HOME

Northern Sewerage Project – Liner Selection in a Corrosive Environment

G W Davidson[1], M E Trim[2], D G Franklin[3], J V Myers[4] and P J Hansen[5]

ABSTRACT

The Northern Sewerage Project (NSP) is an upgrade to one of Melbourne's ageing, under-capacity trunk sewers. It will reduce the volume and frequency of wet-weather overflows to the Merri and Moonee Ponds Creeks and facilitate new housing developments in the northern suburbs of the city. A total of 12.4 km of tunnel and eight vertical access shafts will be excavated as part of the two project stages: Stage 1 (NSP1) will be owned and operated by Melbourne Water (MW) and Stage 2 (NSP2) will be owned and operated by Yarra Valley Water (YVW).

The owners require the project to have a service life of 100 years, a requirement significantly beyond many of the current Australian Standards, which aim to achieve service lives greater than 60 years but are typically assumed to achieve 40 to 60 years. Because of the potentially corrosive natures of the external environment along the tunnels and the internal sewer environment, durability was a key concern for NSP1 and NSP2. Stringent specifications were applicable to the tunnel lining systems. This paper describes the corrosive environments impacting NSP1 and NSP2, explains the key design differences between the two stages and details the lining systems considered and selected to achieve the clients' desired 100-year service life. The project design is complete and construction began in 2007.

INTRODUCTION

The Northern Sewerage Project (NSP) was developed jointly by Melbourne Water (MW) and Yarra Valley Water (YVW) to address future sewerage requirements in the Upper Merri Creek and North Darebin Creek Catchments, of the northern suburbs of Melbourne. Once completed, the NSP will reduce sewage spills into creeks during heavy rainfall, and increase sewerage system capacity to service future development in the region. Figure 1 shows a plan view of the NSP alignment.

The project consists of 12.4 km of tunnel that will be excavated using up to four tunnel boring machines (TBMs). The TBMs will range from 3 m to 4 m in diameter, and will drive through geology ranging from soil (Brighton Group) to weak, interbedded siltstone and sandstone (Silurian Formation), to hard basalt (Newer Volcanics). Eight vertical access shafts will be excavated, the deepest of which will extend 60 m below the existing ground surface. The project consists of two stages: NSP1 and NSP2. NSP1 will be owned and operated by Melbourne Water and NSP2 will be owned and operated by Yarra Valley Water.

The design life (service life) is specified by the owners to be 100 years, considerably longer than the 40 to 60 years typically achieved when applying Australian Standards. Specifically, this requirement was interpreted to mean that the structural integrity of the liner pipe should not be compromised at the end of the design life, and that it should be feasible and safe to refurbish parts of the lining if necessary. The design life requirement presented challenges due to the corrosivity of both the external and internal environments. To provide appropriate corrosion resistance, while maintaining the owners' hydraulic performance requirements, the designer undertook an extensive evaluation of various liner options for both stages of the project. Recommended linings were then presented to project stakeholders for approval.

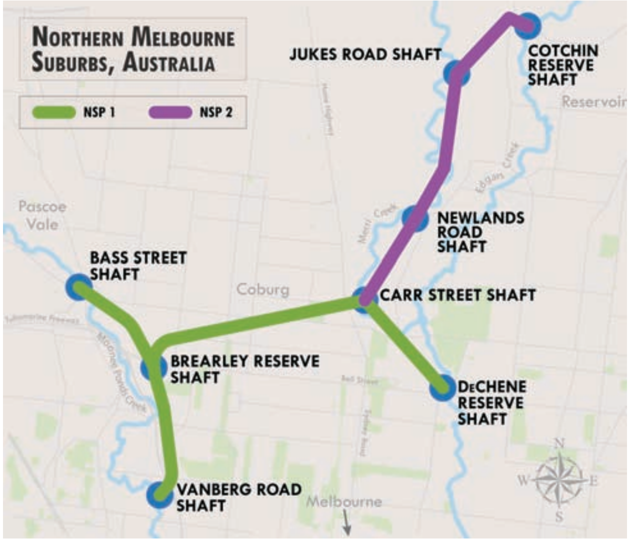

FIG 1 - Plan view of Northern Sewerage Project.

The following sections of this paper describe the corrosive environment, the lining options considered and the selected lining solutions for NSP1 and NSP2.

CORROSIVE ENVIRONMENT

Internal

The internal environment varies along the length of the NSP tunnels. However, vulnerability to, and potential for, corrosion due to internal sulfide attack increases with downstream travel along the proposed alignment.

