International No-Dig 2018
36th International Conference and Exhibition

Cape Town, South Africa
8-9 October 2018

Paper Ref #108

DETERMINING THE REMAINING LIFE OF CONCRETE SEWERS

Alaster Goyns

Pipeline Installation and Professional Engineering Services CC, Centurion, RSA

ABSTRACT: Most large outfall sewers are concrete. Under certain conditions they deteriorate with age due to biogenic corrosion. They generally flow partly full under gravity at reasonable gradients to ensure effective operation. As they are placed at depth below the surface a problem with a sewer invariably results in problems for the services above.

In modern cities surface space is limited and digging trenches to replace aged pipelines is extremely costly and disruptive. Trenchless techniques developed for rehabilitating and replacing buried pipelines minimize surface disruption and are cost effective.

Before making decisions about replacing or rehabilitating a pipeline, an assessment of its performance and condition should be done to establish how well its hydraulic and structural requirements are being met and to estimate its remaining service life. Recently the great strides made with multi sensor inspection systems provide a complete picture inside sewers as well as quantification of internal dimensions.

Combining this information with the loading conditions and an understanding of the corrosion mechanism provides input for the structural analysis of sewers and estimating their remaining life. The extent and severity of the problem can be established and decisions about the appropriate remedial measures taken.

1. INTRODUCTION

The primary function of any pipeline is to convey a fluid. There are however secondary requirements that have to be met to ensure that there are no problems with meeting this primary function. For pipelines conveying water, these are water-tightness, strength and durability. There are significant differences between pipelines that flow full and under pressure, such as water supply pipelines, and those that flow partly full and rely on gravity for their operation, such as sewers. The most significant differences are with the loads imposed on these pipelines which in turn influence the pipe materials that are used.

Pressure pipelines usually follow the surface profile of the terrain and are placed as close to this as is practical. The dominant loading is due to the internal pressure. The external loads due to earth and traffic are usually fairly consistent along their length. As the flow through them is reliant upon pressure, their horizontal alignment usually follows the most direct route from inlet to outlet.

Gravity pipelines, on the other hand, do not necessarily follow the surface profile as they are reliant on gravity and must flow downhill. The dominant loading is external due to earth and traffic. This can vary significantly along the route due to the surface profile and development. As they are gravity systems, they are usually placed below any other services in the area and their horizontal alignment, especially on the larger diameters, closely follows that of natural water courses which are nature's gravity systems.

Most large diameter outfall sewers (≥ 600 mm in diameter) are concrete as this material meets the structural and other requirements. However, under certain conditions, concrete is subject to biogenic corrosion which leads to structural deterioration over time and the need for either rehabilitation or replacement. It is generally more cost effective and far less disruptive to rehabilitate rather than to replace. So when a sewer has corroded, knowing its remaining life and corroded shape will assist with making the decision about whether to rehabilitate or replace.

An understanding is needed of this corrosion mechanism to determine the material loss and how the external loads are carried to calculate the residual strength provided by the remaining wall thickness. The corrosion loss is dependent upon the sewer hydraulics. The remaining life is dependent upon the external loads and actual wall thickness, both of which will probably vary along the length of any given sewer. This paper briefly considers the loading conditions on buried pipelines and how to determine their structural requirements. The actual condition of a sewer at any stage of its life can be assessed by undertaking a multi-sensor inspection (MSI) to establish the material loss due to corrosion.

Combining the output from research undertaken by the author and associates (Goyns, Alexander and Fourie, 2008) on concrete sewer corrosion in South Africa, the structural analysis of buried conduits and the physical dimensions provided by MSI inspections provides the information needed to determine the residual strength and remaining life of sewers so that they can be timeously rehabilitated.

2. SEWER CORROSION

2.1 Corrosion mechanism and corrosion rate

There are three sets of factors contributing to the corrosion phenomenon: those resulting in the hydrogen sulphide (H_2S) generation in the effluent, those resulting in the H_2S release from the effluent, and those resulting in the biogenic formation of sulphuric acid (H_2SO_4) on the sewer walls. These are illustrated in Figure 1.

