydroizolační membrány jsou přídržné k povrchu a představují tak smykové spojovací prostředí mezi primárním a sekundárním ostěním, čímž vytváří tzv. kompozitní ostění. Aby bylo možné plně využít výhod kompozitního ostění, je nutné poruzumět principu a omezení použití stříkaných hydroizolačních membrán.

Použití stříkaných hydroizolačních membrán se v některých státech značně rozšířilo, ale v České republice byla technologie stříkaných hydroizolačních membrán zatím využita jen v omezeném rozsahu. Pro případný širší rozvoj je nezbytně nutné nejen pochopení chování stříkaných hydroizolačních membrán jako takových, ale i vzájemné interakce mezi membránou a primárním a sekundárním ostěním. V rámci disertační práce jsou shrnuty teoretické a praktické poznatky použití stříkaných hydroizolačních membrán a kompozitního ostění a jsou uvedeny příklady použití stříkaných hydroizolačních membrán v tunelových ostěních nad a pod hladinou podzemní vody.

Abstract (English)

One of the currently heavily discussed topics of underground tunnelling technologies is the use of spray-applied waterproofing membranes. Traditionally, waterproofing of a tunnel lining is provided by means of a prefabricated plastic sheet waterproofing membrane, however, there is an option to use the spray-applied waterproofing membranes manufactured on site. The spray-applied waterproofing membranes are very often called innovation of the past few years. The spray-applied waterproofing membranes bond to the substrate and structurally connect the primary and the secondary lining, resulting in so-called composite lining. In order to benefit from the composite lining's behaviour it is necessary to fully understand the principal and the limitations associated with the use of spray-applied waterproofing membranes.

The use of the spray-applied waterproofing membrane has become more popular in some countries but in the Czech Republic it has been used so far on a limited amount of structures. For a potential wider use of the spray-applied waterproofing membranes, understanding of the spray-applied membranes as a material and the interaction between the primary and secondary linings is vital. In this thesis, theoretical and practical aspects of the use of spray-applied waterproofing membranes and the interaction as composite lining are summarized and examples of tunnel linings with the use of the spray-applied waterproofing membranes above and below water table are presented.

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1 Introduction

1.1 General overview

In construction, and especially in underground construction, water management is one of the key issues. Even though waterproofing usually represents a relatively small part of the overall project cost, lack of its durability and functionality may result in significant disruptions and expensive remedial works.

Various types of waterproofing are suitable for variety of conditions. The most commonly used waterproofing system for underground structures such as tunnels and shafts, are plastic sheet waterproofing membranes. The plastic sheet waterproofing membranes are prefabricated, installed as strips in-situ and welded together. The plastic sheet waterproofing membranes are suitable for both drained and un-drained structures.

An alternative to the traditionally used plastic sheet waterproofing membranes are spray-applied waterproofing membranes. The spray-applied waterproofing membranes are produced directly on site by spraying of a liquid substance onto the surface that once cured forms a waterproofing layer. The use of the spray-applied waterproofing membranes can be in certain cases advantageous over the use of the sheet waterproofing membranes. Installation of the spray-applied waterproofing membranes can be faster, allows for the use of sprayed concrete secondary lining and requires less investment in equipment (no need for formwork or scaffolding like in case of the sheet waterproofing membranes).

The spray-applied waterproofing membranes bond to the primary and the secondary lining, contribute to the overall structural behaviour, and create so-called composite lining. The use of the spray-applied waterproofing membranes has been experienced more advantageous in case of low water ingress through the surrounding rock mass because in case of higher water inflow additional measures such as injection or water collection well points are necessary as pretreatment of the primary lining in order to stop or manage the water inflow. The spray-applied waterproofing membranes are suitable for un-drained and locally or systematically drained structures [1].

Selection of the right waterproofing system for the given conditions is an important pre-construction decision. This work includes practical examples, lessons learnt, potential benefits and failure mechanisms of tunnel linings with the spray-applied waterproofing membranes.

1.2 The Problem

Until now, there has been no uniform, systematic and scientifically proven approach to design and build underground structures with the use of the spray-applied waterproofing membranes in the Czech Republic. Designers and contractors often introduce new solutions based on their subjective knowledge and experience but systematic approach shall be in place in order to deliver safe and durable structure to the client. Lack of the systematic scientific approach leads to self-interpretation of diverse published data and manufacturer's recommendations. Some of the manufacturers report that the use of the spray-applied waterproofing membranes allows the tunnel linings to be designed thinner and so the overall costs can be reduced [2]. Material, time and cost savings are the major motivations to deeply look into this problem and evaluate whether such statements are reasonable or if some limitations exist.

1.3 Objective of the thesis

The aim of this thesis is to scientifically analyse facts in relation to the problem described above, provide an insight into the up-to-now experience and introduce design recommendations based on practical experience and lessons learnt.

Over the past few years, research of the structural behaviour of the composite lining (primary lining - spray-applied waterproofing membrane - secondary lining) has been carried out with main focus on determination of the interface parameters - strength and stiffness of the interface in compression, tension and shear by means of laboratory experiments and numerical modelling. It has been found out that further investigation of the impact of the moisture conditions onto the interface parameters and consequently onto the secondary lining shall be carried out. In this work, the use of the spray-applied waterproofing membranes is studied from the theoretical and the practical point of view and conclusions for composite lining are made so that it can be designed and constructed as reliable and effective as possible.

1.4 Structure of the thesis

Chapter 2 presents basis of the topic. For this purpose, current requirements and specifications are evaluated with regards to the design of the tunnel linings with the spray-applied waterproofing membranes.

History and development of sprayed concrete tunnel linings with focus of development of permanent primary lining, tunnel lining design according to various tunnelling methods and tunnel lining design concepts are presented in Chapter 3.

In Chapter 4, lessons learnt from practical use of the spray-applied waterproofing membrane on selected projects are presented.

In Chapter 5, each element of the composite lining (primary lining - spray-applied waterproofing membrane - secondary lining) is identified and its function described with particular emphasis on identification of water path within the primary lining and properties and production of the spray-applied waterproofing membranes.

In Chapter 6, behaviour of the composite lining is described based on numerical modelling and potential failure modes.

Chapter 7 summarizes the results of the work, provides recommendations and suggests further research of the topic.

2 Basis

2.1 Specifications

The spray-applied waterproofing membranes are a relatively new technology. In the Czech Republic, current standards and normative allow for their use; however no detailed guideline is available. In the UK, the use of the spray-applied waterproofing membranes is addressed in the BTS Specification in tunnelling [3] and the ITAtech Design Guide for spray-applied waterproofing membranes [1]. For the composite lining concept as well as the spray-applied waterproofing membrane itself, the following remarks are made:

2.1.1 Czech standards

TKP (Technical Qualitative Conditions) 24/2006 [4] state that the tunnel waterproofing shall be specified within the detailed design. Usually, sheet waterproofing membranes made of PE (PE-HD, PE-LD, PE-LLD, PE-VLD), TPO and PVC-P are used. Other types of waterproofing membranes with other properties and thicknesses can be designed and built only after an acceptance of the client. The acceptance shall be based on performance test results, recommendations (reference projects) and site pre-construction trial tests.

For the use of the spray-applied waterproofing membranes, the statement “other types of the waterproofing membranes … can be designed and built…” applies. However, the rest of the document is based on the assumption that a plastic sheet waterproofing membrane is used and other requirements such as that the waterproofing system shall always include a geotextile layer with drainage and protection function, or that the use of systematic injection for potential future leaks shall be installed, are not applicable. The geotextile is usually not installed where the spray-applied waterproofing membranes are used and installation of systematic injection tubes would not be effective due to the bonding property of the spray-applied waterproofing membrane that would not allow the injection material to flow along the bonded interface.

2.1.2 BTS Specification for tunnelling, third edition

The BTS Specification for tunnelling [3] describes the spray-applied waterproofing membranes as *"waterproofing lining cured in place that must permit safe construction of the secondary lining (cast-in-situ or sprayed) without reduction in waterproofing properties. The spray-applied waterproofing membrane liquid substance prior to application shall be prepared according to the manufacturer´s instructions otherwise a written consent of all the involved parties (manufacturer, client, designer and the contractor) shall be obtained. The spray-applied waterproofing membranes shall bond to the substrate with bond strength greater than 0,5MPa (as evidence of water path obstruction), no water should penetrate through the membrane and the membrane should be able to elongate itself to bridge over gaps up to 2mm wide without losing its waterproofing properties."*

Further information on the system design of the composite lining with the use of the spray-applied waterproofing membrane is not in the BTS Specification for tunnelling [3] included.

2.1.3 ITAtech Design Guide for spray-applied waterproofing membranes

The ITAtech Design Guide for spray-applied waterproofing membranes [1] describes the spray-applied waterproofing membranes for tunnels as *"proprietary construction materials that are applied to the primary lining surface with spray equipment, in order to form a coating that is bonded to the concrete and that can provide an effective barrier to the ingress of liquid water into the structure".* Water-tightness of the lining with the spray-applied waterproofing membranes comes from two key characteristics, water-tightness of the membrane itself and its bonding property. ITAtech [1] states that in a bonded solution, migration of groundwater along the membrane-concrete interface cannot occur, because any potential groundwater paths can be eliminated, mitigating considerably the risk of water ingress into the tunnel. Additionally, a bond between the membrane and the secondary lining can provide a further barrier against water ingress into the tunnel. The membrane should present a minimum thickness according to the manufacturer’s instructions, in order to be watertight. Typically, the spray-applied waterproofing membranes can only withstand active water pressure when they are completely cured and embedded between two concrete linings, [1].

For the composite lining design, the following statements are cited [1]: *“When installed between the primary and secondary concrete linings, the spray-applied membranes may bond to both primary and secondary linings (double-bonding) or only to one lining (single-bonding), depending on the design requirements and the product chosen. In the case of a spray-applied membrane with double bonding properties, the resulting sandwich-structure (concrete-membrane-concrete) may act as a quasi-monolithic structure, depending on the bonding characteristics and properties of the membrane. The bond strength of the membrane to the substrate should be 0.5 MPa or greater within 28 days to maintain the integral bond to eliminate water paths between membrane and sprayed concrete. Composite shell lining systems are based on the single shell lining approach and consist of two concrete linings, which are usually installed at different stages, with a double-bonded spray-applied waterproofing membrane embedded between them.”*

Advantages of the bonded solution are by ITAtech [1] also described. It states that the primary and the secondary linings installed without a waterproofing membrane are often thought as acting as a single shell thanks to the influences of geometry, bond and shear connection through surface roughness. In many cases however, this solution does not offer a suitable water-tightness in the long term. Spray applied waterproofing membranes allow the benefits of both options by connecting the primary concrete lining to the secondary concrete lining by means of a fully bonded (double-bonded) membrane that can transfer some of the shear forces, allowing the linings to work together. Aside from the obvious waterproofing advantages, the fully bonded membrane is also structurally advantageous. If the primary lining is designed for permanent purposes, and suitable load transfer through the spray-applied membrane to the secondary lining occurs, designers have the opportunity to significantly reduce the lining thickness in comparison to the assumption that the whole final load is acting on the secondary lining only. If the primary concrete lining should be designed for permanent purposes and be integrated in the final tunnel lining, double bonded membranes may be used to enable design optimisations, e.g. reduction of the thickness of the secondary lining, [1].

ITAtech [1] demonstrates the general composite principle by comparing the action of two joists placed one on top of the other. If these are simply placed one on top of the other and loaded as a beam there will be some relative movement between the two. However, if these are physically connected, the bending strength and stiffness are significantly improved as the two will act together as a single unit with double the thickness, [1].

Numerical modelling of the composite lining is also included in the ITAtech Design Guide. ITAtech states that the composite lining must be able to withstand all potential loading conditions from the ground, groundwater and surface loads throughout the design life of the tunnel. The lining structure should be watertight, durable, as well as capable of accommodating the loads of internal structures such as lighting canopies and ventilation fans and have a surface finish to achieve the required reflectance and aesthetic appearance. To achieve composite behaviour and guarantee the structural effectiveness of the system, a bond needs to be achieved between the concrete layers and the sprayed membrane to permit the transfer of normal and shear forces between the primary and secondary layers. The bond strength required at the interface between the primary and secondary lining to permit the composite action must be evaluated for each project. The prevailing load conditions must be considered before coming to a judgment on whether or not a composite lining solution is achievable. The properties of the interfaces between the concrete and the waterproofing membrane are required for numerical simulation of the structural composite lining. These properties are usually taken from back-analysis of shear test data. Shear test curves can be replaced with curves derived from numeric simulations of the shear tests. Typical interface parameters used in numerical models are the angle of interface friction, the interface cohesion, as well as the Interface shear and normal stiffness. The exact parameters for the interface elements may vary depending on the theory implemented in each numerical modelling program. Therefore, it is recommended that the input parameters for the model are derived by first back analysing test data and calibrating the numerical model, [1].

Regarding the crack-bridging, ITAtech [1] states that the membrane shall bridge over cracks at least 2,5mm wide.

2.1.4 Evaluation of the standards and specifications

Both the BTS Specification [3] and the ITAtech Design Guide [1] require the spray-applied waterproofing membrane to bond to the surfaces with bond strength higher than 0,5MPa, ability to elongate at least 2mm and to remain watertight.

The ITAtech Design Guide [1] provides guidance of the composite lining design but does not cover all the aspects of the use of the spray-applied waterproofing membrane in tunnel linings, such as behaviour of the membrane on water saturated surface or change of its behaviour depending on its moisture content.

The Czech standards [4] do not provide guidance to the use of the spray-applied waterproofing membrane other than that it shall be dealt with within the detailed design and pre-construction trial tests.

2.2 State-of-the-art

Various underground structures with the use of the spray-applied waterproofing membranes have been recently constructed: underground rail stations, road tunnels, emergency adits, cross-passages or ventilation shafts. So far, the structures have been designed based on the available specifications and design recommendations, laboratory tests or field pre-construction trial tests carried out in cooperation with the manufacturer. However, unified and systematic approach to design and build composite linings does not exist.

The projects where the spray-applied waterproofing membrane has been used are not necessarily comparable one to another. The ground conditions, groundwater table and the secondary lining design are project specific and affected by the missing systematic design approach to design composite linings with the use of the spray-applied waterproofing membranes.

Currently, the largest infrastructure project in Europe where the spray-applied waterproofing membranes were used, is Crossrail (Elizabeth rail line) in the United Kingdom, constructed between 2009 and 2019. This project has brought to the tunnelling industry a lot of valuable theoretical and practical experience concerning the use of the spray-applied waterproofing membrane in soft ground tunnelling, however, a clearly defined state of the art cannot be formulated at present.

2.3 Current status of the composite lining design problematic

The bond character of the spray-applied waterproofing membrane introduces shear and tensile connection between the primary and the secondary lining and these two linings can then act together as a composite lining. Various investigations of the composite lining with use of the spray-applied waterproofing membrane have been carried out. The first main objective has been to investigate the parameters of the cured spray-applied waterproofing membrane. The other main objective has been to investigate the structural behaviour of the spray-applied waterproofing membrane acting as an interface within the composite lining.

2.3.1 Investigation of the waterproofing membrane parameters

Investigation of the spray-applied waterproofing membranes' parameters in the cured state is primarily carried out by the manufacturers and published on their websites or within product sheets. The material parameters are usually based on laboratory tests and the manufacturer's experience from fieldwork during the pre-construction and construction phase in cooperation with the contractor.

An example of the published parameters of a spray-applied waterproofing membrane by one of the manufacturers is the following [2]: *"The spray-applied waterproofing membrane resists water pressures of up to 20 bar in combination* *with concrete lining (inner and outer linings) and subject to a design which addresses the water pressure situation. It has a water vapour diffusion resistance number μ within the range 150 - 300. It bonds to clean/particle free cementitious materials on both sides of the membrane, with a bond strength of at least 1.2 MPa ± 0.2 MPa. It possesses a tensile strength of 1.5 to 3.5 MPa. Its elasticity varies between 80% and 140% at +20°C. When tested with a thickness of 3 mm, it is able to bridge a crack of 3 mm opening (100% elasticity), before failure occurs. The composite system possesses a minimum average flexural strength of 4.5 MPa. The following ranges of shear strength parameters have been estimated for the composite system based on the results of direct shear tests: Friction angle: 24° − 43° / Cohesion: 0.5 - 1.05 MPa. These shear strength parameters have been taken from two direct shear tests carried out under zero normal displacement conditions to a 2 mm thick membrane applied to a smooth substrate and a 5 mm thick membrane applied to a rough substrate. These two specimens represent the two ends of a spectrum. The above mentioned values of friction angle and cohesion are not design values. They are estimated values and may vary also beyond the above mentioned values, depending on the local conditions of application. For design purposes a variation of the above mentioned parameters should be considered."*

In this case, the bond is referred to as “1.2 MPa ± 0.2 MPa” [2]. Other manufacturers refer to “bond strength 1.5 MPa or greater” [5] or “bond strength greater than the cohesive strength of the concrete” [6].

Johnson et al. [7] investigated the structural properties and durability of a polyurea-resin-based spray-applied waterproofing membrane for tunnels and state that the bond to the concrete is about 1MPa and no slip at the interface occurs. They introduce short-term and long-term shear modulus (1MPa and 0,5MPa respectively), and suggest that where no-slip assumption can be made, the shear modulus should be reduced by the thickness of the spray-applied waterproofing membrane. Johnson et al. also state that life expectancy of the spray-applied waterproofing membrane is high and any deterioration will be negligible.

2.3.2 Investigation of the structural behaviour of the composite lining

Investigations of the structural behaviour of the composite lining have been generally carried out by means of numerical modelling and/or laboratory testing.

In 2010, Holter, Bridge and Tappy [8] presented that the use of the sprayed concrete secondary lining allowed for reduction of the overall lining thickness, shorter construction time and financial benefits. The use of the sprayed secondary lining was technologically allowed by the use of the spray-applied waterproofing membrane.

In 2015, Nakashima et al. [9] carried out investigation of mechanical behaviour of the sprayed concrete lining with the use of the spray-applied waterproofing membrane. Their findings suggest that a tunnel lining with the spray-applied waterproofing membrane behaves as composite with very limited slip at the interface that could potentially lead to optimisation of the secondary lining thickness.

In 2015, Su [10] carried out laboratory experiments in order to investigate the influence of the primary lining surface finish roughness and the membrane thickness on the composite action and found out that there was a significant composite action at the interface between the primary and the secondary lining through the bonded spray-applied waterproofing membrane. The degree of the composite action was controlled by the nominal thickness of the membrane but with little impact of the variation in primary lining surface finish roughness.

In 2016, Holter and Geving [11] investigated moisture transport through concrete tunnel linings. They state that an important question to consider is the risk of a significant water saturation of the membrane material in the tunnel lining. The possible effect of such saturation could be reduction of mechanical strength, particularly tensile bonding strength at the interfaces. The findings, for the investigated cases, indicate that the concrete material exhibits a reduction of saturation on the immediate inside of the membrane with the degree of capillary saturation 100% on the rock side and between 80 to 95% near the membrane, resulting in low capillary saturation of the membrane with no significant impact on its properties.

In 2017, Vogel et al. [12] investigated static response of double shell concrete lining with a spray-applied waterproofing membrane. Their findings are that the spray-applied waterproofing membrane is able to transfer shear and flexural stresses between two concrete linings and suggest that reduction in dimensioning could be achieved.

In 2018, Diez [13] investigated sensitivity of the properties of the spray-applied waterproofing membranes to both moisture content and long-term load in order to evaluate impact on the ability of a double shell lining to act in a composite manner. Diez concludes that EVA-based membranes reduce significantly cohesive strength and stiffness in long-term 'wet' state and questions the degree to which composite action can be assumed.

In 2019, Su and Blootworth [14] investigated the impact of varying interface stiffness and primary/secondary lining thickness ratios on the load sharing between the primary and secondary linings by means of numerical modelling. The results show that high composite action can introduce net tension to the secondary lining, which may be detrimental to the lining capacity. They conclude that for an efficient composite lining design, selection of suitable primary and secondary lining thicknesses rather than refinement of the interface parameters is the key but additional reinforcement of the secondary lining may be required.

2.3.3 Evaluation of the investigations

The parameters of the spray-applied waterproofing membrane presented in chapter 2.3.1, show the bond strength twice higher than the minimum bond strength required by the BTS Specification for tunnelling [3]. The crack bridging performance of the material is compliant with the BTS [3] requirement and the waterproofing property is described in terms of resistance to water pressure and water vapour diffusion resistance.

Majority of the investigations refer to the tests done on 'dry' samples. Even though the spray-applied membrane's primary function is to waterproof so that contact with water can be expected, its performance is usually not tested in 'wet' conditions.

The minimum thickness of the membrane must be achieved so that the membrane is watertight. Higher membrane thickness can increase the safety margin of the water-tightness but with increased thickness of the membrane the composite action may decrease, [10]. Overall, the investigations do not correlate the results to the thickness of the membrane and cannot therefore be reliably compared.

In contrary to the sheet waterproofing membranes that are considered to act as a slipping surface, when a bonded spray-applied waterproofing membrane is used, restraint stresses will develop. The contrary to the principles described in Guideline Inner Shell Concrete, issued by Österreichische Vereinigung für Beton- und Bautechnik in 2006 [15] that states: *"For waterproof inner shells, the air-side surface of the substrate (e.g. sliding film or sprayed concrete) should be as to minimise interlocking between the waterproof inner shell and the sprayed concrete shell."* and *"Separation layers serve to diminish the adhesion and interlocking between the cavity lining and the rock and/or the sprayed concrete lining. They serve to diminish the build-up of restraint stresses in the cavity lining in the course of the setting process and the resulting crack formation."* can be expected.

The development of the use of the sprayed concrete lining and the spray-applied waterproofing membranes that is explained below goes beyond the investigations explained above and includes possible solutions for the design of a composite lining.

3 Theoretical background of sprayed concrete tunnel linings

Sprayed concrete has been used in underground construction for decades. In the Czech Republic, its use is addressed in standard CSN 73 7501 [16] and guidelines TKP 18/2016 [17], TKP 24/2006 [3] and TKP-D7/2016 [18]. In these standards, the primary lining is generally referred to as ‘temporary’ and the secondary lining as a permanent structure. Permanent or partially permanent function of the primary lining is not explicitly forbidden but it is neither a usual praxis.

Recent quality improvements in the sprayed concrete lining production have led to the consideration of using the sprayed concrete not only for temporary support but also for permanent support with the aim of making tunnel linings more economical, [19]. Even though evidence has been provided on long-term performance of the tunnel primary linings [20], it has not yet been accepted by the above-mentioned standards.

In this chapter, based on the historical development of the sprayed concrete, development of its permanent function in the UK is described, function of the sprayed concrete in various tunnelling methods is presented and tunnel lining design concepts are introduced.

3.1 History and development of sprayed concrete tunnel linings

A taxidermist in the USA invented sprayed concrete, then known as gunite, in 1907. Gunite was a method of blowing dry material out of a hose with compressed air and injecting water at the nozzle as it was released. The original mixture consisted of fine aggregates with high content of cement. Nowadays, the term “shotcrete” is generally used for any mix that contains aggregates, cement and water and is applied by spraying, [21].

3.1.1 First sprayed concrete tunnel linings (1st half of 20th century)

The first use of sprayed concrete in underground construction is dated in 1914 in Bruceton Experimental Mine in the USA. However, in Germany, August

Wolfsholz had been developing equipment for spraying cementitious mortar in tunnels for rock support from as early as 1892, and Carl Weber patented a method for spraying concrete in 1919. By the 1920s, sprayed concrete had been used in several tunnels across Europe, [21].

By that time, only dry mix spraying technique was used, wet mix spraying was introduced after the World War II. In Fig. 1 the first spraying “robot” is shown.

Fig. 1 First spraying robot (courtesy of the Portland Cement Association, USA), [21]

While sprayed concrete was used on a few engineering projects to repair concrete structures or for rock support in the first half of 20th century, this material and method first attracted serious attention after its use on a series of pioneering projects in Venezuela and Austria by Ladislaus von Rabcewicz in the 1950s, [22].

Quality of the early sprayed concrete was not high. Large amount of aggressive accelerating additives had to be used in order to provide for adherence of the sprayed concrete to the rock, however high amount of rebound still occurred. Lot of dust and the aggressive accelerators created unhealthy work environment during the spraying operations. Manual application of the dry sprayed concrete mix (Fig. 2) meant that the final product was very sensitive to the skills of the nozzleman and potentially resulting in bad compaction of the sprayed concrete and incorrect water dosage. Therefore, the sprayed concrete lining was of variable quality and the long-term strength was generally lower than cast-in-situ concrete, [22].

Fig. 2 Manual shotcrete application, [23]

3.1.2 Further development of sprayed concrete tunnel linings (2nd half of 20th century)

By the 1950s, sprayed concrete lining had become the primary means of support and controlling rock pressures and deformations in rock tunnels and mines. The use of dry spraying technique was gradually overruled by the use of the wet mix spraying technique. In Scandinavia, for example, no dry mix has been used since 1970s. By the same time, manual spraying technique was being replaced by mechanized spraying with spraying robots, [24].

Since the 1970s research and development have focused primarily on accelerators and admixtures (to achieve higher early strengths with lower dosages of accelerating additives, without compromising the long-term strength and to reduce dust and rebound) and spraying equipment (to improve quality, spraying quantity and automation). Research into the durability and mechanical properties of sprayed concrete other than strength and stiffness followed later as the early challenges were overcome and the design approaches and usage developed, [22].

Addition of microsilica and fibres into the sprayed concrete mix started also in 1970s. In the Czech Republic, the use of sprayed concrete began to increase since 1989 with the New Austrian tunnelling method, [24].

Steel fibre reinforced sprayed concrete was first used in the Czech republic on underground storage of natural gas in Pribram to construct a water- and gas-sealing plug. The structure of the plug had to meet the water- and gas-tightness criteria in the condition of pressure difference effect up to 13.5MPa. A dry mix was prepared on the surface and water and steel fibres were mixed with the dry mix in an underground mini batching plant located at the point of application. A piston pump was equipped with a high precision accelerator additive dosage unit and satisfied the need of pumping fresh concrete containing a high portion of steel fibres (90kg/m^3), [25].

In Fig. 3, spraying robot for steel fibre reinforced concrete application in Pribram gas storage is shown.

Fig. 3 Spraying robot for steel fibre reinforced concrete in 1994, [25]

The use of the steel fibre reinforced sprayed concrete in the Pribram underground concrete plug was the first application of such material with such equipment as a permanent structure in the Czech Republic. It has been stated though that the dosage of accelerator provided the mix only with higher adhesiveness without significant acceleration of the hydration process, [26].

It should be noted that nowadays the common dosage of steel fibres is lower, between 20 and 60kg/m^3, [22].

3.1.3 Current best praxis (1st half of 21st century)

In the last couple of decades spraying robots, admixtures, accelerators and quality control methods have significantly developed, resulting in high quality of the final product. Today's technology allows for sprayed concrete lining to be applied with such precision that it has been in some countries approved to be used as permanent structure with design life 120 years, [24].

