Durability design for large sewer and drainage tunnels

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ABSTRACT: In the last 10 years there has been a number of major deep gravity sewerage and drainage tunnels constructed. The projects provide a sustainable solution to increase the capacity of large sewer/drainage systems and include the DTSS in Singapore, the STEP in Abu Dhabi, the IDRIS in Doha, the Thames Tideway in UK and the Dubai Stormwater project. They are large tunnels, mostly in excess of 5 m in diameter, constructed with a segmental lining and in most cases a secondary in-situ lining. These tunnels need to have a long service life, thus the durability design of the concrete segmental or in-situ lining to resist the deterioration mechanisms associated with the ground conditions and sewerage is of primary importance. Clients and Consultants have adopted quite different strategies and solutions in order meet the service life requirements. These strategies together with the experience from a number of recent projects is presented.

1 INTRODUCTION

Global urbanization including growth in population of major cities calls for expansion and improvement of crucial infrastructure, such as systems for transport of sewer, groundwater and stormwater. Within the past decade, a large number of construction projects have been initiated worldwide, e.g. construction of networks of pipes collecting sewer, groundwater and the like transporting it to a large diameter (main) tunnel, which is connected to treatment facilities or outfall to the sea.

Considering the return on investment and their importance to the society, major assets for the infrastructure such as tunnels for sewer and drainage are usually designed for extended service life, i.e. 80–120 years. Moreover, as the accessibility to these assets is limited during operation, it is often requested that the design of such assets is based on a need for very limited maintenance.

Traditional design codes, such as Eurocode, provide guidance on the durability design of concrete structures up to 100 year service life. However, the durability design of sewer and/or drainage tunnels often needs particular attention; either because the required service life exceeds that covered by the standards, or because the special exposure conditions of sewer tunnels, i.e. the risk of microbiological microbiologically influenced corrosion (MIC), is not covered by the standards.

Therefore during the initial design phase of such projects, there is a need to assess the additional durability measures required compared to those given by the usual codes and standards. Alternatively, there is a potential risk that durability-concerns are not handled correctly jeopardizing the durability and operation of the asset in question.

This paper focuses on the durability design of segmental (concrete) linings for bored tunnels used for sewer and drainage. This includes presentation of durability design strategies to mitigate the following, selected deterioration mechanisms:
• Chloride-induced reinforcement corrosion,
• Sulphate attack of the concrete, and
• Sulphuric acid attack of the concrete, i.e. microbiologically influenced corrosion (MIC)

Specifically for MIC, Figure 1 presents schematically the issue of sulphuric acid attack of concrete, referred to as "corrosion" in the figure.

2 REFERENCE PROJECTS

The authors of this paper have been involved in the durability design of a number of sewer and drainage tunnels worldwide for the past decade. This section contains brief descriptions with regard to the durability design of the selected sewer and drainage tunnels, see Figure 2 for an overview of the location of the tunnels described and Table 1 for selected details of the tunnels.

2.1 Step, Abu Dhabi, Uae

The Strategic Tunnel Enhancement Programme (STEP) was constructed to improve the waste water system in Abu Dhabi and it is designed to carry 1.7 million m³ sewage each day. The project was divided into three contracts of which COWI was the designer (structural and durability) for two of the contracts, i.e. STEP 2 and STEP 3 with a combined length of the bored tunnel of 25 km. In addition those two contracts covered other types of structures, e.g. 10 shafts.
Three options were considered for the design of the segmental lining of the bored tunnel in the initial phase of the project:

- Pre-cast concrete segments with traditional (carbon steel) reinforcement cages
- Pre-cast concrete segments with stainless steel reinforcement cage, and
- Pre-cast segments with steel fibre reinforced concrete (SFRC)

The bored, segmental lining is located in an area with very high chloride (10–12%) and sulphate content (up to 5,000 mg/l) in the soil/groundwater. Moreover, as the tunnel is designed for carrying sewage, special attention was given to the risk of MIC at the internal surface of the tunnel. Considering the very high content of chlorides in the soil/groundwater the first option for the segmental lining, i.e. pre-cast segments solely reinforced with traditional carbon steel reinforcement cages, was ruled out. The reason for that was that, this option would require a very high concrete cover thickness ($\geq 80$ mm) even when using a highly durable concrete. Such a high concrete cover thickness is impractical for tunnel segments as there is a significant risk that the (un-reinforced) concrete cover of the segments would crack during installation due to splitting stresses caused by the push rams of the TBM.