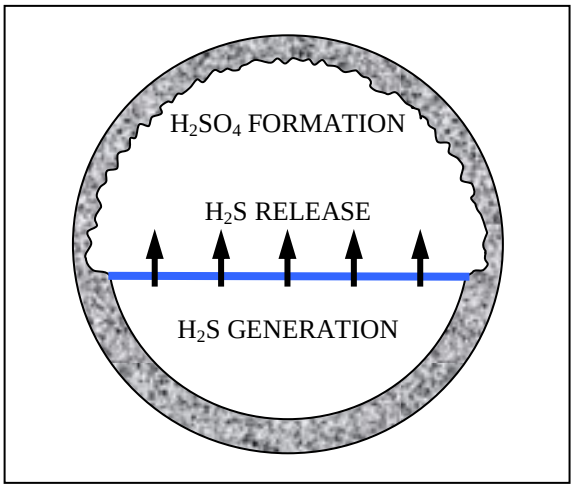


Figure 1: Corrosion mechanism in sewers

If there is insufficient oxygen in the effluent (less than 1mg/l) the bacteria living in the slimes layer on the sewer walls strip oxygen from the sulphates in the effluent, forming sulphides. A proportion of these will be in the form of gas, H_2S. When a sewer flows full as in a rising main or siphon, there is no gas release, so the gas accumulates in the effluent. The first set of factors influences the rate at which this occurs. When there is an imbalance of H_2S in the sewage and the sewer atmosphere, this gas comes out of solution until the gas concentrations in the sewage and the sewer atmosphere are in equilibrium. The second set of factors 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.

As concrete has an alkaline component, this will react with the acid formed, resulting in corrosion above the flow level. The corrosion products are about five times the volume of the original material, and they are porous and absorb moisture. The saturated products of corrosion have little strength and fall away from the pipe wall when they reach a certain thickness, thus exposing fresh concrete to further acid attack. With fibre reinforced concrete (FC) pipes, the saturated corrosion products are held together by the fibres for a longer period and the pipe walls eventually swell to several times their original thickness and mask the true pipe condition. As shown in Figure 2. With both pipes, the loss of sound material results in a loss of strength.

Figure 2: Corroded RCP (front) and FC (back)

If an inert coarse aggregate (SIL) is used, the mortar

between the coarse aggregate corrodes, it initially protrudes from the surface, then loosens and falls out. This exposes more binder that in turn is attacked by the acid and the process continues. The deterioration of the pipe wall can be rapid. If concrete is made using a calcareous aggregate, such as limestone or dolomite (DOL) which is acid soluble, the acid attack is spread over both binder and aggregate. As calcareous aggregate is somewhat more resistant than cement to acid attack, the rate at which the acid attacks this is slower than the rate at which it attacks the binder and this aggregate will also protrude from the surface. However the surface is much smoother and it takes much longer for the aggregate to loosen and fall out. The aggregate fallout problem is minimised and the deterioration rate of the sewer wall is reduced. By inspecting the close circuit television (CCTV) images taken inside sewers the differences between FC pipes, concrete pipes using inert aggregate and concrete pipes using acid soluble aggregate can be clearly seen.

Concrete corrosion is determined by the rate at which the H_2S flux, ϕ_{sw} to the pipe wall is oxidised to H_2SO_4. The EPA Manual [2], states that "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". If all the H_2S is oxidised, the annual corrosion rate [2] is predicted by:

$$C_{avg} = 11.5\ (k/A)\ \phi_{sw} \qquad [1]$$

Where C_{avg} - average corrosion rate, mm/year

k - efficiency coefficient for acid reaction and ranges from 0.3 to 1.0.

A - alkalinity of concrete expressed as calcium carbonate ($CaCO_3$) equivalent.

ϕ_{sw}- flux of H_2S to the pipe wall in $g/m^2/h$

11.5 - converts ϕ_{sw} in $g/m^2/h$, into C_{avg}, in mm/year

When applicable, ϕ_{sw} is increased to include the effects of turbulence and temperature. Equation [1] is used in conjunction with the design life (L) to determine the additional cover over reinforcement (z) needed to ensure serviceability for this period. The Life Factor Method (LFM) (McLaren, 1984) given by equation [2] is used.

$$Az = 11.5\ k\ \phi_{sw}\ L \qquad [2]$$

The Life Factor, Az, is used to compare different concrete mixes. The left-hand side of the equation describes the pipe material properties in terms of additional reinforcement cover and alkalinity, and the right-hand side describes the conditions within the sewer in terms of effluent properties, flow characteristics, sewer atmosphere and the required service life. The options adopted for preventing or minimising the corrosion in concrete sewers are preventing acid formation, modifying the concrete, or protecting the concrete. Which of these options has been used needs to be taken into account when assessing a sewer's condition.