In the UK, the following improvements allowed for the sprayed concrete in SCL (Sprayed Concrete Lining) tunnels to be considered permanent:

- The utilisation of wet spraying allowed for higher quality, less rebound and increased health and safety conditions, [21];
- The improvement in the quality has enabled the sprayed concrete to be considered of comparable quality to cast-in-situ concrete, with the same long-term strength, low permeability (in the order of 10^{-12} to 10^{-14} m/s) and durability performance, [22];
- The adoption of alkali free accelerators that are less hazardous and have positive effect on the final strength and durability, [26];
- The use of fibre reinforcement instead of mesh reinforcement eliminated (i.e. voids behind reinforcement bars), shortened construction programme and saved overall cost, [22];

- The shift from hand spraying to robotic spraying with nozzleman certification scheme. In Fig. 4, spraying robot with nozzle operator is shown, [24];
- The development of total stations and 3-D scanning survey equipment provides excellent shape control for both excavation and spraying, and allows shotcrete lined tunnels to be constructed without lattice girders, [28].

Fig. 4 Current spraying robot, [28]

For permanent sprayed concrete, modern specifications typically require compressive strengths at 28 days of 30MPa or greater, higher standards of workmanship and better quality control, [22]. Typical requirements specified for a permanent sprayed concrete to achieve those basic criteria are shown in Tab. 1:

Tab. 1 Permanent sprayed concrete parameters, [22]

Parameter	Value
Max. water-binder ratio	0.45
Min. cement content	400 kg/m^3
Min. compressive strength	Depends on lining loads - typically 30 to 40 MPa
Max. accelerator dosage	Keep as low as possible
Water permeability	<= 10^{-12} m/s
Max. water penetration	<= 50 mm
Max. crack width	0.4 mm
Curing period	Seven days
Bond between layers of concrete	1.0 MPa

In general, it can be considered that the strength of the permanent sprayed concrete does not degrade over time. The permanent sprayed concrete shall be well compacted, dense, with low permeability. In temporary tunnel primary lining, steel bar reinforcement is typically used. In permanent tunnel primary lining, the steel bar reinforcement is replaced by steel fibre reinforcement. The spraying through the steel bar reinforcement often results in quality issues because it is difficult to achieve complete encasement and voids can create behind the steel bars, especially when large diameter bars or combination of wire mesh and steel bars is used. Voids behind the steel bars might result in corrosion of the reinforcement and deterioration of the primary sprayed concrete lining. The use of steel fibres eliminates the risk of poor steel bar encapsulation, [22].

As already stated above, the permanent primary lining in the Czech Republic is not a usual praxis. The fibre reinforced sprayed concrete has been used in underground construction only on a limited number of structures and trial sections, [24]. However, following the experience gained in the UK, the primary lining could be considered permanent when the above mentioned parameters of the sprayed concrete are achieved.

3.2 Sprayed concrete tunnel lining in various tunneling methods

Tunnelling methods, using sprayed concrete lining as the element to support the excavation, have many forms and have evolved in different geological conditions and countries. In hard rock tunnelling, rock bolts, thin layer of sprayed concrete and a drainage system without an internal structural permanent lining generally support the excavated tunnel profile. In soft ground, thick primary lining usually with closed primary lining invert, and thick secondary lining are the common supporting structures.

Tunnelling methods have different names: Drill&Blast, NATM (New Austrian Tunnelling Method), SCL (Sprayed Concrete Lining), SEM (Sequential Excavation Method), the observational method etc. They all apply to the same excavation process, to different degrees, and so often to very personal understanding and qualification. Even the term “conventional tunnelling” or “cyclic excavation” is sometimes applied to this “open faced excavation method” to differentiate it from TBM (Tunnel Boring Machine) tunnelling, and elements of the method are being applied to support regime designs in TBM drives, [29].

In the Czech Republic, the most commonly used tunnelling method is NATM, [24]. SCL is for the purpose of this thesis, referred to as tunnelling method used in the UK. Experience from the UK regarding the use of the spray-applied waterproofing membranes in SCL tunnels will be applied to the Czech Republic environment and therefore these two tunnelling methods, SCL and NATM, are presented in the next chapters.

3.2.1 NATM (New Austrian Tunnelling Method)

The term ‘NATM’ was introduced by Ladislaus von Rabcewicz during a lecture at the Geomechanics Colloquium in 1962, [30].

The origins of NATM are linked to the empirical knowledge gained in tunnelling and use of new elements to support the excavation that gradually led to abandonment of vault theories for determination of loads on the tunnel lining. NATM is a tunnelling method that uses the self-supporting property of the ground to optimize the excavation process and the excavation support in order to minimize the associated costs. In NATM tunnel construction, the excavation is usually stabilised by the primary lining and the permanent support of the tunnel (secondary lining) is only built after the stress-strain state around the excavation has stabilized, [31].

The main structural elements of the primary lining are sprayed concrete and anchor system. An integral part of NATM is geotechnical monitoring based primarily on measurement of tunnel excavation deformations. From the geotechnical point of view, NATM belongs to the group of observational methods, in which the progress of construction is continuously monitored, and the method of excavation advancement and the excavation support by the primary lining are adjusted according to the actual behaviour of excavated rock mass. Mobilisation of the self-supporting function of the massif near the excavation is achieved by as little disruption during the excavation as possible and by installation of the primary support by means of sprayed concrete and radial anchors as fast as possible. The interaction of the rock mass with the primary lining creates a load-bearing system transferring loads / stresses developed in the massif by the excavation process. The massif has been in a steady state of equilibrium for a very long time. Construction of a tunnel means disruption of the original equilibrium, rearrangement of stress in the rock mass and development of a new equilibrium between the load and the lining reaction, [31].

The principal of the primary lining loading can be described as follows: the stiffer the primary lining is the more load it bears. In other words, the pressure on the primary lining will decrease if the primary lining allows the massif to deform. This principle is expressed by so-called Fenner-Pacher curve (Fig. 5), which shows the rock mass reaction to the increasing deformation of the excavated rock, [32].

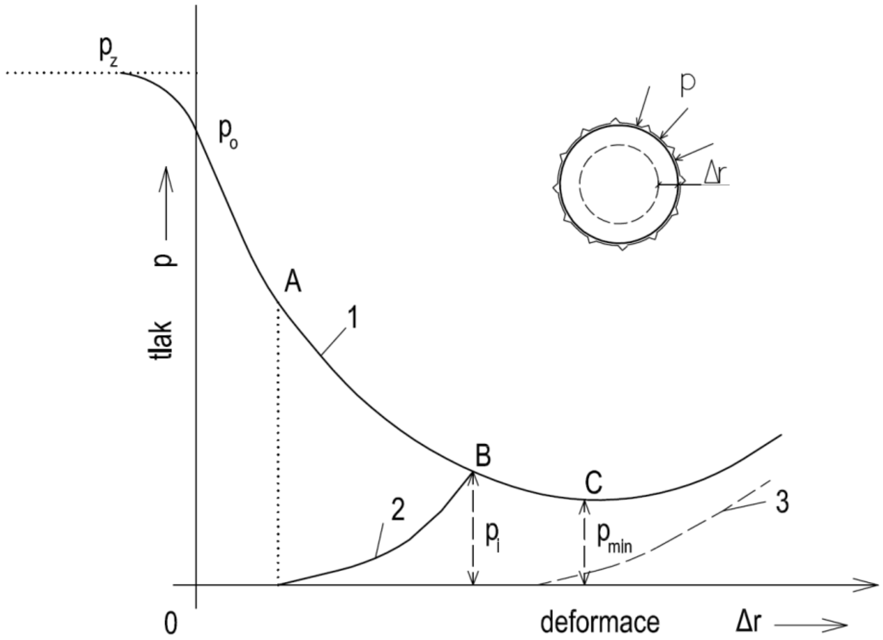

Fig. 5 Fenner – Pacher curve, [32]

The curve “1” represents the decrease of the rock mass pressure as the excavation deformation increases. The value "p0" expresses the reduction of the original geostatic state "pz" due to deformations of the massif occurring ahead of the face. After excavation, before the primary lining is installed, some of the excavation deformation takes place and the rock pressure drops. Point “A” represents the value of the rock pressure at the moment of installation of the primary lining. Curve “2” shows the primary lining installed at the right time. The flexible lining allows the necessary deformation of the rock mass, gradually decreasing the rock pressure and increasing the loading of the lining up to the point "B", where the level of decreasing rock pressure is balanced with the degree of lining stress, when the whole process comes to equilibrium. If the primary lining is installed too late, at point "C" a steady state will not develop and without immediate additional support installation there is a risk of collapse of the excavation. The rock mass reaction curve has different pressure and deformation parameters at different points along the tunnel perimeter, [32].

Therefore, continuous geotechnical monitoring and correct interpretation of the measured data are required during the excavation. In addition to the geotechnical monitoring of the deformations (convergences) of the excavation face, monitoring of the stress-state of the surrounding rock mass is also performed, usually by means of extensometers. For this reason, NATM is also referred to as the 'controlled deformation method', [31].

The excavation face is typically divided horizontally or vertically. Horizontal subdivisions of large-size tunnel constructions are used only during excavation in favourable geological conditions, vertical subdivisions are proposed in more difficult geological conditions, or if there is an increased requirement to limit the settlement of the surface. The main support element of NATM tunnels is sprayed concrete, which is reinforced with steel meshes with different mesh sizes, wire diameters and lattice girders, see Fig. 6.

Fig. 6 NATM tunnel – installation of lattice girder and wire mesh

The final (secondary) lining is usually made of cast-in-situ concrete (plain or reinforced) and is usually protected by a sheet waterproofing. In accordance with the project requirements, it is also possible to make the final lining of waterproof concrete without sheet waterproofing or to leave the primary lining shotcrete as final (single-shell lining), [31].

3.2.2 SCL (Sprayed Concrete Lining), LaserShell^{TM}

3.2.2.1 SCL tunnelling method

The SCL tunnelling method has been used in the UK for decades, [33]. The SCL tunnelling originally started in a way similar to that of NATM tunnelling, considering the primary lining temporary, utilising the secondary lining for permanent support with the use of a sheet waterproofing membrane separating the primary and the secondary lining, and protecting the internal tunnel space from groundwater ingress.

Uhrin and Su [33] summarize the difference between the soft ground SCL tunnelling method and the NATM. There are two significant differences between the SCL and the NATM. In SCL, that is generally referred to as excavation in London clay, much lower deformation mobilises the ground arch in clay compared to NATM tunnelling in rock. This means that the excavated tunnel ring has to be closed quickly with the primary lining invert and thick primary lining shell is usually designed to support the ground load and prevent the deformation exceed the foreseen limits. Secondly, the typical support element used in NATM, rock bolts, are not used in clay, and the primary lining is considered structurally as a shell. The SCL tunnels are usually designed as undrained with intact waterproofing all along the tunnel perimeter. The design of an SCL tunnel shall reflect the time-dependent behaviour of the ground. Undrained ground parameters are used for short-term design and drained parameters are used for long-term design due to consolidation of the ground. Therefore, the secondary lining as well as the primary lining is usually designed fairly thick and robust. The improvements of the sprayed concrete quality and durability described in the previous chapter, led to optimisation of the SCL tunnel design, considering the primary lining permanent or at least partially permanent. On top of that, with the use of the spray-applied waterproofing membrane, the idea of a composite lining design was born. As will be discussed in the next chapters, the SCL composite lining design has the potential to optimise the overall lining thickness and result in lower shotcrete consumption and reduced excavation area and volume of excavated ground.

Thomas [22] states that there was initially great enthusiasm for SCL tunnelling in the UK. However, following the collapse of a series of SCL tunnels in 1994, SCL tunnelling method was subject to criticism. The SCL tunnelling method was reviewed mainly from the health and safety point of view and risks associated with the construction utilising this method in soft ground tunnelling. The UK Health and Safety Executive (HSE) issued an exhaustive report about the safety of NATM tunnels [34], and together with the Institution of Civil Engineers (ICE) established that SCL tunnels can be constructed safely in soft ground, and provided guidance on how to design and construct SCL tunnels. The review of the SCL method also highlighted the sensitivity of the method to quality of workmanship. According the HSE and ICE reports, certification of nozzlemen, improvements of instrumentation and monitoring and risk management have allowed for safe and sustainable SCL tunnel construction. The skills of the nozzleman have direct influence onto the quality of the final product (the sprayed concrete lining). Especially, when thick lining is to be applied in subsequent layers or when reinforced sprayed concrete is to be constructed, a skilled nozzleman is a must. The SCL tunnelling method is an observational method. Stability of the primary lining must be monitored by means of convergence measurements. The monitoring data are reviewed regularly and the excavation progress is adjusted accordingly. As mentioned previously, it is of critical importance that in SCL tunnelling, the deformations are minimised otherwise strain-softening and plastic yielding of the ground in the vicinity of the excavated face can lead to collapse of the tunnel. The proposed excavation sequence shall reflect this and prevent from delay of ring closure within acceptable distance from the tunnel face and depending of development of deformations in time. The excavation sequence will also reflect the overburden height, while in shallow tunnels, the time between the tunnel face opening and the tunnel collapse can be short. Certification schemes such as EFNARC endorsed by the International

Tunnelling Association (ITA) or educational and apprenticeship programs organised by the Tunnelling and Underground Construction Academy (TUCA) have contributed to the improvement of the quality and safety of the SCL tunnel construction. The UK tunnelling industry has incorporated much of this into its standards and best practice guidelines. The use of SCL method in the UK has recovered since the collapses in 1994 and was recently the choice of construction for shafts and tunnels in the London Clay on 15 billion pound project Crossrail in London. On the Crossrail project, not only the SCL tunnelling method but also the permanent primary lining approach was utilised, [22].

3.2.2.2 LaserShell^{TM}

A special modification of the SCL tunnelling method is so-called LaserShell^{TM}. According to Hilar et al. [36], the concept of LaserShell^{TM} was developed by two of the tunnelling companies at Heathrow Terminal 5: Morgan Est (UK) and Beton- und Monierbau (Austria). The main features of the method are that the tunnel face is domed and inclined providing so for a canopy of already existing tunnel lining above the head of the personnel entering the tunnel face, see Fig. 7.

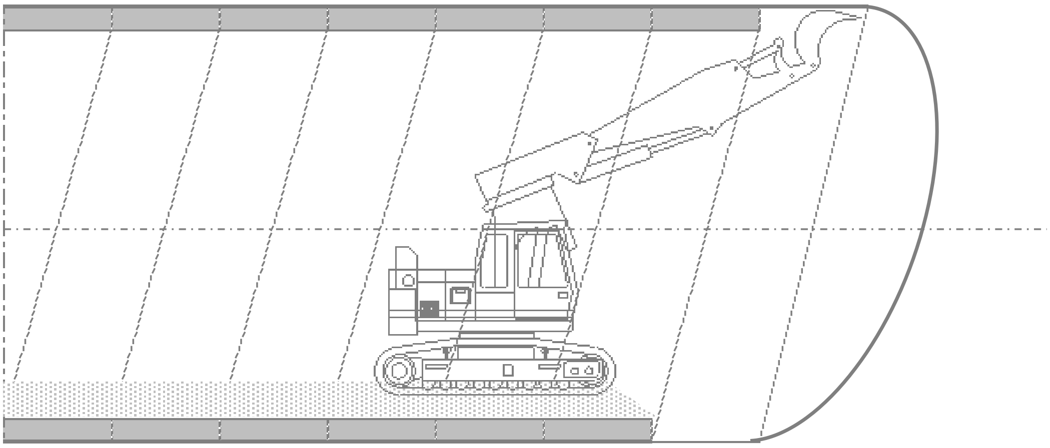

Fig. 7 LaserShell^{TM} longitudinal profile

The lining is fibre reinforced with none or almost none steel bar elements (steel mesh of lattice girders) reducing so significantly the risk of the personnel entering the unsupported excavated ground. Moreover, as discussed previously, better quality of the sprayed concrete lining can be achieved since the concrete is no more sprayed through bar reinforcement and the risk of shadowing behind the steel bars is reduced significantly and therefore the risk of the corrosion of the steel bars elements is eliminated. Since there are no lattice girders or mesh to install, also the production rates can be higher compared to the typical SCL or NATM tunnelling methods. The excavation and lining geometry is controlled using TunnelBeamer™ laser distometer, which is usually operated by a Tunnel Shift Engineer that instantly communicates with the nozzleman or excavator operator and reports the distometer readings so that precise excavation and sprayed concrete lining geometry and thickness can be achieved.

Fig. 8 LaserShell™ excavation, [35] (left), Shift Engineer with Tunnel Beamer™(right)

The Tunnel Beamer™ compares the theoretical and real position of excavation or sprayed concrete lining profiles and displays the information on a monitor hold and read by the Shift Engineer. The shape of the face and fast ring closure may also help to reduce the surface settlement. The tunnel is constructed full face (up to 5m diameter in the London Clay) or at maximum horizontally divided into top-heading and invert to minimise number of construction joints and to improve productivity, [36].

3.3 Sprayed concrete tunnel lining design concepts

According to [19], permanent sprayed concrete can be used in tunnelling for two types of application:

- Use as a single-shell sprayed concrete lining. In this case, the sprayed concrete outer (primary) lining represents the final structure and carries all the long-term loads.

- Use as a double-shell sprayed concrete lining. In this case, the outer (primary) and the inner (secondary) lining work separately and the primary lining does not have any long-term load-bearing functions.

The use of the sprayed concrete lining and the spray-applied waterproofing membrane in a composite lining is not by [19] covered. The choice of the waterproofing system directly affects the static design of the lining. Theoretically, the designers may choose between three sprayed concrete lining design concepts - single-shell lining, double-shell lining, or composite lining.

There might be some restrictions regarding the use of the sprayed concrete as the inner lining connected to maintenance requirements. For example, in road tunnels, the bottom part of the secondary lining might have to be constructed with smooth surface and therefore cast-in situ concrete may be required. From the point of view of the tunnel lining design concept, it is considered that sprayed concrete can be used as secondary (inner) lining.

3.3.1 Single-shell lining

Single-shell lining is schematically shown in Fig. 9. No waterproofing is installed and the lining consits only of permanent sprayed concrete.

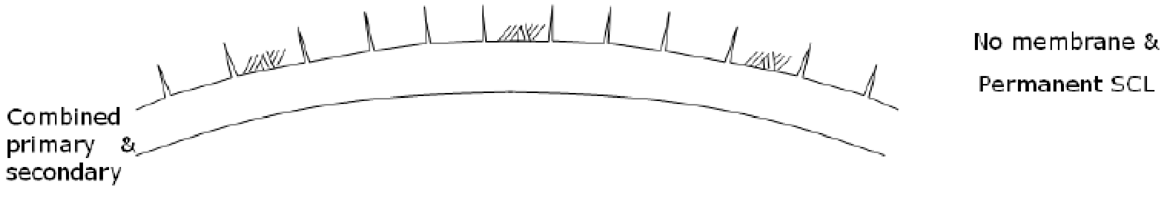

Fig. 9 Single-shell lining

According to Thomas [22], the “single-shell” may consist of several layers of sprayed concrete, placed at different times. The main principle is that all the applied sprayed concrete carries all the loads over the lifetime of the tunnel, and that the different layers act together as a single element. The single-shell design concept has been used mainly on hydroelectric power projects and especially in dry hard rock. Tab. 2 contains some examples:

Tab. 2 Examples of single shell lining tunnels, [22]

Project	**Type of tunnel**
Munich sewer	Sewer
Munic metro	Metro
Heathrow Baggage Transfer tunnel	Non-public
Heathrow Terminal 5	Water, road and rail tunnels
SLAC Project	Research facility

For single-shell lining, part or all of the sprayed concrete is considered as permanent load-bearing element. The use of single-shell lining eliminates the application of waterproofing and installation of the secondary lining, which leads to significant savings in time and cost. On the other hand, long-term load-bearing capacity, permeability and durability of the lining shall be guaranteed. Single-shell tunnel linings are usually used without the use of steel bar elements (lattice girders or mesh) in order to avoid the problem of corrosion of the reinforcement. Single-shell linings are usually only used in relatively impermeable ground. The permeability of the lining depends on the permeability of the shotcrete mass and the construction joints. Minimising the number of joints can reduce the potential groundwater inflow. Construction joints cannot be eliminated but their quality and bond between the shotcrete layers can help improve the permeability and reduce amount of groundwater inflow. Clean surface of the joint and good spraying techniques will provide for well bonded joints. Geometry of joints can also help to improve the final quality (permeability) of the lining. Staggering joints can also help to reduce the potential water path for groundwater, [22].

3.3.2 Double-shell lining

Double-shell lining is schematically shown in Fig. 10. Sheet waterproofing membrane is installed between the primary and the secondary lining.

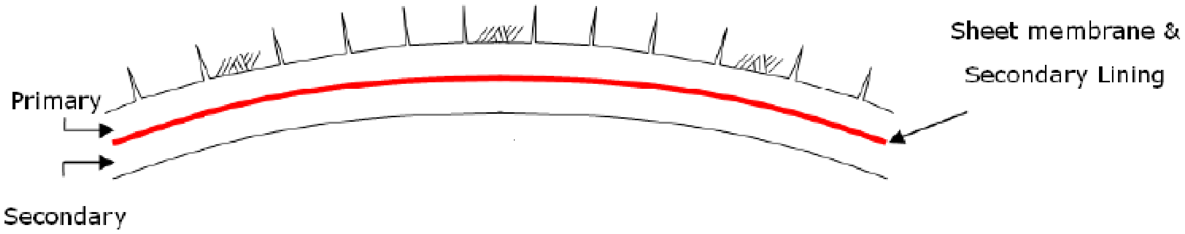

Fig. 10 Double-shell lining

Traditional double-shell lining consists of primary and secondary lining, separated by a geotextile layer and a waterproofing membrane. The tunnel may be designed fully or partially drained or fully undrained. The primary lining is typically designed to carry the short-term loads and is assumed to degrade in time. The secondary lining is designed to carry all the long-term loads. From the design point of view, the primary and the secondary linings are assumed to be fully separated (two separate shells). Although there may be some degree of interaction of the two shells, investigation of such interaction is generally irrelevant to the designers because the primary lining is considered only temporary. Since the secondary lining is placed inside of a sheet waterproofing membrane, it is typically designed to carry the water pressure and most or all of the ground loads.

3.3.2.1 Common issues of the double-shell tunnel linings

The double-shell lining is the most commonly used tunnel lining design concept. The plastic sheet waterproofing membranes have been used for decades and normative and best practice guidelines have been developed to maximally optimise their application and eliminate repetitive failures based on systematic incorporation of lessons learnt arising from projects' realizations. Even though such systematic approach has been adopted, some failures still occur.

The plastic sheet waterproofing membranes in a double-shell lining are usually installed on a geotextile fleece. The geotextile works as a water transport layer that brings the groundwater into the drainage (in case of a drained tunnel), or as a protection layer in case on an undrained tunnel. The geotextile fleece is generally saturated with water and represents the interface where the groundwater pressure acts on the extrados of the plastic membrane and secondary lining respectively. Direct contact of the membrane and the water-saturated geotextile creates a risk of groundwater finding a puncture or non-intact weld of the membrane and entering the intrados of the membrane, i.e. extrados of the secondary lining. In that moment, the secondary lining is no longer protected from the groundwater and deterioration of the secondary lining and water inflow into the internal spaces can occur. Generally, blocks of the secondary lining are divided into “grouting segments” and water-stops with grouting tubes are installed for the case that a failure of the waterproofing occurs. Since the exact location of the water penetrating the membrane is not known the grouting procedure is “blind” and sometimes large areas have to be grouted to solve the problem. The spray-applied waterproofing membranes are believed to eliminate such problem thanks to their bonding nature to the substrate. In Fig. 11, plastic membrane with water-stops and spray-applied waterproofing membrane with no water-stop in an undrained tunnel are shown.

Fig. 11 Installation of sheet and spray-applied waterproofing membranes

Another example of a potential issue regarding the use of a double-shell lining is connected to the concreting of the cast-in-situ secondary lining. Generally, sprayed concrete secondary linings are not used when a plastic sheet waterproofing membrane is used because the sheet waterproofing does not provide for a rigid substrate that would allow for the sprayed concrete secondary lining to be applied. In Fig. 12, an example of a not fully concreted block of the secondary lining with a void created in the tunnel vault is shown. Such void has to be backfilled depending on its extent and static impact onto the secondary lining. If sprayed concrete secondary lining had been used such void would not have probably happened thanks to the nature of the sprayed concrete application bonding directly to the waterproofing.

Fig. 12 Cast-in situ and sprayed concrete secondary lining vault

3.3.2.2 Double-shell 'sliding interface'

The double-shell secondary linings can be designed reinforced or unreinforced (plain) concrete cast-in-situ linings. The shape of the tunnel can be optimised in order to minimise the magnitude of the bending moments and adequate mix design and short secondary lining blocks can reduce the risk of shrinkage cracks, [22]. In double-shell lining design concept, the secondary lining is installed against a 'sliding surface'. According to [15], the airside surface of the substrate (e.g. sliding film or sprayed concrete) should be as to minimise interlocking between the waterproof secondary lining and the sprayed concrete primary lining. Separation layers can be used to diminish the adhesion and interlocking between the secondary and the primary linings. In order to assume the interface to be sliding, limits of roughness and waviness of the surface are generally specified by the project requirements. However, the 'sliding surface' may be an idealistic case and in a real structure certain degree of composite action may develop even in a double-shell lining. Lorenz and Galler [37] carried out an investigation of the interface connection between the primary and the secondary linings in a double-shell lining with the use of a sheet waterproofing membrane.

According to [37], different types of tests were performed to examine the behaviour at various mechanical loads of a sandwich structure made of sprayed concrete, geotextile, sheet membrane and cast-in-situ concrete. The investigations have shown the influence of the surface roughness of sprayed concrete onto the sheet membrane and geotextile, and provided information on the load-sharing effects of the interaction between the primary lining and secondary lining depending on the properties of the waterproofing sheet membranes and geotextile. Additionally, the results delivered basics for numeric simulations of the sheet membranes between tunnel linings, [37].

The impact of the surface roughness onto the geotextile and the waterproofing membrane introduced during casting can be seen in Fig. 13, where a block of secondary lining had to be demolished (for other reasons than with respect to the double-shell lining design concept). This activity allowed for inspection of the waterproofing membrane state in short-term (couple of months after the secondary lining had been cast). The surface roughness imprinted into the geotextile and the sheet waterproofing can be observed.

Fig. 13 Sheet waterproofing after secondary lining demolition

According to [37], the sheet waterproofing membranes in a tunnel structure were tested under different types of load conditions that have an effect on the sheet membranes during application and during tunnel operation - tests for mechanical resistance of the sheet membranes under uniaxial load and shear tests. The tests of mechanical resistance in compression gave information about the limits of the maximum allowable compressive stress before damaging the membrane placed on sprayed concrete with different roughness. The surface roughness simulated real tunnel conditions in compliance with the relevant requirements for sprayed concrete and tunnel waterproofing systems. The stress-strain behaviour of the sheet waterproofing membrane sandwiched between the primary and the secondary lining was performed by means of shear box test. Based on the shear tests the acting forces for the interface connection of the tunnel linings were determined for the implementation in numerical simulations. The tests were carried out with different load stages, representing the loss of load-bearing capacity of the degrading sprayed concrete primary lining. Shear and normal forces developed along the interface. These shear forces transfer additional loads to the secondary lining. Taking the parameters into account, a more realistic system behaviour for the load transmission between the tunnel linings in double-shell lining composition could be calculated, [37].