Hydrogen sulfide (H_2S) is a gas that develops in sewers and can cause sulfuric acid to form on internal surfaces. In sewerage systems constructed with concrete, the sulfuric acid reacts with the alkaline component of the concrete and corrodes the structure.

Forced ventilation can be used to dry the sewer walls and prevent the growth of the bacteria that form sulfuric acid. However, H_2S is odorous, so expensive air treatment may be required for any air to be discharged to the atmosphere through ventilation. In addition, forced ventilation is only effective over a limited distance. Consequently, many sewers – especially those in warmer climates and those that carry industrial discharges or ageing/septic sewage – suffer from H_2S corrosion.

To understand the potential for H_2S formation within the NSP sewers, a detailed sulfide model was developed to replicate how

---

[1] Associate, Jacobs Associates, Suite 407, 811 1st Avenue, Seattle WA 98104, USA. Email: davidson@jacobssf.com

[2] Senior Design Engineer, Jacobs Associates, Suite 207B, 757 Bourke Street, Docklands Vic 3008. Email: trim@jacobssf.com

[3] Senior Associate, Sinclair Knight Merz, 590 Orrong Road, Armadale Vic 3143. Email: DFranklin@skm.com.au

[4] Principal, Sinclair Knight Merz, 590 Orrong Road, Armadale Vic 3143. Email: JMyers@skm.com.au

[5] Formerly: Sinclair Knight Merz. Currently: Manager, South East Water Limited, 20 Corporate Drive, Heatherton Vic 3202. Email: Paul.Hansen@sewl.com.au

H_2S corrosion would affect tunnel and shaft linings if unprotected concrete linings were used. The model was based on work by Matos and de Sousa (1992) and Melbourne and Metropolitan Board of Works (MMBW) (1989). The main outputs of the model were predicted corrosion rates of unprotected concrete. The outputs are summarised in Table 1.

TABLE 1

Northern Sewerage Project predicted concrete corrosion rates of unprotected concrete.

Location	Sulfide-induced concrete corrosion (upper bound rate, mm/yr)	Comments
NSP1 – Tunnels		
NDS 1	1.0	These predictions were made prior to several changes in the drop structures that would have increased the predicted corrosion rate. As by this stage the decision had been made to line the pipe with a non-corrosive liner, more up-to- date predictions were not made.
NDS 2	1.0	
NDS 3	0.5	
MPIS	0.6	
NSP2 – Tunnels		
Section 1	1.5	
Section 2	1.0	
Section 3	0.1	This section serves a smaller catchment with little forecast growth and is upstream of any of the major drop structures.

The predicted corrosion rates vary due to the variability of the inputs, such as sewage temperature and pH, predicted upstream residential/commercial growth and wastewater chemistry to name a few. The upper end of the range has been used in the final lining selection for two reasons. First, the risks and costs associated with corrosion and repair are high. Second, local changes during the 100-year life of the sewer (eg the addition of an industrial development with a major trade waste discharge, increased use of pump stations in the upstream catchment, or warmer sewage temperatures due to climate change) could significantly increase the predicted corrosion rate.

A key issue addressed in modelling was the presence of large vertical drops (ranging from 10 m to 28 m) in both NSP1 and NSP2. Vertical drops can cause significant concrete corrosion, as the turbulence generated in the sewage in these areas can release large amounts of H_2S. While there are published correlations for predicting H_2S release from an ordinary waterfall-type drop, a literature search revealed no information on H_2S release from vortex drops. As the models used for predicting sulfide generation are empirical, they need to be calibrated to real sewer conditions. In the absence of published data on real conditions, the design team undertook a sampling program on two existing vortex drops in the Melbourne sewerage system to collect data that could be correlated to the models. Melbourne Water has installed a series of corrosion monitoring pins at critical locations in its sewerage system, including the sewers downstream of NSP1. The pins were monitored regularly to measure the rate at which concrete is being lost from the sewer walls. The data from these pin locations were checked against the predicted corrosion rates from the models. Ultimately, vortex drop structures were included in the NSP1 and NSP2 designs to minimise the release of H_2S.

