# 2 APPLICATION OF CONDITION ASSESSMENT PRINCIPLES TO THE BLACKMAC SEWER

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## ABSTRACT

South Africa's municipal engineers and others involved with providing basic services face a multitude of challenges. Amongst these are technological developments and the demographic changes resulting from urban densification. Those responsible for technical decisions can be overwhelmed with these challenges and this influences their decision making. Hence at times the basic engineering principles for ensuring quality services are not always followed.

Recent water shortages have highlighted that South Africa is a water scarce country. New pipelines alone won't resolve the future water supply and wastewater disposal problems. Many performance problems with existing pipelines have probably been designed or built into them. The below surface holes are actually the assets; pipelines merely ensure their effective and efficient operation. Rehabilitating the existing 'holes' to enhance their performance can significantly reduce the service backlog.

The developments with multi-sensory inspection systems over the past decade provide a quantified as well as visual representation of conditions inside pipelines. Combining this with a corrosion and structural analysis of a sewers ability to meet its structural requirements means that the remaining life can be estimated.

This approach was applied to a 7.8 kilometre section of the Blackmac outfall sewer across the Cape Flats, consisting of 800 to 1 000 mm diameter coated fibre cement pipes installed during 1983. Most of the upstream 3.8 kilometres had sufficient capacity for the required flow and adequate structural integrity. The downstream section had been de-commissioned, had inadequate capacity and sections were severely corroded. A remaining life analysis indicated that sections had collapsed. At the end of 2016 contracts for rehabilitating and replacing sections of this sewer were awarded.

## INTRODUCTION

### Historical background and site description

Before going into the details of the technical and practical aspects of this project the historical background and a description of the site are given so that the condition assessment, design aspects and construction details can be seen in terms of the site constraints.

The Blackmac outfall sewer to the east of Cape Town is 14.4 km long. It ranges in diameter from 400 to 1 000 mm and was completed in 1983. Commencing at the southern boundary of the Blackheath Industrial area it drains the mainly residential areas of northern Blue Downs, Eerste River, Croydon and Macassar, before discharging into the Macassar pump station from where it is pumped to the Macassar wastewater treatment works (WWTW). It crosses under the Eerste River via an inverted siphon. To minimize solids settling out along the sewer and blockages in the siphon a screening and grit removal station was constructed between Old Faure Road and Baden Powell Drive where there was a change to a flatter gradient.

Sections of this outfall run parallel to, or very close to two other outfalls. The 1600 to 1900 mm diameter new Delft sewer was constructed in 2008 to alleviate the load on the 1 000 to 1 100 mm diameter Blue Downs sewer servicing the N2 Gateway housing development. These outfalls drain the areas of Delft, Driftsands, Mfuleni, the southern area of Blue Downs and Eerste River, before discharging into the Zandvliet WWTW.

The upper reaches where the three sewers run close to each other has a further complication as they run for some distance between a large storm water channel and Baden Powell drive.

During the construction of the new Delft sewer it was found that where the two sewers were supposed to cross each other just north of the N2 highway that they actually intersected each other. It was then decided to divert the Blackmac flow at this point into the new Delft sewer. Thus, all flow generated within the Blackmac sewer's catchment area north of the N2 highway was diverted and treated at the Zandvliet WWTW. The lower portion of the Blackmac sewer continued to drain the Croydon and Macassar residential areas into the Macassar pump station.

Recently the Zandvliet WWTW became overloaded due to a higher than expected increase in the flows from Delft outfall sewer's drainage area, as well as an increase in the organic loading of the sewage and it was unable to effectively treat the flows received. Flows from the diverted Blackmac exacerbated this problem. To mitigate this the decision was taken to re-connect the Blackmac outfall at the Delft intersection, thus allowing the flows in the Blackmac outfall to again drain to the Macassar pump station and be treated at the Macassar WWTW.

### Client's requirements

To ensure that the re-connected Blackmac outfall would effectively convey the required discharge to the Macassar WWTW the client, the City of Cape Town briefed the consultants, to assess the performance and condition of the 7.8 km of sewer, from the screening and grit removal station (Figure 1) to the Macassar pump station (Figure 2), before any design work was done. Apart from determining the condition of the Blackmac itself and the decisions made based on this as described in the main body of this text, this assessment showed that:

- The expected future peak sewage flows from the upper Blackmac, Blue Downs and Delft catchments when fully developed were 517 ℓ/s, 564 ℓ/s and 2 132 ℓ/s respectively. However the maximum hydraulic capacity of the Blackmac system was 347 ℓ/s. So it was not feasible to re-divert all of the required 517 ℓ/s via the Blackmac to the Macassar WWTW.
- Due to theft of the mechanical and electrical equipment and vandalism of the civil infrastructure at the screening and grit removal station at the upstream end of the Blackmac section under consideration this station was non-operational. This station had to be rebuilt to prevent siltation of the Eerste River siphon.
- The Macassar pump station had sufficient capacity to handle the expected future sewage flows including those from the Blackmac. However it required extensive refurbishment to extend its operational lifespan.

**FIGURE 1:** Screening and grit removal station

**FIGURE 2:** Macassar pump station

## THE THEORY

### Requirements to meet

When embarking on the design of a new sewer or rehabilitation of an existing sewer an understanding of the relationship between the various requirements is essential. The primary requirement of hydraulic capacity is based on a projection of the population at a date usually taken as 40 or 50 years into the future in the catchment area. Projecting further than this could risk seriously oversizing sewers. This is a judgement decision as the impact of urban densification will be mitigated by water conservation measures.