3.3.2.3 Un-bonded double-shell lining

For soft ground SCL tunnelling in the UK, the latest design option is called un-bonded double-shell lining. This consists of a layer of permanent sprayed concrete primary lining, a layer of spray-applied waterproofing membrane and a layer of sprayed or cast-in-situ secondary lining, with no adhesion and shear bond assumed at the sprayed concrete – membrane interface. This design assumption was made due to the lack of evidence on the existence of long-term tensile and shear bonds and therefore no bond is assumed across the interface, [22]. Such design option has been adopted on several projects, such as A3 Hindhead tunnel and Crossrail and will be discussed in the next chapters.

3.3.3 Composite lining

Composite lining is schematically shown in Fig. 14. Spray-applied waterproofing membrane is installed between the primary and the secondary lining.

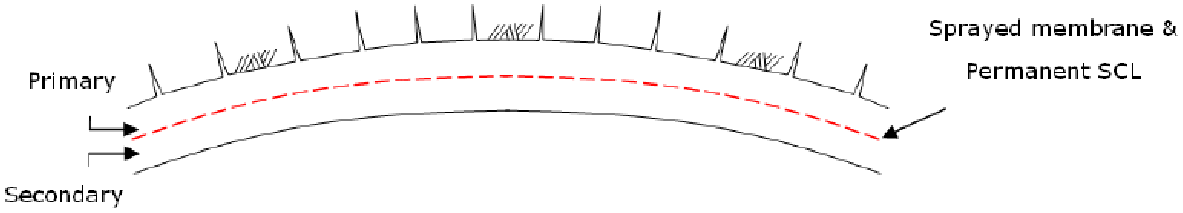

Fig. 14 Composite lining

The composite lining design concept goes in many ways in contradiction to the traditional double-shell lining design concept. The interface is no more sliding, but bonded and the waterproofing membrane has no more only waterproofing but structural function. As mentioned previously, the bond to the primary and the secondary lining may potentially provide for load sharing between the primary and secondary linings and the interaction between the two linings may allow for construction of a thinner secondary lining and more economic design. However, it is a new design concept that has not yet been widely applied. Large projects, where the spray-applied waterproofing membranes have been used, have not relied on the bond in shear and tension at the membrane. Under this assumption, typically the secondary lining has been designed the same thickness as in the traditional double-shell lining concept, [22].

The composite action of the composite lining is further discussed in the next chapters.

3.4 Summary

The progress achieved in recent years in the field of sprayed concrete technology and material engineering has led to the idea of using sprayed concrete not only for temporary structures but also as permanent structures in tunnelling. The use of sprayed concrete as permanent primary lining in form of single-shell lining or part of the composite lining is not in most countries clearly defined. Tunnelling methods have developed according to the local geology. Self-supporting function of the rock mass and groundwater pressure govern the loading of the tunnel lining. If primary lining is considered at least partially permanent, bonded secondary lining could be assumed in order to increase the benefit of the permanent primary lining and provide for composite lining action. The design concept shifted from double-shell lining on a ‘slipping surface’ to composite lining on a bonded surface, with many aspects of the use of the spray-applied waterproofing membrane as the element of the composite lining yet to be clarified.

4 Examples of practical use of the spray-applied waterproofing membrane and lessons learnt

The spray-applied waterproofing membranes have been used in construction of a number of tunnelling projects over the past few years. In the Czech Republic, the spray-applied waterproofing membranes have also been used on several underground structures. The first realization was carried out on the pumping pit on the IV. C 2 line from Prosek to Letnany in 2005. Other realized projects are, for example, elevator shafts at stations Florenc and Narodni trida in 2006 or revitalization of Stodulky metro station. The spray-applied waterproofing membranes were also used for tunnel rehabilitation - for example, the old railway tunnel in Prague under Vitkov, the rehabilitation of the tramway tunnels in Prague under Barrandov, or the rehabilitation of the old brick railway tunnels Oselinsky and Pavlovicky. An important realization has recently been the waterproofing of the Veleslavin triple station on the V.A metro line, which was connected with the solution of demanding technical details and transitions to the track tunnels, [38].

Practical applications can eventually reveal gaps and important aspects omitted during the design or the work preparation phase. Sharing of lessons learnt arising from the practical application could provide feedback to those who carry out the desk studies and can help to optimise the technical solutions and verify the pre-construction assumptions made. In the following chapters, examples of the practical use of the spray-applied waterproofing membranes are presented.

4.1 Hindhead highway tunnel, UK

Location: Hindhead, United Kingdom, highway A3 London to Portsmouth;

Owner: Highways England;

Contractor: Balfour Beatty;

Designer: Mott MacDonald;

Geology: mostly sandstone with occasional thin beds of fine sand;

Groundwater: tunnel excavated above water table;

Tunnelling method: SCL (Sprayed Concrete Lining);

Year of construction: 2008 - 2011.

The Hindhead tunnel is a 1.8 km long twin-tube highway tunnel with cross-sectional area of ca. 72 m^2. The horseshoe shaped primary lining was supported on elephant's feet with no primary lining invert. The tunnel was excavated mainly above the water table (see Fig. 16). In a few locations where the water table was reaching the tunnel invert and creating risk of perched water the groundwater was probe drilled and drained. The tunnel was described as particularly dry during excavation with few areas of ground-water dampness and no instances of dripping water ingress, [39].

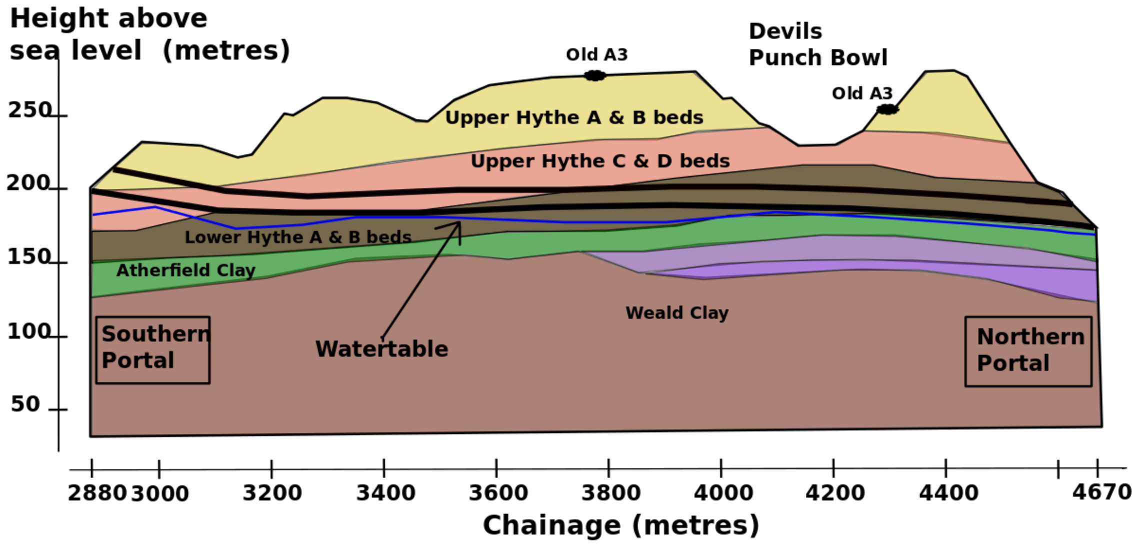

Fig. 15 Hindhead tunnel geological profile, [39]

The primary lining was designed using NATM principles considering self-supporting function of the ground, resulting in a relatively thin 200 mm thick fibre reinforced sprayed concrete lining. The secondary lining was designed to support only the hydrostatic pressure (if any) and loads from the electro-mechanical equipment as well as for fire resistance with addition of polypropylene fibres. The secondary lining was permanent sprayed concrete lining 150 mm thick in the crown and 340 mm thick cast in-situ concrete sidewalls rising 4 m above the walkways for a painted reflector surface and easier wash-down maintenance, [27].

Originally, the secondary lining was designed cast-in-situ even in the tunnel crown. However, based on observations during the excavation and the primary lining construction, the secondary lining design was changed and a mixed waterproofing system was proposed. A non-drained system with the spray-applied waterproofing membrane in the tunnel crown and bench to prevent leakage from percolating rainwater, and a drained system with a geotextile fleece layer at the invert level. Temporary drainage of water inflow was achieved by installation of drainage strips that were covered with a sprayed concrete layer, [39].

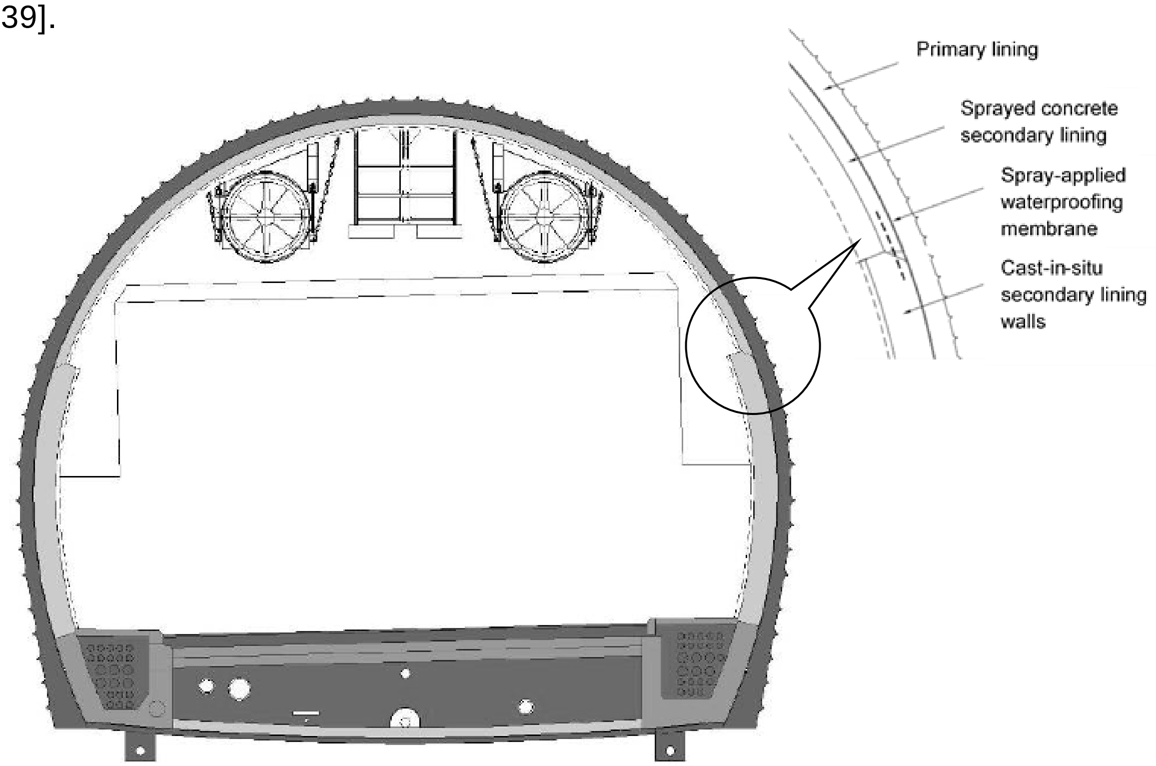

Fig. 16 Typical Hindhead tunnel cross-section: 1. SFRS Primary lining 2. Spray applied membrane 3. Sprayed concrete Secondary lining 4. Plain cast in-situ concrete walls, [40]

The principal innovation with the support measures is the design of the primary lining as permanent. 3-D scanning survey equipment was used that provides excellent shape control for both excavation and spraying, and allows shotcrete lined tunnels to be constructed without lattice girders. Self-drilling Glass Reinforced Plastic dowels were used in several locations with adverse geology, in order to avoid durability issues. Some of the key aspects of a permanent primary lining relate to construction techniques and workmanship, such as the shotcrete mix design and accelerator selection and use of robotic spraying equipment. In order to achieve a durable shotcrete mix suitable for use as a permanent lining the specification included requirements for the base mix concrete as well as specific fibre reinforced shotcrete requirements. The durability of the base mix was assured through the specification of a maximum w/c ratio of 0.45 along with a water penetration requirement of less than 50 mm, [27].

Hindhead, with 80,000 m2 of application area, was the largest application of spray-applied waterproofing membrane in the world to date (2010). Following the Hindhead experience, the system was considered for application in the SCL (spray concrete lined) underground stations and intermediate shafts on London's Crossrail project. There was the acceptance that the tunnel is a 'dry tunnel' and its need for a full, comprehensive waterproofing system was marginal compared to other possible applications. There was also the argument that the permeability specification of 10^{-12} m/s for the primary shotcrete provided a waterproofing barrier of quality itself, [39].

Based on the Hindhead tunnel construction, the following remarks are highlighted:

- Permanent primary lining with no steel bar elements;
- Secondary lining designed to carry no ground load;
- High precise profile control and workmanship quality with 3D scanning survey equipment and automatic spraying robots;
- ‘Dry tunnel’ prior to application of waterproofing;

- Decision to use spray-applied waterproofing membrane was made during construction based on observations of real water ingress.

Experience with the use of the spray-applied waterproofing membranes in the tunnel Hindhead was of significant importance for selection of the waterproofing system for the by-that-time-upcoming Crossrail project.

4.2 Crossrail underground railway stations, UK

Sprayed concrete linings have been used extensively on the £14·8 billion Crossrail project to deliver the Elizabeth line east west across London, in particular at the central stations along the route. Sprayed concrete linings are ideal for the construction of short tunnel drives with varying cross-sections, as well as the large number of tunnel junctions with non-standard and complex geometries and alignments. The new Elizabeth line stations at Bond Street, Tottenham Court Road, Farringdon, Liverpool Street and Whitechapel have all been constructed using sprayed concrete linings, [41].

Generally, the primary lining was designed to carry all short-term ground loads as well as the effects of other loads such as compensation grouting and any surcharge loads applied at surface level during the construction works. It was also designed to resist a certain percentage of the long-term ground loading apart from hydrostatic loads, which the secondary lining was designed to resist. The secondary lining was also designed to resist internal forces induced by its own self-weight, long-term ground loadings, temperature and shrinkage effects, services fixing loads and degradation of 75 mm of the secondary lining due to the effects of a fire in the tunnel. The lining system is therefore a double-shell with both linings considered part of the permanent load-bearing structure throughout the design life of the tunnel. The thickness of the primary lining was typically 300–350 mm, although it was usually greater at tunnel junctions. Secondary lining was made of sprayed concrete 250–300 mm thick with a 50 mm thick concrete fire protection layer. The selection of waterproofing was dictated by the likelihood of water ingress. At Farringdon station, virtually all of the sprayed concrete lining tunnels was waterproofed using a sheet membrane with an underlying geotextile to avoid damage to the waterproofing. A similar approach was adopted at certain locations in the tunnels at Liverpool Street and Whitechapel stations. Elsewhere, a sprayed membrane up to 6 mm in thickness was adopted. This membrane was tested regularly through in situ bond tests to confirm adequate adhesion with the substrate. A spray-applied waterproofing membrane was used throughout the Fisher Street caverns, as they were fully excavated in London Clay. In the Whitechapel and Stepney Green caverns, a spray-applied waterproofing membrane was used above invert level with a sheet membrane applied below due to the active water ingress encountered in the inverts associated with the proximity of the Lambeth Group, [41].

4.2.1 Bond Street & Farringdon Crossrail Stations, UK

Location: Bond Street & Farringdon Stations, London, United Kingdom;

Owner: Transport of London;

Contractor: Joint Venture BFK (BAM, Ferrovial and Kier);

Designer: Mott MacDonald;

Geology: London Clay at Bond Street, Lambeth Group and Thanet Sand at Farringdon;

Groundwater: spray-applied waterproofing only in low permeable clay;

Tunnelling method: SCL (Sprayed Concrete Lining);

Year of construction: 2011 – 2019.

The Bond Street and Farringdon Stations are similar size and layout including platform tunnels, cross-passages and escalator tunnels connecting to ticket halls, see Fig. 17, [42].

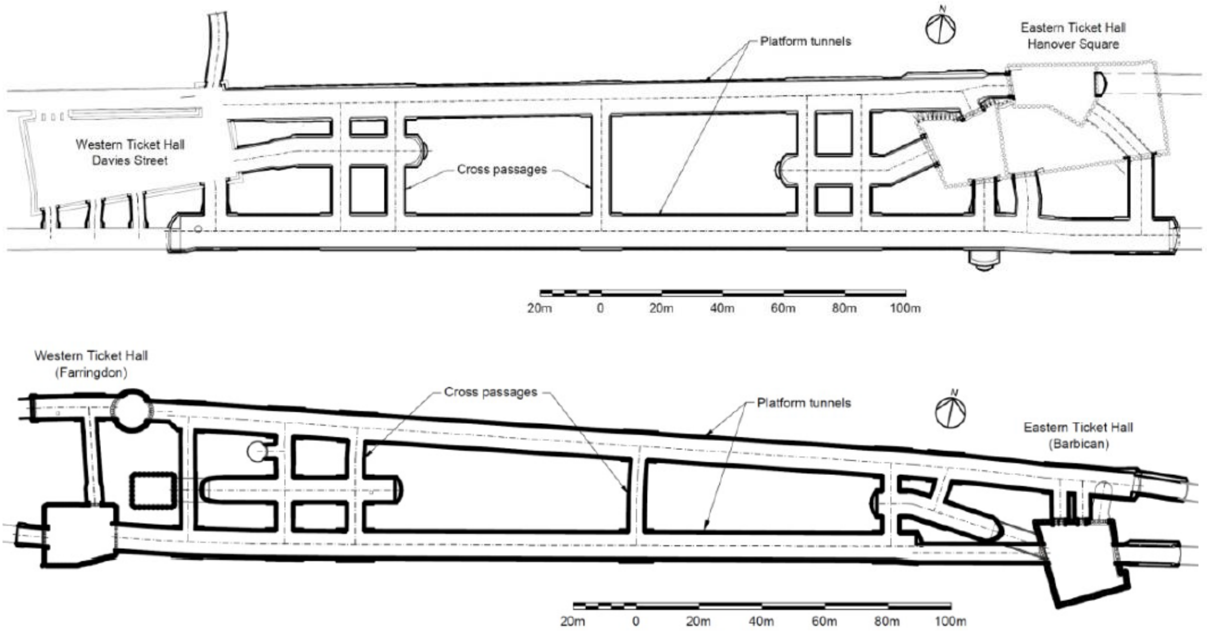

Fig. 17 Station tunnels (Bond Street above, Farringdon below), [42]

The platform tunnel cross-section was designed to satisfy the internal space requirements and to be as much as circle-like with closed invert, see Fig. 18.

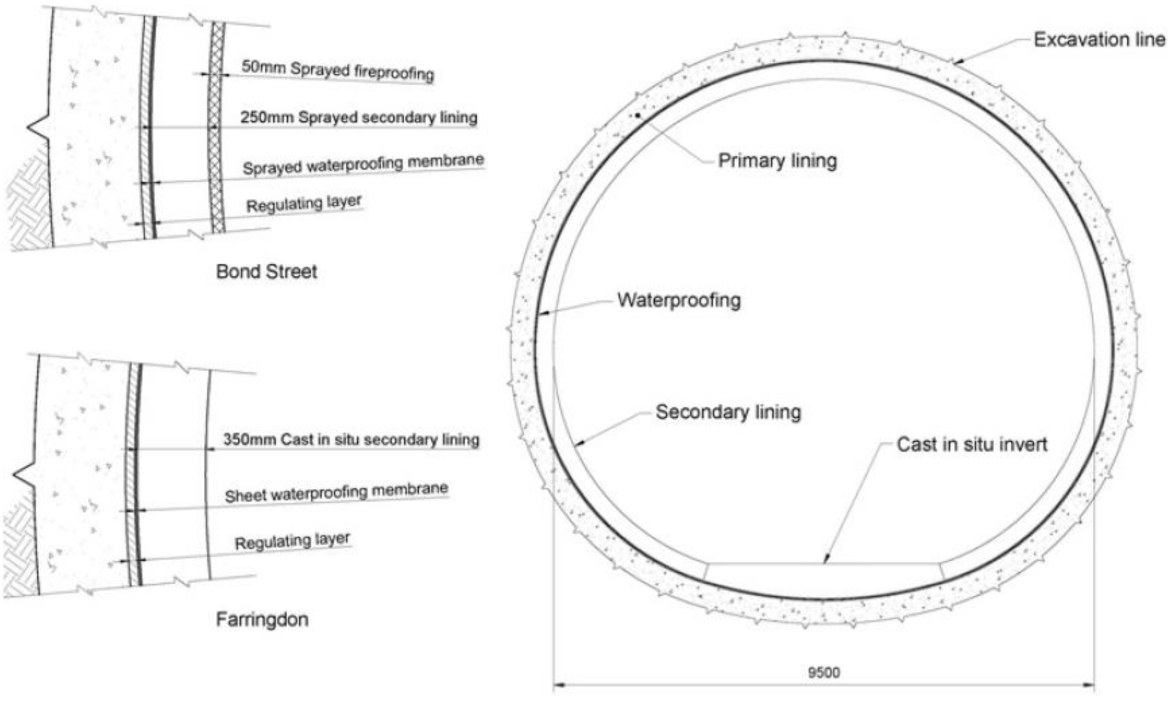

Fig. 18 Typical cross-section of Bond Street and Farringdon platform tunnel, [42]

At Bond Street Station, spray-applied waterproofing and sprayed secondary lining were designed but at Farringdon Station, sheet waterproofing with cast-in-situ secondary lining were designed and constructed. The reason for the different design was the different hydrogeological situation at the two stations. Bond Street tunnels were located in London Clay and Farringdon Station in Lambeth Group and Thanet Sand with high water content and water pressure, [42].

The spray-applied waterproofing membrane was applied using a dry mix and hand spraying. The membrane was generally sprayed in two consecutive layers, with a minimum 3 mm thickness in total, first to the crown and then the invert. In the tunnel junctions, double thickness was required to provide improved crack bridging performance in these areas. At Farringdon, a 2 mm thick PVC membrane laid on a geotextile layer was installed. Additionally, a system of PVC water-stops and re-injectable grout hoses were installed at each joint, see Fig. 19. Since the twos stations were constructed by the same contractor, this allowed him to compare both solutions, [42].

Fig. 19 Spray-applied waterproofing membrane at Bond Street Station (left) and sheet waterproofing at Farringdon (right), [42]

According to [42], even though no water ingress through the primary lining in London Clay at Bond Street was expected, groundwater was present and required considerable time to seal before the spray-applied waterproofing could be applied. The waterproofing production rates were higher for the sheet membrane at Farringdon. The sprayed concrete secondary lining at Bond Street provided reduced mobilisation periods and a greater flexibility over the sequencing of the works. Nonetheless, these benefits had little impact on achieved production rates as technical challenges presented throughout the construction affected the programme. The work-studies suggest that, once the required mobilisation had taken place, the cast methodology at Farringdon provided a higher overall production rate (6.0 m/day) compared with the sprayed option at Bond Street (4.1 m/day). The man-hours required to construct 1 m of platform tunnel were similar, 32.0 compared to 34.9 man hours/m respectively, [42].

4.2.2 Liverpool Street Crossrail Station, UK

Location: Liverpool Street Station, London, United Kingdom;

Owner: Transport of London;

Contractor: Joint Venture BBMV (Balfour Beatty, Morgan Sindall and Vinci);

Designer: Mott MacDonald;

Geology: London Clay in top heading, occasionally Lambeth Group or Harwich formation in invert;

Groundwater: tunnels excavated below water table;

Tunnelling method: SCL (Sprayed Concrete Lining);

Year of construction: 2011 – 2019.

Liverpool Street Station was the most complex station of the Crossrail project. The Station consisted of access shaft (AS1), platform tunnels, concourse tunnels, cross passages and ventilation ducts at a lower level; and escalators and pedestrian links at the upper level. Above the concourse tunnels are the geotechnical adits, which were used for compensation grouting works. 3D model of Liverpool Street Station is shown in Fig. 20.

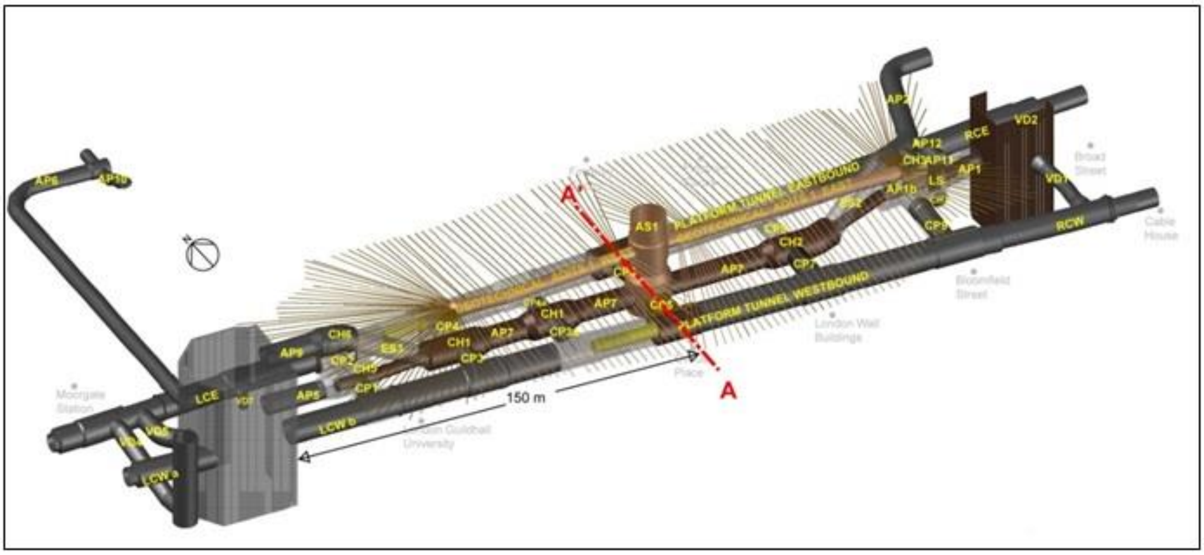

Fig. 20 Crossrail Liverpool Street Station 3D model, [43]

The ground profiles at Liverpool Street comprised superficial Made Ground on top of River Terrace Deposits, London Clay, Harwich Formation, Lambeth Group, Thanet Sands and Chalk, see Fig. 21.