The second option, i.e. pre-cast segments solely reinforced with stainless steel reinforcement was effectively ruled out due to the large cost with stainless steel reinforcement being approximately ten times the cost of carbon steel. Moreover, the initial structural design revealed that the third option (pre-cast segments solely reinforced with steel fibres, SFRC) was feasible. Hence this option was initially considered for the segmental lining. At a later stage of the design it was noticed that additional reinforcement, i.e. steel bars, was required to cope with splitting forces at the radial joints. The development of the concrete mix design for the pre-cast segments (SFRC) took about one year in order to tune the concrete mix to achieve the durability-related requirements arising from the use of carbon steel reinforcement in combination with 65 mm concrete cover.

Hence, for the first segments produced, the additional reinforcement constituted of stainless steel reinforcement, and once the acceptable concrete quality in terms of resistance to chloride ingress was achieved, traditional (carbon steel) reinforcement bars were used as additional reinforcement, together with the steel fibres.

It is generally accepted that steel fibres embedded in un-cracked concrete has a high intrinsic resistance to chloride-induced corrosion, i.e. a high chloride threshold value, several times higher than that of traditional (carbon steel) bar reinforcement, even when manufactured from the same virgin material, see e.g. (Dauberschmidt, 2006). This is, among other factors, due to their limited size, the casting condition which ensures a dense steel/matrix interface protecting the fibres, and the manufacturing process (cold-drawing) which evens out defects at
the surface of the steel fibres prone to initiation of corrosion. Hence, the use of un-cracked SFRC for the pre-cast segments is an obvious choice to ensure the durability of the tunnel. By design, the segments are designed un-cracked (SLS).

The concrete mix design for the pre-cast segments contained a triple blend binder; 50% ordinary Portland Cement (OPC), 20% fly ash (FA), and 30% ground granulated blast-furnace slag (GGBS), all by weight of total binder content. The w/b ratio of the concrete for the pre-cast segments was ~0.33, to ensure a sufficiently dense concrete. In order to protect the additional traditional carbon steel reinforcement bars against chloride-induced corrosion, strict requirements were established for the concrete’s resistance to chloride ingress. The requirements to the concrete cover thickness and the chloride migration coefficient were established using the full-probabilistic approach for chloride-induced corrosion presented in (fib, 2012), yielding 65 mm concrete cover and a maximum chloride migration coefficient of 2.4 x 10^-12 m²/s when tested in accordance with (Nordtest, 1999). While the selected concrete mix design was advantageous with regard to resistance to chloride ingress, the selected binder combination was also sufficient to mitigate the risk of sulphate attack of the concrete.

It is a well-known fact that concrete subject to sewer is prone to deterioration due to attack of the gaseous sulphuric acid formed above the sewage transported in the tunnel. To achieve the required service life of the tunnel, the Employer’s requirements specified the use of a corrosion protection lining (CPL) at the intrados of the segmental lining. The cross section of the bored tunnel including the CPL is presented in Figure 3.

As seen from Figure 3, the CPL at the intrados of the segmental lining consists of a concrete lining, 225 mm thick, lined with a high density polyethylene (HDPE) membrane (2.5 mm thick) at the upper 330° of the cross section. The thicknesses of the concrete lining and the HDPE membrane were pre-defined by the Employer, however in-situ casting of a concrete lining also requires a certain nominal thickness around 225–250mm due to practical reasons. After installation of the segmental lining, the cast-in place concrete lining at the intrados was cast against the HDPE membrane which was placed in the formwork. Installation of the HDPE membrane in one part of the tunnel is shown in Figure 3. The applied system is often referred to as a two-pass lining system, where the first pass is the installation of the pre-cast segments, and the second pass is the construction of the in-situ cast concrete layer with or without the HDPE membrane.