The secondary requirements of sewer strength, water tightness and durability are far more predictable and should be designed for a much longer service life (at least 100years). This approach should be coupled to designing to minimize operational and maintenance costs. So when the capacity limit of a sewer is reached this should not mean that it is no longer serviceable and has to be replaced or rehabilitated. A clear distinction should be drawn between the amortization period for a sewer which will probably correspond to its capacity limit and the service life which should be at least double this. The impact of urban densification and water conservation measures also influences these requirements and needs to be taken into consideration. There will be less space for digging trenches in the future and the effluent is likely to have higher biological and chemical concentrations resulting in a greater corrosion potential for certain materials and a more serious environmental impact if there are leakages. The financial implications of designing and installing sewers with minimal operation and maintenance costs and a service life that is at least double the time to reach capacity will mean a slight increase in capital costs, but a significant impact in reducing maintenance and operating costs and in the long term an even greater reduction on the life cycle costs.

Taking a broader view this means that more funds will be available for constructing new sewers, rather than replacing or rehabilitating the old ones, when the need arises. In the 1960's the then Johannesburg municipality held the view that if an outfall sewer lasted for 50years instead of 40years that it was worthwhile to pay double for its construction. As far as can be ascertained most, if not all the major concrete outfalls sewers installed in the Johannesburg area since this date are still operational and the increase in capital costs was apparently minimal. (prior to the 1960's there were outfall sewers that lasted less than 10 years)

### Loads on buried pipelines

Buried pipelines are subjected to loads that cause stresses in the pipe walls. These loads can be broadly defined as primary loads and secondary loads. Primary loads can be calculated and include mass of earth fill above pipe traffic loading and internal pressure. Other primary loads are the pipe and water masses that can be ignored, except in critical situations. For sewers that in most cases operate as gravity systems flowing partly full, internal pressures other than the possibility of the pipeline being surcharged due to a blockage, do not have to be considered. For the latter the pipes should be able to handle a nominal internal pressure that is well within the capability of the standard strength concrete and fibre cement pipes. Secondary loads are due to movements within the soil and are difficult to predict. They are accommodated by the pipe joints that are designed to seal even when movement takes place.

The calculation of earth loads on a buried conduit from first principles is complex. For a thorough understanding, reference should be made to SANS 10102 Part 2. The prime factors in establishing earth loads on buried conduits are the installation method, fill height over conduit, backfill density, trench width or external conduit width and the settlement of foundation material.

Although tables have been compiled for the various installation conditions an understanding of the differences between these is needed before using these tables. The two basic open cut installation types and the corresponding loading conditions are the trench and the embankment conditions. These are defined by whether the frictional forces developed between the column of earth on top of the conduit and those adjacent to it reduce or increase the load that the conduit has to carry. A useful concept is that of the geostatic or prism load. This is the mass of earth directly above the conduit assuming that there is no friction between this column of material and the columns of earth either side of the conduit. The geostatic load will have a value between that of the trench and embankment condition. These conditions are illustrated in Figure 3.

The trench condition occurs when the conduit is placed in a trench that has been excavated into the undisturbed soil. With a trench installation the frictional forces that develop between the column of earth in the trench and the trench walls act upwards and reduce the load that the conduit has to carry. As a result the load on the conduit will be less than the mass of the material in the trench above it.

For the embankment installation condition the conduit is installed at ground level and is covered with fill material. All the earth surrounding the conduit is homogeneous and the compaction is uniform. With an embankment installation the frictional forces that develop between the column of earth directly above the conduit and the columns of earth adjacent to the conduit, act downwards and increase the load that the conduit has to carry. Hence the influence of the founding material on embankment loading is significant. The load on the conduit will be greater than the mass of the material directly above it due to the frictional forces that develop.

### Pipe strength

Factory test loads and reactions are concentrated, but field loads and reactions have a uniform, parabolic or radial distribution. The structural