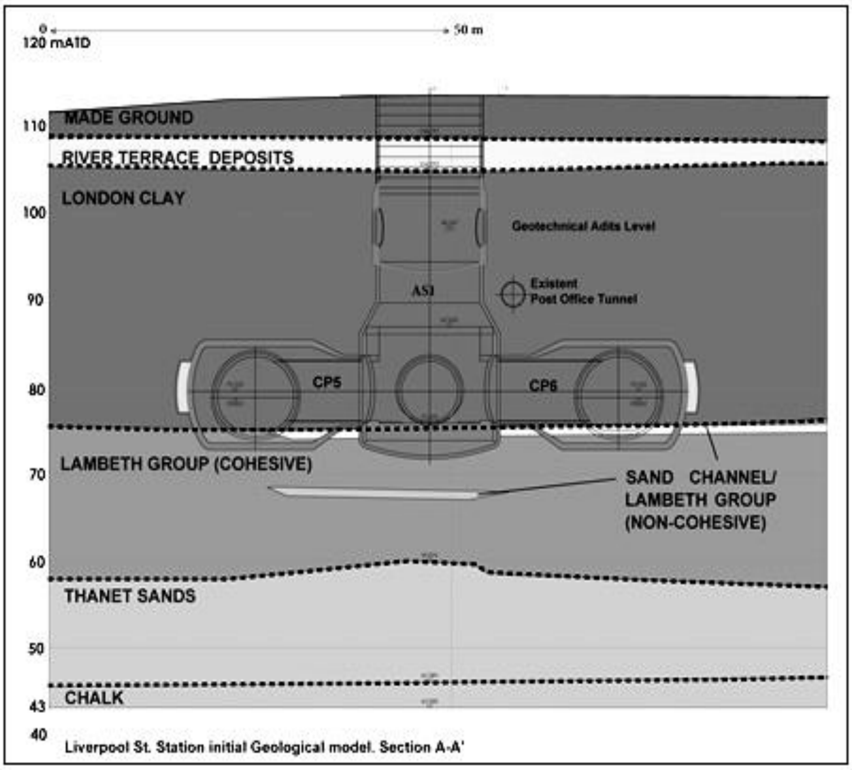

Fig. 21 Initial geological profile at Liverpool Street Station, [43]

The tunnel were excavated mainly in 'impermeable' London Clay, only the inverts of the tunnels were entering the permeable soil of Lambeth Group. During the excavation, the geological profile was updated with the real geology encountered; see Fig. 22, yellow colour is the permeable water-bearing Lambeth Group layer.

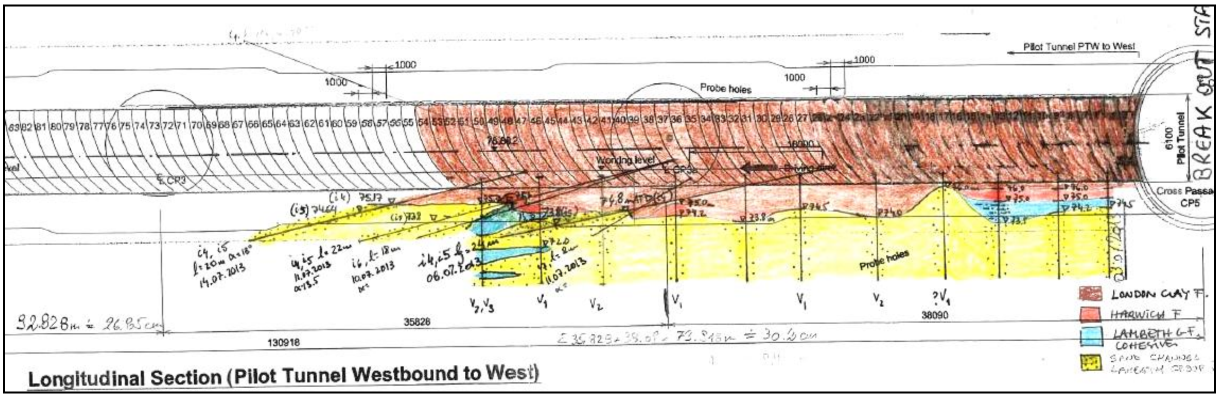

Fig. 22 As-built geological profile

The platform tunnels were excavated in two stages: an initial pilot tunnel of approximately 6m diameter was excavated first; followed by approximately 11m diameter enlargement, see Fig. 23.

Fig. 23 Pilot tunnel excavation followed by platform tunnel enlargement

In-tunnel depressurization was executed in order to dewater the sand layers of Lambeth Group. For the enlargement excavation, the in-tunnel depressurization was located in the pilot tunnel ahead of the platform tunnel enlargement face; see Fig. 24 (blue vertical tubes).

Fig. 24 In-tunnel depressurization in the pilot tunnel

The effect of the depressurization was generally effective; ensuring stable excavation face, see Fig. 25.

Fig. 25 Dry sand of Lambeth Group after depressurization

In the case that the depressurization was not on or not working properly, unstable tunnel face with flowing sand with water ingress into the excavation happened. In such case, it was difficult to stabilise the tunnel face with sprayed concrete, see Fig. 26.

Fig. 26 Tunnel face with flowing sand (left) difficult to be sealed with shotcrete (right)

Due to the water ingress through the invert primary lining that can be seen on Fig. 27, the spray-applied waterproofing membranes were applied only in the tunnel crown in combination with sheet waterproofing membrane in the invert.

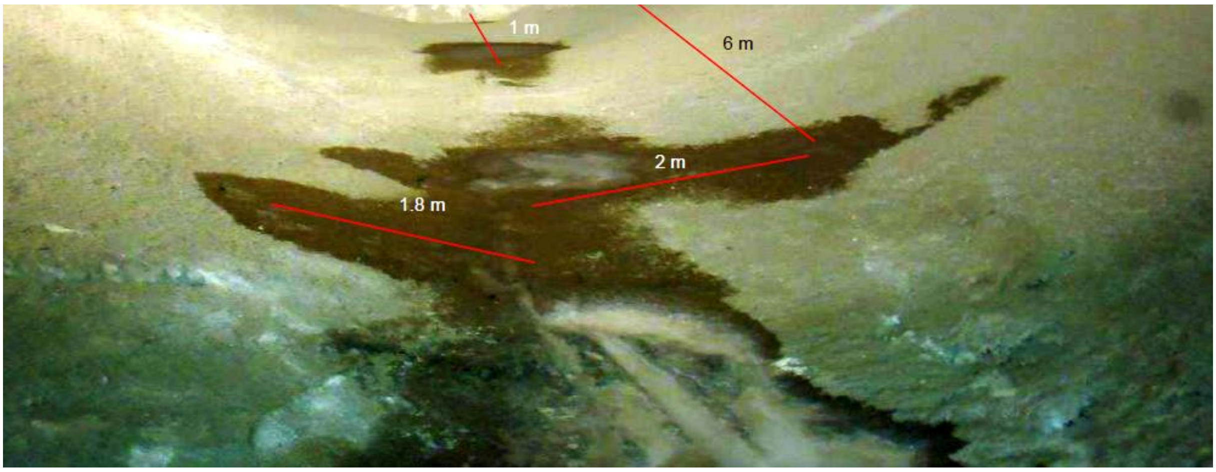

Fig. 27 Damp patches in the tunnel invert

Sheet waterproofing membranes with cast-in-situ invert and sidewall lining were installed in the tunnel invert, see Fig. 28.

Fig. 28 Invert with sheet waterproofing membrane

The spray-applied waterproofing membrane was then applied to the tunnel crown, see Fig. 29.

Fig. 29 Application of spray-applied waterproofing membrnae in the tunnel crown

4.3 Veleslavín Prague Metro Station, Czech Republic

Location: Veleslavín Station, Prague, Czech Republic;

Owner: Prague Public Transport Company (Dopravní podnik hlavního města Prahy);

Contractor: Joint Venture Metrostav and Hochtief CZ;

Designer: Metroprojekt Praha;

Geology: Ordovician sediments of Šárka Formation (dark clayey-silty shales);

Groundwater: below water table;

Tunneling method: NATM;

Year of construction: 2010 – 2014.

Waterproofing of the Veleslavín Station was provided by double system: watertight cast-in-situ secondary lining with special elements sealing construction joints and spray-applied waterproofing membrane. This double system of waterproofing was designed to increase reliability of the water-tightness of the secondary lining, The spray-applied waterproofing membranes were selected suitable for the complicated shape of the station, complicated connection details and construction sequence of the left, right and the central tunnel, [44].

Typical cross-section is shown in Fig. 30.

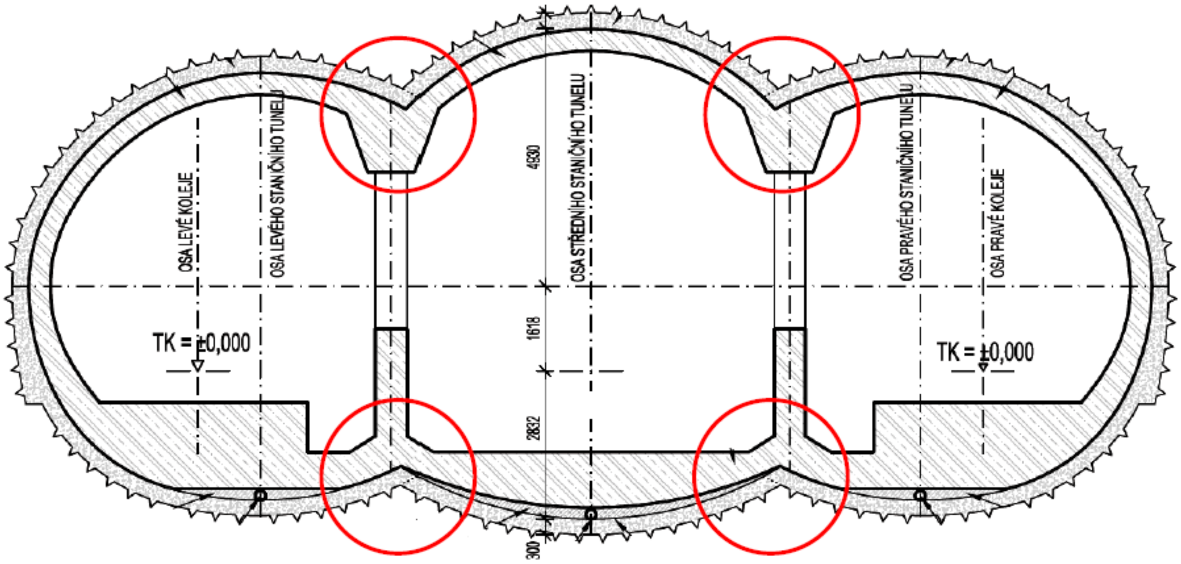

Fig. 30 Veleslavín Station, [45]

Primary lining had to be extensively sealed prior to application of the spray-applied waterproofing membrane. After grouting of local seepage in larger areas, water was pushed by the grout and appeared in other parts of the lining. It caused increase of water inflow in already existing seepage points or created new ones. Local drainage of water in water collecting hoses was found more effective than grouting. During application of the spray-applied waterproofing membrane, also dew point temperature had to be controlled. Thin film of condense water appeared on each layer of the spray-applied waterproofing membrane preventing it from proper curing process according to the technological procedure and manufacturer's recommendations, [45].

Not only active water ingress but also high humidity can result in unsuccessful spray-applied waterproofing membrane application (Fig. 31). Spray-applied waterproofing membrane de-bonded from the surface due to high humidity, [46].

Fig. 31 Debonded spray-applied waterproofing membrane, [46]

4.4 Remarks and lessons learnt

Experience with application of EVA-based spray-applied waterproofing membranes has shown that the membrane cannot be applied on surface with active water ingress or high humidity.

Observation of water ingress through the rock mass and the primary lining during the excavation phase can be used in order to change the secondary lining design during construction based on the real encountered conditions and the spray-applied waterproofing membrane can be incorporated into the design. The permanent primary lining constructed above the water table with no steel bar components, only steel or polypropylene fibres can be successfully accompanied by the spray-applied waterproofing membrane.

Application of the spray-applied waterproofing membrane even in impermeable strata such as London Clay experienced water ingress through the primary lining. Groundwater rose up from the water bearing permeable strata below the London Clay and through the water path within the primary lining entered the tunnel. The groundwater drawdown until the spray-applied waterproofing is applied, cured and covered by the secondary lining should be considered.

Comparison between the spray-applied and sheet waterproofing membranes showed that both solutions could be successfully applied in geometrically complicated tunnel structures. The system of spray-applied waterproofing membranes does not include items such as water-stop or re-injectable grouting hoses due to the assumption that potential leak through the secondary lining would correspond to the point of the membrane perforation and point of water ingress through the primary lining.

Drainage of water ingress was found more successful than immediate injection. The injection increased pore water pressure near the injection point and caused further need for injections (pushed groundwater away from the injection point that travelled away and found another ingress point). Water ingress was drained, then the spray-applied waterproofing membrane was applied and finally after the membrane was cured the drain was sealed.

Even though the bond of the spray-applied waterproofing membrane to the substrate was present, the Crossrail design did not relied on this bond and did not apply the composite lining concept, [41]. Permanent primary lining was designed in Hindhead and Crossrail but not at the Veleslavín Station. The use of the sprayed concrete as permanent lining requires challenging profile control that can be provided by modern surveying methods and sprayed concrete robots.

It has been shown that the spray-applied waterproofing membranes can be used in double waterproofing system with watertight secondary lining.

On all the projects, any issues during the application have been overcome and the projects successfully completed.

5 The elements of composite tunnel lining

5.1 Introduction

As already stated above, the waterproofing layer, traditionally the plastic sheet waterproofing membrane in the double-shell lining is the layer separating the primary and the secondary lining and its primary function is to waterproof. The primary function of each tunnel support element in the double-shell lining can be summarized as follows:

- Primary lining – immediate support of excavation face, temporary structural function;
- Waterproofing – permanent waterproofing function, transferring loads only in compression;
- Secondary lining – permanent tunnel support, on sliding surface.

For the use of the spray-applied waterproofing membrane within the composite lining, the following functions of each element apply:

- Primary lining – immediate support of excavation face, permanent or partially permanent tunnel support;
- Waterproofing – permanent waterproofing function and permanent tunnel support transferring all loads;
- Secondary lining – permanent tunnel support bonded to the substrate (to the primary lining through the spray-applied waterproofing membrane).

The problem is that new functions and boundary conditions to each of the elements are introduced. The spray-applied waterproofing membrane is no longer only a waterproofing element but it becomes an important component of the composite structure (composite lining) transferring the acting loads. The primary lining is no longer sacrificial and its permanent structural function is fully or partially introduced. The secondary lining is no longer cast against a separating layer (sliding surface) but it is structurally connected to the primary lining and shares the permanent loads through the spray-applied waterproofing membrane. Elements of a composite lining from an SCL tunnel are presented in the next chapter.

5.2 Primary lining

Primary lining is traditionally constructed using sprayed concrete reinforced by either wire mesh or fibres. The primary lining can be considered temporary or permanent. For the permanent primary lining, generally steel or polypropylene fibres are used with no steel bar elements. If anchors are used as rock support within the permanent primary lining these, have to be permanent as well.

In the permanent primary lining design, an initial layer of sprayed concrete is usually considered sacrificial. Thickness of the initial lining is up to 75 mm and is applied directly against the excavated ground, see Fig. 32.

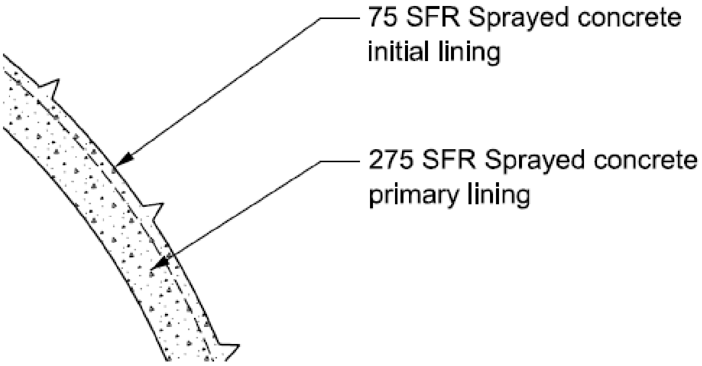

Fig. 32 SFR (steel fibre reinforced) permanent primary lining

The initial lining does not usually satisfy the requirements for the permanent sprayed concrete, mainly due to its poor compaction and high porosity, see Fig. 33.

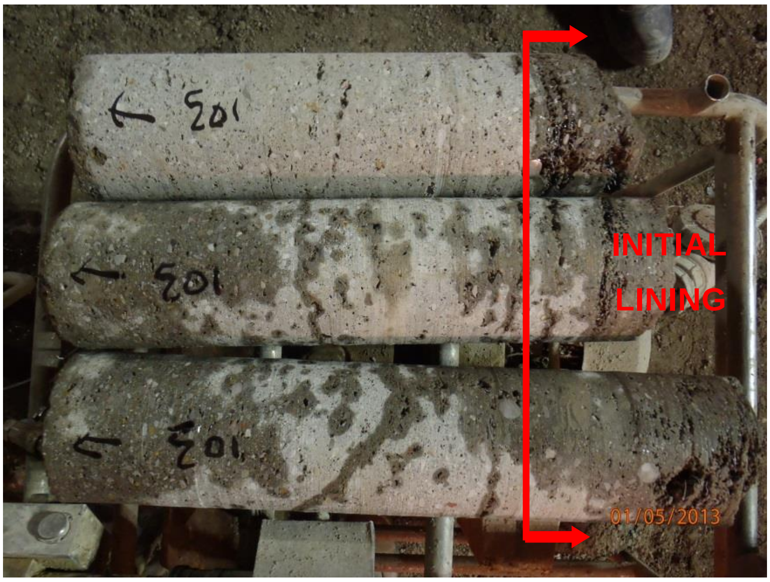

Fig. 33 Primary lining with initial lining

After the application of the initial lining, the primary lining is constructed. Depending on its thickness, it is either applied as one or multiple layers. Prior to application of the subsequent layer, the surface must be properly cleaned so that bond between the sprayed concrete layers is provided and no lamination occurs. In Fig. 34 primary lining with no lamination and with lamination is shown. The lamination can occur during spraying of subsequent layer on not properly cleaned surface. The lamination layer usually exhibits lower bond and higher permeability.

Fig. 34 Primary lining with no lamination (left) and laminatiom (right)

The application of sprayed concrete is limited by technologicaly possible maximum thickness of one layer of sprayed concrete at a time, [26]. Thicker primary lining has to be applied in subsequent layers that creates higher risk of lamination.

Sequence of spraying can help to reduce the number of radial construction joints. An example is shown in Fig. 35, where the excavation / spraying sequence is: 1 x topheading, 1 x topheading, double invert.

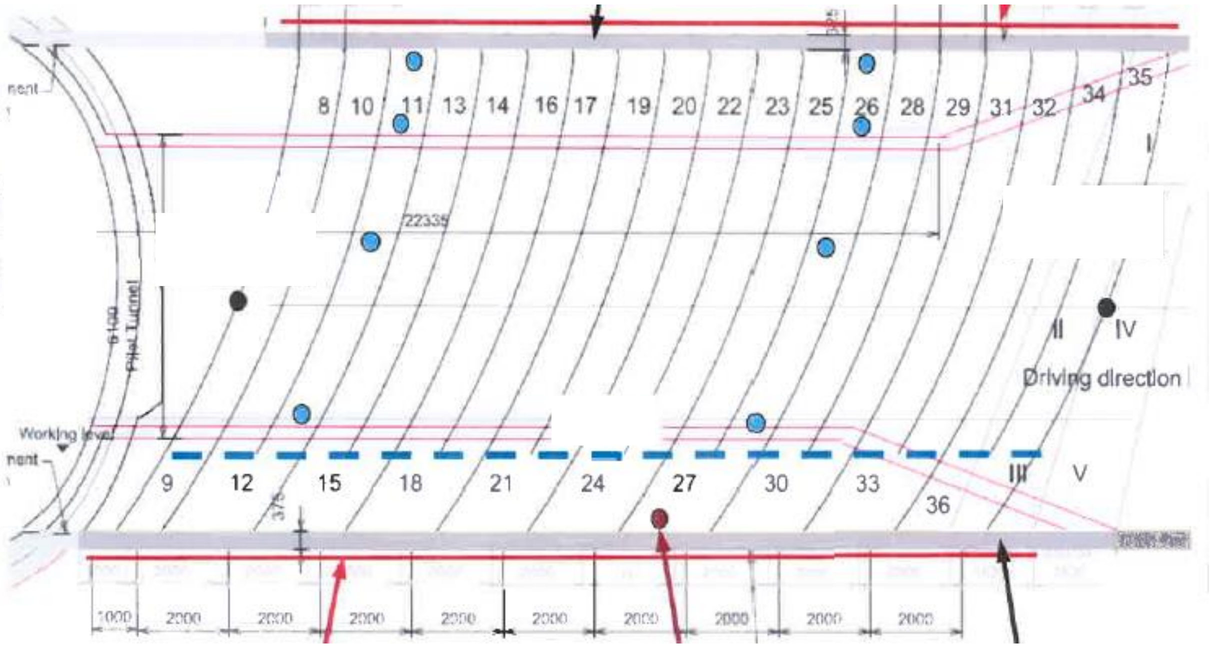

Fig. 35 Excavation sequence: Topheading, Topheading, Double Invert

During construction of the primary lining in the invert second layer over two advances of the topheading can be applied reducing so the number of radial joints that can potentilly leak, see Fig. 36.

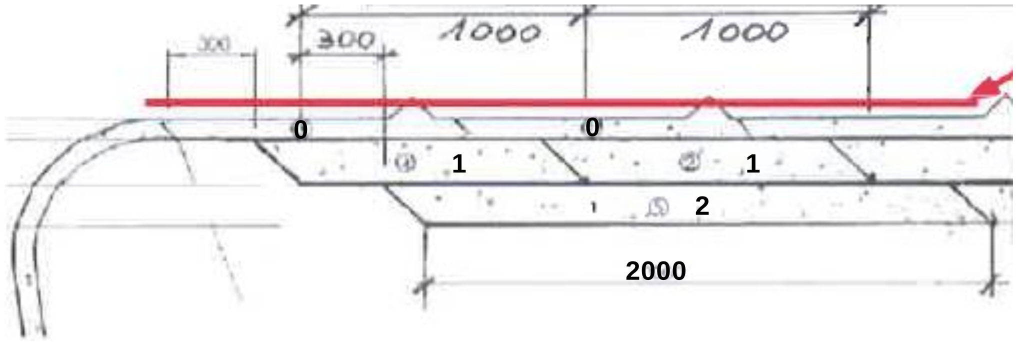

Fig. 36 0 – initial lining (75mm), 1 – first layer of primary lining (150mm), 2 – second layer of primary lining (100mm) applied every second advance together with invert primary lining construction

It can be seen in Fig. 37 that the water ingress occurs through the second layer of the primary lining in every second advance, in accordance with excavation / spraying sequence above.

Fig. 37 Water ingress through the second layer of the primary lining

The primary lining is usually not designed to carry groundwater pressure load and is usually assumed permeable. In some cases, weep holes or drainage pipes (see Fig. 38) can be installed to prevent the groundwater pressure build-up behind the primary lining. The drainage pipes are micro-fissured and in case of presence of fine materials can be protected by geotextile fleece.

Fig. 38 Groundwater drainage intervention – drainage holes

Usually, when the excavation is not full face but divided into partial excavation faces – horizontally or vertically, connection in the construction joint is provided by continuity steel bars. An example of longitudinal construction joint of horizontally divided face with steel continuity bars (or ‘kwikastrip’) is shown in Fig. 39 and Fig. 40.

Fig. 39 Continuity bars ‘kwikastrip’ (left), self-prefabricated bent continuity bars (right) - installation during topheading excavation

Fig. 40 Continuity bars between top-heading and invert

However, quality issues such as shadowing, honeycombing or poor compaction may frequently occur. Even with such defects, the lining may satisfy the short-term structural capacity requirements but it may exhibit higher permeability and durability issues. In Fig. 41, ‘kwikastrip’ plate left in place resulting in poor quality concrete (left) and extensive rebound that will need to be jiggered out prior to connection to the invert lining (right) are shown.

Fig. 41 Quality issues with continuity bars

Instead of pre-installed continuity bars (kwikastrip), post drilled bars can be installed into the construction joint. However, even installation of the post-drilled continuity bars can result in quality issues during spraying through the reinforcement; see Fig. 42.

Fig. 42 Poor compaction caused by combination of steel fibres and steel bars

Such primary lining construction joints with poor quality and high permeability are considered as potentially weak points for the spray-applied waterproofing membrane application. An improvement is suggested in Fig. 43 in order to avoid installation of the longitudinal continuity bars. This ‘scarf joint would not include any steel bar elements, only steel fibres. The joint shall be properly cleaned and wetted before application of the next shotcrete layer. Performance of such joint can be verified by tensile splitting test and compression test with the configuration as suggested below with on side of the sample supported to simulate the groundside of the primary lining.

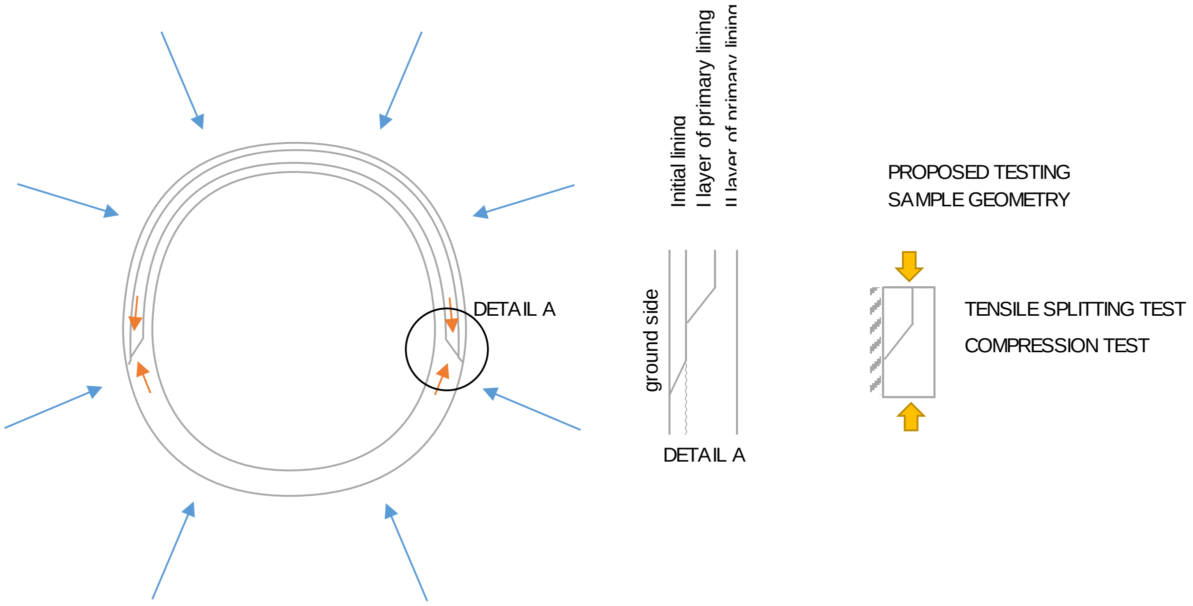

Fig. 43 Proposal of joint with no continuity bars (only steel fibre reinforced)

From the spray-applied waterproofing membrane application point of view, the primary lining has to be without active water ingress at the time of the membrane application. Tunnel fixings, monitoring targets or proof drilling are potential water path that may have impact onto the application of the spray-applied waterproofing membrane, see Fig. 44. As mentioned earlier, the function of the primary lining is to support the ground load temporarily or permanently. Further requirements on the primary lining as the substrate for the waterproofing application will be described in the next chapters.