External

The corrosion potential of the external environment depends mainly on the permeability of the geologic units and the chemistry of the groundwater in the area. The groundwater along NSP1 stems from alluvium and siltstone aquifers. NSP2 groundwater comes from basalt aquifers. Infiltration rates were higher along the NSP2 section of the alignment. Groundwater samples from NSP2 also contained more total dissolved solids (salt or chlorides) than the samples from NSP1. However, the most important difference between the two was in the risk for mineral precipitation or ‘scaling’.

Mineral precipitation (scaling)

Mineral precipitation, or scaling, is a significant risk to lining systems that rely on internal drainage to relieve groundwater pressure. If the drainage path becomes obstructed due to mineral (usually calcium carbonate) precipitation, groundwater pressure will build up behind the liner and may cause the liner to fail if the built-up pressure exceeds the capacity of the lining system.

To assess the scaling potential of groundwater along the NSP1 and NSP2 alignments, the design team looked at the Langelier Saturation Index (LSI) and Calcium Carbonate Precipitation Potential (CCPP) of water samples from the bores.

The LSI is a qualitative indication of the tendency of calcium carbonate ($CaCO_3$) to deposit or dissolve. If the index is positive, calcium carbonate tends to deposit. If it is negative, calcium carbonate tends to dissolve. If it is zero, the calcium carbonate in the water is at equilibrium. The groundwater samples taken from NSP2 boreholes showed positive Langelier Indices between +0.1 to +1.6. NSP1 groundwater samples indicated both negative and positive LSIs (-0.6 to +0.3).

CCPP is a quantitative measure of the calcium carbonate deficit (or excess of water) in a sample, and is a more accurate measure of the likely extent of $CaCO_3$ precipitation than qualitative indices such as the Ryznar Stability Index and the LSI. CCPP can be determined graphically, analytically, or by computer analysis. The CCPP analysis, carried out for NSP2 borehole No P3-127, was performed by the designer’s material and durability specialist, Hunter Water Australia. Results are shown in Table 2 and suggest that the groundwater sample will have a maximum potential for precipitation at a pH of about 10.3.

TABLE 2

Northern Sewerage Project Stage 2 calcium carbonate precipitation potential (CCPP).

pH	CCPP (mg/L)
9.16	24
9.5	39
10.0	69
10.25	84
10.5	80
10.75	60
11	29
>11	Outside program limit

The amount of calcium carbonate that deposits from the groundwater depends on:

- the initial degree of calcium carbonate saturation of the groundwater, and
- the rate of replenishment of the calcium-carbonate-saturated groundwater.

The calcium carbonate saturation of the groundwater along NSP1 is different than that along NSP2. The basalt aquifer groundwater encountered by NSP2 is saturated in calcium carbonate and has the potential to scale. The siltstone and alluvium aquifers encountered by NSP1 are not saturated in calcium carbonate and are slightly corrosive (calcium-absorbing) in nature.

A continuing supply of calcium-carbonate-saturated groundwater is necessary for scale deposits to accumulate. Thus, replenishment and supply of calcium-carbonate-saturated groundwater is a key factor in the risk of scale developing over time. If water cannot reach the tunnel, either because of low-permeability ground or a physical barrier like watertight tunnel segments, the risk of scaling is much lower. The likelihood of groundwater replenishment is higher on NSP2, which is the main reason why the final lining solution for NSP2 is different than that of NSP1. Table 3 presents selected groundwater chemistry values for NSP.

TABLE 3

Selected groundwater chemistry.

Test	NSP1	NSP2
LSI (range)	-0.6 - +0.3	+0.1 - +1.6
Chloride (mg/L, max)	2000	2900
TDS (mg/L, max)	4400	6300
pH	7.0 - 9.2	

Salt (chlorides)

Another property of groundwater that affects its corrosion potential is the amount of chloride ions it contains. Chloride ions in saline groundwater can diffuse into reinforced concrete and, once present in sufficient quantities, can depassivate the steel by breaking down the protective oxide layer maintained by the alkaline environment. The environment provided for steel reinforcement in concrete is one of high alkalinity (generally pH >13). The concentration of chloride ions required to initiate corrosion varies depending on the alkalinity. As long as the alkaline environment is maintained, the steel remains passive and any small 'breaks' in the protective oxide film are soon repaired. If the alkalinity of the surroundings is reduced (eg by reaction with atmospheric carbon dioxide), or if depassivating chloride ions are made available at the surface of the steel, then corrosion may begin. The result is loss of steel and subsequent spalling of cover concrete. To limit this risk, a low-permeability concrete mix with sufficient concrete cover is recommended. The required depth of cover depends on the permeability and absorptive ability of the design mix, the groundwater head and quality (levels of chlorides) and the design life of the element. As shown in Table 3, the chloride concentrations observed in NSP2 samples were slightly higher than those in NSP1 and both showed levels greater than 2000 ppm. Australian Standard AS2159 indicates that chloride levels between 2000 and 6000 ppm should be classified as mildly aggressive to reinforced concrete elements.