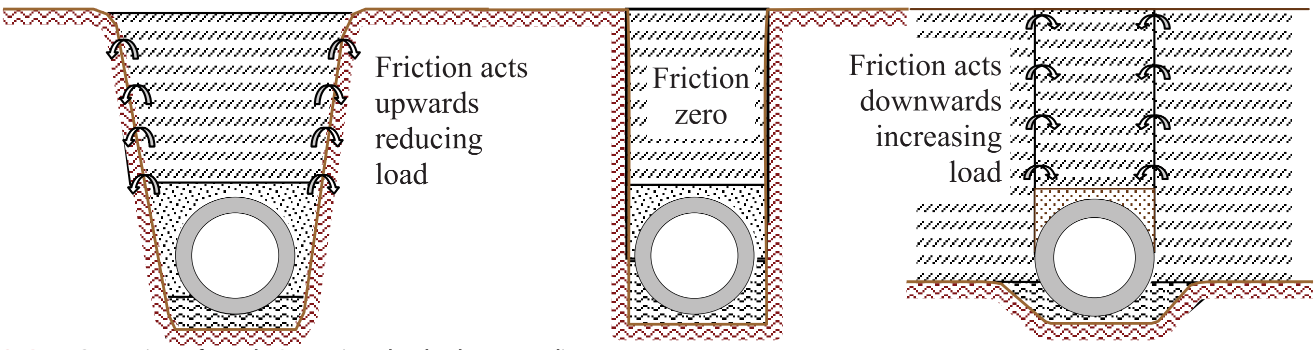


**FIGURE 3:** Comparison of Trench, Geostatic and Embankment Loading

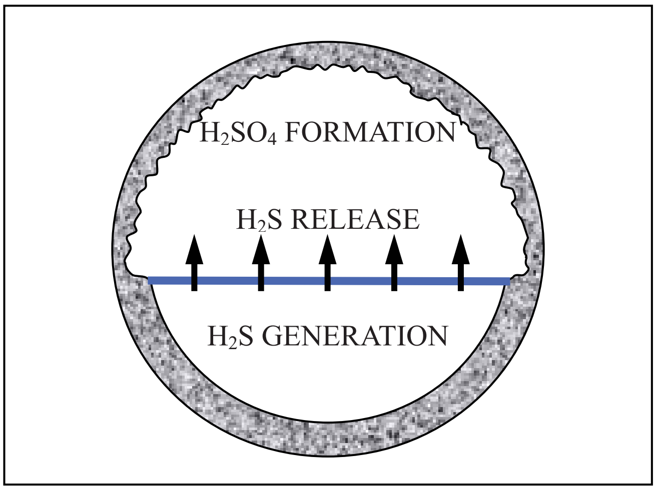


**FIGURE 4:** Corrosion mechanism in concrete sewers

requirements for rigid pipes are specified in terms of the pipe strength, whereas the structural requirements of flexible pipes are defined in terms of their deflection. It is assumed that in-situ loads are uniformly distributed over a pipe and that reactions are either parabolic or uniform, depending upon the bedding material. This is realistic for sewers as they are usually placed with at least 600 mm of ground cover over them, except in the case of larger diameter pipes where this cover should be at least half the pipe diameter so that any traffic loads are distributed over the whole outside pipe diameter.

### Corrosion of cementitious sewers

There are three sets of factors contributing to this phenomenon: those resulting in the generation of hydrogen sulphide gas ($H_2S$) in the effluent, those resulting in the release of $H_2S$ from the effluent and those resulting in the biogenic formation of $H_2SO_4$ on the sewer walls. These are illustrated in Figure 4. If there is insufficient oxygen in the effluent (less than 1 mg/lt) the bacteria that live in the slimes layer on the sewer walls strip the oxygen from the sulphates in the effluent to form sulphides. A proportion of these will be the gas $H_2S$. The first set influences the rate at which this occurs. When there is an imbalance of $H_2S$ in the sewage and the sewer atmosphere this gas will come out of solution until there is equilibrium between the gas concentration in the sewage and the sewer atmosphere. The second set influences this. The $H_2S$ released into the sewer atmosphere is absorbed into the moisture on the sewer walls and is oxidised by another set of bacteria to $H_2SO_4$ under the influence of the third set of factors.

When the pipe material has an alkaline component, as is the case with cementitious pipes, this will react with the acid formed resulting in corrosion above the flow level. These products of corrosion are about five times the volume of the original material and as they are porous they absorb moisture and become heavier. On concrete pipes the saturated products of corrosion fall off the pipe wall when they reach a certain thickness and mass as they have little strength thus exposing fresh concrete to further acid attack. With fibre cement pipes the saturated products of corrosion are held together for a much longer period and the pipe walls eventually swell to several times their original thickness. This masks the condition of the pipe wall and makes it difficult to determine how much sound material is left to give the pipe strength. In both situations the loss of sound material results in a loss of pipe strength.

If an inert aggregate is used the mortar between the course aggregate corrodes and loosens it leading to aggregate fall out. This exposes more of the binder that in turn is corroded by the acid and the process continues. The deterioration of the pipe wall can be rapid. If concrete is made using a calcareous aggregate which is alkaline, the acid attack is spread over both binder and aggregate, the aggregate fallout problem is minimised and the rate at which the sewer wall deteriorates is reduced. As the pH of calcareous aggregate is less than that of cement the rate at which the acid attacks this is slower than the rate at which the cement binder is attacked and there will still be some aggregate fallout, but at a much reduced rate.

Concrete corrosion rates are determined from the rate at which the $H_2S$ flux to the pipe wall is oxidised to $H_2SO4$. According to Bowker & Smith, 1985 "34 g of $H_2S$ are required to produce sufficient $H_2SO_4$ to neutralise 100 g of alkalinity expressed as calcium carbonate ($CaCO_3$) equivalent".

There are three options for preventing or minimising the corrosion in concrete sewers:

- preventing acid formation;
- modifying the concrete; and
- protecting the concrete.

Acid formation can be prevented or minimized by adjusting the hydraulic design of the sewer. If self-cleansing gradients at all flow levels can be maintained throughout the whole system then sufficient oxygen (>1.0 mg/lt) should be entrained in the effluent to prevent the formation of sulphides. However, due to physical constraints this is not always possible and some corrosion should be anticipated. To minimize this careful attention should be given to the detailing of transitions to minimize turbulence and gradients should be adjusted to eliminate supercritical flow. In most sewers, modifying the concrete by changing the concrete components and/or providing additional cover over reinforcement is the most cost-effective option. Protecting concrete by using an inert lining or coating is effective, but only economically justifiable when severe corrosion is predicted and for larger diameter sewers (1 200 mm diameter and greater).

### Remaining life

Most large diameter outfall sewers are made with cementitious materials such as reinforced concrete or fibre reinforced concrete and these can deteriorate with age, depending upon the operating conditions. The critical issue for the owner is the sewer's remaining life before it needs rehabilitation or replacement. A secondary issue is how effectively and efficiently the sewer will perform during this remaining life. Answers to these questions will depend to a large extent on the pipe material used.

For sewers using concrete or other rigid pipe materials the strengths initially required along the sewer to carry the actual loads are calculated based on the installation conditions. Assuming with time that the material around the pipes remains intact it will consolidate and the loads on the pipes will probably be less than those originally used to determine the pipe strength. On the other hand, if cavities have formed around the pipes and bedding support has been lost, the load carrying capacity will be less than it was when the pipes were installed and premature collapsed can occur.