Fig. 44 Escalator tunnel with installations during construction

5.3 Primary lining thickening

In some cases, and especially in tunnel junctions, primary lining thickening may be designed. It is usually steel bar reinforced sprayed concrete lining installed in multiple layers. An example of steel bar reinforced tunnel junction is shown in Fig. 45.

Fig. 45 Steel bar reinforced tunnel junction primary lining thickening

Quality of the primary lining thickening can be verified by non-destructive hammer tapping (sounding) test to detect hollow spots and lamination; or by destructive tests – core drilling, see Fig. 46.

Fig. 46 Hollow spots identified by hammer tapping (left), core showing poor embedment of steel bars (right)

Quality of the cores can be evaluated according to ACI standards, [21]. It classifies cores according to their imperfections into five grades.

Fig. 47 Core grading according to ACI 506, [21]

Such defect lining can be jiggered out and resprayed (see Fig. 48) or filled with injection (see Fig. 49).

Fig. 48 Remedial works of hollow spot – jiggering out

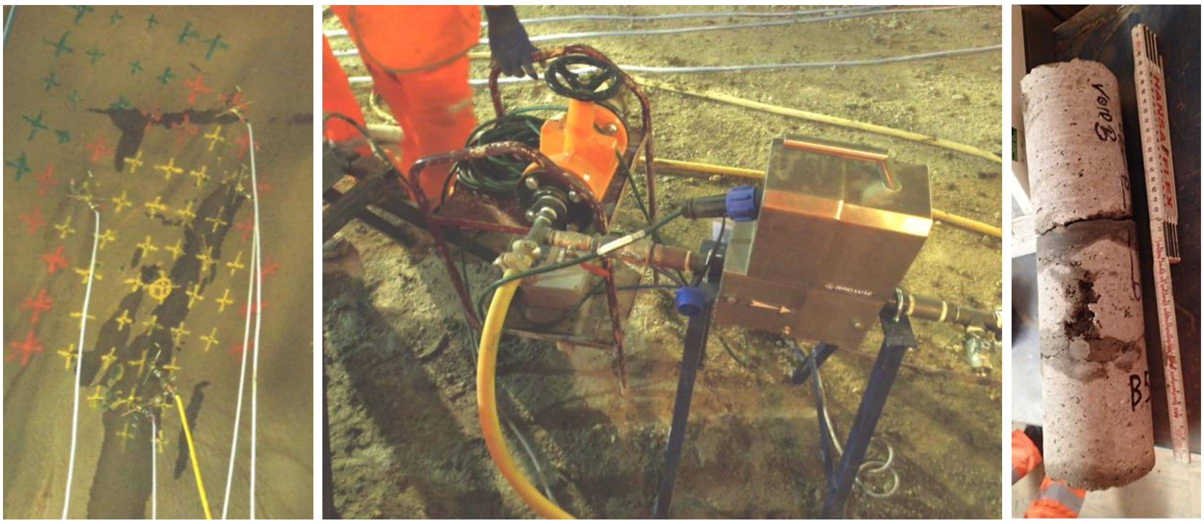

Fig. 49 Remedial works of hollow spot – injection

From the spray-applied waterproofing point of view, either the primary lining or the primary lining thickening represent the substrate layer for its application. In some cases, a regulating (smoothening) layer may be required. In case of fibre reinforced primary lining, the regulating layer may be required to cover the steel fibres protruding from the surface. The steel bar reinforced primary lining thickening does not usually include steel fibres even though combination of steel fibre reinforced and steel bar reinforced sprayed concrete primary lining thickening can also be constructed.

5.4 Regulating layer

Regulating layer can be applied in order to rectify the primary lining profile before the waterproofing and the secondary lining are applied. In Fig. 50, scanning procedure and the scanning result are shown.

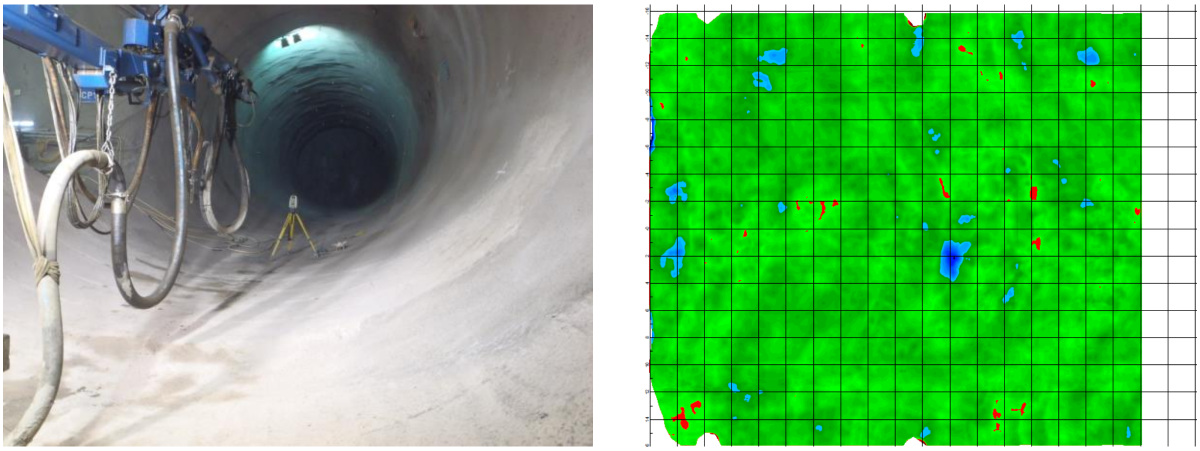

Fig. 50 Primary lining profile scanning (left), scanning result: red – underprofile, blue – overprofile, green - OK (right)

From the application of the spray-applied waterproofing membrane point of view, the surface roughness rather than profile is more important, [1].

ITA [1] states: *"The encountered substrate roughness and quality do influence the time needed for the substrate preparation works, the consumption of material and the speed of application. It is recommended that very rough surfaces are regulated in order to maximise the efficiency of the waterproofing membrane, using a finer aggregate sprayed concrete or specific surface regulating material."*

ITA [1] also states: *"If a regulating layer is used, a typical thickness of 1 to 3 cm with a maximum aggregate size of 4 mm shall be applied to the primary lining prior to membrane application. It is important to ensure a proper application of the regulating layer (e.g. surface preparation, correct accelerator dosage that allows proper setting time, correct spraying angle, correct air content and pressure), in order to avoid pitting and large craters on the surface, and achieve minimum bonding requirement of 0.5 MPa."*

The regulating layer is usually fibreless fine aggregate shotcrete or another suitable cementitious material applied in one layer not more than 5 cm thick. The regulating layer can temporarily seal the water ingress through the primary lining but considering its thickness and permeability it is recommended to manage the water ingress through the primary lining before the regulating layer is applied.

5.5 Spray-applied waterproofing membrane

5.5.1 Properties of the spray-applied waterproofing membrane

5.5.1.1 Chemical composition

The properties and behaviour of the spray-applied waterproofing membrane depend on its chemical composition. There are different types of spray-applied waterproofing membranes: non-reactive, cured by hydration or air drying, and reactive, cured by polymeric reaction. The most commonly used type of the spray-applied waterproofing membranes are non-reactive EVA (ethylene-vinyl acetate-free) – based membranes, [1].

The spray-applied waterproofing membranes content plastic polymers that practically do not degrade over time and do not contain chemical plasticizers (do not lose their flexibility when exposed to the effects of flowing water). Polymeric content of the membrane product above approximately 70% seems to be required for sufficient elasticity performance. The tested membranes with polymeric content over 71% show high and sufficient crack bridging capacities at 20°C, [47].

The sprayed waterproofing membranes may be susceptible to ultraviolet radiation, elevated temperatures, and some chemicals, but the nature of the membrane inlay between the concrete linings does not usually occur with these types of stress. Sprayed waterproofing membranes are designed to be chemically stable against water containing pollutants that form an acidic or alkaline environment, [1].

Some products are incorporating cement compounds (e.g. as fillers), which may allow the built up of crystals on the interface with other cementitious layers, adding water (non-reactive systems) or suspending agents for vertical applications or using de-airing additives to reduce the air-content, which is mixed into the material matrix during its application. The differences are seen in the product performance in, for example, water absorption, water permeability, chemical resistance, re-softening in contact with water, tensile strength or finally in the costs. On the other hand some products, for example those based on polyurea- or methyl-methacrylate resins, could have some contents of an activator, for example isocyanate, amine and/or peroxide, which are - individually - known to have a significant odour and the potential of detrimental health effects, depending on its concentration rate and type. This is the case, especially during its application, where the components are not polymerized and are airlessly sprayed with high pressure. Therefore, the potential of health and fire risk (e.g. explosion of dust/air mixture based on a very high reaction surface) has to be assessed. In addition, some components of both material groups (non-reactive and reactive) may be classified as having a low hazard reaction when in contact with water, [48].

5.5.1.2 Thickness

The membrane should present a minimum thickness according to the manufacturer’s instructions, in order to be watertight, [1]. The minimum thickness is usually between 2 and 3 mm. It shall be distinguished between wet and dry thickness. Wet thickness is the thickness of the freshly applied material before its cured. It is tested by a non-destructive test carried out by a simple depth gauge that is penetrated into the freshly sprayed membrane and it is assumed that the point of penetration will close itself when the depth gauge is pulled out. Dry thickness is the thickness of the cured membrane. It is tested by a destructive test when a patch of waterproofing is cut out from the lining and its thickness is measured, see Fig. 51.

Fig. 51 Dry patch thickness (left and middle) and depth gauge for wet thickness test (right)

The dry patch thickness test can be combined with bond test that is also destructive and allows checking the membrane dry thickness (see Chapter 5.5.1.5). The membrane thickness can also be calculated from the material consumption per metre squared. The correlation between the wet thickness, dry thickness and the material consumption shall be calibrated during site trials. According to [41], which refers to the EVA-based spray-applied waterproofing membranes: *“Depending on the curing conditions, there is usually a 2–3 mm thick shrinkage for an 8 mm wet film thickness membrane, leading to dry patch thickness of 5–6 mm.”*

According to [48], the material consumption is related to the surface roughness and for a ‘good sprayed concrete surface finish’ consumption from 3 to 4 kg/m^2 (dry powder) for an average 3 mm sprayable membrane thickness can be expected. For a ‘moderate surface finish’ and 4 to 6 kg/m^2 (dry powder) for an average 3 mm sprayable membrane thickness can be expected. For the moderate and coarser surface roughness, application of regulating layer shall be considered (Chapter 5.5.2.1). An example of on-site measurements of the wet thickness, dry thickness and the material consumption is shown in Tab. 3.

Tab. 3 Wet thickness, dry patch thickness and material consumption

CHAINAGE (m)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
CONSUMPTION RATE										
Layer 1 (BAGS)	18									
Layer 1 (kg/m2)	calculated in bags									
Layer 2 (BAGS)	21									
Layer 2 (kg/m2)	calculated in bags									
PERIMETER (m)	20.85									
RUNNING METERS (m)	8.5									
Total Consumption in kg	780									
TOTAL CONSUMPTION RATE kg/m2	**4.4**									
WET FILM THICKNESS (mm)										
Layer 1										
9 o'clock	4		5		5		5		4	4
12 o'clock	2		2		5		4		5	5
3 o'clock	5		5		5		4		4	5
Average thickness layer 1	**4.33**									
Layer 2										
9 o'clock			2	2.5		3.5		2		
10 o'clock					6				6	
11 o'clock		2				2	5			
12 o'clock	7				2			1		
1 o'clock					4			2		
2 o'clock		3		7			2			
3 o'clock	3		3		3			6		
Average thickness layer 2	**3.52**									
Total average thickness (mm)	**7.86**									
DRY PATCH THICKNESS										
9 o'clock										
10 o'clock					5				3	
11 o'clock				3			4			
12 o'clock										
1 o'clock				4			3			
2 o'clock										
3 o'clock		3						5		
Average dry patch thickness (mm)	**3.9**									

The thickness of the membrane has impact onto the water-tightness of the membrane as well as the interface performance.

5.5.1.3 Permeability

According to [3], the spray-applied waterproofing membranes shall exhibit no penetration of water. The water-tightness is the fundamental property of the waterproofing membranes. The principle of water permeability and water vapour permeability of the EVA-based sprayed waterproofing membranes is similar to the Gore-Tex system where the membrane pores are smaller than a water drop but larger than water vapour molecules to prevent ingress of water into the structure but to allow water vapour to escape from the interior out, [48]. The water-tightness control is carried out in such a way that the application of the membrane is continuous and continuous and the thickness of the membrane should be between 3 and 10 mm. If the thickness is less than 2 mm, the membrane is not considered watertight and the thickness must be increased. Thicknesses greater than 10 mm are not recommended due to the risk of imperfect maturation of the membrane, [1].

Holter [47] states: *"The water vapour conductivity of the membranes is within the range of water vapour conductivity of sprayed concrete."* Moreover, that: *"The sprayed membrane material is significantly less hygroscopic than sprayed concrete."*

5.5.1.4 Elongation (crack-bridging)

Because the spray-applied waterproofing membrane interacts with the primary and the secondary lining, it must be capable to transfer deformation of the lining and settlement of the structure (naturally without affecting its functionality). The ability to elongate the membrane is directly dependent on the thickness of the membrane. Generally, the manufacturer guarantees the ability to elongate the membrane 100%, but not more than 3 mm. Any requirement for greater elongation must be consulted and approved by the manufacturer. The elongation of the membrane is related to its fragility and plasticity. Mostly, membrane elongation tests are performed only in the pre-construction phase of the project and not in the construction phase, however the parameters controllable on the site that affect the elongation of the membrane are membrane thickness, water content of the applied waterproofing, membrane Shore A hardness, temperature, humidity and ventilation, [1].

According to [3], the spray-applied waterproofing membranes shall be capable of bridging a gap 2 mm without diminishment of resistance to water permeation.

5.5.1.5 Bond

The bond is an important property of the spray-applied waterproofing membranes with respect to the migration of water and the structural behaviour of the composite lining.

According to [3], the bond shall be tested at 28 days age of the membrane as long-term evidence of water path obstruction and shall be greater than 0,5MPa. The bond of the membrane to the primary lining is usually tested by a pullout test using a special device measuring the force needed to pull out a patch of the membrane of a given area at the age of the membrane generally less than 28 days, see Fig. 52.

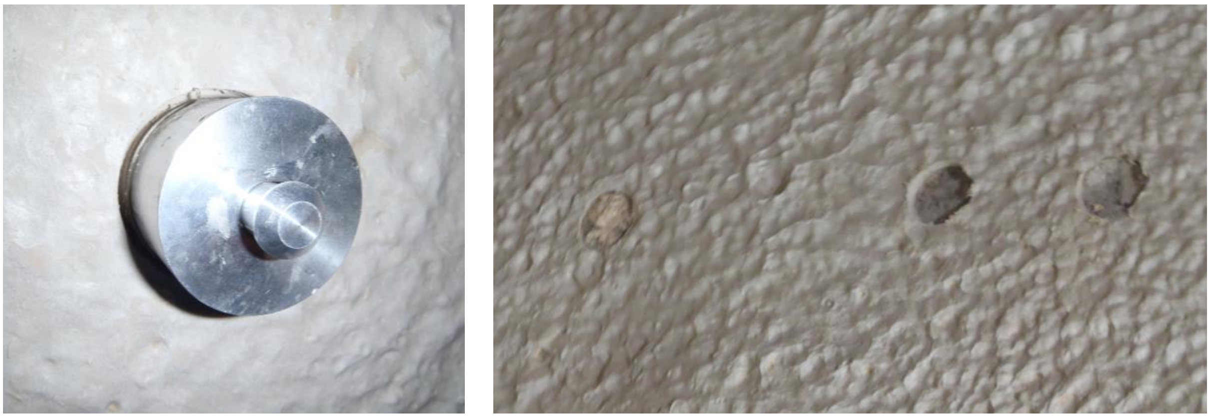

Fig. 52 Pull-out dolly (left and membrane after test (right)

The dolly will be glued to the membrane and the membrane will be cut along the dolly’s perimeter so that pure bond of the membrane to the surface can be tested. The failure plane will then be examined to determine whether it is at the bond plane in the membrane or in the shotcrete or substrate. If failure occurs at the bond line and the tensile bond value is less than the specified minimum, quality of the substrate should be reviewed. The bond between the membrane and the secondary lining is generally not tested on the lining but on test panels. The bond of the sprayed waterproofing membrane to both linings is the critical parameter for the design of the composite lining.

5.5.1.6 Behaviour under various humidity conditions

It has been observed that not only active water ingress during the application of the membrane but also long-term humidity conditions have impact onto the EVA-based spray-applied waterproofing membrane behaviour. Questions, such as whether the primary lining will be saturated or whether the groundwater penetrates only through the cracks within the primary lining may not be important for the application of the sheet waterproofing membranes but it is an important aspect for the use of the EVA-based spray-applied waterproofing membranes.

Holter [47] studied the influence of moisture on the EVA-based spray-applied waterproofing membranes. It can be seen in Fig. 53 that at a relative humidity of 90-95% the membrane is saturated only from 25-30%. The moisture content is expressed here as the degree of saturation in equilibrium relative to the relative humidity.

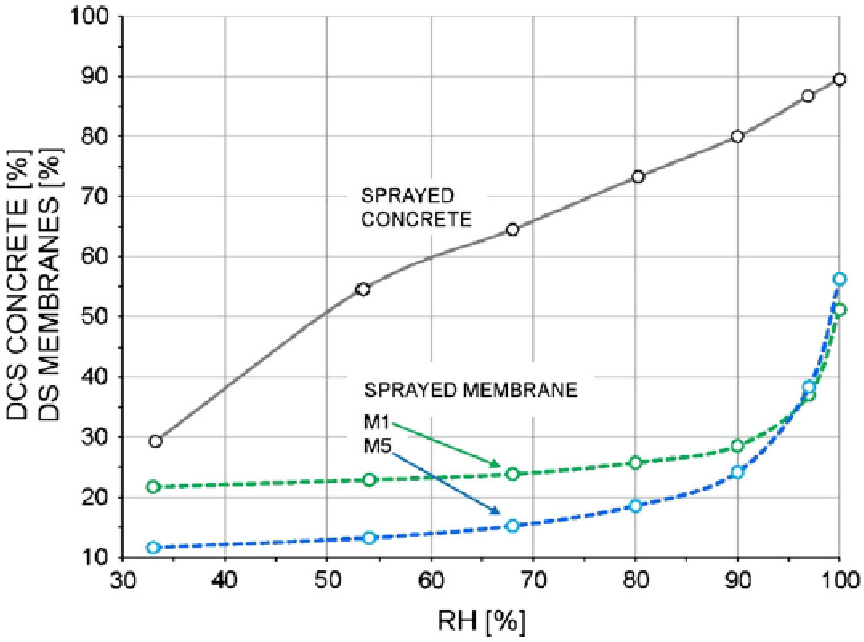

Fig. 53 Desorption isotherms for sprayed concrete and sprayed membrane obtained at 25°C for different values of RH. Values are shown as degree of saturation at immersion (DCS for concrete, DS for membrane) versus RH, [47]

According to Lemke [48], the significant effects of the moisture state of the material on its physical properties are related to the nature of the material EVA polymer colloid containing many long-chain polymers, which on curing lose moisture, allowing the polymers to coagulate into a film. On exposure to liquid or vapour phase moisture, the spray-applied waterproofing membrane re-absorbs water. This appears to have an effect on physical properties of the membrane, including bond strength and elasticity. On absorption of water, the tensile strength of the membrane reduces significantly, while its elongation at break increases.

Diez [13] presents testing of no. 2 EVA-based samples and one polyurea-resin-based sample of the spray-applied waterproofing membranes. Rapid tensile tests to failure were performed and the results are shown in Fig. 54. Peak load at failure indicated the lowest of the membrane bond strength, membrane cohesive strength or the concrete/regulating layer strength.

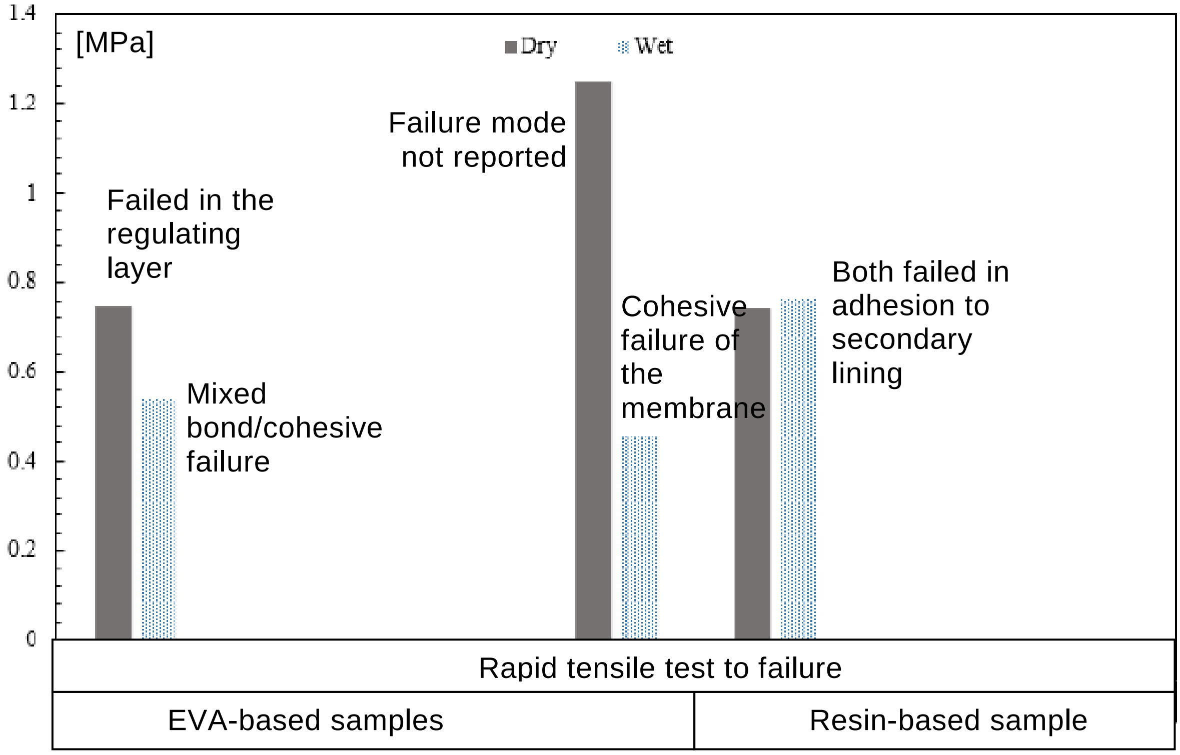

Fig. 54 Ultimate failure strength on ‚dry‘ and ‚wet‘ samples, [13]

From the tests above, it appears that the moisture conditions of the EVA-based spray-applied waterproofing membranes affect the mode of failure and the tensile strength of the material. With increased moisture, the adhesive failure of the bond shifts to the cohesion failure of the membrane. This can be explained as lower tensile strength of the material with increased moisture conditions. Resin-based samples both ‘dry’ and ‘wet’ failed in adhesion between the secondary lining and the membrane that means lower sensitivity to the humidity conditions.

5.5.1.7 Shore A hardness

Shore hardness is a measure of the resistance a material has to indentation [50]. The membrane shall comply to a minimum Shore A hardness 50 for the secondary lining installation [3] that equals to ‘medium to somewhat flexible’ according to the shore hardness scales shown in Fig. 55. The Shore A hardness is measured by durometer prior to installation of the secondary lining. The Shore A hardness develops in time, for certain membranes from 50 ‘medium soft’ up to 85 ‘hard’, [48].

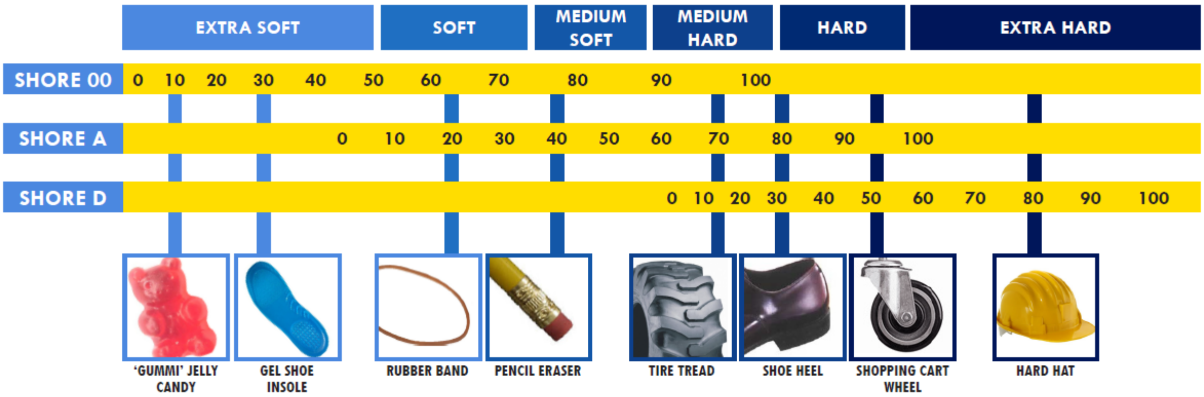

Fig. 55 Shore hardness scales, [50]

5.5.2 Production of the spray-applied waterproofing membrane

Correct preparation of the substrate (roughness, cleanliness, humidity), correct water coefficient of the waterproofing mixture (proper water inlet valve), correct spraying method (nozzle distance, angle at which material falls on the substrate) etc. are key to successful membrane production. The production of sprayed waterproofing membranes takes place on site, which naturally means the lower quality of the resulting product if the technological process is not followed, [1].

5.5.2.1 Preparation of surface

As already stated before, the primary lining (primary lining thickening) has to be survey-checked prior to application of the waterproofing membrane and the secondary lining. The roughness of the surface shall be evaluated and in case of high roughness, the surface shall be smoothened. The surface roughness will have impact onto the spray-applied waterproofing membrane material's consumption but it also may cause air locked between the membrane and the surface or uneven drying of the membrane and development of micro-cracks on the airside of the surface of the membrane. Application of the spray-applied waterproofing membrane onto a surface with protruding steel fibres is possible but the clients usually desire smooth surface with no fibres protruding.

According to [48], the waterproofing must be sprayed onto a clean and cohesive surface. A dusted or otherwise polluted surface reduces the bond of the waterproofing layer. It is therefore necessary to clean the surface with pressurized water or compressed air before spraying. The EVA-based spray-applied waterproofing membranes may only be applied to a sufficiently dampened surface without running water, otherwise the dry surface will remove the freshly sprayed waterproofing layer by mixing water, thereby causing a substantial deterioration in the physical properties of the waterproofing layer (this is particularly likely to be caused by dry spraying).

As already stated before, the spray-applied waterproofing membranes can only be applied on surface with no active water ingress. Temporary spot water ingress drainage (see Fig. 56), injection or application of fast setting mortar (see Fig. 57 have to take place prior to the membrane application. Permanent dimple membrane drainage can be installed to divert the water ingress into the permanent tunnel drainage system in case of drained tunnels, [1].