COMPARISON OF NSP1 AND NSP2 INITIAL SUPPORT AND FINAL LINING OPTIONS

Concurrently with the evaluation of the corrosion potential along the NSP1 and NSP2 alignments, the designer reviewed and recommended initial support and final lining options. Recommendations were based on corrosion concerns and other design philosophies driven by the needs of the owners.

Two-pass tunnel lining systems were proposed and accepted for NSP1 and NSP2. The initial support systems are described below, followed by a review of the final lining options that were considered.

NSP1 initial support

The majority of NSP1 will be excavated in soft ground or weak rock (mostly alluvium and sandstone/siltstone). Hence, NSP1 has been designed with a bolted and gasketed segmental lining system (precast reinforced concrete segments).

The bolted and gasketed segmental lining system is almost impermeable by groundwater. It will reduce infiltration considerably, allowing the NSP1 final lining (liner pipe) to be designed as a drained pipe (ie pipe joints will not be sealed). In addition to impeding groundwater inflow, the bolted and gasketed segmental lining system will be the primary and permanent ground support. The function of the NSP1 liner pipe is mainly hydraulic. The liner pipe will be installed within precast tunnel segments and low-strength (3 MPa) grout backfill will be used to secure the liner pipe in place.

The NSP1 bolted and gasketed segmental lining system is designed to resist the maximum groundwater pressure for the service life of the tunnel(s). To achieve a 100-year watertight design, a factor of safety of two has been applied to the groundwater pressure. Therefore, if the tunnel segments are installed in accordance with the contract documents, little or no infiltration will occur during the life of the structure. Even if the bolted and gasketed segmental lining system allows minor infiltration, the hydrostatic pressure would never increase to the full groundwater head, since the liner pipe joints are not sealed and will alleviate any pressure.

NSP2 initial support

NSP2 will be excavated mostly in medium to hard, largely self-supporting rock (basalt) with only a small portion being excavated in weak rock and soil (approximately 500 m in soft ground). The proposed two-pass tunnel lining system consists of an initial support system (rock bolts, shotcrete, steel sets, timber lagging, etc) in Northern Intercepting Sewer (NIS) Sections 2 and 3 (the hard rock sections), a bolted and gasketed segmental lining system in NIS Section 1 (the weak rock and soil section), and a final lining (liner pipe) in all three sections.

For NIS Sections 2 and 3, the initial system provides temporary support of the ground during construction. It is assumed to deteriorate completely over the life of the structure. Therefore, the final lining will support long-term ground and groundwater loads and needs to meet the infiltration, exfiltration, hydraulic and durability functional requirements.

In NIS Section 1, the bolted and gasketed segmental lining system will provide the initial and permanent ground support with the liner pipe required to meet infiltration, exfiltration, hydraulic and durability functional requirements.

To avoid long-term drawdown of aquifers along the NSP2 alignment, the liner pipe is designed as a sealed system. To prevent groundwater inflows, all NSP2 liner pipe joints will be sealed and designed to withstand the maximum groundwater pressure (about three bar).

Final lining options

Various final lining options were considered. All options needed to address functional and performance requirements, including environmental, groundwater, structural, durability, hydraulic, construction and sewer access/operation/maintenance issues.

Alternatives to liners, such as chemical dosing to control sulfide generations and ventilation schemes to dry concrete walls, were also considered. But, due to the large sewage volumes and long distances between shafts, none of the alternatives were as economical as the short listed liner options. Tables 4 and 5 show the short list of options for NSP1 and NSP2, respectively.

Cast-in-place (CIP) concrete with polyethylene (PE)

General

Similar to the reinforced concrete pipe (RCP) with polyethylene (PE), described later in this paper, the PE is a flexible membrane which is integrally cast into a CIP concrete lining. There are

TABLE 4

Northern Sewerage Project Stage 1 short listed final lining options.

