CORROSION PROTECTION LININGS FOR THE STRATEGIC TUNNEL ENHANCEMENT PROGRAM, ABU DHABI

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ABSTRACT

Abu Dhabi Sewerage Services Company (ADSSC) commissioned development and delivery of the Strategic Tunnel Enhancement Programme (STEP), which intercepts flows upstream of existing pumping stations and conveys the sewage via gravity through a new tunnel sewer network. The tunnel was designed using precast concrete segments as its permanent structural lining. In order to mitigate internal corrosion to the structural lining, a Corrosion Protection Lining (CPL) system was required, which comprises a mechanically anchored high density polyethylene (HDPE) lining cast into an unreinforced cast-in-place concrete secondary lining. Following construction, various CPL defects were observed. After field inspections and review of information on similar systems, it was determined that all bulging defects were related to workmanship issues with the CPL concrete secondary lining, with no indications that the HDPE membrane was failing. The conclusion reached was that the installed CPL system remains a robust solution to meet the required 80-year design life.

KEY WORDS

Corrosion protection lining, high density polyethylene, deep gravity tunnel, odor control facilities, tunnel boring machine, precast segmental lining, hydrogen sulfide, two-pass CPL system

INTRODUCTION

Background

In 2007, the Abu Dhabi Sewerage Services Company (ADSSC) commissioned a masterplan study for the sewerage system in the Abu Dhabi metropolitan area. The study identified that a major overhaul or replacement of the existing shallow pumped system was required in order to provide capacity for future growth. One of the identified options was a deep gravity tunnel system.

At a similar time, the Abu Dhabi Government’s Urban Planning Council released ‘Abu Dhabi Plan 2030’, which was the urban structure framework for development out to a planning horizon of 2030. This plan included updated population projections for the various future areas of development/redevelopment throughout Abu Dhabi.

In March 2009, ADSSC commenced the Strategic Tunnel Enhancement Programme (STEP) via the initiation of a Programme Management Office (PMO) to develop and procure STEP, and act as Engineer under the contracts. The concept, feasibility and preliminary design of STEP were developed throughout 2008. Design and build construction tenders were first floated to the market starting late 2008 through mid-2009.

Description of STEP System

The overall design of STEP is indicated on Figure 1, and includes the following elements, from upstream to downstream:

- 45 km of micro-tunneled link sewers, with finished diameters between 200 mm and 3100 mm. These link sewers intercept flow upstream of existing pumping stations, allowing the future decommissioning of thirty-five (35) existing pumping stations. Flows are conveyed by gravity to the deep sewer tunnel.
- 41.3 km deep sewer tunnel, running from central Abu Dhabi Island (tunnel depth 25 m) to the new Independent Sewage Treatment Plants (ISTPs) at Al Wathba (tunnel depth 85 m). The finished internal diameter of the tunnel ranges from 4.0 m at upstream end to 5.5 m at downstream end. Seventeen (17) permanent shafts are included, allowing for access to the tunnel for inspection and maintenance and for future hydraulic connections.
- Terminal pumping station at downstream end of tunnel, to lift flows to ISTP's for treatment. The ultimate capacity of this facility is 39 m^3/s. The pumping station shaft is approximately 50 m diameter and 100 m depth, making it one of the largest facilities of this type ever constructed.
- Two additional surface regional Odor Control Facilities (OCFs), to treat and discharge foul air from the tunnel system.

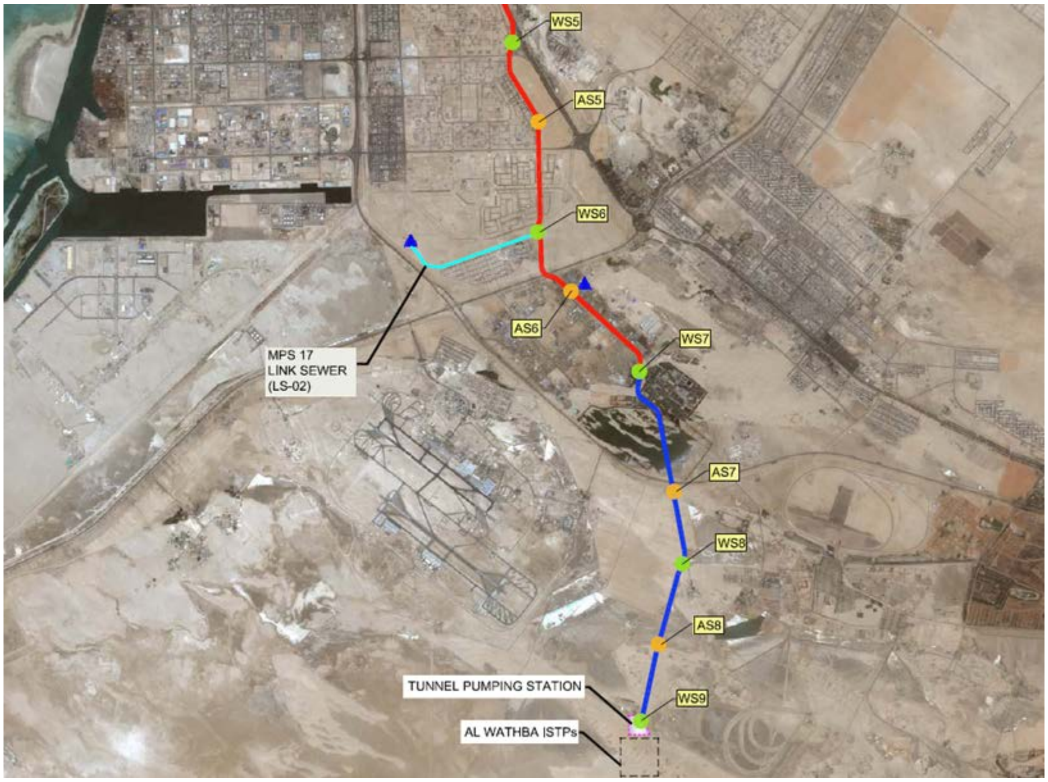
The focus of this paper is on the corrosion protection system adopted for the deep sewer tunnel component.