Acid formation can be prevented or minimized by adjusting the hydraulic design. If self-cleansing gradients at low flow levels can be maintained throughout the system, sufficient oxygen (> 1.0mg/l) should be entrained in the effluent to prevent sulphide formation. Due to physical constraints this is seldom possible and some corrosion can 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.

The traditional approach, taken in South Africa, to handle sewer corrosion is to modify the concrete by using a calcareous, typically (DOL) in a Portland cement (PC) concrete and providing additional cover to the reinforcement, called a sacrificial layer (SacL). When flow velocities are slow (< 1.0 m/s – 1.5 m/s) the products of corrosion may remain intact on the pipe wall around the whole circumference of the sewer and mask the actual condition of the pipe wall similar to what happens with FC pipes. When the velocities increase (> 2.0 m/s) and in particular when they are supercritical the products of corrosion are washed away at the water level. Under these circumstances the material lost just above the average daily water level can be far greater (up to 5 times more) than that on the sewer crown due to the combined action of corrosion and erosion. This results in

Figure 3: Mushroom shaped pipe

a longitudinal almost horizontal sill either side of the sewer below which there is little or no corrosion and above which the corrosion is severe. The term used in South African to describe a sewer with an internal bore shaped like this is a 'mushroom' shaped pipe as illustrated in Figure 3. What this figure also shows is corrosion products along the pipe crown that have not as yet fallen away.

Over the past two decades protecting the concrete with an inert lining, such as polyethylene has frequently been used. This is effective, but only economically justifiable when very severe corrosion is predicted and for larger sewers (≥1200 mm diameter). It however does not address the issue of how to handle the problem with existing sewers that have already started to deteriorate and will at some time in the future need rehabilitation. The problem is to determine when this rehabilitation should take place and what technique should be used.

2.2 Output from research of sewer corrosion

In 1989 a 65 m long experimental section was installed as part of a 900 mm diameter sewer where very aggressive conditions were expected. The purpose of this was to compare corrosion rates of various binder /aggregate combinations subject to these aggressive conditions. A bypass line was constructed so that the flow could be diverted and the various pipes physically inspected and estimates of the corrosion losses made. With successive inspections it became clear that the PC/DOL pipes had performed better than the PC/SIL pipes and concrete using calcium aluminate cement (CAC) and SIL had performed significantly better than the PC concretes. It was predicted that the control pipes made using PC and SIL would have corroded through after 10 years. A CCTV inspection indicated that this had occurred in places. A physical inspection (shown in Figure 4) confirmed that this had in fact happened.

Figure 4: PC/SIL pipe wall gone in 10 years

In 2003 (Goyns, 2004) the whole experimental section of the pipeline was exposed with the intention of removing sections of pipe so that the actual wall losses could be measured. There were sections of the PC/SIL pipes were the concrete (84 mm thick) above the flow level had disappeared completely. What remained of the three PC/SIL pipes was removed as well as short sections of the pipes either side of them. The estimates of wall loss from the internal measurements and those taken on the pipes removed are given in Table 1.

TABLE 1: MEASURED & ESTIMATED CORROSION RATES & MATERIAL FACTORS (Goyns, 2004)

Cement/ Aggregate	5 year estimate		12 year estimate		14 year measured		Material factor**
	Total (mm)	Average (mm/year)	Total (mm)	Average (mm/year)	Total (mm)	Average (mm/year)	
PC/SIL	>30	>6,0	>64	>6,0	> 105	> 7.5	1.000
PC/DOL	10 – 15	2 – 3	20 – 30	1,7 – 2,5	43	3.1	0.410
CAC/SIL	5 – 10	1 – 2	10 – 15	0,8 – 1,2	26	1.9	0.250
FC	10 - 12	2 +	20 - 25	1,7 – 2,1			0.270
CAC/DOL *	3,0	0,6	7,2	0,6	8,4	0,6	0.085

*Values estimated from other materials and performance of University of Cape Town core samples in sewer
**Average of maximum loss at side divided by corresponding value for PC/SIL.