No	Option	Description
1	RCP with sacrificial cover	Unprotected reinforced concrete pipe (RCP) with a 'sacrificial concrete' layer on the internal surface, standard cover on the external surface, supplementary cementitious materials and possibly calcareous/limestone aggregate.
2	RCP + PE	RCP with a mechanically anchored polyethylene (PE) sheet lining. Both medium density (MDPE) and high density (HDPE) are acceptable.
3	CIP + PE	Cast-in-place (CIP) concrete with a mechanically anchored PE interior lining.

TABLE 5

Northern Sewerage Project Stage 2 short listed final lining options.

No	Option	Description
1	RCP with sacrificial cover	Unprotected reinforced concrete pipe (RCP) with a 'sacrificial concrete' layer on the internal surface, additional cover on the external surface, supplementary cementitious materials and possibly calcareous/limestone aggregate.
2	RCP + PE	RCP with a mechanically anchored polyethylene (PE) sheet lining. Both medium density (MDPE) and high density (HDPE) are acceptable.
3	CIP + PE	Cast-in-place (CIP) concrete with a mechanically anchored PE interior lining.
4	FRPP	Fibreglass reinforced plastic pipe (FRPP) also known as GRP.
5	Polycrete®	Polymer concrete pipe (PCP), manufactured by Meyer in Germany or Amiantit in the USA.

several different trademark names for this type of lining: GSE Stud Liner, AGRU Sure-Grip, AKS, Nuae Carbofix and Linabond to name a few. Depending on the manufacturer, the thickness of PE membrane typically ranges from 1.5 mm to 5 mm. The membranes are manufactured as sheets, which have anchors or knobs on one side that form a mechanical bond with the concrete. Depending on the depth and frequency of studs per metre, various allowable pull-out capacities can be achieved. AKS and AGRU indicate that their liner systems can withstand up to four bar of external water pressure.

Feasibility and performance

CIP concrete with PE has been used worldwide. If installed correctly, the PE will provide the necessary internal corrosion protection. John Holland Group, the contractor, was engaged during the design process to provide preconstruction advice. John Holland indicated that the minimum internal diameter for feasible CIP linings without PE is about 2 m. The added step of installing a membrane with each pour increases this minimum dimension greatly.

Placing concrete in a fully circular tunnel section is challenging. The addition of a PE lining makes installation even more complicated. Special formwork and staging procedures are required to install the membranes and flaws often occur. Because PE liners require a positive mechanical connection with the concrete, flaws which go unnoticed will likely result in failure over time if water pressure builds up behind the sheet. Quality control issues can be addressed with a thorough inspection and testing plan, along with contingency plans for repair procedures.

For NSP1 and NSP2, the CIP option was believed to be capable of providing sufficient protection. However, John Holland indicated that constructability and safety issues would be of concern, making this option less viable.

Polymer concrete pipe (PCP)

General

Polymer concrete pipes (PCPs) are proprietary products manufactured in the US and Germany to standards such as ASTM D 6783. PCP is manufactured from polyester resins (ie without Portland cement) and mixed with coarse and fine aggregates to produce a concrete-like product. This material is resistant to sewer-related H_2S corrosion. PCP provides long-term corrosion resistance if there are no aggressive chemicals in the sewer. Although polymers are subject to creep, creep rates are low compared to PVC or PE pipe, and the proprietary products are regarded as rigid. PCP does not utilise steel reinforcement so there is no possibility for corrosion to the reinforcement. To provide a fully corrosion-resistant system, the joint collars would have to be made of stainless steel or fibreglass reinforced plastic (FRP) material.

Feasibility and performance

It is widely accepted that a design life of 100 years can be readily achieved with PCP. If PCP is installed using similar methodologies as RCP, buckling should not be a concern during installation.

PCP has been used on numerous jacked-pipe projects around the world, due to its durability and robustness (for handling). PCP would meet, and might even exceed, the owner's functional requirements and the design criteria on NSP. At the time this design decision was made, PCD was not manufactured locally, and was therefore fairly costly. This was considered a drawback.

The extra cost associated with PCP was not warranted on NSP1 since the liner pipe does not carry the long-term ground loads and therefore does not need to be as robust. For NSP1, PCP was not short listed. On NSP2, the final lining will support the long-term ground loads, and PCP was short listed due to its inherent corrosion resistance and ability to handle long-term ground and groundwater loads.

Reinforced concrete pipe (RCP) with sacrificial concrete

General

Plain, unprotected RCP is normally produced with 10 mm or 20 mm concrete cover to the steel reinforcement. For sewerage applications, additional 'sacrificial' concrete is often provided, and at least one pipe manufacturer's catalogue recommends up to 35 mm of cover. Similarly, the draft Australian Standard for Precast Concrete Pipes specifies 35 mm of cover for marine exposure (with unspecified service life).