DESIGN CONSIDERATIONS

Overview

The ground conditions in Abu Dhabi consist of weak carbonate rocks, and were considered appropriate for mechanized tunneling utilizing Tunnel Boring Machines (TBMs). Further consideration of the risk of karst features (e.g. cavities and voids) and high groundwater pressures also directed the tunneling method towards closed face/pressurized face TBM tunneling. An aggressive project delivery schedule further drove the project towards TBM execution. The bid specification permitted the use of either Slurry TBMs or Earth Pressure Balance Machine (EPBM) TBM's, but all the tunnel contractors opted for the use of EPBMs, utilizing a precast concrete segmental lining system to provide initial and permanent support to the ground. A minimum maintenance-free design life of 80 years was specified by ADSSC.

Upstream of WS5



Downstream of WS5

Figure 1. Strategic Tunnel Enhancement System

Corrosion Considerations

In order to ensure that the minimum design life of the tunnel structural precast segmental lining is achieved, it is necessary to consider both external and internal corrosion of tunnel linings.

The groundwater chemistry in Abu Dhabi is highly saline (typically more than three times that of seawater) and is extremely aggressive to steel reinforcement. Therefore careful consideration of external corrosion, particularly chloride penetration rate through concrete, was very important. In the end, two of three tunnel contracts adopted steel fiber reinforcement, while the third adopted conventional steel reinforcement with appropriate cover. All contracts made careful selection of concrete mix design for durability.

With regards to internal corrosion, it is well known phenomenon that separate sewer systems generate significant quantities of hydrogen sulfide (H_sS) “sewer gas”. The sewer gas is digested by microbial bacteria lining the sewer walls above the water line, and converted into sulfuric acid (H_2SO_4). The sulfuric acid gradually dissolves the cementitious matrix of concrete, resulting in a slowly travelling ‘corrosion front’ into the concrete. Without adequate protection, this corrosion front can eventually result in loss of concrete cover to reinforcement and loss of structural section, both of which can lead to tunnel lining failure and collapse. For a maintenance-free facility, this is an unacceptable outcome. It is also noted that the ambient sewage temperature and chemistry in Abu Dhabi make for particularly onerous sewer gas generation potential.

Options Considered for Internal Corrosion Protection

Various options for protecting the tunnel lining from internal corrosion are available and some have been historically tested. The following options were considered for the STEP tunnels:

1. One-pass lining systems:
    a. High-quality concrete
    b. Acid-resistance concrete
    c. Polymer concrete tunnel segments (only ever used on prototype demonstration, not yet demonstrated to be cost-effective for segmental tunnels)
    d. Attached liners, e.g. mechanically anchored plastic membranes (e.g. high density polyethylene [HDPE]) cast in to concrete segments, glass-fiber reinforced plastic (GRP)
2. Two-pass lining systems:
    a. Carrier pipe used as the second liner
    b. Secondary sacrificial lining of unreinforced concrete with cast in mechanically anchored plastic membrane
3. Adhesive/spray on coatings to tunnel lining

Given the highly aggressive sewer conditions expected, coupled with ADSSC’s low risk tolerance and expressed desire for zero maintenance, it was decided to adopt a two-pass Corrosion Protection Lining (CPL) system comprising a secondary cast in place lining of unreinforced concrete incorporating a mechanically anchored HDPE membrane. This combination was considered to be the most robust of the available and proven systems, and had been successfully implemented on Singapore's similar Deep Tunnel Sewer System (DTSS) Phase 1 without any known significant issues.

Tender Requirements

All three tunnel contracts utilized a modified 1999 Federation Internationale des Ingénieurs-Conseils (FIDIC) design and build form of contract. The contracts stipulated the following key requirements in respect of the tunnel lining:

1. All main sewer tunnels to be excavated by pressurized face (closed face) TBMs, either slurry or EPBM, utilizing precast segmental concrete lining to provide initial and permanent structural support to the ground.
2. Other tunnels, e.g. manually excavated adits to offline access shafts, to be adequately supported by temporary support (e.g. shotcrete, ribs, mesh, rockbolts) and permanent support by cast-in-place concrete.
3. All internal tunnel and shaft surfaces to include an internal CPL, comprising a minimum 200 mm thickness unreinforced concrete lining, and incorporating a minimum 2.5 mm thick anchored HDPE membrane on the internal face (refer Figure 2).
4. The HDPE membrane coverage was to be 360°, except at the invert where a 30° omission of HDPE membrane was required to allow relief of pressure for any groundwater penetrating through the segmental lining and unreinforced secondary concrete lining.