The design of SFRC for the pre-cast segments was carried out in accordance with the German Guideline for SFRC, (DBV, 2001). The SFRC was manufactured with hooked-end steel fibres (length = 47 mm and diameter = 0.8 mm), 40 kg/m³, yielding fibre class F1.4/0.6 in accordance with the aforementioned reference. Prior to production of the pre-cast segments, a strict testing regime was set up in order to ensure that the expected mechanical and durability-related properties of the concrete mix design were achieved. The distribution of steel fibres in the fresh concrete was examined by simple wash-out testing, while the distribution of steel fibres

![Figure 3. Cross section of bored tunnel incl. CPL, STEP](image1)

![Figure 4. Installation of HDPE lining, STEP](image2)
fibres throughout the pre-cast segments was examined from saw-cut segments, see Figure 5. To confirm, that the specified chloride migration coefficient was achieved, a segment was cast from the concrete mix design (without steel fibres) and subsequently cores were taken for round robin testing at three independent laboratories in Abu Dhabi and Denmark, Figure 6.

The introduction of pre-cast segments reinforced with steel fibres was, according to the authors’ knowledge, the first time this innovative construction material was used for this purpose in the Middle East. Furthermore, testing of the concrete’s chloride-migration coefficient in accordance with (Nordtest, 1999) was applied for the first time in the Middle East for tunnels. Since then, the approach has been adopted on all the tunnel projects since in the Gulf such as the Doha Metro, Abu Hamour and on the Dubai Stormwater water project, as a measure during running production for the concrete’s durability-performance.

2.2 Abu Hamour Tunnel, Qatar

The Abu Hamour Tunnel in Qatar was constructed for transport of storm and groundwater in Doha, Qatar. As for all underground projects in Qatar, the structures of the Abu Hamour Tunnel project are in contact with soil/groundwater with very high levels of chlorides as well as sulphates. According to the Employer’s geotechnical investigations the content of chloride and sulphate in the soil/groundwater is up to 30,000 mg/l and 5,000 mg/l, respectively at the location of the Abu Hamour Tunnel. The tunnel is designed for the same aggressive conditions on the outside as well as the inside.

For this project, the Employer’s Requirements, i.e. the contractual requirements, had stipulated tight durability-related requirements to the permanent concrete structures in order to meet the design service life (100 years). The durability design for the segmental lining of the bored tunnel conforming to the Employer’s Requirements is presented to the left of Figure 7, referred to as the “Original solution”.

As seen from Figure 7, two types of segmental linings are used; one with “Typical segments”, reinforced with steel fibres (comprising the vast majority of the segments for the bored tunnel) and “Special segments”, reinforced with steel fibres and rebar (used in selected locations where additional structural capacity was required, e.g. close to adits/shafts). While the durability design of the segmental lining, as illustrated in the left sketches of Figure 7, addresses the exposure conditions, the required service life, and the Employer’s Requirements, the Designer together with the Contractor decided to value-engineer the durability design of the segmental lining. The motivation for this exercise was to optimize the durability design without compromising the overall project requirements to durability and service life, as a number of the requirements given by the Employer were considered superfluous for a tunnel designed for stormwater. The outcome of the value-engineering is schematically illustrated in the right of Figure 7 showing the “New Solution”.

As seen from a comparison of the two solutions presented in Figure 7, the HDPE membrane at the internal surface and the epoxy coating at the external surface were removed while
the carbon steel reinforcement of the special segments was replaced by stainless steel reinforcement. The use of an HDPE membrane at the internal surface of a tunnel is generally speaking considered for tunnels transporting sewerage effluent, to protect the permanent concrete lining against sulphuric acid attack, as previously described. However, as the Abu Hamour Tunnel only carries stormwater and groundwater, i.e. no risk of sulphuric acid attack of the concrete, the HDPE lining was considered superfluous.