The improved performance of PC/DOL concrete appears to be purely due to increased alkalinity. There was still aggregate fallout, but at a slower rate than with PC/SIL concrete. With CAC concretes, the performance is enhanced as the aluminates have a 'stifling' effect on the bacteria's reproductive cycle, as well as a greater neutralizing effect on the acid formed. In addition, CAC concretes are more acid resistant than PC concretes and appear to take longer before they start corroding. When used with and acid-soluble aggregates such as DOL, they are at least an order of magnitude more effective in controlling corrosion than concretes made with PC and inert aggregates. The CAC/DOL concrete was also significantly more effective than the traditional PC/DOL. When CAC binder and aluminate aggregate (ALM) were used in combination as with later samples installed in this sewer, the performance was even better.

Where the pipes were removed manholes were build and 230 mm long sections of pipe made from refinements of the materials given in Table 1 were installed. The top sections of these pipes can be removed as shown in Figure 5 so that measurements and material samples can be taken. These samples have now been in the sewer for almost 15 years.

The original pipes have now been exposed to these aggressive conditions for 29 years. The results have provided really useful quantitative information on the corrosion rates of traditional sewer pipe materials and can now be used it predicting what will happen in existing sewers. It has also provided the criteria for evaluating the performance of CAC based concretes using the LFM which would be useful for the mortar relining of sewers.

Figure 5: Inspecting lid in experimental sewer

3. PIPE STRENGTHS

3.1 Differences between non-reinforced and reinforced pipes

The structural performance of a non-reinforced (NR) pipe depends on the properties of one material. It fails when the maximum stress in either compression or tension exceeds the relevant strength. The structural performance of a reinforced concrete pipe (RCP) depends upon the properties of two materials. The reinforcement enables the pipe to carry more than the NR pipe with the same wall thickness. With a FC pipe the fibres are uniformly distributed throughout the pipe wall, thus increasing the flexural strength, but failure still occurs when the flexural tensile stress is exceeded. In effect the performance of the FC pipe is the same as a NR pipe with a higher flexural strength.

3.2 Installed loads on buried pipelines

The installed pipeline is subject to earth and traffic loading, and these impose vertical and horizontal forces on the pipes. At low fill heights traffic loading is significant, but as these loads are distributed through the fill, their influence on the pipes decreases with fill height and at greater than 2.5 m, the live loads are minimal.The calculation of earth loads on a buried conduit from first principles is complex. For a thorough understanding, reference should be made to national standards or other guidelines covering the subject. Earth loads are dependent upon installation conditions and surrounding material properties. The two basic installation types are the trench and embankment. As most large diameter sewers follow natural watercourses, the installation conditions are variable and unpredictable. Although a trench has been excavated, the trench sides can collapse and the embankment loading condition will apply. Unless the actual conditions are known it is advisable to use equations (4) and (5), as these cover the most severe conditions. The earth load, W_e on a rigid pipe under an embankment loading condition with an outside diameter of B_c, a fill height H that exceeds about 1.7 B_c and a material density of γ for sandy soils and clayey soils can be calculated from Equations 3 and 4.

$$W_e = 1.69\ \gamma\ B_c\ H \text{ (sandy soils)} \quad [4]$$

$$W_e = 1.54\ \gamma\ B_c\ H \text{ (clay soils)} \quad [5]$$

3.3 Pipe strengths for installed conditions

The bending moments generated in the wall of an installed pipe are determined by the distribution of the loads and reactions around the pipe. The loading cases and the appropriate moment coefficients are given in the Appendix. As sewers are installed on a bedding to enhance their load carrying capacity, the applicable loading cases are numbers 3 to 10 in the Appendix. The critical points are usually at the crown and invert, but under certain conditions may occur just below the spring line. The moment M at these points for a pipe with a mid-wall diameter D, mass W_p and subject to a total installed load, W_I will be:

$$M = C_i\ W_I\ D + C_i\ W_p\ D \quad [6]$$

Where the values of C are obtained from the Appendix for the particular loading cases (4) to (8) and location on the pipe circumference and W_I calculated from these.

