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PERFORMANCE AND CONDITION ASSESSMENT OF GRAVITY PIPELINES

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ABSTRACT:A holistic evaluation of hydraulic performance and condition assessment of gravity pipelines (pipes and manholes) should not just be viewed as a means of determining their current status. What was done in the past must be evaluated, so what learnt at present, is applied to future planning and service provision.

South African experience with performance and condition assessment of pipelines from 100 mm to 1800 mm in diameter has progressed significantly by combining the latest technical developments with the basic engineering principles. This shows that the information gathered is of more value than just reporting the present conditions. Identifying the problems, their location, extent, and severity provides the information needed to make decisions about whether or not to rehabilitate and where needed, the action to take.

Generally, with some additional effort, the underlying causes of problems can be identified. In many cases, these are due to design or construction errors that may, or may not have been considered significant at the time. Identifying these underlying causes and reporting them to asset owners and designers means their future occurrence can be avoided when new pipelines are planned and designed, thus providing better service levels at lower life cycle costs.

1. INTRODUCTION

Next to air the most important need for life is water. For healthy lives we need clean air and clean water. For the latter we need healthy pipelines that supply clean water and take away dirty water. In the developing world the focus is on supply, rather than matching supply and disposal. This lack of attention to wastewater disposal in high density areas means its accumulation and potential health problems. Hence the focus of this paper on sewers.

To ensure that sewers remain healthy they should be periodically checked and when necessary maintained or rehabilitated to that they remain effective and efficient. This evaluation of their health should not be left, as so often happens, until it is obvious that has deteriorated, as shown by manhole surcharging, ground subsidence or sinkhole formation. It should be a planned for when it has reached a certain age and then periodically repeated so that preventative measures are taken rather than having to handle unplanned, unexpected and costly failures. Such check-ups should consist of a holistic evaluation of a pipeline's hydraulic performance and a condition assessment of the pipes and manholes. This should not be viewed as a means of determining their current status. What was done in the past must be evaluated, so what is learnt at present, is applied to future planning and service provision.

In order to effectively evaluate the performance and condition of a pipeline the basic functions and the theory of how these were applied during the design of the pipeline being investigated should be understood. With this any differences between performance and condition expected after studying site conditions, drawings if they are available, and the details obtained from the inspections can be investigated and the underlying causes established.

2. PIPELINE FUNCTION

The primary function of any water conveying pipeline, whether a gravity or pressure system, is to provide the required hydraulic capacity. To effectively and efficiently do this there are three support functions needed:

- Water- tightness so that there are no losses due to exfiltration and no additional flows due to infiltration.
- Structural soundness so that both internal pressures and external loads can be handled.
- Durability so that the pipeline can continue conveying the required quantity of water without there being any losses or additional flows and carrying the loads imposed upon it.

This paper covers gravity pipes which are flowing partly full. A distinction needs to be made between stormwater drains and sewers when doing inspections. Stormwater drains, particularly those in the warmer parts of the globe only flow a few times a year as the rainfall is seasonal. Hence access to them is easy. On the other hand sewers flow continuously and access may have to be done at periods of low flow or under certain conditions may require the use of over-pumping.

The conditions in sewers can result in the generation and release of the gas hydrogen sulphide (H_2S) which poses a serious corrosion potential in cementitious sewers, resulting in strength loss. This gas is toxic and inhalation even at low concentrations can be fatal so the necessary precautions have to be taken during inspections.

A realistic assessment of pipeline performance and condition requires onsite inspection, in addition to an understanding of the theory used in their design and then combining this information. This will identify problems as well as their underlying causes. This paper will therefore consider both the output from multisensory inspections (MSI) and the basics of pipeline design.

3. INTERNAL INSPECTIONS OF GRAVITY PIPELINES

The traditional approach of doing an internal inspection by sending a camera on a tractor through a pipeline when empty or at low flows only gives a visual output showing the problems, their location, their extent and an indication of their severity. Typical problems noted are leaking pipe and manhole joints, settlement along the invert, longitudinal and circumferential cracks, siltation, wall material loss and distortion of the pipeline circumference. However, this does not necessarily give the actual severity of problems, or their underlying causes.