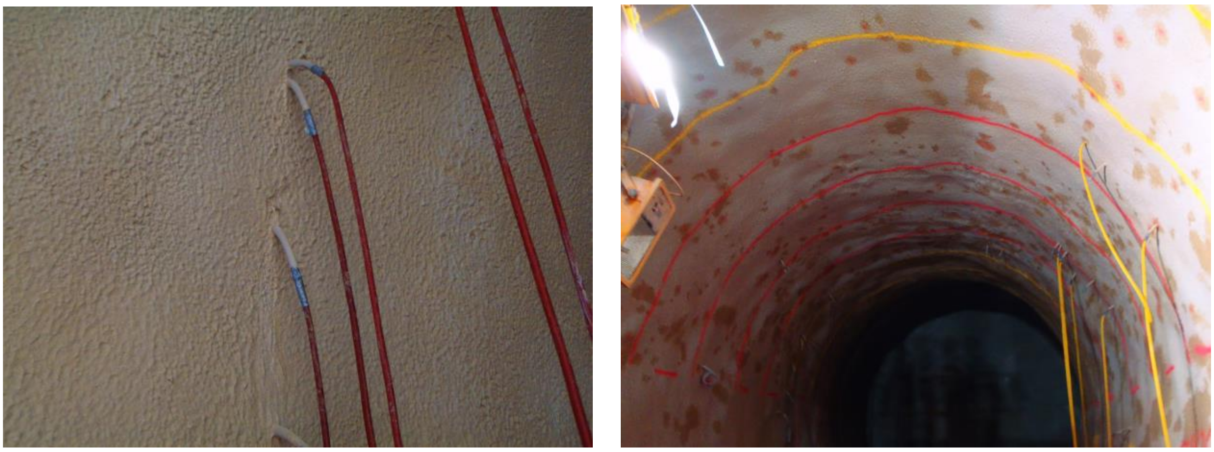

Fig. 56 Temporary spot water ingress drainage

Fig. 57 Application of fast setting mortar – water ingress (left), water ingress sealed (middle) and curing protection (right)

5.5.2.2 Membrane production

The spray-applied waterproofing membranes can be produced by ‘dry’ or ‘wet’ spraying, manually or with a remotely operated spraying robot (Fig. 58). With all application methods, sufficient control of the entire process of production is required to achieve the desired membrane quality.

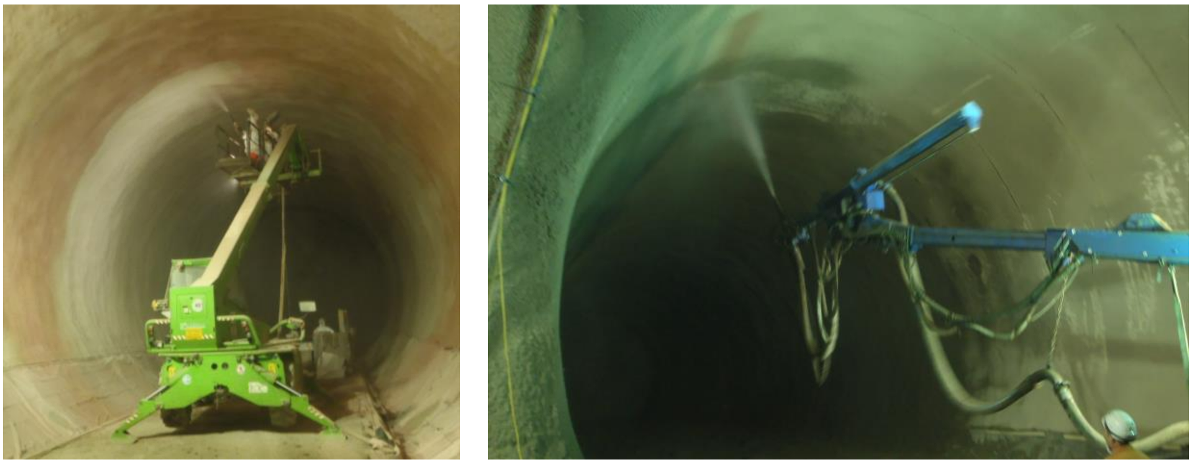

Fig. 58 Manual spraying from a mobile elevating platform (left) and remotely operated robot spraying (right)

During the membrane application, the environmental conditions may affect the works. The manufacturer’s recommendations to ambient temperature, ventilation and other requirements shall be followed. The application of the membrane can affect other works. When products, such as those based on polyurea- or methyl-methacrylate resins that can have some contents of an activator, for example isocyanate, amine and/or peroxide, with significant odour and the potential of detrimental health effects [48], are used management of ventilation is very important. Odour that is produced during spraying shall not spread to other work places where the personnel might not be equipped with the suitable PPE (personal protective equipment) needed for application of the spray-applied waterproofing membrane. An example of odour management during application of the polyurea-resin-based spray-applied waterproofing membrane is shown in Fig. 59.

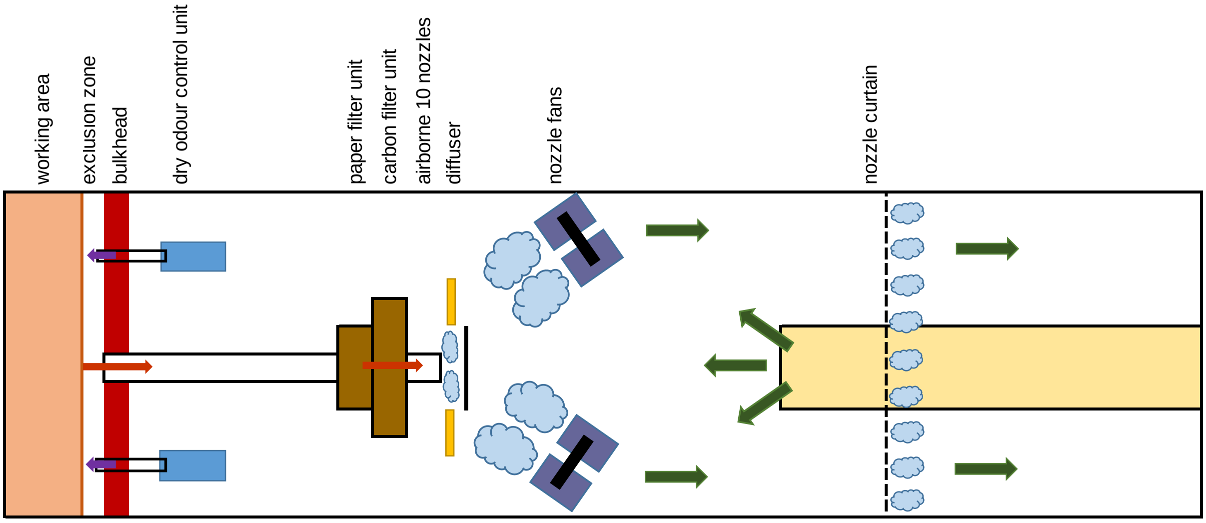

Fig. 59 Odour management for application of polyurea-resin-based membrane plan view

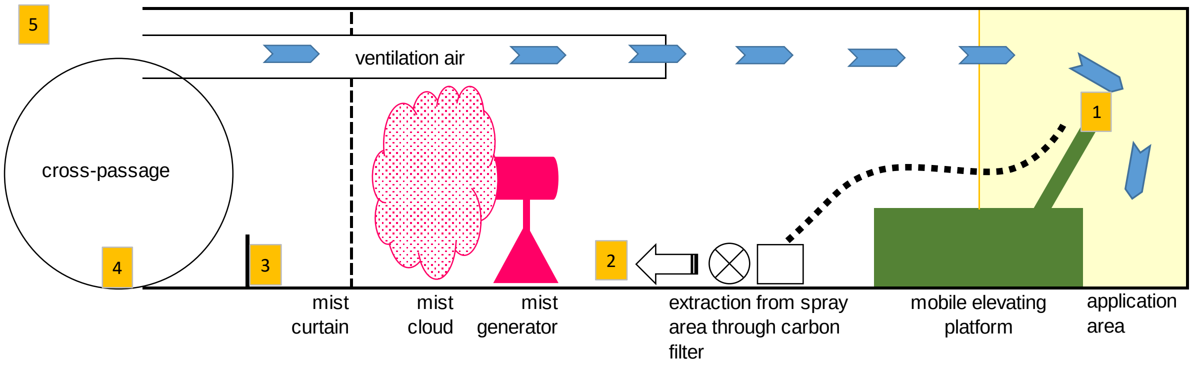

Fig. 60 Odour management for application of polyurea-resin-based membrane cross section view

Experience has shown, however, that the odour control in large complex underground structures, such as station tunnels with many junctions and interconnections, is very challenging and in some cases it was decided not to apply this material because of the odour spreading overall the station causing skin irritation and headache to the tunnel personnel.

As already stated, the spray-applied waterproofing membranes cannot be applied onto a surface with active water ingress. It is not only necessary to prevent the water ingress during application but also to provide the right water content during spraying. The membrane should not be sprayed ‘too dry’ neither ‘too runny’. Application of the spray-applied waterproofing membrane by competent and trained workmanship is the key to reduce defects and erroneous application of the membrane.

5.5.2.3 Defects and erroneous application

Before the secondary lining can be installed, the membrane shall be cured and compliant to all the specified requirements. In such case, the membrane shall be inspected for defects and repaired if necessary. According to [3], defective spray-applied waterproofing membrane lack uniformity, exhibit lamination or cracking, lack adequate bonding, lack water-tightness, or fail to meet the specified strength and toughness requirements. Any such membrane shall be removed and replaced including any associated water ingress control measures or regulating layer.

High humidity of the surface may prevent the bond to develop between the spray-applied waterproofing membrane and the concrete surface. The membrane shall be removed, the area dried and the membrane re-applied with a minimum overlap of 200mm from the boundaries of the defect, [3].

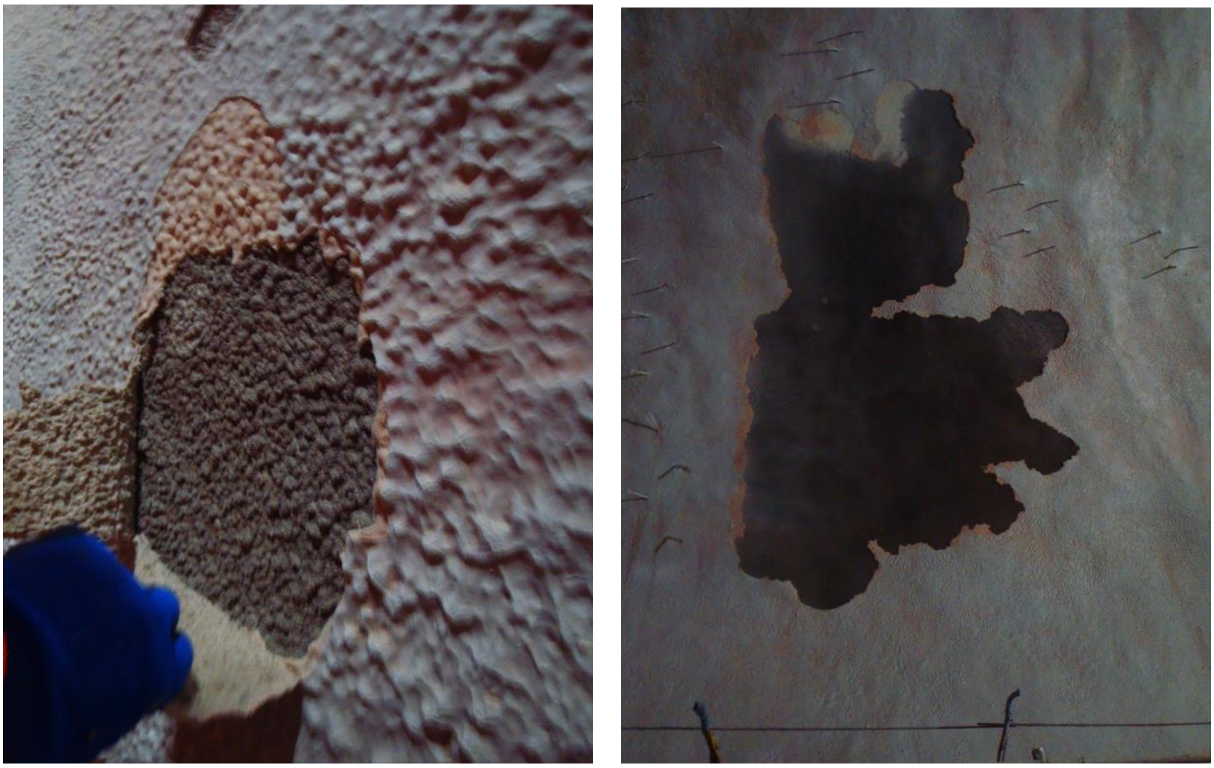

Fig. 61 Membrane without bond to the surface

A visual inspection of the spray-applied waterproofing membrane shall be carried out. Areas with the substrate still visible, or where there are pinholes, cracks or other areas of impaired integrity shall be marked and repaired. Depending on the nature and extent of the defect, another layer of the membrane shall be sprayed or the defective membrane shall be removed, the area cleaned and new membrane sprayed. Pinholes are usually repaired by brush, see Fig. 62.

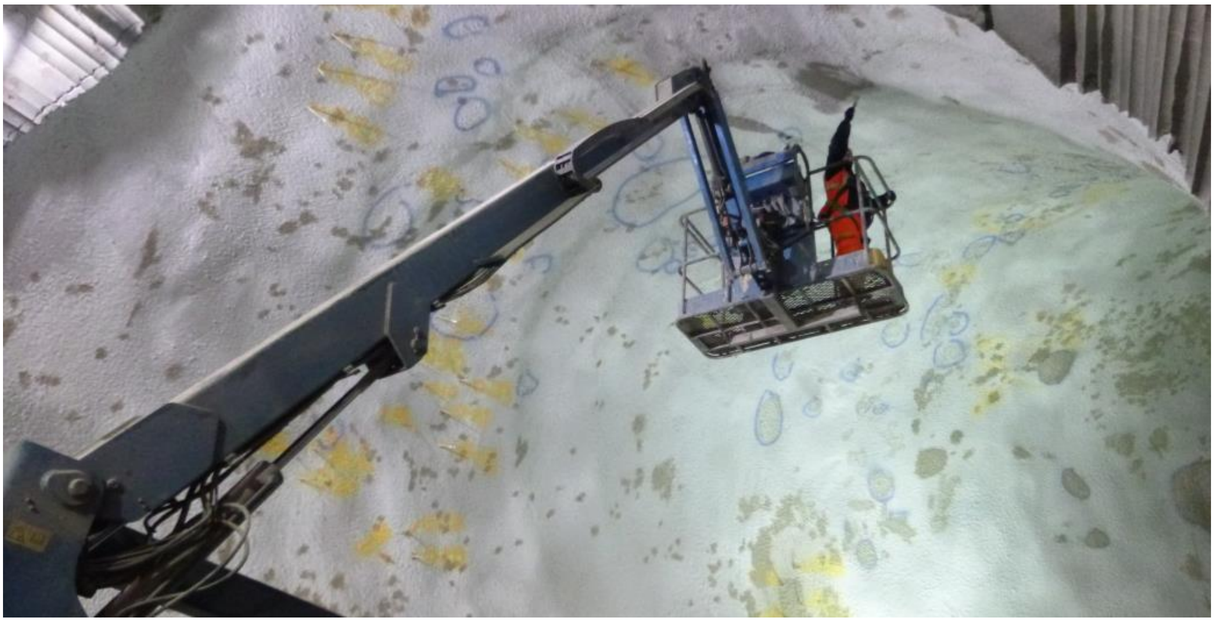

Fig. 62 Visual inspection of pin holes

In Fig. 63, micro-cracks on the surface of the membrane are shown, caused by differential curing of high and low spots of the membrane on a rough surface.

Fig. 63 Micro-cracks on the membrane's surface

In addition, excessive thickness of the membrane can be considered as a defect. The spray-applied waterproofing membrane of excessive thickness shall be removed and replaced in order to fulfil the design requirements and the manufacturer´s recommendations. Example of removal of excessively thick membrane is shown in Fig. 64.

Fig. 64 Removal of overly thick membrane

5.6 Secondary lining

Cast-in-situ or sprayed concrete secondary lining can be installed onto the spray-applied waterproofing membrane. Sprayed concrete secondary linings do not require formwork and based on the ground conditions and the tunnel geometry may or may not require steel bar reinforcement. The secondary lining thickness and amount of structural reinforcement is based on the foreseen acting loads and/or function of the secondary lining. In some cases, the secondary lining can be designed only as protection/fireproofing layer with maximum thickness of 4-5 cm and no steel bar reinforcement. In other cases, the fixing depth of the installations and services governs the minimum secondary lining thickness. In case that the secondary lining is designed to carry the ground and/or the groundwater load, the lining thickness is usually greater than the minimum thickness necessary for the fixings. When sprayed concrete secondary lining is installed, depending on the secondary lining thickness, it may be sprayed in more layers. Profile bars can be used as guidance for the nozzleman in order to achieve the correct profile and the lining thickness. These are usually installed into the penultimate layer of the sprayed concrete when multiple layers of sprayed concrete are to be applied, however the final surface finish of a sprayed concrete lining might be slightly uneven, Fig. 65.

Fig. 65 Guidance profile bars (left), final layer of sprayed concrete secondary lining (right)

In soft ground/weak rock tunnelling, it is common to use closed secondary lining profiles with monolithic invert. If a combination of a monolithic invert with sheet waterproofing membrane and spray-applied waterproofing membrane is proposed it is necessary to provide for a reliable connection between the spray-applied and the sheet waterproofing. An example of a connection detail is in Fig. 66.

Fig. 66 Sheet and spray-applied waterproofing membrane connection detail

From a composite lining point of view, in the case of the use of the sheet waterproofing membrane in the invert, the composite action cannot be considered for the whole tunnel perimeter but only for the part where the spray-applied waterproofing is installed.

5.7 Discussion of findings

According to [1], migration of groundwater along the membrane-concrete interface cannot occur because the bond eliminates potential groundwater paths. According to the sketch in Fig. 67 [49], water can only leak when a crack through the primary lining together with defect waterproofing membrane and a crack in the secondary lining all in one intersection occur (orange arrow).

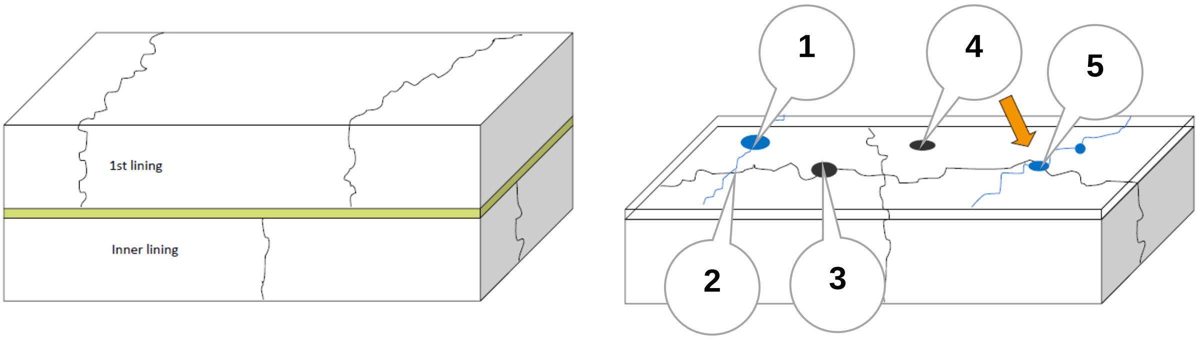

Fig. 67 Bond reducing the potential groundwater inflow through the secondary lining, [49]

At scenario ‘1’, there is a water-bearing crack through the primary lining and defect membrane. It is assumed that no leak will occur since the membrane around the defect is bonded and will prevent migration of water between the membrane and the secondary lining and water-tightness of the secondary lining concrete will block the water itself.

At scenario ‘2’, there is a water-bearing crack through the primary lining that intersects with a crack in the secondary lining but the waterproofing membrane blocks the water migration and water penetration.

At scenario ‘3’, there is a defect in the waterproofing membrane where there is a crack through the secondary lining but since there is no water-bearing crack through the primary lining it is assumed that no leak will occur.

At scenario ‘4’, there is a defect membrane but no water-bearing crack through the primary lining and no crack through the secondary lining so it is assumed that no leak will occur.

At scenario ‘5’ (orange arrow), it is, according to [49], the only scenario when a leakage through the secondary lining occurs.

The time required for full penetration of groundwater will vary, [48]. Site observations showed that groundwater could enter through any crack, hole or concrete imperfection with higher permeability and can potentially migrate along any layer of lamination, poor compaction or voids behind the steel bar reinforcement. The time required for saturation of the primary lining affecting the spray-applied waterproofing membrane should be calculated from the last water-bearing layer closet to the membrane, see Fig. 68. This may also be the regulating layer, which is in direct contact with the spray-applied waterproofing membrane.

Fig. 68 Primary lining water path

From the tunnel lining design point of view, the primary lining may not be designed to carry groundwater load and it is therefore in line with the design assumption when the groundwater penetrates through the primary lining and no water pressure builds-up behind the primary lining. On the other hand, from the spray-applied waterproofing point of view, the groundwater penetrating through the primary lining is a problem. The spray-applied waterproofing membranes cannot be installed on a surface with active water ingress. High humidity of the surface may prevent the bond between the membrane and the surface to develop and the long-term high humidity conditions may reduce the cohesion and tensile strength of the EVA-based membrane. It is therefore recommended to minimise the use of the steel bar reinforcement when the primary lining is designed permanent. If the interface de-bonds or the membrane loses its cohesion, the overall stress distribution in the structure changes. The ‘no bond’ and ‘full bond’ composite action is investigated in the following chapter.

6 The mechanism of composite tunnel lining

6.1 Composite action

The composite lining with the use of the spray-applied waterproofing membrane to be considered a composite, the constituent elements must work as a single member. To make it possible, the spray-applied waterproofing membrane is used to tie the elements together. The extent of the composite action varies, such that the effects on the member's structural properties may vary. The lower bound of the composite action can be described as no interaction and the upper bound as full interaction, with all levels of interaction in between classed as partial interaction. Therefore, the composite action is defined as the shear transfer between the sprayed concrete lining layers limited by the interface strength stiffness, adhesion and mechanical interlocking through the interface.

6.1.1 No interaction

When there is no interaction between the elements of the composite lining and it is subjected to a point load perpendicular to the span, each element will act independently and their combined capacity will be the sum of the individual element's capacities. This is due to none of the loading force being transferred horizontally and hence the interface being exposed to no axial force.

The mid-span strain distribution and interface shear (q) for this load-case is shown in Fig. 69. It is assumed that the materials used for each element behave elastically in both compression and tension. In addition to this, if it is presumed that the two elements remain in contact with no vertical separation, the element curvatures (k) will be identical along the span. It can be seen clearly in Fig. 69 that due to the lack of connection, and therefore interaction, the strain difference (e) at the interface is maximal.

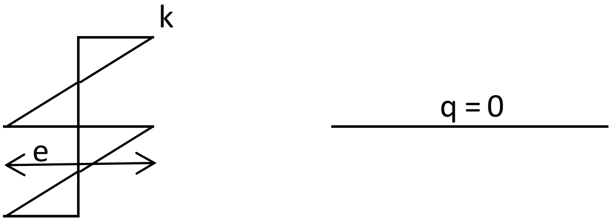

Fig. 69 Mid-span strain distribution (left) and interface shear (right) for a beam with no interaction, [51]

6.1.2 Full interaction

Full interaction is at the opposite end of the composite action scale to no interaction. For full interaction to occur between two elements, the interface connection must be suitably rigid such that slip is non-existent. This therefore indicates that the strain difference is zero and can be neglected. It is shown in Fig. 70 that the strain distribution over the full depth of the composite lining is continuous. The lining consequently acts as one element. The interface shear force along the span of the lining with full interaction is shown in Fig. 70 to be constant, with a change of sign occurring at mid-span due to the direction of slip reversing.

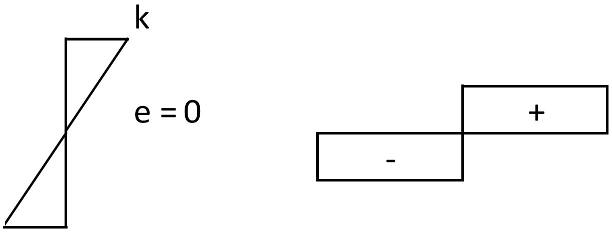

Fig. 70 Mid-span strain distribution (left) and interface shear (right) for a beam with full interaction, [51]

6.1.3 Partial interaction

Partial interaction between elements of the tunnel lining with the use of the spray-applied waterproofing membrane occurs when the connection is sufficiently flexible such that slip along or within the interface arises. When this slip induces a significant strain difference at the interface, the analysis of the composite lining must be adjusted to consider this.

If a simply supported lining with flexible interface is subjected to a central point load, equal to the load applied to both the no interaction and full interaction, the strains experienced by both members will be lower than that experienced by the no interaction, but slightly higher than that experienced by the full interaction. This is due to the spray-applied waterproofing membrane reducing the slip observed in the no interaction case, resulting in a reduced strain difference at the interface. The general partial interaction strain profile and interface shear are shown in Fig. 71.

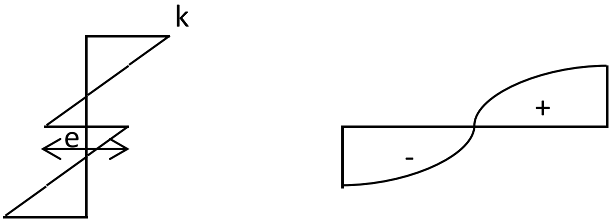

Fig. 71 Mid-span strain distribution (left) and interface shear (right) for a beam with partial interaction, [51]

The role of the spray-applied waterproofing membrane within the composite lining is of high significance, as it is required to transfer shear stress at the interface. The effectiveness of a composite lining is therefore directly related to the properties of the spray-applied waterproofing membrane used.

Firstly, the spray-applied waterproofing membrane must provide adequate resistance to the shear forces created due to interface slip. Secondly, uplift forces may occur between the different layers, [51]. To counter this, the spray-applied waterproofing membrane should be designed to resist also uplift. Initially, the circumferential stiffness of the interface in shear enables flexural composite action to occur between the linings, but if the shear stress exceeds the in-plane resistance, this flexural composite action is lost.

6.1.4 Summary

It is acknowledged that neither ‘no interaction’ nor ‘full interaction’ is a fully realistic case. There will always be some kind of partial interaction due to the surface roughness and the mechanical interlocking; and there will not be full interaction due to the flexibility of the spray-applied waterproofing membrane allowing for certain amount of the interface slip. Nevertheless, in the next chapter, the two extreme ends of the composite action scale are investigated and impact onto the secondary lining is evaluated.

6.2 Numerical modelling case study

6.2.1 Introduction

The author builds-up on her study on tunnel primary lining design and construction of large underground structures [32] carried out within the MSc. Civil Engineering programme. The purpose of the numerical analyses carried out in this work is to investigate the impact of the membrane-concrete interface bond onto the secondary lining. The motivation to design a composite lining is to take advantage of the primary lining being permanent together with the spray-applied waterproofing membrane acting as the interaction element between the primary and the secondary linings. In such way, the thickness of the secondary lining can be reduced and so the overall thickness of the composite lining, see Fig. 72.