Based on the predicted corrosion rates due to sulfide attack, unprotected RCP would require 10 to 150 mm of internal sacrificial concrete. The MPIS (NSP1) and NIS Section 3 (NSP2) tunnel sections would require the least amount of sacrificial cover (50 mm and 10 mm, respectively).

The external concrete cover is also a concern due to the elevated chloride levels in the groundwater, especially on NSP2. For NSP1 the standard cover requirement (10 mm) would provide the appropriate level of protection, but 40 mm cover would be required for NSP2.

Feasibility and performance

The requirement for 50 mm or more of sacrificial concrete is significantly more than average for concrete pipes and would increase the weight of each pipe from approximately 4.0 tonnes to more than 10.0 tonnes. Manufacture, transport and installation of these pipes would be problematic.

Also, after considering the diameter of the proposed TBM, the external diameter of the liner pipe, initial ground support, pipe transport within the tunnel and tunnelling tolerances, it was clear that there was insufficient space available to effectively and efficiently install RCP with any considerable amount of sacrificial cover within any of the NSP tunnel sections in which a precast concrete tunnel segment had been proposed. Thus, the only viable locations for this option were the NIS Section 2 and 3 tunnels. After considering the predicted corrosion rates for the NIS Section 2 and 3 tunnels, it was evident that NIS Section 3 (corrosion rate of 0.1 mm/yr) was the most viable tunnel section for this option due to the thinner required sacrificial concrete thickness.

Reinforced concrete pipe (RCP) with polyethylene (PE) (mechanically anchored lining)

General

Polyethylene (PE) is available in a number of variations based on densities. PE pressure pipes, for example, are manufactured from either high- or medium-density PE and have a recognised ability to provide long-term performance. As stated previously, it is widely accepted that PE can provide a 100-year service life. However, resistance to environmental stress cracking induced by detergents is a potential issue with low-density PE (LDPE) in a sewerage application. Stress cracking could possibly occur in areas of high stress such as at welds. For this reason, LDPE was not recommended without further information. RCP with high-density PE (HDPE) or medium-density PE (MDPE) sheet liners were considered acceptable. Figure 2 presents a sample of HDPE showing one form of mechanical anchors.

Non-black materials are recommended for fabrication to assist in internal and visual inspections.

Feasibility and performance

PE liners, whether HDPE or MDPE, have equivalent corrosion resistance and there is little concern that there will be any short- or long-term corrosive effects on a PE liner under normal operating conditions. PE is a material of choice for many national and international water agencies for the transportation of sewage. A suitable quality of PE material would meet AS/NZS 4131 or equivalent ISO standards. Plasticised PVC has been in use long term with few corrosion issues. The most significant problem with PVC was due to high levels of chlorine in a sewer, which resulted in the leaching of plasticisers, embrittlement and changes in volume. This was considered a rare case and unlikely to be repeated, but supports the view that the plasticised PVC has less corrosion resistance than HDPE or MDPE.

Sheet-lined concrete pipe systems require welding at joints to provide a continuous corrosion barrier across the joint. This requires in-tunnel welding. The welding of the sheet requires clean, dry, well-prepared surfaces and well-established welding procedures to achieve suitable welds. In this application, where groundwater, high humidity and dew point conditions may be present, welding is a risk to the long-term performance. This is more risky on NSP2, where the primary support does not restrict groundwater inflows. On NSP1, the proposed primary lining, precast concrete segments, will provide a more controlled environment by restricting groundwater inflows during pipe installation, thus reducing the long-term risk.

FIG 2 - Sample of high-density polyethylene (HDPE) with mechanical anchors.

As all concrete cracks to some extent, groundwater with 30 to 40 metres head would seep through the wall of a concrete liner pipe. Depending on the quality of the groundwater, there is a risk that scaling could occur within the pipe. This risk applies more to NSP2 as the groundwater along NSP1 has less potential to precipitate and NSP1 utilises a bolted and gasketed segmental lining system which will provide another positive barrier in preventing sustainable groundwater inflows.

If scaling occurs behind a PE sheet liner over a long period, bulging and failure of the sheet anchoring system can occur.