Using a combination of camera with laser and a sonar profilers mounted on a pontoon floated through the pipeline adds value by providing full circumferential dimensional details along the length of pipeline. When the external and internal dimensions of the original pipe are known this allows for the material loss and remaining wall thickness around the pipe circumference to be calculated. This means that the extent, severity and orientation of cracks, the loss of wall material, the distortion of the pipeline circumference and amount of siltation can be determined. In addition this information indicates the probable underlying causes of the problems.

The development of the camera on a pole used in combination with a surface level survey along the pipeline route greatly simplifies the initial gathering of information and gives a good understanding of the pipeline conditions without the need to send a camera on a crawler, or pontoon through a sewer. On the basis of this an initial hydraulic and structural analysis can be done. As an initial investigation this shows where:

- there are blockages that would have to be cleaned before sending inspection equipment into pipeline
- ponding has occurred indicating invert settlement
- there is cracking and its location and type
- jointing is poor or misaligned
- there is ground water infiltration
- H_2S corrosion has taken place above the water line.

This will provide the information needed to decide about whether a more detailed inspection of the section of sewer is needed or not. If this shows that the condition of a section is still adequate as there are no problems, the cost and time of doing a detailed internal inspection of it will not necessary and rehabilitation will not be needed.

4. EXTERNAL INSPECTION OF PIPELINE ROUTE

This internal inspection should be complemented by a surface study of the pipeline route including obtaining ground levels and the location of structures and transport routes over the pipeline. Combining this surface information with that obtained from the internal inspection can be used to do a hydraulic and structural analysis of the present conditions which will give a realistic view of the potential problems and their underlying causes.

By following the route of the pipeline along the surface various external loading conditions such as transportation corridors, buildings and natural features such as water courses, wet lands and ponds can be obtained. The seasonal variations in the latter are very important because this will indicate the annual variation of groundwater levels. This is particularly important for larger diameter sewers that closely follow the alignment of natural water courses.

Part of this investigation should be a survey confirming the surface level and invert level at each manhole along the sewer route as well as the condition of the manhole. If the surface profile is undulating levels the distances of the high points and transportation routes between the manholes should be taken. Based on this information a long section of the pipeline showing invert levels, assuming no pipeline settlement and the surface profile can be drawn. From the manhole invert levels and the distances between them the theoretical hydraulic performance of the pipeline can be determined assuming that the gradients between the manholes as shown by the long section are correct. The earth and traffic loading along the pipeline can then be determined and the required pipe strengths calculated.

The location of any surface settlement should be recorded as this could indicate that the pipeline has for one or other reason settled. In addition to this the local authority, who may be the client for the project should be asked as to whether there have been any problems along this pipeline route due to overtopping of manholes, settlement or the formation of sinkholes. The local authority should also be asked whether drawings with the actual pipe and bedding class details are available so that these details can be checked.

5. HYDRAULIC PERFORMANCE

5.1 The basic principles

There are differences between the hydraulics of pipelines flowing partly full under gravity and full under pressure. The energy level above invert in a gravity pipeline has two components, the depth of flow and the velocity head whereas this energy level in a pressure pipeline consists of three components, pipe diameter, velocity head and pressure head. Ideally a pipeline should be designed throughout its length to operate as either a gravity or pressure system and that there are no sections where the flow changes from being partly full to completely full as this can seriously affect the hydraulic performance and the corrosion potential in cementitious pipes.