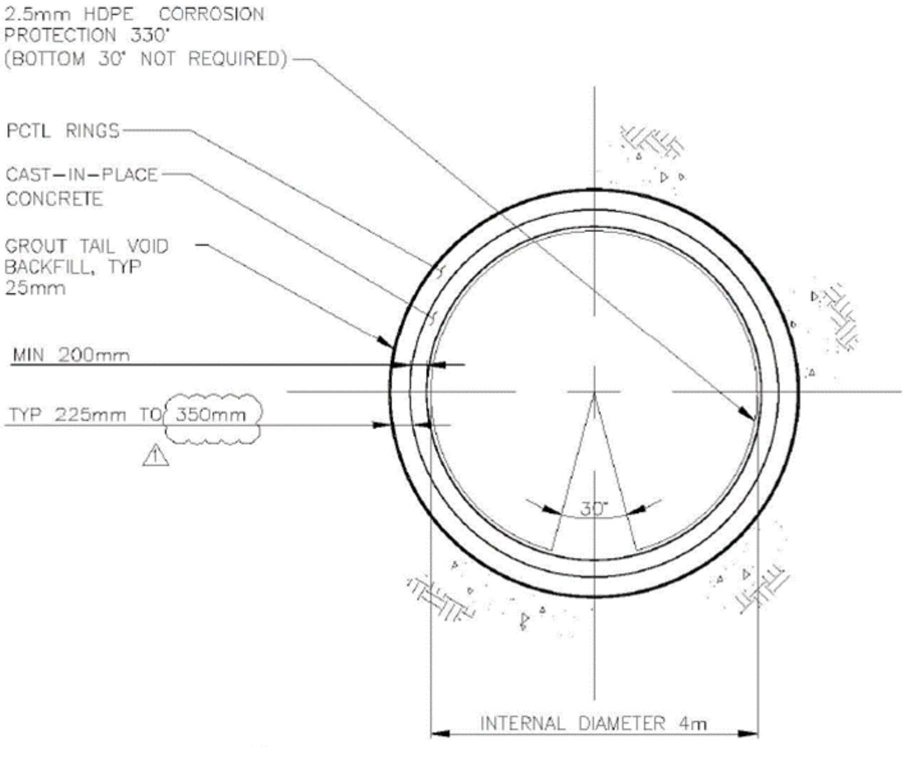


Figure 2. Required STEP Corrosion Protection Lining System

Contractor Obligations

While the tunneling and CPL concepts were prescribed via performance or minimum requirements under the contract, the contractors were obligated to develop the detailed design and construction methodologies for their tunnel and shaft linings. For the CPL in particular, there is a close relationship between casting methodology, construction logistics, and constraints such as tunnel curvature and access distances. It is critical that the design and equipment selection consider issues associated with handling of HDPE membrane and delivery of concrete in constrained, hot, wet, underground conditions with significant travel times between the concrete batching plant and the tunnel formwork (shutter).

The contractor was responsible for developing all details of the CPL systems, such as:

- Concrete mix design(s)
- HDPE membranes to meet minimum requirements including pull-out resistance
- Configuration of vault/invert sections – dependent on method of pouring, e.g. vault first then invert second, or invert first then vault second, or vault and invert monolithically
- Ease of positioning and tensioning of HDPE membranes on the shutter
- Consideration of shutter length(s), number and positions of concrete pouring ports/windows, contact grouting ports, method(s) of vibrating and curing the concrete
- Method of stripping and moving shutter (e.g. hydraulic operation or mechanical)
- Number of shutters in each tunnel section and direction of travel, including consideration of how to get concrete from the surface down to the shutter(s)
- Treatment of cold joints between shutter pours
- Groundwater pressure relief at cold joints
- HDPE jointing and welding details

CONSTRUCTION AND INSTALLATION METHODOLOGY

Tunnel Structural Lining

A precast segmental concrete primary lining forms the permanent structural lining to the tunnel, supporting ground loads, hydrostatic loads, and any superimposed loads or internal loads. The STEP linings were reinforced by either steel bars, or steel fiber reinforcement with conventional reinforcement bursting ladders. The primary lining is installed by the TBM and the excavated annulus between the ground and the segmental lining is filled with low strength grout as the TBM advances. The precast concrete lining is not intended to be completely watertight, and a nominal infiltration (1 liter/day/m^2) of groundwater is allowed under the specifications.

The contractor’s designs all utilized a six segment tapered ring design (five plus key segment), allowing the lining to negotiate curves as required. The various TBM segmental lining designs are summarized in Table 1. An example of the constructed segmental lining for one of the contracts (Contract T-01) is shown in Figure 3.

Table 1. STEP Tunnel TBM Segmental Lining Details

Parameter	Contract		
	T-01	**T-02**	**T-03**
Segmental Lining ID	4.5 m	5.5 m	6.0 m
Segments per Ring	6	6	6
Lining Thickness	225 mm	280 mm	350 mm
Ring Width	1.50 m	1.40 m	1.40 m
Reinforcement Type	Conventional reinforcement	Steel fiber, with additional bursting reinforcement	Steel fiber, with additional bursting reinforcement

Figure 3. TBM Tunnel Segmental Lining (Contract T-01)

Corrosion Protection Lining (CPL)

The CPL was installed using purpose built vault shutters (refer to Figure 4), designed to travel on the tunnel locomotive tracks. The HDPE membranes were fabricated into rolls of the correct dimensions, then transported by rail to the shutters. The general steps of CPL installation are as follows:

- Step 1: Cast CPL vault sections (with HDPE membrane)
- Step 2: Cast CPL invert sections (without HDPE membrane)
- Step 3: Contact grouting of any voids between CPL lining and segmental lining
- Step 4: Finishing works (HDPE welding and repairs)

The CPL vault installation sequence is described in more detail below.

1. Position and expand shutter
2. Feed HDPE membrane and around exterior of shutter

3. Strut the shutter invert, clamp and tension the HDPE membrane
4. Install stop ends to shutter
5. Pour concrete using a sequence of 1m high pours on alternating sides, to balance shutter loads
6. After curing to the target early strength, strike shutter and relocate

Figure 4. Corrosion Protection Lining Shutter (Contract T-02)

The shutters for all three contracts were provided by the same supplier, but T-01 was 9.5 m long whereas T-02 and T-03 utilized 12 m long shutters. The shutters were equipped with two levels of sidewall ports, along with crown ports. The side wall ports were located at approximate positions of 2:30/9:30 o'clock and 4:00/8:00 o'clock. Further shutter details are provided in Table 2.