Fibre reinforced plastic pipe (also known as glass reinforced plastic)

General

Fibre reinforced plastic pipe (FRPP) is made from polyester resin and fibreglass. It is inherently resistant to hydrogen sulfide attack, and therefore a corrosion resistant internal lining is not necessary. The structural design of the liner pipe will allow for backfill grouting of the annulus between the liner pipe and the tunnel wall (similar to RCP options). The pipe material is generally impermeable and gasketed joints between pipe sections create a watertight final lining if required. For buried FRPP and pipes used in sewers, the typical pipe stiffness range is SN5000 to SN15000.

Pipe stiffness is the product of the ring flexural modulus of elasticity (E) of the pipe wall material, and the moment of inertia (I) of a unit length of the pipe divided by the mean diameter cubed (EI/D^3). The pipe stiffness does not reflect a specific pipe thickness or elastic modulus but a combination of the two. Different manufacturers will achieve the specified stiffness by different means. As is typical with FRPP production, full-scale test specimens are produced and tested to confirm the properties specified.

Non-black materials are recommended for fabrication to assist in internal and visual inspections.

Feasibility and performance

FRPP has been widely used for sewer applications. Where there have been problems, they have been related to the use of low stiffness pipes (SN1250 - SN2500) and inadequate construction practices, leading to ovality and buckling problems. Stiffer pipe and cementitious grouts can be used to control these problems.

Creep and the reduction of stiffness over time are known issues with FRPP. These issues can be addressed by detailed structural design, a well-defined testing program, and use of a pipe class of SN5000 or greater.

Appropriate corrosion resistance is obtained using isophthalic polyester resin systems for internal surfaces exposed to the sewage in conjunction with ECR (corrosion resistant glass) glass fibres. This combination provides resistance to strain corrosion in a sewer environment. Corrosion would not need to be considered in the future, as strain corrosion is the mechanism whereby long-term performance of FRPP can be compromised. Using glass fibres with high resistance to corrosion and minimising strain by ensuring there is minimal ovalisation of the pipe reduces the likelihood of this form of degradation. It is likely that a service life well in excess of 100 years could be achieved by the use of this material. During grouting there may be some temperature increases; however, as the material is thermoset, short-term temperature increases will not affect its performance.

Generally, due to the high tensile strength of FRPP, the wall thickness tends to be much less than that of reinforced concrete pipe and Polycrete pipes; therefore, FRPP would be lighter and less rigid. For this reason, a detailed procedure for installation of FRPP is necessary. Loads due to floatation and high grouting pressures are leading causes of FRPP failures during installation. These issues can be avoided with proper blocking, staging of grouting and a well-designed grout mix. Of course, the extra care during placement adds to the installation cost.

FRPP was not short listed on NSP1, due to the lack of local suppliers during the NSP1 selection period (NSP2 selection period occurred about two years later), cost and Melbourne Water stakeholders' risk assessment of FRPP.

Selection

For both projects, constructability, cost and durability assessments were carried out for all of the short listed options during the detailed design phases (which, as stated above, occurred at different time periods) to determine the most economically viable solution. These assessments involved discussions with the contractor and owners. Throughout the evaluation period, various workshops were carried out with Yarra Valley Water and Melbourne Water stakeholders to get their opinions and comments on the final lining recommendations.

NSP1 and NSP2 tunnels are different in terms of geology, ground support requirements, groundwater chemistry, predicted corrosion rates, flow rates and risk. These differences led to different solutions being selected for the final lining options. Constructability issues dictated that a liner pipe, rather than a cast-in-place system, would be the best option for the NSP tunnels. The proposed options for NSP are as follows:

- NSP1 – RCP with HDPE; and
- NSP2 – NIS Sections 1 and 2 are FRPP, and NIS Section 3 is RCP with sacrificial concrete.

Figure 3 shows the two-pass tunnel lining systems for NSP2.

CONCLUSIONS

All of the short listed options, for both stages, would meet the owner's functional requirements. Each option has advantages and disadvantages. The final decision considered lowest cost options,