With NR pipe failure occurs when the material's flexural stress, σ_t is exceeded. The flexural stress at any point where the wall has a thickness, t will be:

$$\sigma_t = 6\,M / t^2 \qquad \text{or} \qquad M = 0.167\,t^2\,\sigma_t \quad [7]$$

3.4 Pipe performance under factory test load

The required factory test load, W_T is obtained by dividing the installed load W_I by a bedding factor B_F which is dependent upon the amount of support provided by the bedding.

$$W_T = W_I / B_F \qquad [8]$$

The test load is converted and rounded up to the nearest standard pipe class. In many countries concrete pipe strength classes are defined in terms of 'D-Loads', being the strengths at the serviceability limit expressed in kN/m of pipe diameter/m of pipe length.

The design of a steel RCP is based on moment capacity and steel stress, whereas that of the NR pipe is based on the flexural stress of the concrete. The moments for a steel RCP are dependent on pipe diameter, whereas those for a NR pipe depend on the square of the wall thickness. With a steel RCP, the strength can be adjusted to give a collapse load that is three to four times that of a NR pipe, with the same wall thickness. With a NR pipe with a given wall thickness and material properties the strength cannot be adjusted and the moment capacity at anywhere around the pipe circumference is calculated by rearranging equation [7].

3.5 Significance of pipe strengths

The above shows that pipe design is a set of iterative interactions for providing the adequate strength and durability to obtain the required service life. As the wall thickness reduces due to corrosion the structural properties of the pipe will change and it becomes important to determine where the losses have taken place and how these will influence the actual pipe strength and the remaining life along the length of a particular sewer as this may vary significantly depending upon the external loads and surface development.

4. CONDITION ASSESSMENT

Condition assessment involves gathering data from as many sources as possible, such as a desktop study, hydraulic performance, water tightness, details of the pipe soil system and effluent composition. This data is used to determine the sewer performance as well as the condition of pipes, joints and the soil around them both qualitatively and quantitatively. The addition of the digitized output from laser and sonar scanners to the CCTV data from the above-water and below-water scanning provides internal pipe profiles along the whole sewer with the actual dimensions that show the impact of corrosion and the siltation levels that influence the hydraulic capacity.

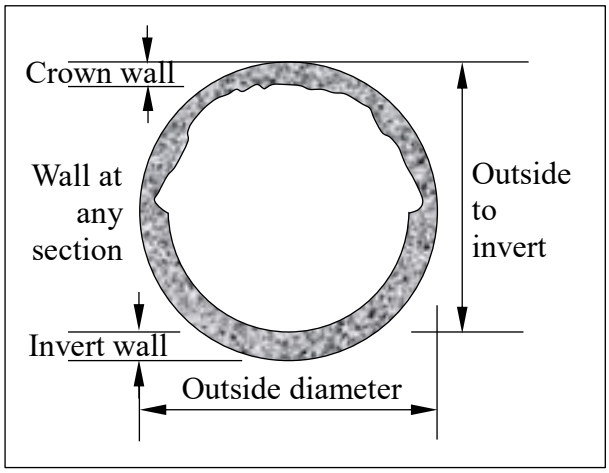


Figure 6: Physical dimensions to check

It is recommended that the details provided by this multi-sensor inspection (MSI) are complemented by making a few spot measurements as shown in Figure 6. This means identifying sections of the sewer where severe corrosion is anticipated and which are easily exposed from the surface, cutting inspection windows into the sewer so that physical inspections can be done and the required measurements, photographs and material samples taken. This inspection can be done concurrently with the MSI survey, and the physical measurements used to calibrate and verify the digitized data, thus providing a comprehensive detail of the sewer's condition.

5. REMAINING LIFE

5.1 Residual strength

The critical issue for the utility owner is the sewer's remaining life before it needs rehabilitation or replacement and then the most the most suitable method for doing this. A secondary issue is how effectively and efficiently the sewer will perform during this remaining life. This paper is concerned with the former.