When the pipe material has been subject to corrosion this must be taken into account. The corrosion just above the average effluent flow level (about half way up the pipe) is usually greater than that at the crown of the pipe, so the residual strength will have to be calculated for both the wall thickness on the pipe crown and at the sides to determine which is critical. As these pipes are generally reinforced and this reinforcement generally accounts for at least half the pipe's strength, a good indicator of the residual strength is whether or not the reinforcement is exposed, where it is exposed and the extent to which it has corroded. If the steel at the crown of a pipe is corroded through at places then the pipe could be very close to collapsing and will probably have to be replaced. On the other hand if the steel is exposed and corroded at the sides of a pipe and not exposed at the crown, the pipe will still have some strength and the pipe can probably be rehabilitated. With a non-reinforced cementitious pipe the residual strength will be determined using the actual wall thicknesses at the crown and side of the pipe and an assumed flexural tensile strength of the material.

The required pipe strength based on the actual installation conditions needs to be compared to the predicted pipe strength based on the remaining wall thickness and whether or not the steel reinforcement if any is still intact. This will indicate just how much residual strength the pipes have. The remaining life of the pipes can then be estimated by applying the Life Factor approach to their residual strength or by calculating the annual rate of material loss over time. This is a fairly complex exercise for a reinforced concrete pipe as there will be a dramatic loss of strength once the reinforcement is no longer intact, but a simpler exercise for a non- reinforced cementitious pipe.

### Condition assessment

Condition assessment involves more than gathering and processing the visual data from inside a pipeline using a CCTV camera and categorising faults. More broadly, it involves gathering data from as many sources as possible, including:

- desktop study
- hydraulic performance (size)
- water tightness (joints)
- all aspects of the pipe soil system (structure)
- effluent composition (durability).

This information is used to determine the sewer performance as well as the condition of the pipes, the joints and the soil around them both qualitatively and quantitatively.

The desktop study should consist of a preliminary overview that is done before undertaking any internal inspections with emphasis on the system hydraulics to locate where there are:

- flat gradients or changes from steep to flat gradients and deposition is likely to occur
- rising mains, rising mains feeding into the sewer or siphons where $H_2S$ is likely to be generated
- steep gradients where $H_2S$ is likely to be released as downstream of where $H_2S$ is likely to be generated

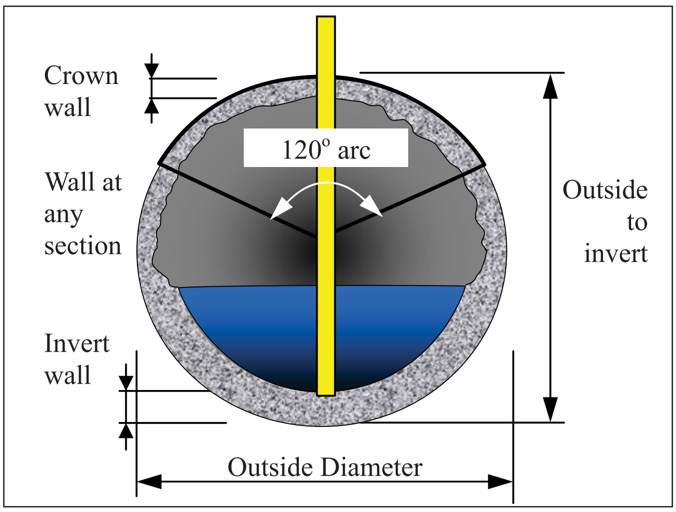


**FIGURE 5:** Illustration of an inspection window

- sudden changes in vertical and horizontal alignment, as this is typically where $H_2S$ release is a problem
- residential, commercial or business developments in close proximity to the sewer
- other services in close proximity to the sewer
- sections of sewer running in close proximity to transportation routes
- high fills over the sewer in particular where these are below transport routes
- sections of sewer traversing wet lands, adjacent to watercourses or below the 50/100 year flood lines

This preliminary study should identify any critical sections on the sewer where it may be necessary to do some preliminary checks by doing short inspection either side of manholes to determine whether there are sections of sewer that need to be cleaned before inspection and whether the camera should be transported through the sewer on a tractor or a pontoon. Together with the surface inspection of the site it will greatly assist in planning the subsurface inspections.

The introduction of lasers for above water scanning and sonars for below water scanning can now be added to a pontoon carrying the CCTV camera and provide a digitized profile of the whole pipe surface and its internal dimensions, including siltation levels at very close centers. As the information from this multi-sensor inspection (MSI) is digitized the full 360° of the pipe surface along a prescribed length of sewer can be represented in two dimensions as a colour coded 'flat sheet' which illustrate the extent of defects. The MSI provides valuable information, but still do not provide a complete picture. It is therefore recommended that a few spot physical measurements be made. This involves identifying sections of a sewer where severe corrosion is anticipated which can be exposed easily from the surface and cutting a window into the sewer so a physical inspection can be done. If necessary measurements, photographs and material samples can be taken. Such a window is illustrated in Figure 5. This type of inspection can be carried out concurrently with a MSI survey and the physical measurement used to calibrate and verify the digitized data to provide a comprehensive impression of the sewer condition.

When there is the potential of gas in the system which there will be if corrosion has taken place it is essential that the sewer be ventilated before doing any physical measurements and a gas detection meter should be a standard part of the equipment to check for $H_2S$.