The very high sulphate content of the soil/groundwater corresponds to exposure class S3 in accordance with (Concrete Society, 2008). To mitigate the risk of sulphate attack of the segments, the concrete mix design for the pre-cast segments contained 30% OPC, 65% GGBS, and 5% micro silica (MS) all by weight of total binder content. Furthermore, the concrete mix design for the pre-cast segments was verified by the recently developed short-term test of the sulphate-resistance, i.e. the German SVA method. That test method allows for a significantly faster evaluation of the concrete’s resistance to sulphate attack; the duration of the test method is approximately 3 months, compared to the traditional test method, e.g. (ASTM, 2015), which is usually taking 6 – 18 months. The testing was carried out at the Technical University of Munich. As an illustration, Figures 8 and 9 present a failed and a passed test specimen, respectively, after testing in accordance with the SVA test method.

The concrete mix design passed the SVA tests and the time gained by using the SVA test method, meant that the contractor at a much earlier stage than usually, felt comfortable that their concrete mix design fulfilled the Owner’s requirements, reducing his risk and potential, associated delays in the construction phase. In following projects in the Middle East the Designer has convinced Owners to allow this test method instead of more traditional methods (and with longer duration) to the benefit of Contractors as well as Owners.

The “New Solution”, which was approved by the Employer’s engineer, resulted in substantial savings (cost and materials) for the Employer and the Contractor without compromising the overall requirement to 100 year service life.

The SFRC segments for the segmental lining were designed in accordance with fib Model Code 2010, (fib, 2012), and the post-cracking classification of the SFRC in accordance with the criteria established in that reference was 4c achieved by using 40 kg/m³ hooked-end steel fibres.

2.3 IDRIS MTS 01, Qatar

The IDRIS MTS 01 project in Doha, Qatar is part of the major IDRIS project which since its inception has been reduced in scope, with the MTS 01 project being the only part of the main tunnel to be constructed. It is designed for the transport of sewage from urban areas to sewage treatment facilities and is currently (2018) under construction. The main trunk sewer (MTS) is
constructed as a bored tunnel with segmental lining, with a design service life of 100 years. The length of the bored tunnels for MTS 01 is approximately 16 km with an inner diameter varying in the range 3–4 m.

Considering the use of the tunnel, i.e. transport of sewage, with the risk of MIC of the concrete, the Employer required a double-protective design to mitigate such attack of the segmental lining, i.e. a sacrificial concrete layer (not to be considered as part of the permanent structure) and an HDPE membrane on the internal surface of the tunnel, see Figure 10. The sacrificial concrete layer and the structural part of the segments were cast together with an over thickness segment that allowed for the sacrificial layer within its thickness. For the concrete mix design, a high content of supplementary cementitious materials (GGBS) and a low w/c ratio (< 0.40) was used. The HDPE membrane was attached to the internal surface of the segments during casting, see Figure 11. After installation of the segments in the tunnel, all joints between HDPE membranes, i.e. joints between each ring, and joints between individual segments of a ring were welded on site.

The approach presented above i.e. pre-casting the structural part of the segment together with the sacrificial layer and the HDPE membrane is often referred to as a one-pass lining system. This approach has a number of benefits, of which the major benefit is the omission of in-situ casting of the sacrificial layer and installation of HDPE membrane after ring-build. This was particularly important given the small diameter of the tunnel with a finished inside diameter of 3 m making an in situ secondary lining difficult to construct.

The thickness of the sacrificial layer of concrete was 120 mm, see (Olliver & Lockhart, 2017). The thickness of the sacrificial layer of concrete was determined based on CFD modeling and estimation of the annual loss of concrete, using the Pomeroy approach. For the determination of the thickness of the sacrificial layer of concrete, it was conservatively assumed that the sacrificial layer locally would be exposed to sewer shortly after opening of the tunnel, i.e. the protective effect of the HDPE membrane was not considered in the determination of the thickness of the sacrificial layer of concrete.

The durability of SFRC against chloride-induced corrosion as well as the resistance of the concrete mix design towards sulphate attack considering the prevailing exposure conditions in Doha are already discussed in this paper.