Table 2. Corrosion Protection Lining Vault Shutter Details

Item	Contract		
	T-01	**T-02**	**T-03**
Supplier	CIFA S.p.A	CIFA S.p.A	CIFA S.p.A
Shutter Length (m)	9.5	12.0	12.0
Vibration	22 formwork vibrators	36 formwork vibrators	36 formwork vibrators
Pouring Port Levels	2 levels sidewall ports (8 total), 4 crown ports	2 levels sidewall ports (10 total), 6 crown ports	2 levels sidewall ports (10 total), 6 crown ports

The installation process for the CPL concrete lining is summarized in the steps below and further shown in Figure 5:

1. Concrete delivered to site from batching plant using ready mix trucks
2. Concrete discharged into hopper at shaft surface, gravity fed through a 12” diameter steel tremie pipe down the shaft
3. Concrete discharged at shaft bottom into rail mounted remixer cars for transport to CPL work zone
4. Concrete pumped from remixer cars into shutter using a rail mounted concrete pump located adjacent to the shutter
5. Concrete placement was executed by placing the discharge hose from the concrete pump through the shutter walls using the various ports in the shutters
6. The pouring sequences were designed to balance loads on either side of the shutter
7. After curing and when target early strength was reached, the formwork (shutter) was struck and re-positioned

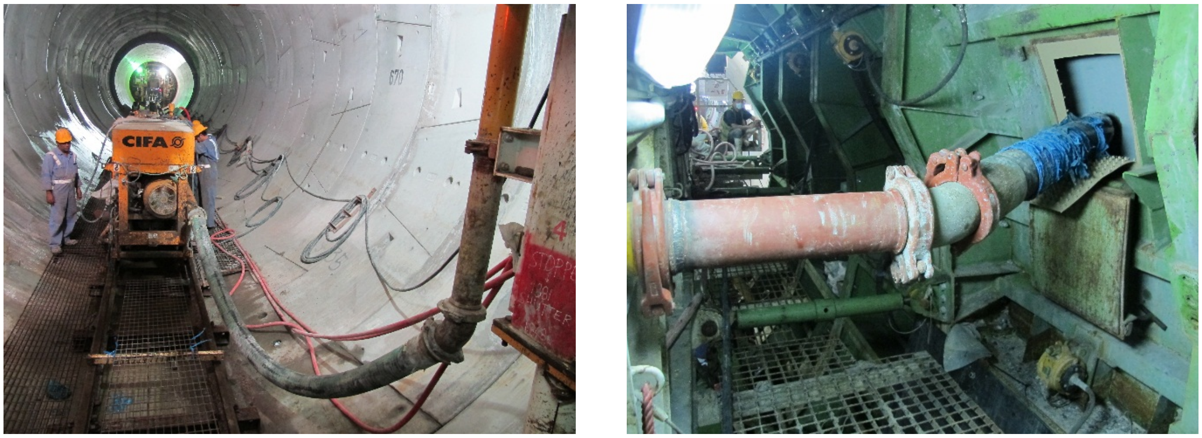
Following casting, rail tracks were removed and invert sections were poured in 24-60 m lengths.

a – Concrete Discharged to Hopper

b – Hopper and Tremie Pipe in Shaft

c – Discharging Concrete into Remixer Cars at Shaft Bottom

d – Transporting Concrete into Tunnel at Pour Location



e – Pumping Concrete to Shutter

f – Pumping Concrete into Sidewall Port

g – Pumping Concrete into Crown

h – Shutter Plate Vibrator

Figure 5. Corrosion Protection Lining Placement Cycle

The various concrete mix designs used for the CPL works are summarized in Table 3.

Table 3. Corrosion Protection Lining Vault Concrete Mix Details

Parameter	Contract		
	T-01	**T-02** (1)	**T-03**
Target Slump (mm)	240 ± 30	--	--
Target Flow (mm)	--	670 ± 30	700 ± 30
Target Strength (at de-shuttering) (MPa)	8	12 @ 10 hrs	12 @ 10 hrs
Characteristic Strength (MPa)	40	50	50
Max. Aggregate Size (mm)	20	20	20
Total Cementitious Material (kg/m^3)	440	425	425

Table 3. Corrosion Protection Lining Vault Concrete Mix Details

Parameter	Contract		
	T-01	**T-02 (1)**	**T-03**
Water/Cement Ratio	0.33	0.32	0.33
Admixtures (2)	Glenium 111 (BASF)	Sikaplast 1300 HE	Sikaplast 1300 HE

Notes:
(1) Two mixes were used on T-02.
(2) The admixtures are superplasticizers, designed to improve workability and strength gain when micro-silica, fly ash, and Ground Granulated Blast Slag (GGBS) are used in the mix.

The materials selected for the anchored HDPE membranes were as follows:

- T-01: Ultra Grip 562, manufactured by Agru
- T-02 & T-03: Anchor Knob Sheet (AKS), manufactured by Anchor Lining Systems

Quality Considerations

Cube samples were taken at the surface after discharge from the ready mix truck for density and strength testing (10/12 hr, 7 day, 28 day). Temperature was measured at the time of discharge, if greater than 29° C, the batch was rejected. Concrete was not poured when ambient temperature was above 40° C on a rising thermometer or 43° C on a falling thermometer. Slump and flow table tests were performed at the point of discharge on the surface. Additional cube samples were taken in the tunnel for strength testing at the point of concrete placement into the vault shutter.

All three contracts followed a similar approach to the construction sequence of the CPL works. In each case, the contractors worked simultaneously on upstream and downstream fronts from access shafts (e.g. AS1-AS8) towards the adjacent work shafts. For T-01 and T-02, the CPL work for each contract was executed using three parallel operations. For the shorter T-03 tunnel, the CPL work was executed using two parallel operations.

After completion of the works and prior to issue of the Taking Over Certificate (TOC), final inspections using gantries (to access tunnel shoulders and crown) and sounding rods were carried out at each CPL section to check the concrete integrity behind the liner. Sounding tests were carried out (refer to Figure 6) using hollow testing rods. Knocking with the test rods was carried out on the entire HDPE covered CPL arch, longitudinally and transversely. The method was effective in detecting where concrete segregation / honeycombing / voiding had occurred that had not already been identified by visual inspection.

CPL RELATED CHALLENGES

During construction, Non-Conformance Reports (NCRs) were raised by the Contractor's Quality Control Consultant (CQC) for a range of quality issues affecting the CPL vault construction. The main root causes of bulge defects recorded in the NCRs are summarized in Table 4.