There are two flow regimes in a gravity line flowing partly full, namely supercritical flow where momentum has the dominant effect on the hydraulics and subcritical flow where gravity has the dominant effect. At a particular energy level there can be either subcritical or supercritical flow. With the former the flow is deep and the velocity is slow. With the latter the flow is shallow and the velocity high. The transition between these two flow regimes occurs at critical flow where there is a fixed depth to discharge relationship. With supercritical flow the fast flowing water wants to carry on going in the same direction. Any obstructions to flow, even if minor, such as entering a poorly benched manhole will result in turbulence. When the obstruction is severe such as when there is a blockage in the pipeline, a hydraulic jump where the flow regime changes from super- to subcritical can occur and this turbulence will result in energy and velocity losses, deposition of transported solids and a release of any H_2S gas that may have accumulated in the effluent. With subcritical flow the water flows relatively slowly and dams up behind obstructions causing a backwater effect. The deposition of transported solids occurs and the slow velocity could result in the formation and accumulation of the gas H_2S within the effluent.

5.2 Problems that arise

Probably the most serious hydraulic problem on long gravity pipelines and in particular sewers arises because of the changes in gradient made during the initial design, where this gradient followed as close as possible to the surface level but maintaining sufficient slope for what was considered necessary for self-cleansing velocities. This minimized the initial capital cost. Manning's Equation 1 is generally used for calculating pipeline velocity.

$$V = (1/n)\, R^{2/3}\, S^{1/2} \qquad [1]$$

Where V is velocity in m/s
n is Manning's roughness coefficient
R is the hydraulic radius of the pipe in m. R = flow area/wetted perimeter
S is the gradient of pipeline

This shows that for a given roughness and flow depth velocity is dependent upon the gradient to the power of ½. So if the gradient increases by 50 % the velocity will increase by 22,5 % and if it decreases by 50 % the velocity will decrease by 29,3 %. This change in velocity is not a problem if it is just clean water being conveyed. However, as the wastewater in sewers transports floating items, particles in suspension and a bed load of heavier objects that get pushed along their inverts, any changes in velocity will have a significant effect on the size of particles that can be carried in suspension, be picked up again once they have been deposited or only shifted along the invert. The velocity at which a given particle will settle is given by Equation 2.

$$Vs = (R^{1/6)}/(n[B(SG-1)Dg]^{1/2}) \qquad [2]$$

Where Vs is the settlement velocity in m/s
R is the hydraulic radius of the pipe in m
n is Manning's roughness coefficient
B is related to the particle material. For materials as sand and stones can be taken as 0,04
SG is the specific gravity of the particles
Dg is the diameter of a particle that is approximately circular in m

By rearranging this equation the particle size velocity relationship is given by Equation 3.

$$Dg = (n\ Vs/R^{1/6})^2/[B(SG-1)] \qquad [3]$$

These two equations show that the particle size is related to the square of the velocity. By combining Equations 1 and 3 for given values of 'n', 'B' and 'SG' of 0,013, 0,04 and 2,65 respectively, which are typical values for sands and stones, this formula can be simplified to give Equation 4 which can be used for estimating siltation in sewers.

$$Dg = 15{,}15\ R\ S \times 10^3 \qquad [4]$$

For a 600 internal diameter (ID) pipe flowing half full at a gradient of 1/400 using these parameters in Equations 1 and 4 gives a velocity of 1,09 m/s and a particle diameter of 5,68 mm. It is significant when looking at the output from these two equations that velocity is determined by $S^{1/2}$ whereas the stone size is directly related to S.

From the above it can be seen that although changes in sewer gradient influence flow velocity, they have a greater impact on the size of particles carried in suspension and will settle out when the velocity drops. Hence the gradients of sewers should wherever possible be maintained so that what enters the sewer can be transported through them.

A distinction needs to be drawn between the items carried in the effluent. There are those that remain in suspension whether the effluent is moving or not, called the suspended sediment, those which are carried when the effluent is moving called the suspended load and the heavier items which are not carried in suspension and that slide or bounce along the invert called the bed load. There is obviously no clear distinction in the classification of these particles. However within these broad categories they cause different problems which may be temporary as occurs with blockages due to floating objects, siltation due to the suspended load that can be dropped at low flows and can't be picked up again thus reducing the capacity and the bed load of bigger and heavier objects that probably initiated siltation. These various items are mixed in the sediment, making its surface rougher and can make the cleaning more difficult. These larger objects can damage the invert as they are shifted and bounce along it during high flows.