The strengths at three stages in a sewer's life need to be determined, namely, the initial when installed to meet the design specification, the residual at time of investigation, and the minimum required to take the actual loads imposed on the pipes. Although the strengths for a specified pipe class as determined at time of installation will be constant, the minimum initial strengths needed along the sewer will depend on the actual loading. The residual strength along the sewer length may also vary as the corrosion losses over time may differ due to the changes in conditions along the sewer. The minimum strength needed will also vary along the sewer length, depending on the actual loading conditions and corrosion losses. Assuming that the soil around the pipes remains intact, it will consolidate over time. The vertical loads and moments generated on the pipes will then probably be less than those originally designed for, as the lateral pressures will have increased and countered these loads. On the other hand, if some of the material surrounding the pipeline has infiltrated into it through leaking joints, cavities will probably have formed around the sewer resulting in a loss of bedding support. The load-carrying capacity of the pipe/soil system will then have deteriorated, and collapses can be expected.

When the pipe wall has corroded, this must be taken into account in determining the residual strength. As mentioned earlier the effect of velocity needs to be considered As Figure 6 shows, corrosion just above the average flow level is frequently greater than at the pipe crown. So the residual strength has to be calculated for both the wall thickness at the crown and sides to determine which is critical. The actual wall thicknesses at intervals around the pipe circumference are obtained from the measurements provided by the MSI inspection. As large diameter sewers are generally RCP and the reinforcement accounts for at least half the pipe's strength, a good indicator of the residual strength is whether and where the reinforcement is exposed, and the extent to which it has corroded. If the crown steel has corroded at places, the pipe could be close to collapsing and will probably have to be replaced. On the other hand, if the steel is exposed and corroded at the sides and not exposed at the crown, the pipe will still have some residual strength and the pipe can probably be rehabilitated. With a NR cementitious pipe, the residual strength is determined using the actual wall thicknesses at the crown and side of the pipe, assuming a flexural tensile strength and applying equation [7].

5.2 Determining remaining life

The minimum required pipe strengths along a sewer are based on the actual installation conditions and this need to be compared to the residual pipe strength based on the remaining wall thickness and condition of the steel reinforcement. Dividing the material loss around the pipe circumference (difference between original wall and residual wall thicknesses) by the operating period will give the average material loss per annum. The average annual wall loss determined in this way can be compared to that estimated by applying the Life Factor approach, using equation [1]. This requires that characteristics of the pipe material, the amount of H_2S flux to the pipe wall are determined and the efficiency coefficient of acid reaction estimated. Explanations for any differences in the output from these two approaches should be sought, and if necessary the estimated annual rate of material loss should be adjusted, so that a more realistic value of the residual life can be obtained.

A typical situation where the measured material loss is greater than that calculated using the LFM, is when measurements are taken downstream of a siphon or rising main where there has been an accumulation of H_2S in a pipeline that is flowing full. When the flow is then released into open channel flow there is a sudden release of H_2S into the sewer atmosphere resulting in severe corrosion. The opposite situation occurs where the calculated corrosion is more than the measured corrosion, such as along sections of sewer that flow full most of the time.

Based on actual installation conditions along the length of sewer and corresponding wall thicknesses, the minimum required strengths can be determined. Dividing the differences between wall thicknesses at the residual and those needed for the minimum strengths at any location along the sewer by the adjusted corrosion rates will give the remaining life. This needs to be done along the entire sewer length, taking into account the actual loading conditions, such as where the sewer passes under transportation routes where the loading may be significantly greater, and considering severe corrosion at certain sections of the sewer where there is excessive H_2S release due to localized turbulence. This is a fairly complex exercise for a RCP as there will be a dramatic loss of strength once the reinforcement is no longer intact, but simpler for a NR cementitious pipe.

Based on these calculations a profile of the remaining life along the whole sewer length showing the critical sections can be drawn. This will be a critical input for the risk analysis, as it will indicate where the sewer has sufficient strength to be rehabilitated as a partially deteriorated conduit, where it has to be structurally rehabilitated to prevent it collapsing in the near future, the so called fully deteriorated case as described in ASTM F 1276 (ASTM, 1999) or where it may have to be replaced as it has already partly or completely collapsed. This will provide the owner with priorities and a time frame within which decisions can be made.