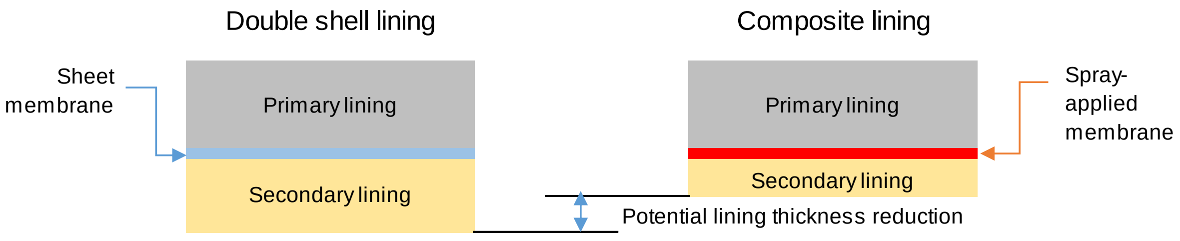

Fig. 72 Double shell vs. composite lining thickness

In order to investigate the impact of the secondary lining thickness (thin/robust) and the interaction through the membrane (full/no), a set of numerical analyses have been carried out using program FLAC [52] (Fast Lagrangian Analysis of Continua), version 6.00.398, which employs an explicit finite difference formulation for the analysis of continuum.

6.2.2 Calculation model

6.2.2.1 Tunnel geometry

The basis for the secondary lining analysis i.e. model geometry, ground conditions, groundwater profile and structural details were taken from the final short-term stage of the primary lining numerical analysis. For the purpose of the analyses, the invert geometry has been simplified and constant thickness of the secondary lining in the crown and the invert is considered. The cavern is of non-circular shape with maximum span of 16m and maximum height 13 m. The cavern is vertically symmetrical. The cavern geometry is shown in Fig. 73.

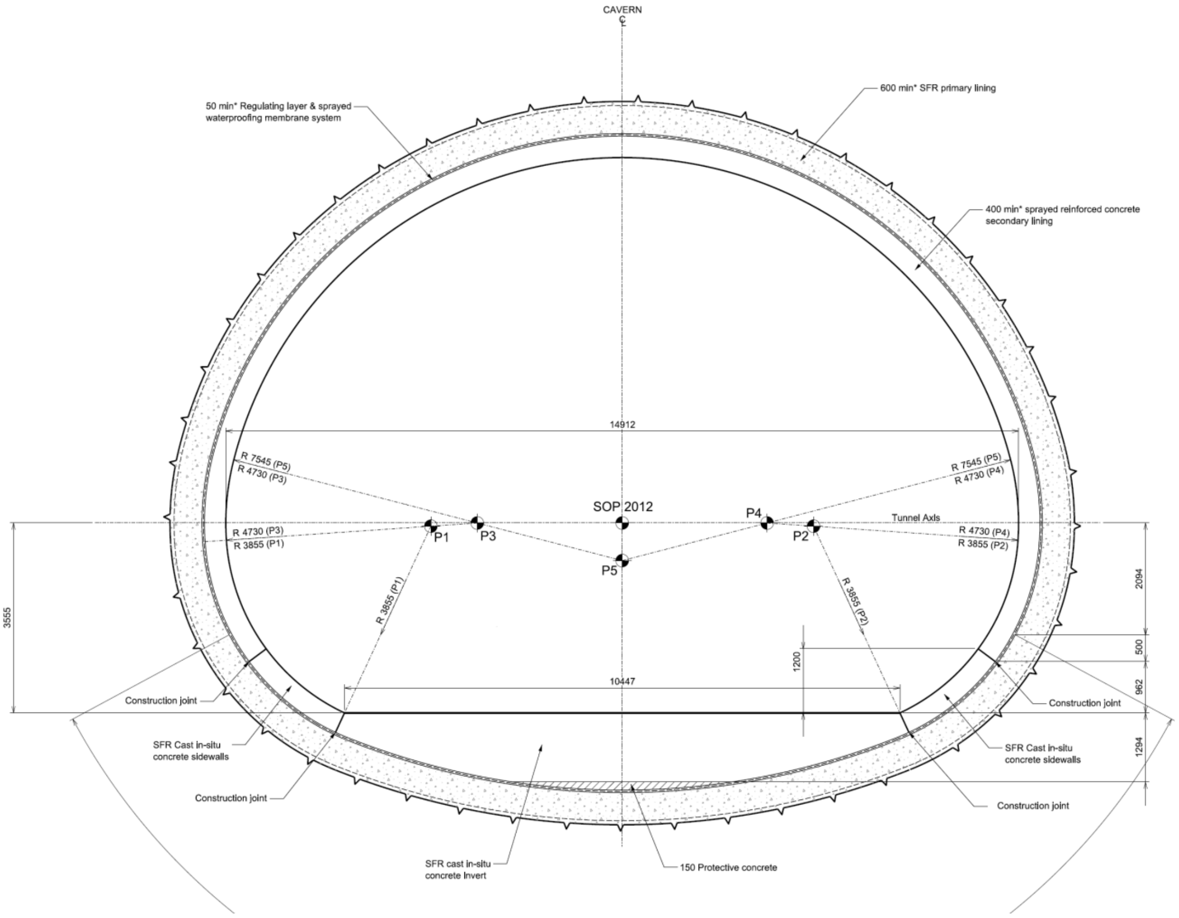

Fig. 73 Tunnel geometry

6.2.2.2 Lining properties

The concrete properties for the secondary lining are the following:

- Concrete Grade: C32/40 at 90 days
- Density = 2549kg/m³
- Poisson ratio = 0.2
- Elasticity coefficient = 17.67GPa

For the primary lining, 90-day concrete properties have also been used (Grade C32/40, corrected stiffness 17.67GPa). The primary lining was reduced by removing the 75mm initial layer of concrete from the original primary lining thickness used in the short-term analysis. The stiffness of the primary lining was updated based on 90 days strength.

The secondary lining in FLAC is placed as an attached beam to the existing primary lining at the excavated boundary of the tunnel. Both the linings are connected to each other via interface elements that can transfer normal stresses between each other (indicating allowance of full shear slip between primary and secondary linings) or can simulated the bond between the primary and the secondary lining through the spray-applied waterproofing membrane (indicating full composite action). For both cases, the secondary lining will carry the pore water pressure transferred via the waterproofing membrane. The secondary lining is considered steel fibre reinforced sprayed concrete with constant thickness.

6.2.2.3 Ground conditions

The cavern will be excavated in clay of different soil groups. Majority of the cavern is located in the London Clay A3/A2 formation and the invert enters the zone of clays of Lambeth Group – Upper Mottled Beds, see Fig. 74.

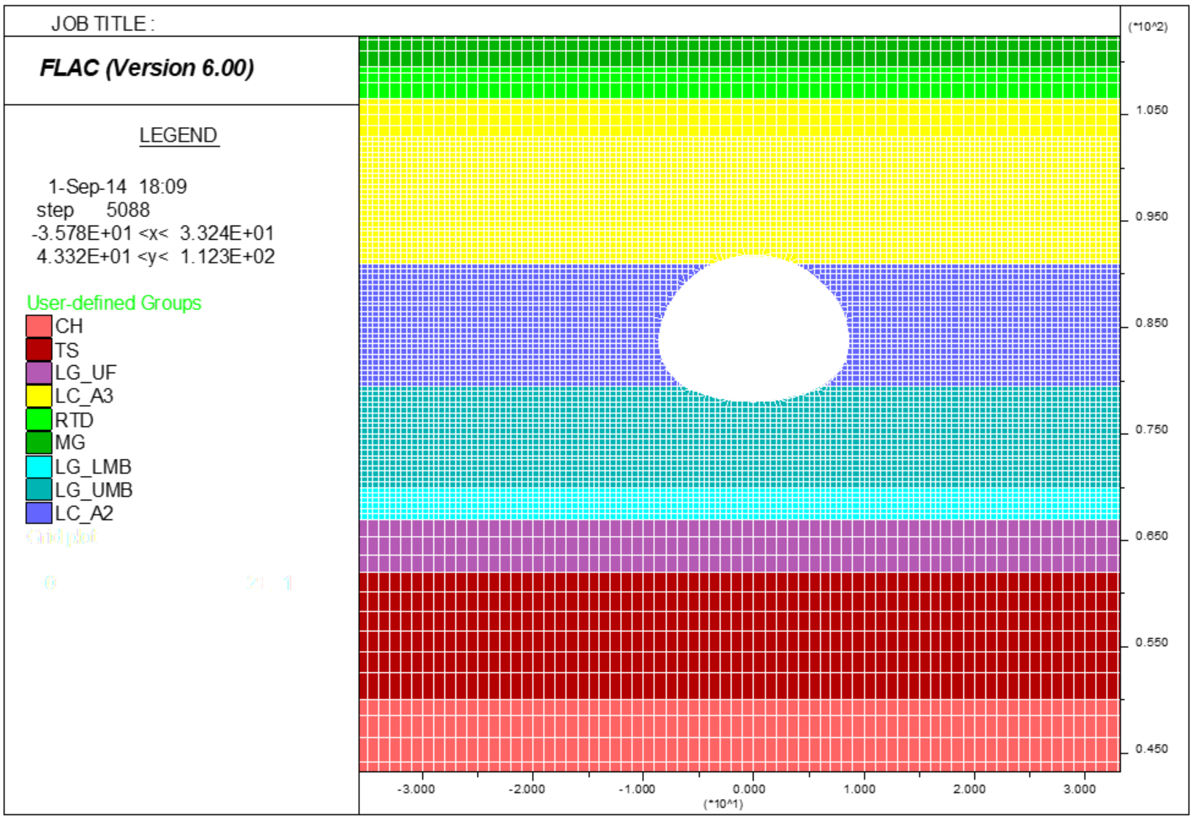

Fig. 74 Model geometry (FLAC) with ground profile

The soil parameters applied in the calculation model are listed in Tab. 4. For the long-term, the ground properties are changed to their drained values and the model is run to equilibrium.

Tab. 4 Soil properties, [32]

Soil stratum	**Bottom level**	**Unit Weight**		**Cohesion**	**Friction**	**Poisson's Ratio**	**Porosity**	**Dilation**	**K_0**	**Undrained Shear Strength**
		Wet	**Dry**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
		γ	γ'	c'	μ	ν	ψ	ϕ'		Cu
	mATD	kN/m^3	kN/m^3	kN/m^2	Deg	-	Deg	Deg	-	-
Made Ground	106.0	20.0	16.5	0	25	0.3	35	0	0.5	24
River Terrace Deposits (Terrace Gravel)	104.8	20.0	17.0	0	38	0.3	30	6	0.5	-
London Clay [A3] Above 100mATD	99.0	20.0	15.5	10	22	0.1	45	0	1.2	70+11z*
London Clay [A3] Below 100mATD	91.0	20.0	15.5	10	22	0.1	45	0	1.2	110+5z*
London Clay [A2]	79.2	20.0	15.5	15	26	0.1	45	0	1.2	110+6z*
Lambeth Group – Clay above MLGH	70.5	21.0	16.5	25	27	0.1	45	0	1.2	100+8.5z*
Lambeth Group – Sand above MLGH	65.8	21.0	16.5	25	27	0.1	45	0	1.0	75+10z**
Lambeth Group – Clay below MLGH	61.8	21.0	17.5	0	37	0.2	35	8	1.0	-
Upnor Formation	49.5	21.0	17.5	0	39	0.2	35	10	1.0	-
Chalk	4.0	20.0	16.5	0	25	0.25	35	10	1.0	-

* z is depth below the top of London Clay

** z is depth below 110mATD

The cavern is located at elevation from 78 to 91mATD. The pore water pressure diagram is shown in Fig. 75.

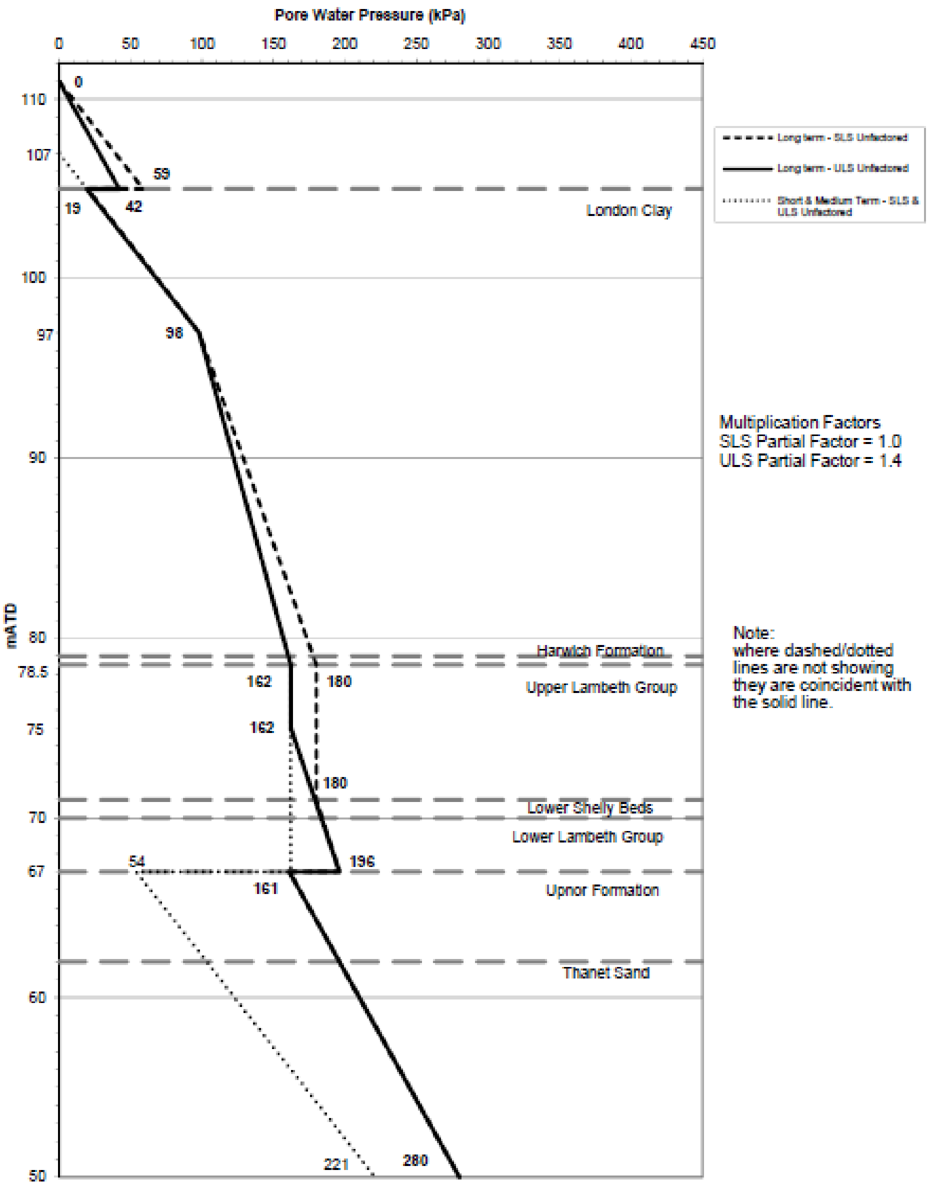

Fig. 75 Pore water pressure diagram, [32]

6.2.2.4 Interface definition

In FLAC [52], an interface connected to structural elements was used. Beams of the primary lining interact with the beams of the secondary lining via the interface. The ‘INTERFACE’ command was used

6.2.3 Calculation steps

In FLAC, no. 4 sets of analyses were carried out in order to understand what impact the bond between the membrane and the primary and the secondary lining has onto the design of the secondary lining thickness. The calculation (logical) sequence is shown in the following diagram (Fig. 76). Step 1 represents an analysis of bonded interface with thin (200 mm thick) secondary lining. Step 2 is an analysis of slipping interface (no bond) with thin secondary lining (200 mm thick). Step 3 is an analysis of slipping interface and increased secondary lining thickness to 400 mm (robust lining). And step 4 represents an analysis of bonded interface and the robust (400 mm thick) secondary lining.

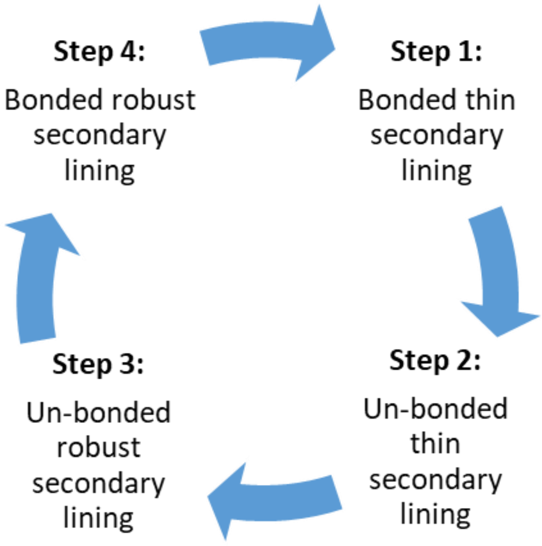

Fig. 76 Diagram of calculation sequence, [53]

6.2.3.1 Step 1: Design of thin bonded secondary lining

In step 1, the secondary lining is modelled 200 mm thick with bond strength of the interface between the primary and the secondary lining 1 MPa and compressive strength of 20 GPa. The lining forces that have developed in the secondary lining are shown in Fig. 77. The M-N interaction diagram (structural design check in accordance to Eurocode 2) shows that the 200 mm thick steel fibre reinforced sprayed concrete lining capacity is sufficient.

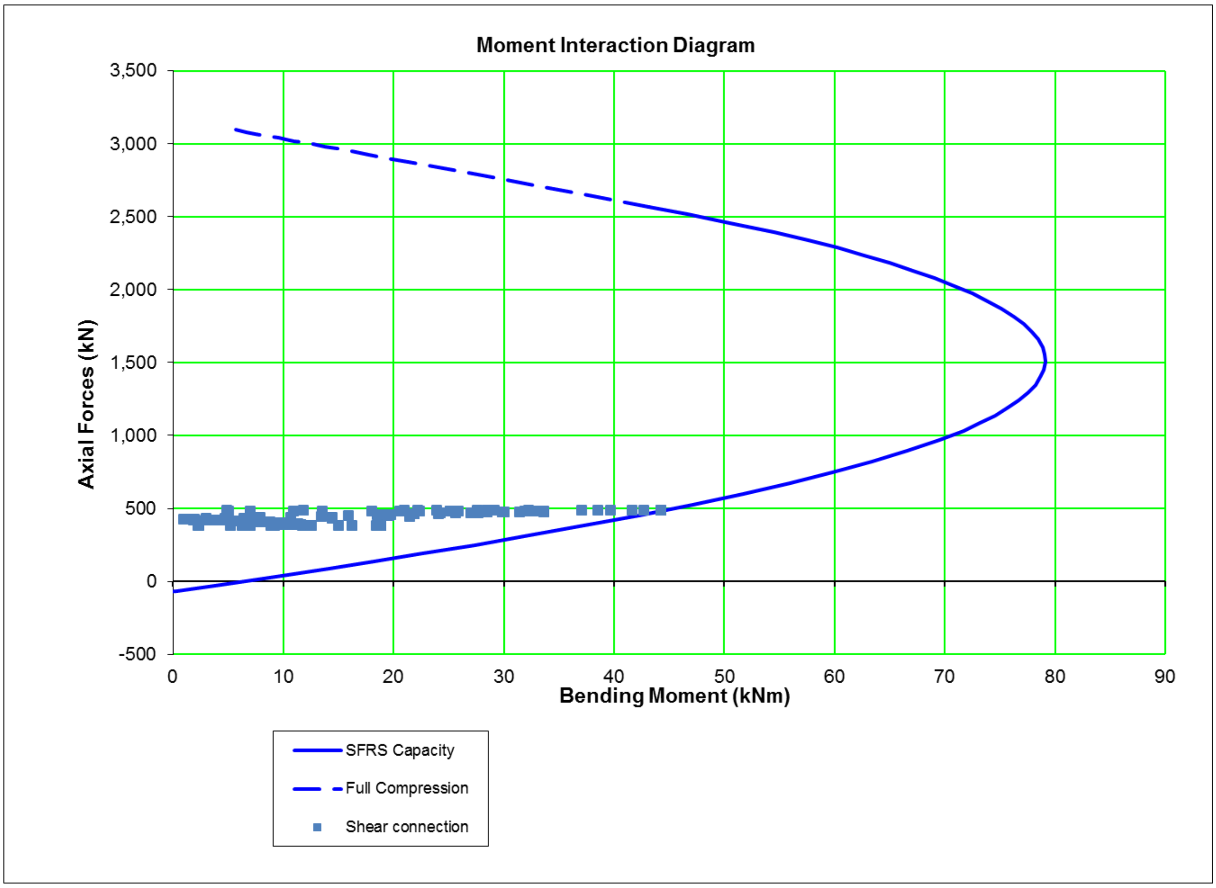

Fig. 77 M-N interaction diagram, secondary lining 200 mm thick with bonded interface, [53]

6.2.3.2 Step 2: Design of thin un-bonded secondary lining

In step 2, the secondary lining is modelled 200 mm thick on slipping surface (no bond between the primary and the secondary lining). The lining forces that have developed in the secondary lining are shown in Fig. 78. The M-N interaction diagram shows that the 200 mm thick steel fibre reinforced sprayed concrete lining capacity is not sufficient. The secondary lining is too thin to withstand the acting loads.

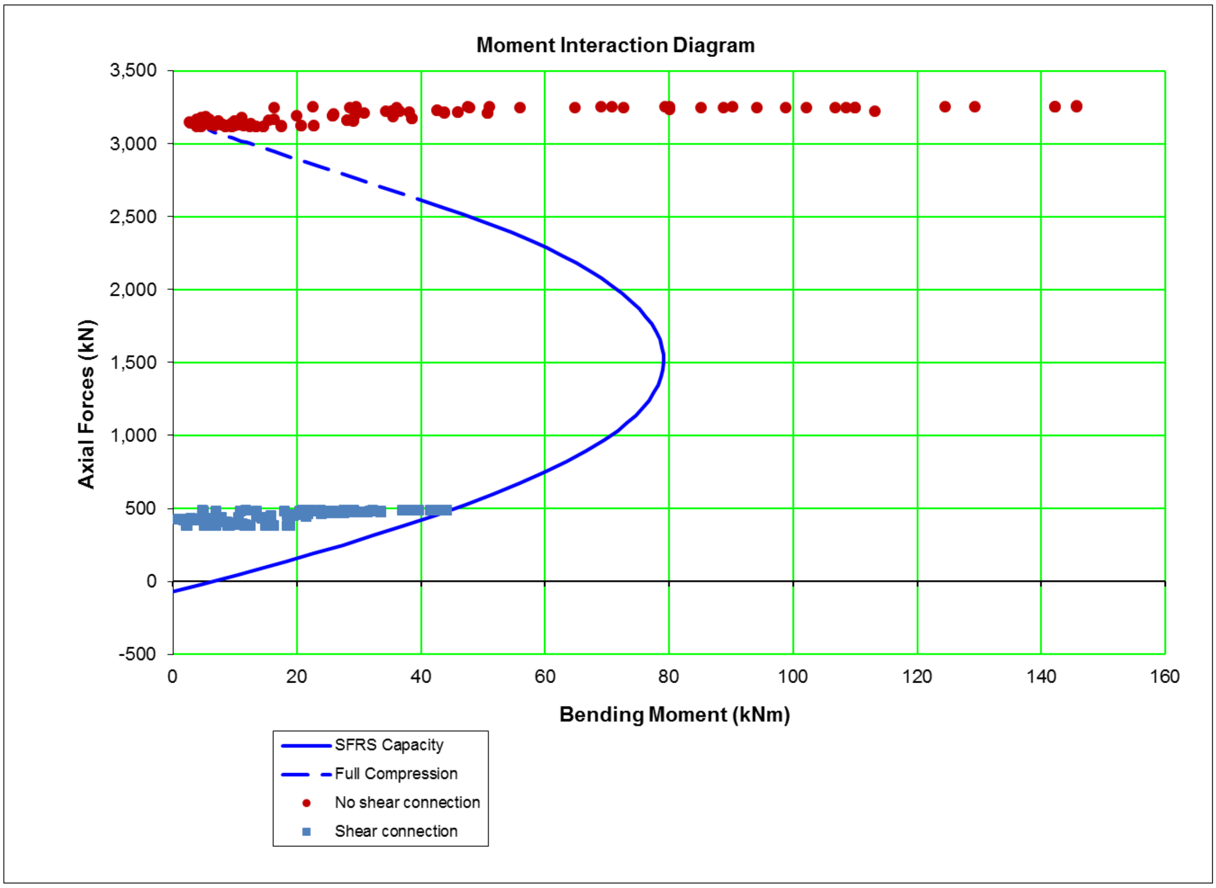

Fig. 78 M-N interaction diagram, secondary lining 200 mm thick (red – un-bonded secondary lining, blue – bonded secondary lining), [53]

6.2.3.3 Step 3: Design of robust un-bonded secondary lining

In step 3, the secondary lining is modelled 400 mm thick on slipping surface (no bond between the primary and the secondary lining). The lining forces that have developed in the secondary lining are shown in Fig. 79. The M-N interaction diagram (structural design check in accordance to Eurocode 2) shows that the 400 mm thick steel fibre reinforced sprayed concrete lining capacity is not sufficient and steel bar reinforcement will be needed.