24/02/2013 08:45

a – Sounding Rod b – Gantry Used for 360° Sounding

Figure 6. Sounding Tests

Table 4. Root Causes of Bulge Defects, as Documented in NCRs

- Failure to follow the approved concrete placement sequence
- Substantial honeycombing in CPL sections cast integrally with cast-in-place reinforced permanent structural lining sections of the tunnels, namely the launch and reception tunnels
- Honeycombing/poor membrane bond or bulging
- Cold joints within vault pour

Not all available ports (longitudinally) were used for concreting by the contractors but a satisfactory degree of compaction was achieved if the prescribed pour sequence was followed. In a few cases documented in NCRs, the contractor did not follow the prescribed pour sequence, resulting in honeycombing and/or segregation occurring.

The following section further describes the CPL bulging issues that occurred on some pours.

HDPE Membrane Bulging

The defect of most concern that was encountered was the inward bulging of the anchored HDPE membranes, usually in isolated sections. The extent of the bulging ranged from ‘fist sized’ up to 1.0 m^2, but typically bulges were observed to be less than 0.5 m^2. Bulges were usually elliptical in shape, with the long axis parallel to the tunnel. Occasional observations showed bulges running diagonally along a linear feature, presumably an unintended cold joint in the secondary concrete. A typical bulge is shown in Figure 7.

Figure 7. Typical Bulge Defect Being Drained for Repair

Upon cutting and removal of the HDPE membrane at bulges, it was observed that either the HDPE anchorages were not embedded into concrete (due to voids or honeycombing) or had pulled out of an aggregate-deficient cement paste without shearing the concrete, with a typical example of this latter situation shown in Figure 8. This zone was observed to be typically 10-20 mm deep, as schematically indicated in Figure 9.

When voids/honeycombing were identified visually or by sounding shortly after construction, these defects were often not associated with water pressure (i.e. there was no bulging, just de-bonding of the HDPE) since localised water pressure behind the HDPE takes days or weeks to develop. So, it was only after construction had been completed and time had elapsed, that water pressure combined with concrete defects (honeycombing/segregation) were observed to cause bulging of the HDPE membrane.

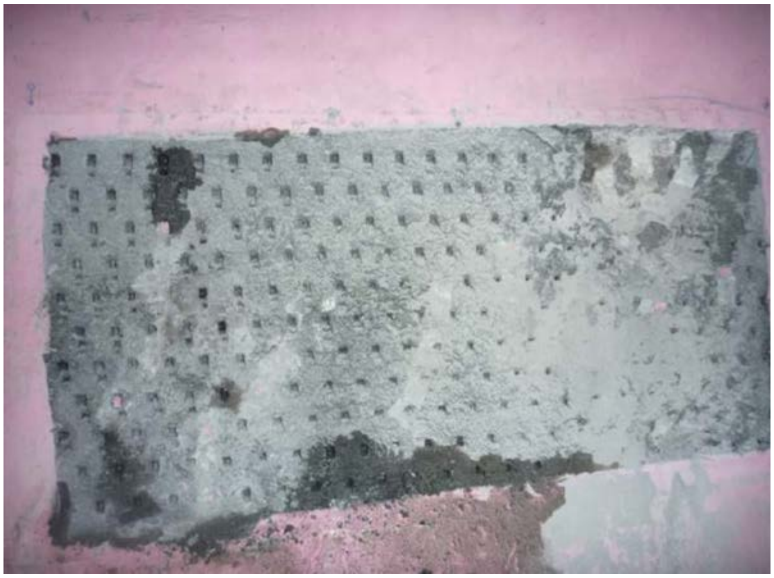


Figure 8. Typical Bulge Defect after Removal of HDPE

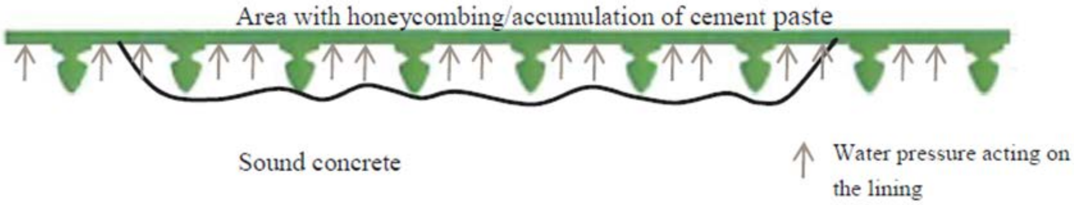


Figure 9. Schematic Section of Typical Bulge Defect

Various phases of Defects Notification Period (DNP) and post-DNP inspections were carried out after issuing the Taking over Certificate (TOC), with participants from the Contractor, the CQC, the Client, and the Engineer. The timing of these inspections is summarized in Table 5. The observations of new bulges with time since the start of CPL construction are shown in graphical form in Figure 10. While the graphs are based on a limited number of data points and simplifying assumptions have been made, it is apparent that the rate of new bulge observations is relatively high during or upon construction completion, and then significantly drops off during the DNP and post-DNP phases. Most of the defects observed in the post-DNP phase are relatively small in area.

Table 5. Defect Notification period Inspections and Bulge Observations

Parameter	Contract		
	T-01	**T-02** (1)	**T-03**
CPL Start	31 Oct 2013	30 May 2012	12 Feb 2013
CPL Finish	16 Aug 2014	24 Apr 2013	24 Aug 2013
Bulges before TOC	79 (1)	472	380
TOC Issued, DNP Starts	28 Feb 2015	19 Oct 2013	3 Apr 2014
DNP Finish	27 Feb 2016	18 Oct 2014	2 Apr 2015
1st DNP Inspection	28-30 Sept 15 14 No.	10-14 Aug 2014 11 No.	21 Jan – 4 Feb 2015 16 No.
2nd DNP Inspection	-	22 Mar - 5 Aug 2015 27 No.	Sept 2015 (WS7-AS7) TBD
3rd DNP Inspection	-	Oct 2015 15+	-
Total Bulges	93	525+	396+

Notes:
(1) NCR's identifying honeycombing or voids have been considered as bulge defects, as they result in inadequate anchorage of HDPE to concrete and would develop into bulge defects with time.