## ASSESSING CONDITION OF BLACKMAC

### Desktop study

An evaluation of the hydraulic performance of the sewer using the gradients, pipe dimensions and other details on the long sections and plans of the 'as built' drawings and the manhole (MH) numbers given on these the sewer was divided into several sections, although the relevant sections for this paper are between the pump station and the grit removal station:

- Pump station upstream to siphon: MH 122 – MH 89
- Siphon: MH 89 – MH 88
- Siphon upstream to N2: MH 89 – MH 81
- Under N2: MH 81 – MH 80
- N2 upstream to MH 63: MH 80 – MH 63
- Grit chamber section: MH 63 – MH 59
- MH 59 upstream to MH 46
- Upstream section: MH 46 – MH 1

Figure 6 gives a schematic plan of this sewer showing the main features

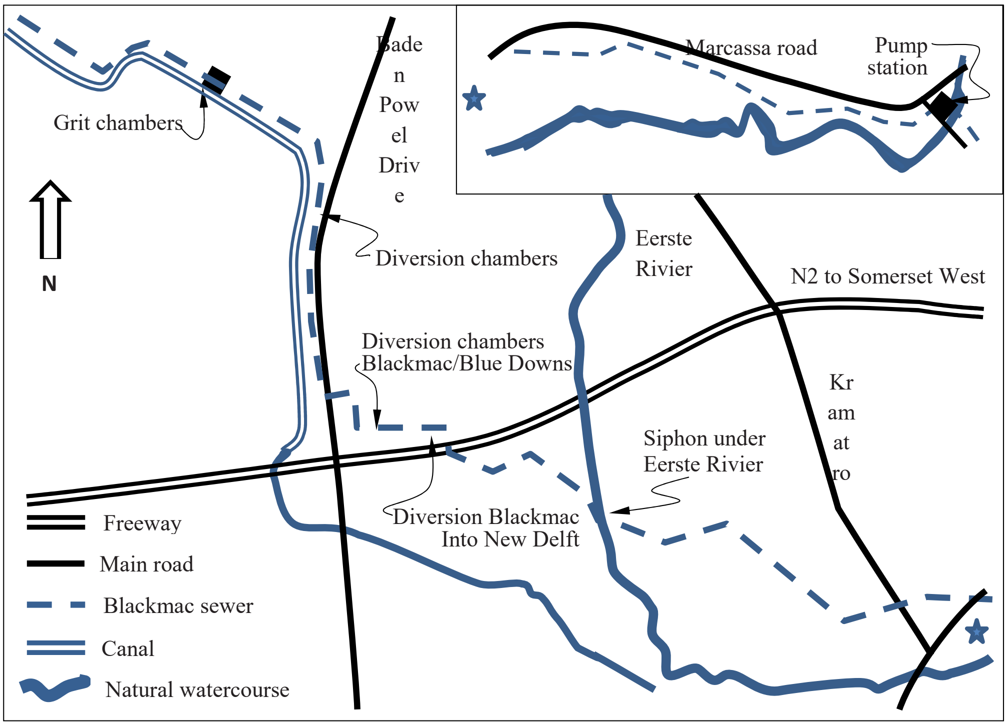


**FIGURE 6:** Schematic layout of Blackmac outfall sewer showing location of main features

section downstream of Macassar road ran along the edge of the wetlands adjacent to the Eerste River. Surcharging of the manholes or leaking joints would flow directly into these wetlands causing pollution.

A study of CCTV inspections of sections of sewer done during 2009 and 2011 confirmed that the condition of the sewer upstream of the siphon was not too serious, but was deteriorating and that the sections downstream of the siphon were not in good condition and required urgent attention.

From a structural perspective the fill height over the pipes could be obtained directly from the long sections. The fill heights, except for those at the road crossings and for a short section near the downstream were all less than 3.0 m and unless corrosion was serious would not pose a structural problem. There was initially conflicting information about the pipe wall thicknesses. The 'as built' drawing details indicated that 900 mm diameter class 18 FC pipes with a 54 mm wall were used for most of the downstream section. A 2011 investigation done on behalf of the client indicated that class 6 pipes with a 28 mm wall were used. For 900 mm ND pipes the crushing loads for these walls would be 188 and 58 kN/m, equivalent to 64 and 208 D loads respectively. Alternatively these could have been series '2' or '3' pipes as per SABS 819 – 1985, with 28 or 36 mm walls and which were equivalent to 48 and 72 D load pipes respectively. It was therefore necessary to determine the thickness of the corroded material on the pipes and on the basis of this estimate the remaining wall thickness.

A detailed analysis of the sewer's hydraulic capacity showed that this was inadequate for the future flows and that downstream of the siphon this was seriously inadequate. However as there were diversion chambers the flow could be redirected into the other sewers limiting the flow through the Blackmac to 347 l/s (30 Ml/day) which could be accommodated in the sewer upstream of the siphon. Due to constrains on gradient and the additional flows anticipated a larger diameter pipe was needed downstream of this.

along the route between the pump station and just upstream of the grit chambers. To avoid clutter the manhole numbers are not shown. Tracing the route on Google Earth was also done and gave a useful overview of the route and surrounding area.

From a hydraulic perspective this study indicated several locations where siltation could be expected either due to severe changes in vertical alignment or sharp bends. In theory the velocity downstream of the siphon to the pump station was between 0.7 and 0.75 m/s at a flow depth that was 50% of the diameter. At velocities as low as this siltation could be expected and once this is initiated the flow profile and roughness of the pipe invert change, resulting in a reduced flow capacity. In addition to this the theoretical capacity of this section of sewer, when flowing full was 347 l/s which was significantly less than the 517 l/s required.