5.3 Choice of rehabilitation or replacement technique

Once the rehabilitation and replacement priorities have been set the decisions about the most appropriate technique to use need to be made. Although the utility owner will invariably want to choose the rehabilitation method based on price, this should not be done if it compromises the functionality or technical soundness of the service. There are basic factors that should be taken into consideration before making this choice.

The primary requirement for any water carrying pipeline is its capacity. For a circular conduit the capacity is a function of the actual diameter to the power of 8/3. This means that a 5 % reduction in diameter can amount to a 13% reduction in capacity. Most liners will have a smoother bore than the host pipe and have no joints so even with the 5 % reduction in diameter the capacity could still be about 5 % greater.

The most economic solution would generally be slip lining however as is not a tight or close fit liner it would not provide the capacity needed. In addition there would be a gap between the liner and host pipe and this gap would have to be grouted to prevent a water path developing next to the sewer and loss of soil support if joints on the host pipe had been leaking.

When the internal cross sectional profile of an existing sewer is not circular due to corrosion and has sharp longitudinal deviations from this, as with a 'mushroom' shaped pipe with a longitudinal sill a tight or close fit liner would form a sharp bend over the sill and could become highly stressed. So instead of a cured-in-place or a fold and form liner which would match the sewer profile a spirally would liner which fitted along the sewer invert and maintained a circular profile could be a better option. This would also require that the annulus between the host pipe and the liner is grouted.

For a NR pipe where capacity is a problem or a sill has developed, as frequently happens with reticulation and collector sewers due to urban densification, replacing the sewer online using pipe bursting solves both the capacity and structural problems and as the host pipe is pushed into the surrounding material there is no annulus the needs grouting.

6. CLOSING COMMENTS

A clear distinction needs to be drawn between sewer system design, which is dictated by primary requirements of hydraulic capacity and the physical constraints of the route to be followed, and pipe design which is dictated by the secondary structural and durability requirements consequent upon the route chosen, the hydraulic performance, and the effluent properties.

Concrete is the most frequently used material for large diameter sewers. Although pipe durability is a secondary requirement, it is probably the one with the greatest impact on the useful life and life cycle costs of these large diameter sewers. There is a short-coming of PC concrete pipes, as they are subject to severe biogenic corrosion under certain conditions. On the other hand the inherent strength of concrete pipes enables them to carry a large proportion of the imposed loads with minimal soil support. This means that they can be effectively rehabilitated using a variety of trenchless techniques even when they appear to have seriously deteriorated. This in itself offers a considerable saving as concrete sewers can generally be rehabilitated rather than be replaced.

The corrosion mechanism in concrete sewers is reasonably well understood, and the LFM for predicting the rate of corrosion for PC/SIL concretes gives realistic answers. The use of PC concrete with acid soluble aggregates plus a SacL has been used in South Africa since the 1960's and has increased the life of sewers at a reduced cost when the corrosion potential is not severe. With increased corrosion potential, this approach becomes less cost effective and using a PC/SIL host pipe with a CAC/DOL corrosion control layer has proved more cost effective.

The output from research undertaken on finding the appropriate materials for new concrete sewers subject to corrosive conditions by the author and colleagues in South Africa has led to a means of predicting the corrosion

losses in existing sewers. Combining this with the structural analysis of buried conduits and physical dimensions provided by MSI systems provides the information needed to determine the residual strength and remaining life of operating sewers so that timeous decisions can be made about their rehabilitation or replacement. Understanding this combined output has also provided guidelines that assist with the selection of the appropriate rehabilitation or replacement technique needed.

In the developing world urban densification is taking place at rates that far exceed population growth. South Africa is no exception to this phenomenon. Associated with this is a backlog in the provision of essential services that has not kept pace with this development. Although fresh water supply and waste water disposal are essential for healthy communities, the construction of new infrastructure lags behind the increasing demands. To exacerbate matters, the maintenance of the existing infrastructure is frequently neglected and malfunctions. In many countries, water shortages have led to conservation measures, which in turn have led to increased corrosion potential in sewers, due to higher biological and chemical concentrations in the effluent.

As there will be less space for digging trenches, many new sewers will be installed using trenchless techniques below the other services. However, there are many existing sewers below city and urban areas which are aging, have been designed for historic population densities, and their condition is unknown. It is these 'holes through the soil' that are the utility owners real assets; the pipes are merely liners that should enable them to perform effectively and efficiently on a sustainable basis. Before any decisions are made about their rehabilitation or replacement, it is essential that their hydraulic performance and structural integrity is assessed.