2.4 Thames Tideway and Lee Tunnel, England

The Thames Tideway project and the already constructed Lee Tunnel project are a major improvement scheme for London’s waste water system in order to tackle the problem of overflows from the capital’s Victorian sewers and they will protect the River Thames from increasing pollution for at least the next 100 years. The Tideway project is 25 km in length and
connects with a series of the major sewer combined sewerage overflows along the Thames. The Tideway project links with the Lee Tunnel that takes the effluent from a pumping station at Abbey Mills to Beckton where there is an existing treatment works.

The tunnels and shafts are designed for Combined Sewerage Flows, i.e. a combination of raw sewerage and surface water flows together with a number of specific design cases where raw sewerage may be retained in the tunnel for specific periods. The tunnels have an internal diameter of 7.2 m and are designed with a secondary lining (two pass) which has been reinforced with either conventional carbon steel reinforcement or steel fibre reinforcement (SFRC). No inner membrane (HDPE) is used on the Lee Tunnel/Tideway project as the exposure from the sewerage effluent and the consequent deterioration mechanisms such as MIC can be accommodated by the incorporation of a sacrificial layer in the tunnel secondary lining or in the case of the shaft structures by a sacrificial layer in addition to the durability cover to the reinforcement.

The thickness of the sacrificial layer has generally been determined by approaches such as those developed by Pomeroy, and the sacrificial layer thickness varied depending on the particularly environment in each section of the works. The typical sacrificial thicknesses used is approximately 70 mm with additional thickness applied in areas where abrasion was considered to be high.

2.5 Jebal Ali Stormwater and Groundwater Tunnel (DS 233-2), Dubai, UAE

The Jebel Ali Stormwater and Groundwater Tunnel, is located in Dubai, and is currently under design. The main tunnel, having a length of approximately 10.4 km is designed as a bored tunnel with segmental lining and shall, according to the Employer’s Requirements, have a design life of 100 years. The main tunnel is the largest stormwater tunnel constructed in the Middle East.

The main tunnel is in close proximity to the Arabian Gulf, and the chloride and sulphate content in the soil/groundwater is very high, with chloride levels up to 55,000 mg/l and sulphate levels up to 6,800 mg/l being present. Hence, from a durability perspective, the use of steel fibres instead of traditional reinforcement cages would be favoured to mitigate the risk of chloride-induced corrosion. However, as the required internal diameter of the tunnel is 10.0 m, a design solution for the segmental lining without traditional reinforcement bars/cages is difficult to verify and there are very few segmental linings worldwide with an internal diameter of 10.0 m or greater, constructed solely from SFRC (ITA, 2016). In case traditional reinforcement bars are required for the pre-cast segments, due to structural capacity, these will need to be epoxy-coated as specified in the Employer’s Requirements.

While the tunnel is mainly designed for transport of stormwater and groundwater, the tunnel shall, in accidental cases, also carry treated sewage effluent (TSE), i.e. diluted sewage. TSE is significantly less onerous exposure compared to untreated sewage, and considering the fact, that exposure of the concrete to TSE is very limited, it is not necessary to protect the concrete surfaces to mitigate the risk of sulphuric acid attack such as with a HDPE membrane.

2.6 Deep Tunnel Sewer System 2, Singapore

The Deep Tunnel Sewer System 2 (DTTS 2) project in Singapore is a continuation of DTSS 1 which was completed in 2008. The DTTS 2 project contains a total of 40 km deep tunnels, connected to 60 km of sewer pipes. The design service life is 100 years.

Compared to the Middle East, the exposure conditions from soil/groundwater, i.e. sulphate and chloride exposure, are significantly less onerous in Singapore. However, the design for sulphuric acid attack requires particular attention. The deep tunnel is constructed as a bored tunnel, segmental lining. The cross section of the segmental lining and the connection to a mined adit tunnel is schematically illustrated in Figure 12.

As seen from Figure 12, the segmental lining consists of pre-cast reinforced concrete (RC) segments, i.e. segments reinforced with traditional (carbon) steel reinforcement cages, with an inner lining consisting of in-situ cast SFRC (secondary) lining and a HDPE lining. Hence, a two pass lining system is applied.