The total length of the STEP main tunnels is approximately 41.3 km, with an internal surface area of more than 552,000 m^2. Assigning each bulge defect a conservative arbitrary size of 0.5 m^2, it is estimated that <0.09 % of the tunnel lining has been affected by bulge repairs. For Contract T-01 tunnel, 0.01 % of the area is affected by bulges, and for Contracts T-02/T-03 tunnels the percentages comprise 0.12 % and 0.13 % respectively. Putting this another way, more than 99.9 % of the tunnel lining surface area is free of bulge defects.

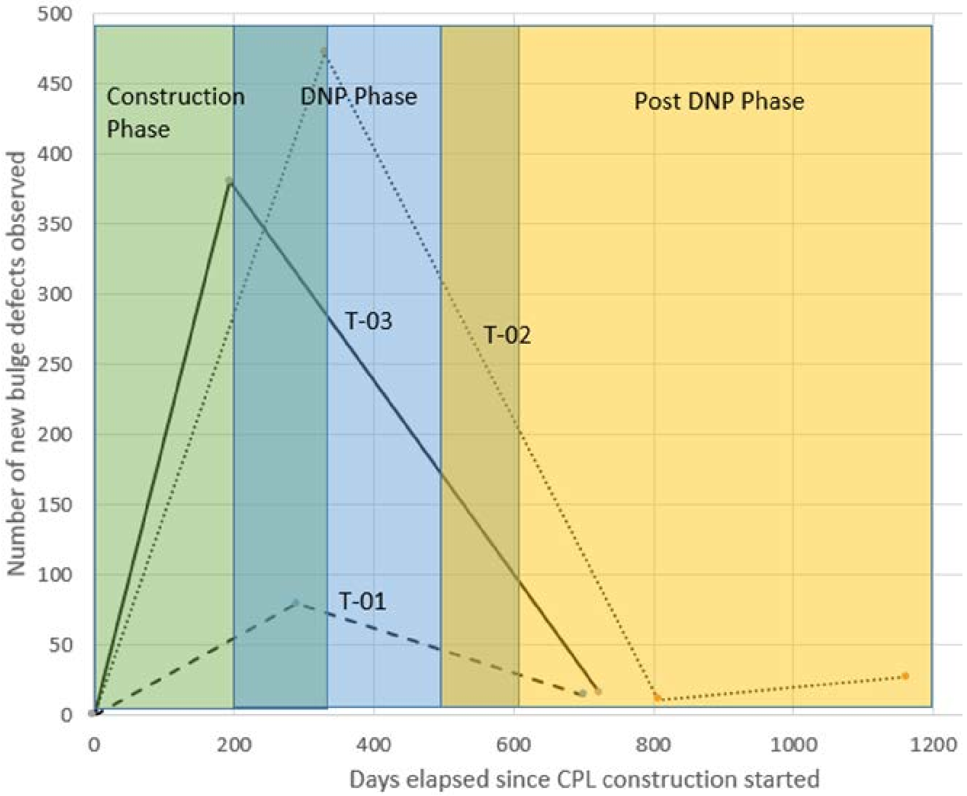


Figure 10. Graphical Summary of New Bulge Occurrence Over Time

Approximately four hotspots of concern were evident in Contracts T-02 and T-03, each approximately 110 m in length. In total this is 0.01 % on a lineal metre basis. These hotspots are further discussed below.

Hotspot Areas

Reviewing the occurrence of bulge defects with location for Contracts T-02 and T-03 yields some important observations (refer Figures 11 and 12 for Contracts T-02 and T-03 respectively). The key observations are as follows:

- Hotspots tend to be associated with the launch and backshunt/reception tunnels. In these areas, the permanent structural lining was provided by cast-in-place concrete cast integrally with the CPL secondary concrete and liner. These areas were heavily reinforced, as compared to the TBM tunnel sections (supported by precast segmental lining) for which the secondary concrete was unreinforced. Quality observations indicated that concrete placement in and around the reinforcement was problematic, whether due to placement, compaction, or close spacing of reinforcement, or a combination of the preceding factors.