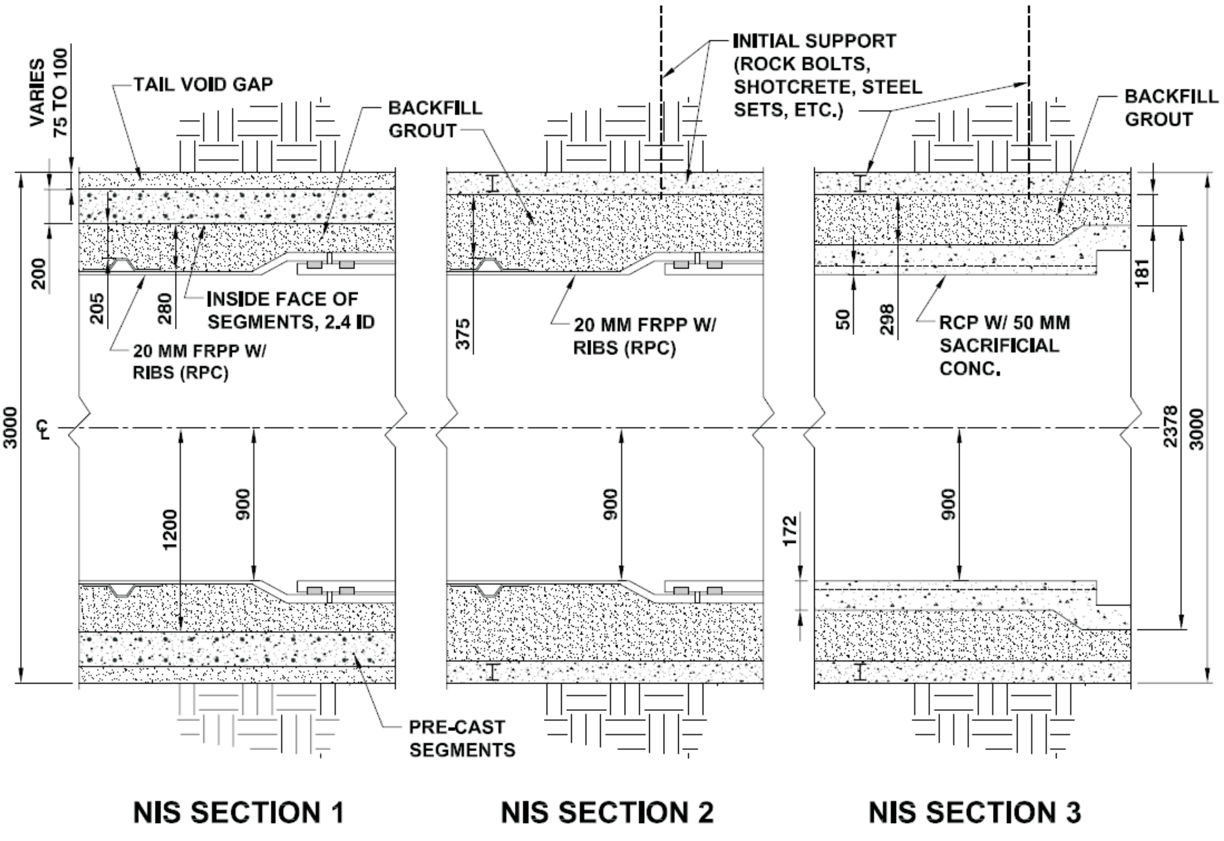

FIG 3 - Northern Sewerage Project Stage 2 initial and final lining systems.

as well as best-value options, which were inherently corrosion resistant, relatively strong and met these functional requirements.

NSP1

The RCP with HDPE option is the lowest-cost option which meets the designer's and owner's requirements. The robust bolted and gasketed segmental lining system, the owners' preferences, and the lower design risk led to the selection of this option over the two other short listed options.

NSP2

The FRPP option for NIS Sections 1 and 2 is the best-value option for a sewer pipe that is inherently corrosion resistant, relatively strong (though reliant on the passive support of surrounding grout) and independent of separate systems (such as PE sheet, anchor lugs and drainage, etc). It is capable of providing watertight joints, thereby eliminating infiltration and exfiltration, and is also likely to have significant post-design-life performance. Based on the constraints of this project, FRPP involves the least risk of structural failure or costly maintenance for NSP2.

Due to the lower predicted corrosion rates for NIS Section 3, RCP with sacrificial concrete option is the lowest-cost option which meets designer's and owner's requirements.

REFERENCES

Matos, J S and de Sousa, E R, 1992. The forecasting of hydrogen sulfide gas build-up in sewerage collections systems, *Wat Sci Tech*, 26(3-4):915-922.

Melbourne and Metropolitan Board of Works (MMBW), 1989. Hydrogen sulfide control manual, septicity, corrosion and odour control in sewerage systems, Technological Standing Committee on Hydrogen Sulfide Corrosion in Sewerage Works.