For the traditional reinforced segments, a 40 mm nominal cover is proposed by the designer, for the internal and external surfaces, following the Singapore standard. A number of requirements
have been specified by the Employer with respect to the concrete mix designs and durability properties for the concrete, e.g. high replacement of OPC by GGBS (80% or more) and/or silica fume (15% or more), water absorption of less than 1% (BS 1881: Part 122), a pressure penetration of less than 10 mm (BS EN 12390-8) and a shrinkage limit of less than 0.01% at 28 days.

To account for the risk of sulphuric acid attack, the inner lining is designed to protect the permanent structural segmental lining against such deterioration. The design takes into consideration that the HDPE lining is not there or it has been punctured, and therefore the SFRC forming part of the inner lining needs to resist against MIC. This sets very tight requirements to the SFRC lining in terms of composition of SFRC and thickness of the lining in order to achieve the required 100 year service life. The MIC resistance of the concrete needs to be tested by an accelerated biogenic sulphuric corrosion test (MPA-Performance test), where the hydrogen sulphide concentration is not less than 100 ppm and the test is to be undertaken for a minimum period of one year. The obtained testing results will be used as the basis to determine the required sacrificial layer thickness for a service life of 100 years.

At the present (initial) stage, it is proposed to use a mix design for the SFRC MIC resistant inner lining with a very low w/c ratio not exceeding 0.35 and a minimum binder content of 400 kg/m³ in order to achieve a sufficiently dense concrete. Based on necessity, the MPA-Performance test results may be verified by the ODOCO (Odour and Corrosion) test, which real site conditions can be simulated. It should be mentioned that the MPA-Performance test was used, among others, in the Emscher project, which is the largest construction project for sewage systems in Germany in the past 30 years (design life of 120 years).

3 CONCLUSION

As discussed above there are now a number of major drainage and sewer tunnels that have been constructed or are under design and construction, they illustrate that a number of
Different solutions have been applied, with the differences being partly understood by different project conditions, requirements and different fundamental approaches. A number of lessons can be drawn from these projects, these are summarised below.

- That the durability aspects for chloride and carbonation are well understood and are well covered by the performance based approaches that are now in use, these approaches can reliably deliver the required service life.

- The deterioration mechanisms and predictive models associated with Microbiologically induced deterioration that causes deterioration of concrete by producing acids that degrade concrete appear to be less well understood and less well defined. The solutions to resist this type of deterioration are therefore more uncertain and different solutions are adopted on different projects. Significant differences are also seen in the thickness of a sacrificial concrete layer used between different projects.

- The majority of the projects considered have used a two pass lining, i.e. a segmental lining and a secondary in-situ concrete lining, either unreinforced, or with carbon steel reinforcement or steel fibre reinforcement. A single pass lining has been used on only very few projects such as IDRIS MTS01 and has many benefits particularly for the smaller diameter tunnels.

- The use of a HDPE membrane, such a membrane has been applied on a number of projects, such as the STEP project, where the tunnel is conveying sewerage, this provides a robust solution which is not dependent on the prediction of the deterioration and thickness of the sacrificial layer. It essentially provides a very robust first layer of defense to microbiological induced deterioration with a sacrificial layer providing a second layer. However, not all comparable projects have included such a solution with evidently differing interpretations of how a reliable system can be developed.

- The use of either unreinforced, carbon steel reinforcement or steel fibre reinforcement for the secondary in-situ lining. Again there is evidently differing opinions on these solutions and where possible an unreinforced lining gives many advantages in terms of durability followed by a steel fibre reinforced lining.

It is evident that further development is possible in order to understand the deterioration mechanisms and to optimise the solutions for large sewer tunnels. This includes the deterioration models particularly for Microbiologically induced deterioration and in the developments in progress with one pass lining systems, where the primary, secondary lining are combined with a membrane such as the Combisegments lining system developed by Herrenknecht. Such systems show significant promise in efficiently developing large gravity sewer systems.

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