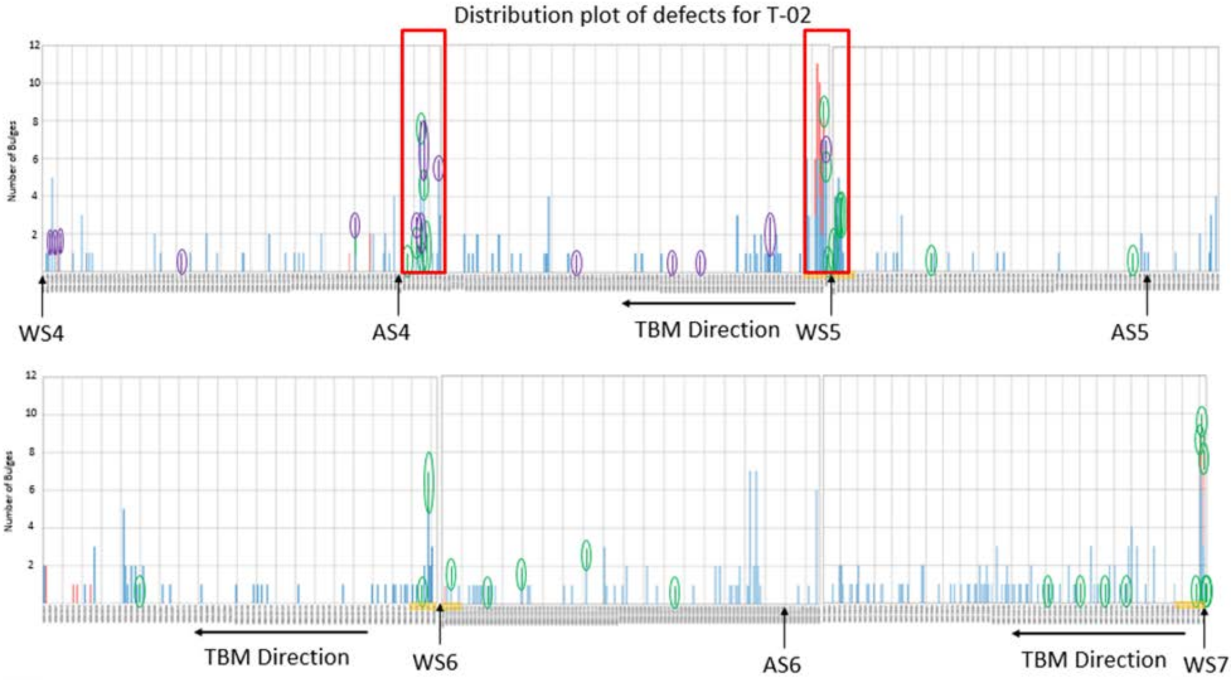


Figure 11. Contract T-02 Hotspots (highlighted in red)

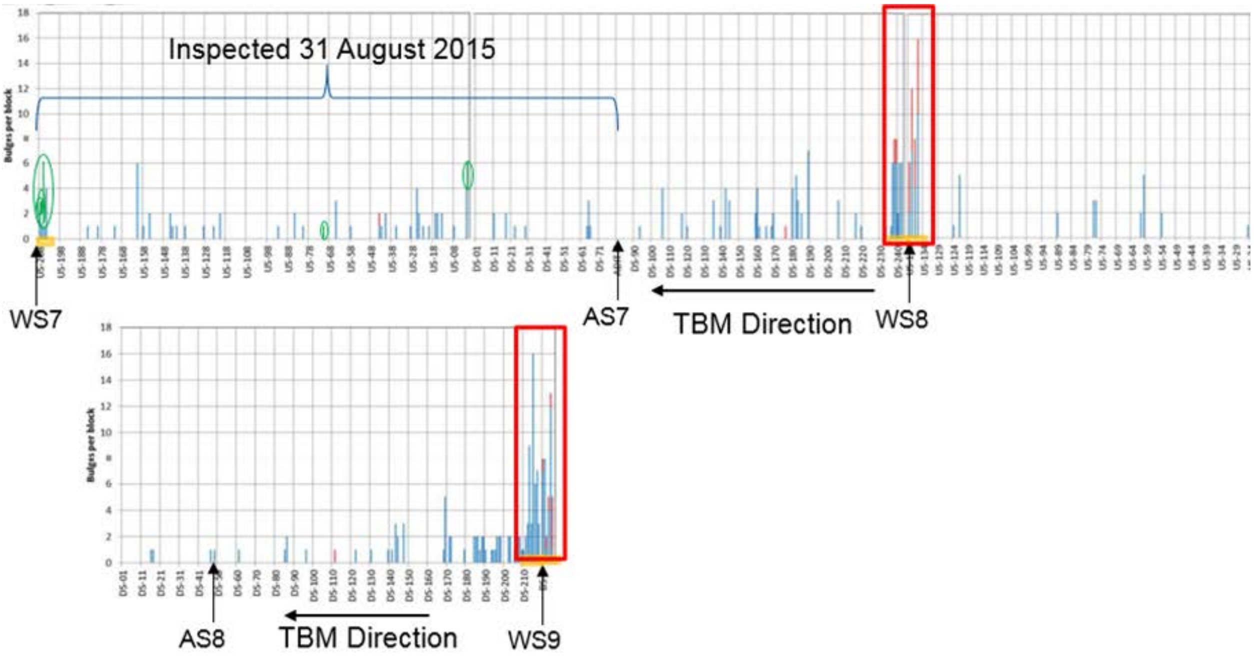


Figure 12. Contract T-03 Hotspots (highlighted in red)

- A hotspot is evident immediately downstream of Access Shaft AS4. This location coincides with the ‘learning curve’ area for the first CPL installation on Contract T-02 in the Work Shaft WS4-WS5 section.

From the Engineer’s observations and after reviewing the available information, it was considered that the main underlying causes of the defective concrete include:

- Interruption of concrete supply / delayed concreting. In some cases, the concrete lines between the pump and placement points became blocked, and concrete was left standing in the remixers for a longer period than planned. This delay caused cold joints, and possible voids or honeycombing.
- Failure to follow pour sequence. In some cases, the shutter crew failed to adhere to the prescribed pour sequence which may have resulted in greater drop heights and segregation of the concrete, along with possible voids where air may have become entrapped in the concrete.
- Under or over-compaction. Either alternative may have resulted in segregation, in particular the cement paste effect where aggregate is not present within the HDPE liner anchorage zone.
- Impediment to concrete placement by reinforcement in non-TBM tunnel sections. The concrete mix may not have been ideally matched to the placement conditions.

Further, it was the Engineer’s view that all bulge defects related to workmanship issues with the secondary concrete lining. There are no indications that the HDPE membrane is failing, i.e. with proper workmanship, the HDPE anchorages perform as required by the Specification in terms of pull out strength.

The Contract T-02 CQC reported after the March 2015 inspections that only three repairs had failed since the TOC was issued out of 472 repairs executed before issuance of the TOC, representing a rate of less than 0.6 %. The CQC and the Engineer considered that the repair methodology was sound, but occasional workmanship issues occurred during repair. In October 2015, during inspections of Contract T-02, the Engineer observed some defects to be very minor bulging associated with previous repairs. These defects are not a concern, but nevertheless required fixing.

Other Observations

Other observations made by the Engineer during the DNP phase include the following:

- There is no indication that the pressure relief aspect of the CPL system (i.e. drainage behind the HDPE membrane to invert) is not performing as designed. Un-anchored pressure relief strips at joints between vault pours are observed to be functioning, and minor levels of seepage water are observed to discharge from under the HDPE at the invert longitudinal joint, as designed.
- Pressure relief is verified by deposition of fans of gypsum salts at discharge points, e.g. pressure relief strips, where the seeping salt-rich groundwater is exposed to air and conditions are favourable for deposition.