As this lack of capacity was downstream of the siphon where gas would be generated it was anticipated that additional $H_2S$ gas would be generated in the sewer itself and its later released could result in corrosion being a serious problem. The probability of deposition would exacerbate the situation as the solids deposition along the sewer invert would provide additional habitat for the bacteria producing sulphides.

From the desktop study, including reference to Google Earth, various topographic features were identified (see Figure 6) that could influence decisions about replacing or re-routing sections of the sewer.

- All the way from the grit station to just upstream of the N2 crossing the three sewers were in close proximity. There were sections where they ran parallel to each other. For part of this distance they ran adjacent to a canal and between this and Baden Powell Drive. Having to excavate in this area would have to be done with care to ensure no damage or unsymmetrical loading to any of these sewers.
- There were three chambers where the flows could be diverted from one sewer into one of the others.
- There were four road crossings, Baden Powell Drive, N2 Freeway, Kramat road and Macassar road.
- A short section of the sewer just upstream of Kramat road and longer

## Site inspection

The route was walked wherever access was possible to gain an overall impression of the conditions along the route and locate, identify and inspect the manholes. Photographs were taken for record purposes. Relevant aspects of this were:

- The grit chamber had been vandalized to the extent that it was in effect non-functional with the sewage just seeping through a jumble of broken slabs and debris.
- Many of the manhole cover slabs had been broken to recover the reinforcement and the lids removed. These open manholes were a serious safety hazard to anyone walking in the area as many were partly covered with vegetation. On the other hand these sewers were ventilated and no $H_2S$ smell was detected.
- Due to this it was not possible to locate all the manholes.

**FIGURE 7:** Severe corrosion just downstream N2

- The steel sluices and other equipment in the diversion structures just upstream of the N2 had been stolen, but the Blackmac had nevertheless diverted as the downstream manholes had been filled with junk.
- As the manholes downstream of the blockage were dry and open they could be accessed and the pipes visually inspected. This was useful as the deterioration of the coating could be ascertained. (Due to the amount of debris in the sewer it was not feasible to inspect several reaches with CCTV). Although the coating had bubbled it was still generally intact. However the pipes had swollen at the joints.
- In the manholes that could be physically accessed the products of corrosion could be scrapped off and an estimate made of the thickness of corroded material.
- The manhole immediately south of the N2 was accessible and it was established that only a short section at the inlet and outlet to this road crossing was severely corroded (see Figure 7).
- There was severe flooding of the farmlands just south of the N2. This would have implications for the design of any lining systems as this water was about 1.0 m above ground level.

### Internal inspections

As the condition assessment and design was done during 2014 further CCTV inspections were done to obtain a visual record of the conditions inside the sewer and determine whether there had been further deterioration since the inspections undertaken during 2009 and 2011. On several sections a MSI was done to obtain the dimensional details of corrosion above flow levels and siltation below these levels. Due to inaccessibility along sections of the route and the amount of siltation along other sections of the sewer it was not possible to do a complete inspection of the whole sewer using all these techniques. Sufficient information was however obtained when combined with that provided by the earlier inspections to make a realistic assessment of the sewer along its whole length.

These inspections confirmed the theoretical evaluation that corrosion had occurred and the fact that it was far more advanced downstream of the siphon than upstream of it. There were locations downstream of the siphon where the coating had disappeared completely and others where the corrosion had caused the coating to form large bubbles.

### Determining remaining life of sewer

Once the coating has deteriorated, as it had, the underlying material will corrode rapidly and the residual strength will be dependent upon the thickness of the remaining sound material in the pipe wall. Clearly from the details of sample thicknesses cut from the sewer near the pump station and given in an earlier report the pipes had lost a significant proportion of their wall thickness and their residual strength cannot be guaranteed should this section of the sewer be commissioned. Figure 8 shows the amount of swell on the pipe wall a few manholes upstream of the pump station.

The swell of up to 44 mm on the 900 mm ND FC pipes indicates that at least 11 mm of material had been corroded away indicating an original wall of between 32 and 38 mm. On the basis of this it was taken that the original pipes were series '3' pipes as per SABS 819 which would be equivalent to 72 D load pipes in terms of the concrete pipe specification. With a protective coating these would be adequate to take the external loads, but once the coating fell away and the pipe wall started corroding the residual strength of the pipes would be compromised.

An analysis showed how much fill the pipes in their condition at the time of the assessment could take and which pipes in theory could have already collapsed. In fact there were two of the four critical areas, namely those under Kramat Road MH 103 – MH 104) and Macassar Road (MH 107 – MH 109) which could not be inspected during 2011 and a third, namely that either side of a measuring chamber (MH 120A –MH120B) which could not be inspected during 2014, apparently due to siltation. These sections may already have collapsed. The fact that two of these sections were under roads that carry fair traffic volumes was serious and meant that the pipes under these roads would have to be replaced rather than rehabilitated.

To predict the remaining life of these sections of sewer would have involved an analysis of the reach between each pair of upstream and downstream manholes based on the remaining wall thickness and a prediction of hydrogen sulphide ($H_2S$) generation and release. As there are no $H_2S$ readings available a more pragmatic way of doing this was to base the analysis on the information available. As the sewer was coated with epoxy tar it would have been protected for at least 10 to 15 years and as lower reaches of the sewer have been out of commission since 2009 the pipe wall was exposed to the corrosive environment for between 4 and 9 years. Based on this the maximum loss of ±16 mm indicates an annual material loss of 1.8 – 4 mm per annum which would indicate very severe conditions. There is however a very real possibility that the $H_2S$ transported into the pump station by the Macassar sewer has also been transported upstream from the pump station into the Blackmac sewer. Under these circumstances the exposure period would be extended to between 9 and 14 years giving corrosion rates of between 1 and 1.8 mm per annum.