ACKNOWLEDGEMENTS

Firstly, the support from Professor Mark Alexander of the University of Cape Town is gratefully acknowledged. For several decades he has championed the research and development of cementitious materials for sewers and, for the past 20 odd years, has encouraged me as a practicing engineer to be a link between research undertaken in the field and laboratory, and its implementation in the market place for the benefit of society. Part of this has been the interaction with his post graduate students on the practical aspects of sewer design and operation.

Secondly, I acknowledge support received over the years from SASTT members who elected me as one of the original board members. This gave me the opportunity to obtain a broad understanding of the various aspects of trenchless technology especially the significance of designing new systems that can be rehabilitated at some stage in the future to extend their service life, and the importance of assessing the condition of existing sewers that have been operating for many years before making decisions about their rehabilitation or replacement.

REFERENCES

ASTM F 1216. Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of Resin-Impregnated Tube. *ASTM standards related to trenchless technology.* ISBN 0-8031-2594-1, Baltimore 1999

Bowker, RPG, Smith, JM, Webster, NA (1985). Design manual: Odor and corrosion control in sanitary sewerage systems and treatment plants. *Centre for Environmental Research Information, US Environmental Protection Agency*, Cincinnati, 1985, p.23.

Goyns, AM, Alexander, MG & Fourie CW.(2008). Applying experimental data to concrete sewer pipe design and rehabilitation, *Calcium Aluminate Cements: Proceedings of the Centenary Conference, Avignon, France, 31 June – 2 July 2008*. IHS BRE Press,.

McLaren, FR. "Design manual: sulfide and corrosion prediction and control". American Concrete Pipe Association, Virginia, USA, 1984.

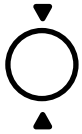
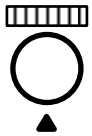
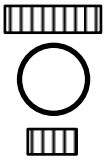
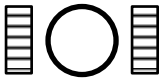
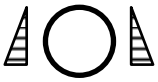
Goyns AM. (2008) Design manual for concrete outfall sewers. *A document prepared for the Pipe and Infrastructural Products Division of the CMA*. Midrand, SA 2008.

Goyns, A. Virginia sewer rehabilitation. Progress Report no 2. *A project being undertaken for the Pipe and Infrastructural Products Division of the CMA*. PIPES CC Centurion, 2004.

Paris, J. M.(1921). Stress Coefficients for Large Horizontal Pipes. *Engineering News Record*. Vol. 87, No. 19. Nov. 1921, pp. 768-771.

APPENDIX: MOMENT COEFFICIENTS FOR COMMON LOADING CASES

(Based on uniform loading conditions by *Paris, J. M. "Stress Coefficients for Large Horizontal Pipes,"* Engineering News Record, Vol. 87, No. 19. Nov. 1921, pp. 768-771 [7]

Case	Loading condition	Details	Crown-Cc	Spring line-Si	Invert-Ci
1	Pipe weight		0.03980	0.04540	0.1190
2	Test load – two edge		0.1590	0.0908	0.1590
3	Horizontal udl top and line load bottom		0.0750	0.0770	0.1470
4	Horizontal udl top + 60° bedding support	Loading  Bedding	0.0720	0.0735	0.0945
5	Horizontal udl top + 90° bedding support		0.0685	0.0705	0.0790
6	Horizontal udl top + 120° bedding support		0.0655	0.0665	0.0690
7	Horizontal udl top + 150° bedding support		0.0635	0.0640	0.0640
8	Horizontal udl top + 180° bedding support		0.0625	0.0625	0.0625
9	Vertical udl		0.0625	0.0625	0.0625
10	Vertical triangular		0.0525	0.0625	0.0730
11	Fluid Weight		0.0398	0.0454	0. 1190

M crown, Mc = CcWD, M spring line, Ms =CsWD, M invert, Mi = CiWD or
M crown, Mc = $CcwD^2$, M spring line, Ms =$CswD^2$, M invert, Mi = $CiwD^2$
W is total load; w is the equivalent distributed load; D is average of the internal and external pipe diameters.