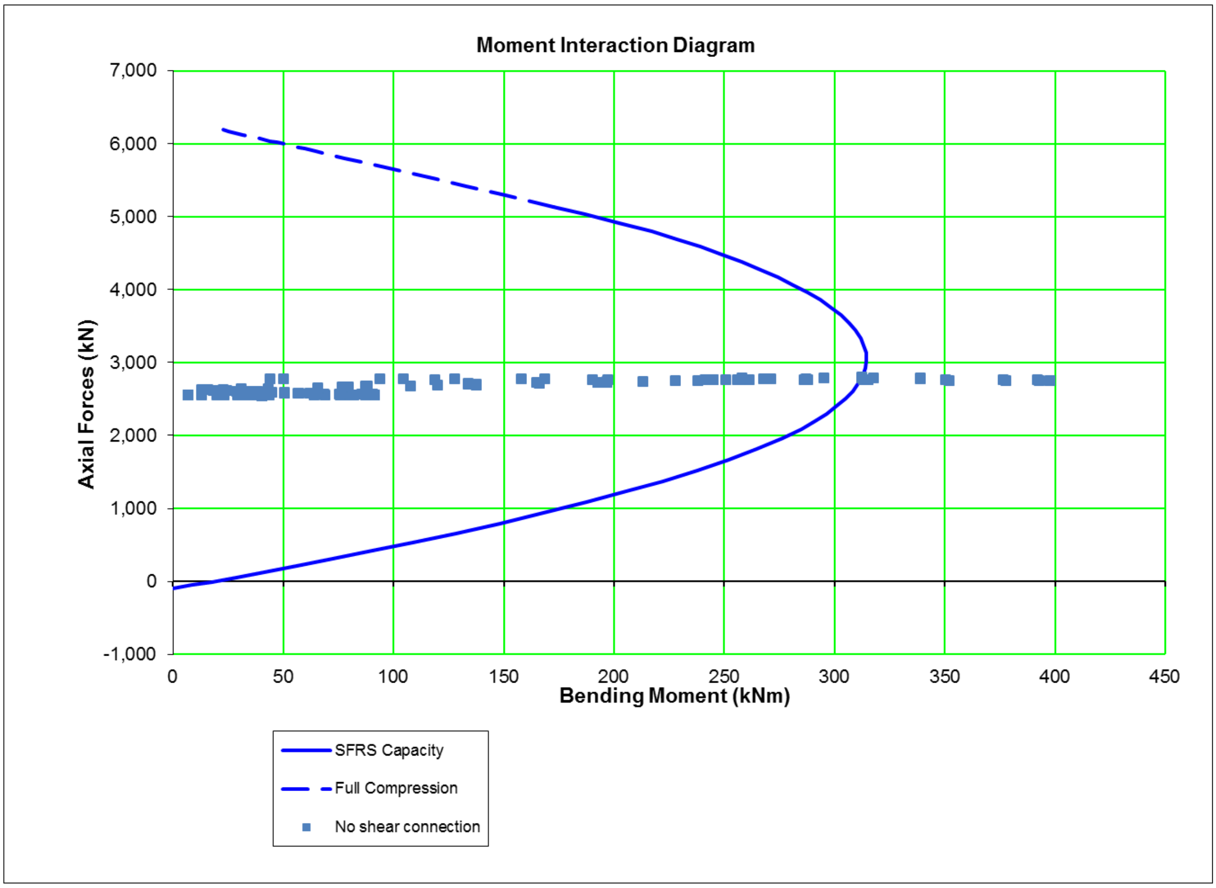

Fig. 79 M-N interaction diagram, un-bonded secondary lining 400 mm thick, [53]

6.2.3.4 Step 4: Design of robust bonded secondary lining

In step 4, the secondary lining is modelled 400 mm thick with bond strength of the interface between the primary and the secondary lining 1 MPa and compressive strength of 20 GPa. The lining forces that have developed in the secondary lining are shown in Fig. 80. The M-N interaction diagram shows that the 400 mm thick steel fibre reinforced sprayed concrete lining capacity is not sufficient and steel bar reinforcement will be needed.

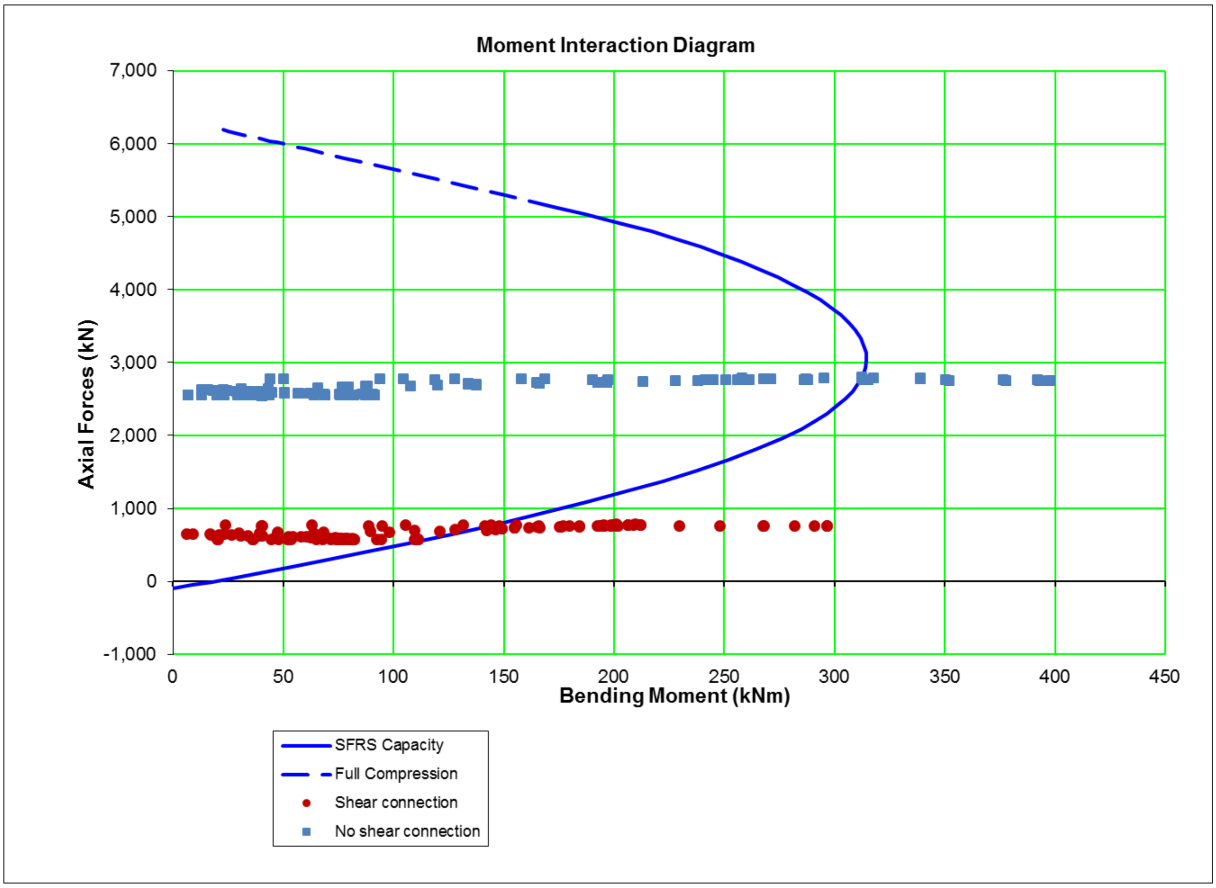

Fig. 80 M-N interaction diagram, secondary lining 400 mm thick (red – bonded secondary lining, blue – un-bonded secondary lining), [53]

6.2.4 Results and discussion

From the analyses that have been carried out, the following conclusions are derived. The full composite lining (bonded interface) has significant impact onto the development of the lining forces. In both cases (for both lining thicknesses), the bond will decrease the normal force value and the magnitude of the bending moment. In case of the thin secondary lining, the normal force is 6,2-times lower and the maximum bending moment is 3,3-times lower. In case of robust secondary lining, the normal force is 3,5-times and the maximum bending moment 1,3-times lower.

The analysis of the robust secondary lining has shown that consideration of the slipping interface might not be the most conservative consideration in case that the bonded spray-applied waterproofing membrane is used. The magnitude of the bending moment has decreased but more points of the secondary lining are outside of the capacity curve, which means that the reinforcement will be needed in larger are of the secondary lining. However, the same amount of reinforcement would cover for both cases to cover for the bending moment outside of the capacity. The tensile reinforcement ratio is 0,54% and the lining capacity is shown in Fig. 81.

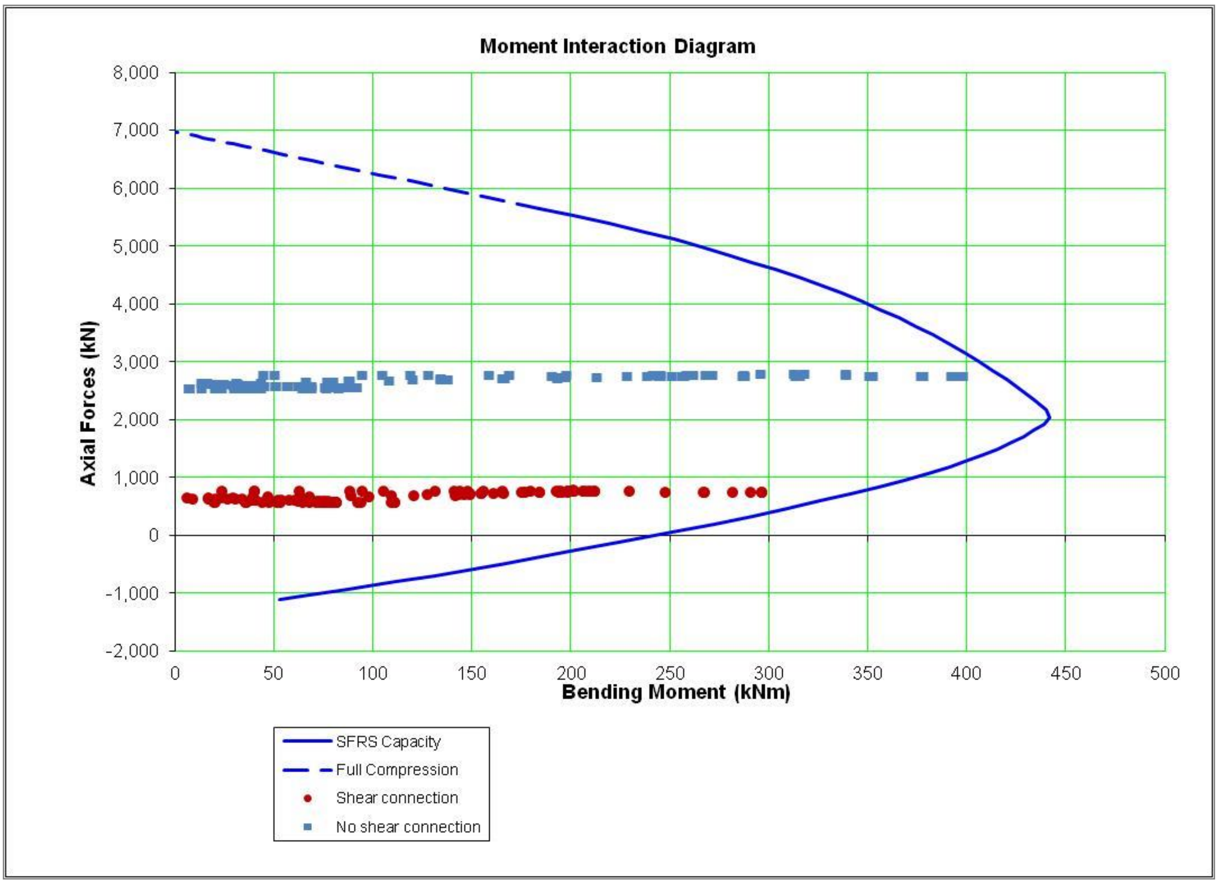

Fig. 81 400 mm thick secondary lining with reinforcement proposal

6.3 Failure mechanisms

The composite lining considers the primary lining to be permanent, the spray-applied waterproofing membrane to provide for tensile and shear strength and stiffness of the interface and the secondary lining to carry the portion of the loads not carried by the primary lining. Therefore, failure of the composite lining may be caused by failure of each individual element or the connection between them.

6.3.1 Failure within the primary lining

Based on the issues that can occur in construction described in the previous chapter, the following potential 'failure' of the primary lining is defined:

(1) Reduced strength, stiffness and increased permeability;

(2) Reduced bond between layers (delamination).

Ad (1), the reduced strength and stiffness of the primary lining can be considered as degradation over time and may result in more load acting onto the secondary lining. Increased permeability may result in permanent contact of the spray-applied waterproofing membrane with water.

Ad (2), the delamination can reduce the structural performance of the primary lining as a single element. The delamination may also function as water path.

6.3.2 De-bonding between the primary lining and the membrane

In case that the interface fails in adhesion between the membrane and the primary lining, the de-bonded interface can create water path that can potentially result in leak through the secondary lining. From the composite lining point of view, the lining capacity will be reduced and only certain amount of mechanical interlocking due to the surface roughness and profile waviness can be accounted for.

6.3.3 Failure within the spray-applied waterproofing membrane

Two types of failure can potentially occur within the membrane; failure of the structural performance and/or failure of water-tightness. The structural failure is represented by loss of the membrane's expected mechanical properties or its rupture. The loss of water-tightness can be caused by chemical instability, mechanical damage or loss of its minimum thickness. The loss of the minimum thickness can be caused by failure of the membrane in cohesion, when the composite lining slips within the membrane separating it in two parts, potentially thinner than the minimum thickness required for water-tightness. Sensitivity of the membrane to failure in cohesion can be increased by addition of colouring dye into the EVA-based spray-applied waterproofing mix as shown in Fig. 82. It was reported in Tunnelling Journal in 2016 [54] that it is much easier for the contractors to guarantee the right thickness and covering if two layers of the membrane with two different colours are used. If a dye is used for colouring the membrane, it should be verified that the colour does not wash off from the membrane and does not influence the microstructure of the membrane resulting in loss of water-tightness.

Fig. 82 Failure in cohesion of coloured EVA-based spray-applied waterproofing membrane, [13]

6.3.4 De-bonding between the membrane and the secondary lining

The interface side between the spray-applied waterproofing membrane and the secondary lining provides usually less mechanical interlocking than the other interface side due to a smother membrane finish. If the secondary lining de-bonds, the interface is likely to be slipping.

6.4 Discussion of findings

Shear (tensile) strength of the interface will be determined by the lowest from the shear (tensile) bond strength between the primary lining and the membrane, the cohesion (tensile) strength of the membrane, or the shear (tensile) bond strength between the secondary lining and the membrane (Fig. 83).

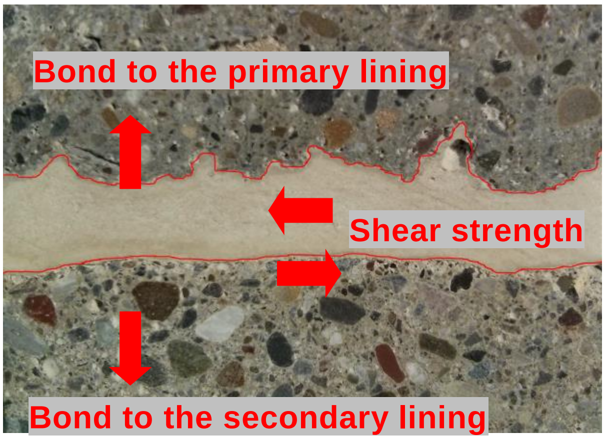

Fig. 83 Composite lining interface

The delamination within the primary lining can be estimated to have the lowest impact onto the composite action performance since the immediate load (ground load) acting onto the primary lining perpendicular to the delamination plane has favourable effect against the shear failure in the delamination plane. The de-bonding between the primary lining and the membrane would likely have the second lowest impact onto the composite action. It can be seen in that there would be higher mechanical interlocking between the primary lining and the membrane compared to the ‘smooth’ surface between the membrane and the secondary lining. The difference of the failure would be that de-bonding between the primary lining and the membrane would allow for a water path to create that might lead to change of water pressure distribution. The cohesive failure of the membrane, especially in ‘wet’ state, is estimated to have the potential to create the ‘best slipping interface’ closest to the ‘no bond’ composite performance. The cohesion (tensile strength) of the EVA-based membrane is therefore pronounced as the most likely composite action-limiting factor.

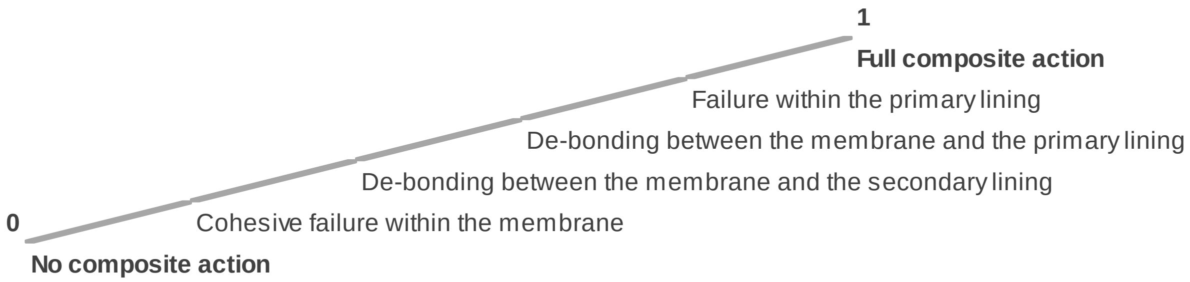

Fig. 84 Composite action scale

From the available test results presented in chapter 5, the membrane most commonly fails in adhesion to the primary lining in short-term 'dry' state. The results of the membranes tested in 'wet' state that simulate the long-term conditions show that the EVA-based can fail in cohesion. Interrelation of the adhesion and cohesion strength in 'dry' and 'wet' can be displayed as shown in Fig. 85. Higher adhesion of the membrane to the primary and the secondary lining can cause the membrane to fail in cohesion. Should the membrane fail in cohesion, its primary function – waterproofing – will most likely be jeopardized. The polyurea-resin-based membranes appear not to be affected by the moisture conditions and exhibit cohesive strength higher than the adhesive strength.

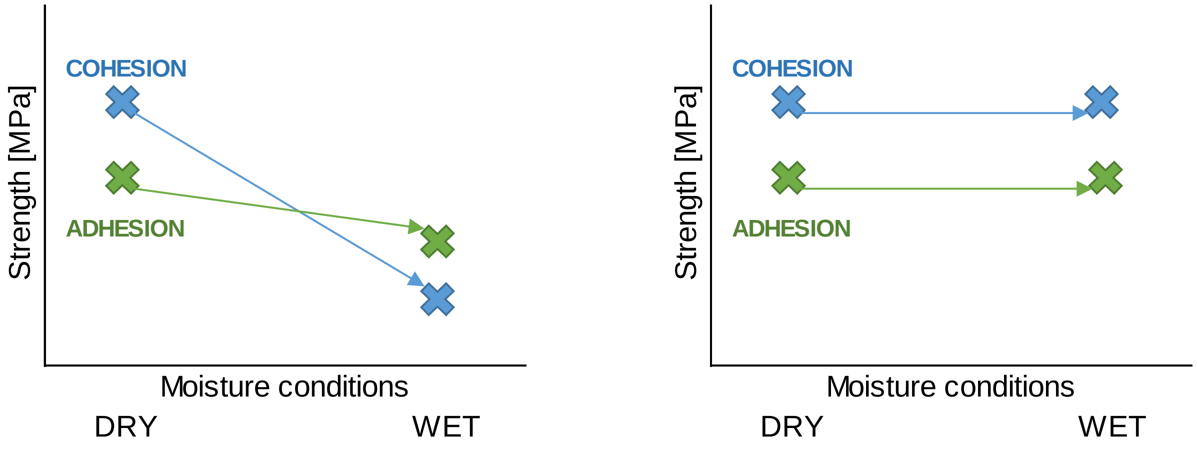

Fig. 85 Interface strength depending on moisture conditions: EVA-based membrane (left), resin-based membrane (right)

7 Conclusions and suggestion of further research

7.1 Actuality of the topic

According to the Italian Ministry of transport, 53% of tunnels built in Europe are in Italy. 60% of these tunnels have been in service for more than 60 years now; many of them experience durability issues and will have to be reconstructed soon. The use of the spray-applied waterproofing membranes could potentially be applicable for such works. Regarding newly built structures, the spray-applied waterproofing membranes have been recently used on major tunnelling projects such as Crossrail in London, United Kingdom or extension of Prague Metro A in the Czech Republic. Both projects were one of the first applications in the given extent, region and ground conditions. Both projects have brought valuable experience that can be used as a basis for upcoming projects, for those clients, designers and contractors have yet to decide whether the use of the spray-applied waterproofing membranes would be suitable and beneficial or not. Even though the spray-applied waterproofing membranes have been increasingly used in the Czech Republic, no systematic approach to design and construction of underground structures with the use of the spray-applied waterproofing membranes is currently available. This leads designers and contractors to rely on their subjective knowledge, experience and self-interpretation of diverse published data and manufacturer’s recommendations. The aim of this work was therefore to summarize current theoretical knowledge and practical experience gained mainly in the United Kingdom, suggest improvements in application process and make recommendations applicable to design and construction of tunnel linings with the use of the spray-applied waterproofing membranes.

7.2 Fulfillment of the Objective

Relevant literature has been reviewed and gaps in the current knowledge of the composite lining with the use of the spray-applied waterproofing membranes have been identified. Site observations have been used to recognize interrelations between the theoretical background and praxis and comparison of applications resulting in suggestions of improvements. Numerical modelling has shown the importance of the bonded/de-bonded scenario and recommendations were developed. The Objective of the thesis has been fulfilled.

7.3 Research methods

Research methods employed in this thesis are:

- Literature review (chapter 2 and 3 of the thesis);
- Site observations (chapter 4 and 5 of the thesis);
- Numerical modelling (chapter 6 of the thesis).

7.4 Conclusions

Only in exceptional cases, tunnels and other permanent underground structures can be constructed without any particular waterproofing measures. Generally, tunnel waterproofing is provided by means of prefabricated plastic sheet waterproofing membranes, however, many tunnel owners have experienced leaks, particularly when built below the water table. Excessive leakage leads to excessive costs and programme delays during construction, and leaves the tunnel owners with maintenance costs and disruption throughout the working life of the tunnel, potentially also with a reduced tunnel service life. Once a tunnel is leaking, it is difficult to stop the leaks entirely. Many sectors of the civil and structural engineering industry have been moving increasingly towards the use of spray-applied waterproofing membranes as an effective alternative way to waterproof belowground structures. It is believed that leaks can be located and repaired more easily and quicker since a seepage point through the spray-applied waterproofing membrane corresponds to the seepage channel in the concrete behind the membrane, [1].

Site observations have shown that application of the spray-applied waterproofing membrane is only effective in dry or almost dry conditions since the treatment of the primary lining in order to stop active water inflow by injection or pinpoint drainage is time consuming and can be disrupting the base line programme of the works. Excavation in London Clay above water bearing permeable strata of Lambeth Group has shown that groundwater can raise from the permeable strata beneath along the interface between the “impermeable” London Clay and the outer face of the primary lining. The groundwater will then enter the tunnel through any pinhole or other parts of the primary lining with higher permeability causing issues with application of the spray-applied waterproofing membrane and its curing process.

The spray-applied waterproofing membranes have not been studied as a single element but as part of a composite tunnel lining made of: sprayed concrete permanent primary lining, spray-applied waterproofing membrane and sprayed concrete secondary lining. For this purpose, investigation of the theoretical background of sprayed concrete was carried out first, by presenting its historical development, its use in various tunnelling methods and various tunnel lining design concepts with the aim to derive its use as a permanent or partially permanent structure. Application of the findings shows that the question of permanent primary lining in the Czech Republic is not clear. Permanent or partially permanent function of the primary lining is by the current standards and normative not forbidden but it is not a usual praxis. As long as sufficient durability of the sprayed concrete can be achieved, no steel bar reinforcement but fibre reinforcement is used and suitable survey equipment that would allow for precise profile control is in place, the primary lining could be considered permanent or partially permanent even in the Czech Republic.

In addition to the sprayed concrete itself, understanding the function of each element of the composite lining is the basis for composite lining design. Therefore, each element of the composite lining was described and its function identified so that behaviour of the composite lining could be studied. Numerical modelling was carried out in order to understand the mechanism of the composite lining behaviour and the impact of the bonding property of the spray-applied waterproofing membrane within the composite lining. The numerical modelling investigation in 4 steps showed that the interface bond through the spray-applied waterproofing membrane has significant impact on the tunnel lining design. An effective composite lining with a thin secondary lining can be designed if the bond can be relied on. Secondary lining with no bond within the same tunnel structure would not have the same structural capacity as in the bonded composite lining and would not sustain the acting loads when de-bonded. On the other hand, bond through the spray-applied waterproofing membrane introduces additional stress to the secondary lining when designed robust. Since the bond cannot be fully relied on, as conclusion of this thesis, the secondary lining is recommended to be designed for both cases with and without bond through the spray-applied waterproofing membrane, even though it is acknowledged that it will not result in an optimised tunnel lining design and reduced secondary lining thickness.

The most frequently used EVA-based spray-applied waterproofing membranes are sensitive to water and change behaviour in contact with moist or water saturated substrate. This has fundamental impact on the composite lining design. The variable properties of the spray-applied waterproofing membrane depending on the water content of the substrate result in variable interface and so variable composite lining performance. The bond is usually tested extensively prior to application of the secondary lining that corresponds to short-term ‘dry’ state. The very limited testing data of the long-term ‘wet’ performance of the EVA-based spray-applied waterproofing membrane [13] has shown ‘softening’ of the membrane. It has shown that the short-term adhesion failure can shift into cohesion failure of the membrane at low peak load in the long-term ‘wet’ state. It is reasonable to assume that the membrane at the cohesion failure loses its water-tightness. It is therefore not considered conservative to carry out a tunnel lining design with the use of the spray-applied waterproofing membrane and assume full slip of the interface since this may have detrimental impact onto the water-tightness of the waterproofing membrane.

For the design of tunnel lining with the use of the spray-applied waterproofing membranes, it is recommended to carry out not only short-term evaluation of groundwater conditions for excavation and primary lining design and long-term evaluation for the secondary lining design but also intermediate-term evaluation for spray-applied waterproofing membrane application. Such evaluation should include realistic assumption of water inflow through the primary lining at the time of the waterproofing application. It was shown that water path through the tunnel lining exist and can be interconnected resulting in frequent leaks. Alternatively, the design of tunnel linings with the use of the spray-applied waterproofing membranes can be changed during construction based on observations of real water inflow during the excavation and the primary lining installation. Such alternative can be especially interesting when ‘shared profit contracts’ are used and flexible design with opportunities is specified during the tender phase.

7.5 Benefit to the tunneling industry

“Quality results from recognizing interrelations and evaluating, categorizing and organizing one’s surroundings. It requires constant and consequent thinking and alert. Quality is identification with one’s own work.”

Understanding of interrelations is the basis for correct application of a method or principal. When applied correctly it can become a basis for further improvement and optimisation. This thesis was aimed to help to recognize the correct application so that quality of the composite lining with the use of the spray-applied waterproofing membrane could be achieved. This work is written in English so that the findings can be shared internationally and potentially developed further.

7.6 Suggestion of further research

The initial question of how the bonded membrane could contribute to the overall performance of the bonded lining and whether for a composite action could be allowed for, shifted into a question of how to prevent the membrane from a cohesion failure so that it remains watertight. If the stress developed on the interface is lower than the adhesion strength but higher than the cohesive strength of the membrane, the membrane will not de-bond but fail in cohesion resulting not only in reduction of the composite action but likely in loss of water-tightness.

For the EVA-based membranes, further research of the long-term moisture conditions shall be carried out, otherwise the following:

- Avoid 'wet' state of the substrate - prove that the substrate will not be saturated and that the 'dry' parameters of the membrane can be used for the design unless it is proven otherwise;
- Provide for other type of bond between the primary and the secondary lining in the composite lining design – such as bolts, nails or studs.

The spray-applied waterproofing membranes might be developed to be used in a double waterproofing system – self-healing primary lining that would seal micro-cracks and provide for 'dry' substrate for the spray-applied waterproofing membrane; the spray-applied waterproofing membrane would then bridge over and seal only larger cracks. For the self-healing sprayed concrete investigation, understanding of the chemistry of the sprayed concrete as well as chemistry of the groundwater after it had penetrated through the sprayed primary lining is referred to as 'drainage water' in [55] and might be a good start for the further investigations in this field.

Overall, due to the complexity of the composite lining problem, depending on the ground conditions, there will be further questions about details that have not yet been dealt with in the course of the previous research and must then be clarified on a project-specific basis.

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