**FIGURE 8:** Swelling due to corrosion of FC pipe

**TABLE 1:** Remaining life of FC pipes based on dimensions taken between manholes 89 and 122

| Initial details | | | 2011 Details | | | Predicted collapse | | | Fill heights | | | Remaining life | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U/S | ND | OD | Wall | Lc | D | Wall | Lc | D | Ultim | Safe | Actual | loss | 1 mm | 2 mm |
| MH | mm | mm | mm | kN/m | Load | mm | kN/m | Load | m | m | m | mm | yrs | yrs |
| Siphon | | | | | | | | | | | | | | |
| 89 | 800 | 864 | 30 | 51.4 | 51.4 | 22.1 | 28.1 | 28.1 | 3.3 | 2.6 | 2.6 | 7.9 | 7.9 | 4.0 |
| 90 | 800 | 864 | 30 | 51.4 | 51.4 | 18.4 | 19.6 | 19.6 | 2.3 | 1.8 | 1.8 | 11.6 | 11.6 | 5.8 |
| 96 | 800 | 864 | 33 | 61.9 | 61.9 | 10.6 | 6.6 | 6.6 | 0.8 | 0.6 | 0.6 | 22.4 | 22.4 | 11.2 |
| 97 | 800 | 864 | 33 | 61.9 | 61.9 | 10.6 | 6.6 | 6.6 | 0.8 | 0.6 | 0.6 | 22.4 | 22.4 | 11.2 |
| 98 | 800 | 864 | 33 | 61.9 | 61.9 | 10.6 | 6.6 | 6.6 | 0.8 | 0.6 | 0.6 | 22.4 | 22.4 | 11.2 |
| 99 | 800 | 864 | 32 | 58.3 | 58.3 | 13.7 | 10.9 | 10.9 | 1.3 | 1.0 | 1.0 | 18.3 | 18.3 | 9.2 |
| 100 | 800 | 864 | 32 | 58.3 | 58.3 | 10.6 | 6.6 | 6.6 | 0.8 | 0.6 | 0.6 | 21.4 | 21.4 | 10.7 |
| 101 | 800 | 864 | 31 | 54.8 | 54.8 | 13.7 | 10.9 | 10.9 | 1.3 | 1.0 | 1.0 | 17.3 | 17.3 | 8.7 |
| 102 | 800 | 864 | 31 | 54.8 | 54.8 | 12.2 | 8.7 | 8.7 | 1.0 | 0.8 | 0.8 | 18.8 | 18.8 | 9.4 |
| 103 | 900 | 972 | 31 | 48.9 | 43.5 | 20.7 | 22.0 | 19.6 | 2.3 | 1.8 | 1.8 | 10.3 | 10.3 | 5.2 |
| Kramat | 900 | 972 | 31 | 48.9 | 43.5 | 34.0 | 58.6 | 52.1 | 6.0 | 4.8 | 4.8 | -3.0 | -3.0 | -1.5 |
| 104 | 900 | 972 | 31 | 48.9 | 43.5 | 21.8 | 24.4 | 21.7 | 2.5 | 2.0 | 2.0 | 9.2 | 9.2 | 4.6 |
| 105 | 900 | 972 | 31 | 48.9 | 43.5 | 20.7 | 22.0 | 19.6 | 2.3 | 1.8 | 1.8 | 10.3 | 10.3 | 5.2 |
| 106 | 900 | 972 | 31 | 48.9 | 43.5 | 21.8 | 24.4 | 21.7 | 2.5 | 2.0 | 2.0 | 9.2 | 9.2 | 4.6 |
| 107 | 900 | 972 | 20 | 20.6 | 18.3 | 21.8 | 24.4 | 21.7 | 2.5 | 2.0 | 2.0 | -1.8 | -1.8 | -0.9 |
| Macassar | 900 | 972 | 20 | 20.6 | 18.3 | 29.3 | 43.8 | 38.9 | 4.5 | 3.6 | 3.6 | -9.3 | -9.3 | -4.7 |
| 108 | 900 | 972 | 20 | 20.6 | 18.3 | 23.9 | 29.3 | 26.0 | 3.0 | 2.4 | 2.4 | -3.9 | -3.9 | -2.0 |
| 109 | 900 | 972 | 20 | 20.6 | 18.3 | 21.8 | 24.4 | 21.7 | 2.5 | 2.0 | 2.0 | -1.8 | -1.8 | -0.9 |
| 110 | 900 | 972 | 21 | 22.7 | 20.2 | 20.7 | 22.0 | 19.6 | 2.3 | 1.8 | 1.8 | 0.3 | 0.3 | 0.2 |
| 111 | 900 | 972 | 21 | 22.7 | 20.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 21.0 | 21.0 | 10.5 |
| 112 | 900 | 972 | 21 | 22.7 | 20.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 21.0 | 21.0 | 10.5 |
| 113 | 900 | 972 | 19 | 18.6 | 16.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 19.0 | 19.0 | 9.5 |
| 114 | 900 | 972 | 19 | 18.6 | 16.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 19.0 | 19.0 | 9.5 |
| 115 | 900 | 972 | 21 | 22.7 | 20.2 | 23.9 | 29.3 | 26.0 | 3.0 | 2.4 | 2.4 | -2.9 | -2.9 | -1.5 |
| 116 | 900 | 972 | 21 | 22.7 | 20.2 | 25.8 | 34.1 | 30.3 | 3.5 | 2.8 | 2.8 | -4.8 | -4.8 | -2.4 |
| 117 | 900 | 972 | 21 | 22.7 | 20.2 | 21.8 | 24.4 | 21.7 | 2.5 | 2.0 | 2.0 | -0.8 | -0.8 | -0.4 |
| 118 | 900 | 972 | 22 | 24.9 | 22.1 | 21.8 | 24.4 | 21.7 | 2.5 | 2.0 | 2.0 | 0.2 | 0.2 | 0.1 |
| 119 | 900 | 972 | 22 | 24.9 | 22.1 | 21.8 | 24.4 | 21.7 | 2.5 | 2.0 | 2.0 | 0.2 | 0.2 | 0.1 |
| 120A | 900 | 972 | 22 | 24.9 | 22.1 | 29.3 | 43.8 | 38.9 | 4.5 | 3.6 | 3.6 | -7.3 | -7.3 | -3.7 |
| Chamber | 900 | 972 | 22 | 24.9 | 22.1 | 31.0 | 48.9 | 43.5 | 5.0 | 4.0 | 4.0 | -9.0 | -9.0 | -4.5 |
| 120B | 900 | 972 | 22 | 24.9 | 22.1 | 27.6 | 38.9 | 34.6 | 4.0 | 3.2 | 3.2 | -5.6 | -5.6 | -2.8 |
| 121 | 900 | 972 | 22 | 24.9 | 22.1 | 15.4 | 12.3 | 10.9 | 1.3 | 1.0 | 1.0 | 6.6 | 6.6 | 3.3 |
| 122 | 900 | 972 | 27 | 37.3 | 33.1 | 13.8 | 9.9 | 8.8 | 1.0 | 0.8 | 0.8 | 13.2 | 13.2 | 6.6 |