- While some crown defects occurred, especially in non-TBM tunnel sections of the CPL, these tended to occur before TOC and were identified by sounding and repaired by contact grouting. The crown is the most likely position for voiding, but crown defects are not recurring. Most of the defects have occurred below tunnel springline.
- Regarding some of the other types of defect that occurred and were accepted without repair (e.g. minor rippling or undulations of HDPE surface), it is evident that there are no issues such as membrane de-bonding from concrete lining associated with these features.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

Based on the work performed to date, the following summary statements can be made:

- The two-pass CPL system selected (sacrificial secondary concrete lining covered internally by mechanically anchored HDPE liner) remains a very robust solution to meet required 80 year design life of the deep tunnel.
- The two-pass system is however sensitive to workmanship, and high-quality placement of concrete long distances underground in a confined environment is challenging. Bulge defects of varying severity and frequency were encountered in the STEP tunnels after taking-over, and these required rectification.
- No evidence has been observed of HDPE material degradation or mechanical failure.
- Evidence shows that the intended pressure relief approach (relieving water pressure from behind HDPE liner) is working.
- Key evaluation points regarding CPL bulge defects:
  - Overall, less than 0.09 % of the surface area of the tunnels were affected.
  - ‘Hot spots’ in the Contract T-02 and T-03 tunnels were observed to be located in non-TBM tunnels, where the CPL secondary concrete was cast integrally with the structural (reinforced) permanent lining.
  - At least one other ‘hot spot’ in the Contract T-02 tunnel is located where the CPL installation was started, which reflects some ‘learning curve’ challenges.
  - Most defects are below spring line of tunnel, and below the long term waterline, whereas highest sewer gas corrosion potential will occur in crown of the tunnel where limited defects were noted.

Conclusions

After considering the nature and occurrence of the CPL bulge defects, the following conclusions were reached:

1. **Is the CPL system, in particular the pressure relief system, working as intended?** The answer is clearly yes. No cases have been noted of internal failure (e.g. rupture or elongation failure) of anchored HDPE membranes, and discharge of seepage water from under the membrane to the invert is visible.

2. **Was the CPL system installed as intended?**
   Overall, the answer was yes. More than 99.9 % of the CPL surface area was unaffected by bulge defects. However, in isolated cases and in four hotspot areas affecting Contracts T-02 and T-03, it was evident that workmanship standards were lacking in respect of secondary concrete lining quality.

3. **What is causing the bulge defects?**
   The bulge defects are always observed to be associated with poor quality concrete. While in some cases voids/honeycombs occurred, most of the bulges are associated with aggregate-deficient zones of concrete in and around the HDPE membrane anchors. The Engineer expects most of these faults are related to placement method, and in a few cases to concrete standing before placement due to blockages or similar in concreting lines.

4. **What are the consequences of the bulge defects?**
   It is considered that the bulge defects were cosmetic in nature. Even if similar defects were to occur in the future, it is not expected that sheets of primary CPL membrane would detach. It is also not expected that the secondary CPL concrete will become exposed. If the secondary CPL concrete is exposed, then there will be sufficient sacrificial concrete to protect the tunnel structural segmental lining for the specified 80 year maintenance free design life. Thus, there is no significant concern about the long term structural integrity of the tunnel in relation to bulge defects. In the worst case, detached pieces of HDPE membrane may cause minor inconvenience to the downstream pumping station, but this risk is low.

5. **What actions were being taken to address the bulge defects?**
   The Engineer monitored DNP phase tunnel inspections, investigations and repairs. Additional non-destructive sonic velocity testing was undertaken to verify that the secondary lining was substantially satisfactory. All CPL defects were eventually repaired and the performance certificates were issued, signifying the contractors had fulfilled their obligations.

6. **Are bulge defects likely to keep occurring?**
   It is expected that the occurrence of the defects is a result of sub-strength concrete in the 12 mm membrane anchorage zone, combined with high groundwater pressures. As most of the tunneling was undertaken in ‘open mode’, it can be assumed that the groundwater around the tunnel was locally depressurized during construction, and is re-pressurizing with time. Thus, the occurrence of new bulge defects is seen to decrease with time, and is expected to keep decreasing. It is further noted that at the time of acceptance of the works (some 3 to 4 years after tunnelling was completed), all defective areas are likely to have been ‘proof-loaded’ by groundwater pressure, given the time that has elapsed since CPL construction. In the author’s experience, re-pressurization of groundwater in similar ground conditions and tunnelling methods is usually complete within several years of tunneling. While new bulge defects are not expected, any that do occur are likely to be minor in surface area and can be regarded as a ‘cosmetic’ level concern. This conclusion is based on the decreasing trend of new bulges observed between the various times of inspections and the limited extent of defects seen in the bulges that have occurred to date.

Recommendations for Future Applications

The following recommendations are made for future applications of two-pass CPL linings incorporating mechanically anchored plastic membranes:

- It is essential that the concrete mix is specifically designed for the application, coupled with tight specification and field control of concrete quality.
- Consider the merits of reducing the maximum aggregate size, so that the risk of segregation around membrane anchorages is decreased.
- Close supervision of concrete placement sequence behind shutters and vibration is also essential.
- Careful inspection and testing of pours is recommended where the concrete supply was interrupted.
- Consideration of longer HDPE anchorages, e.g. 20mm or longer. Anchor shape is an important consideration, some shapes may be more effective/reliable in mobilizing pull-out resistance than others.
- Pre-production test sections are strongly recommended, along with non-destructive and destructive testing to verify workmanship and concrete placement methodology/sequence.
- Consider longer Defects Notification Periods, e.g. up to two years, where CPL is exposed to significant groundwater pressures.
- At the outset, define an acceptance-rejection criteria for bulge defects based on surface area, i.e. the size at which defects must be repaired.
- Non-destructive sonic velocity testing was found to be ineffective for identifying small thicknesses (within or near to the membrane anchorages) of aggregate-deficient concrete behind the obscuring HDPE membrane.

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