## NOTES

1. Lc = 47.37 (t2/D)
   Where Lc is the crushing load; t is thickness; D is average of ID and OD. 47.37 is constant based on a flexural strength of 45 MPa for the saturated FC pipes as given in SABS 819
2. Series 3 pipes with an ultimate crushing strength, Lc of 90 kN/m/m have been assumed
3. The safe in service load has been based on Lc/1.25 and a bedding factor of 2.0
4. Earth loading is assumed to be geostatic as material will have settled and consolidated around pipes
5. Backfill density has been assumed at 20 kN/$m^3$
6. The relationship of D load = Lc/(1.25 *ND) has been used
7. The actual fill heights have been obtained from the 'as built' drawings
8. The lines highlighted in grey and pink are those where calculations relate to samples cut from the sewer.
9. The lines highlighted in pink relate to sections that in theory should have collapsed.

### Decisions taken

The analysis summarized in Table 1 shows the anticipated remaining life of the various reaches of sewer based on the detail gathered and the above discussion. The numbers in red indicate that, in theory several reaches of this section of sewer under higher fills may have already collapsed as the residual strengths, based on the structural wall remaining are inadequate to take the superimposed loads.

By considering the structural condition, hydraulic performance and corrosion potential of sections of this sewer it was clear that the section upstream of the siphon could be rehabilitated and the section downstream of this would have to be replaced.

The selection of rehabilitation technique to be used for the sewer upstream of the siphon and of pipe material for the replacement sewer downstream of the siphon are beyond the scope of this paper. After evaluation all the facts including the condition assessment exercise the final decision was to rehabilitate the upstream section with a cured-in-place pipe and to replace the downstream section with a polyethylene lined concrete pipe.

## CONCLUDING REMARKS

By applying condition assessment principles the problems on this sewer were located and classified, and their extent and severity determined. This output was combined with the basic principles of hydraulics, loads on buried pipelines and the biogenic corrosion of concrete to identify the causes of the problems and access the risks of not addressing them. This meant that sound technical decisions could be made about whether or not to rehabilitate or replace sections of this outfall.

The project went out to tender as three separate contracts; the rehabilitation of the sewer from the screening station to the siphon, the replacement and partial re-alignment of the sewer from the siphon to the pump station and the building of a new screening station plus the refurbishment of the pump station. Details of these were:

1. Upstream of the N2 the existing sewer had the capacity for future flows if cleaned and lined. The proximity of the other sewers and the canal, the reasonable sewer condition and the trench depths required by a new installation favored rehabilitation.
2. The ends of the sewer reach under the N2 needed urgent attention and consideration was initially given to letting this out as an advance contract.
3. Between the N2 and the siphon the existing sewer had the capacity for future flows if cleaned and lined and the structural condition was reasonable. However the ease of access and shallow excavations made the choice of rehabilitation or replacement an economic one.
4. Downstream of the siphon the remaining life of the sewer was limited and there were sections that appeared to have partly collapsed. In addition the capacity was seriously inadequate for future flows. Clearly replacement with a new sewer that had the required future capacity was required.
5. As the downstream section of the original sewer went through the wetlands adjacent to the Eerste Rivier the new sewer was realigned and placed north of the Macassar road to avoid them, even though this required deeper trenches.
6. Due to the small level difference between the siphon and the Macassar pump station the gradient was extremely flat and special requirements for tighter tolerances on the pipes and sewer alignment were specified.
7. The corrosion on the sewer from the siphon to the downstream end was severe, so polyethylene lined concrete pipes were specified as these met the hydraulic, structural and durability requirements and could also be laid at the flat gradient required by using the correct installation technique.
8. The various structures along the sewer, namely the diversion chambers, the siphon and the pump station needed refurbishment and this was included in the construction projects. The screening station was in such poor condition that it was redesigned and its reconstruction together with the refurbishment of the pump station let as a separate project.
9. This is probably a first in South Africa where the output from multi sensor inspection techniques were combined with established design principles to determine the remaining life along a sewer. This provided the information needed for deciding to rehabilitate or replace sections of the sewer.

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