This sediment layer along the bottom of a sewer has a serious impact on the hydraulic properties as there are changes in the shape of the waterway area and roughness at the bottom of the flow area. Sewers are normally designed to flow half full with a flow area with a half round bottom consisting of a smooth pipe surface and a flat top surface which is an interface between water and air. A sewer that is half full of silt has a rough flat bottom consisting of silt and the junk that has collected and a half round top section consisting of a smooth pipe surface. Hence although the flow area is the same, the wetted perimeter is larger, the hydraulic radius is smaller and the composite roughness of the surfaces greater. As a result the velocity and capacity of a sewer half full of silt is reduced to about half that of the intended values for the sewer when flowing half full and about a quarter of the capacity when it is flowing full. Due to this it is unlikely that in a sewer where the velocity is low that the peak flows will scour the material that has settled along its invert. There will just be a progressive increase in the deposition depth over time and a deterioration in the hydraulic performance, eventually resulting in the sewer flowing full and the manholes periodically over topping. The latter is an environmental and pollution issue with the potential for causing health problems.

In addition to the siltation problem, once the sewer velocity drops below a certain value (somewhere between 0,6 or 0,8 m/s) there will be insufficient oxygen entering the effluent to feed the bacteria inhabiting the slime layers along the sides and bottom of the sewer. As a result their oxygen requirements will be met by extracting it from the sulphates in the effluent and the formation of sulphides. A portion of these will be H_2S gas which is noxious, a health hazard and leads to the corrosion of cementitious and metallic materials.

High velocities and in particular when they are supercritical can cause a different set of problems. At velocities exceeding about 2,5 to 3,0 m/s stones being transported by bouncing and sliding along the invert can cause abrasion resulting in a groove being formed along the invert. This will ultimately result in a serious structural problem with the collapse of the pipeline.

When these high velocities occur in sewers where H_2S gas has been generated upstream, the gas is stripped out and corrosion occurs which then has a structural impact. Details of this are given in a later section of this paper.

6. STRUCTURAL INTEGRITY

6.1 Basic principles

Most of the old sewers requiring rehabilitation consist of rigid pipes which are either reinforced or non-reinforced (NR). The pipe strength is determined by testing. The installed load that the pipe can carry is determined from the test load, a factor of safety and a bedding factor. The factor of safety is the relationship between the design load and the collapse load and the bedding factor is the relationship between the test load which is a concentrated load and the installed load which is partially or fully distributed around the pipe. Equation 5 gives the relationship between these factors.

$$Wt = (Wi/Bf)x\ FOS \qquad [5]$$

Where Wt is the test load used for the design in kN/m
Wi is the installed load in kN/m
Bf is the bedding factor
FOS is the factor of safety

The structural performance of non-reinforced pipes depends on the properties of one material, such as vitrified clay or non-reinforced concrete. The pipe fails suddenly with no warning when the maximum flexural tensile stress of the material is exceeded. With fibre cement (FC) pipes 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 FC pipe is similar to that of a NR pipe with a higher flexural strength, with the failure under load also being sudden with little warning. The FOS for NR pipes is usually taken as 1,3 or 1,5.

The structural performance of a reinforced concrete pipe (RCP) depends upon the properties of two materials. The steel reinforcement enables the pipe to carry more than a NR pipe with the same wall thickness. When the pipe is loaded the failure is gradual and usually occurs in three stages. Initially when the flexural tensile strength of the concrete is exceeded and the pipe cracks, but the cracking is controlled by the reinforcement. Secondly as the load increases the crack width increases and at a certain stage it is such that moisture can enter it and cause the reinforcement to corrode. This is called the serviceability limit or proof load and is usually the value used in design. Finally the pipe collapses when the concrete fails in shear or the steel yields. As the ultimate or collapse load of RCP is at least 1,25 to 1,5 higher than the proof load which is used its design the FOS is taken as 1,0.

The installed pipeline is subject to earth and traffic loading, that impose vertical and horizontal forces on the pipes. At low fill heights traffic loading is the most significant, but as these loads are distributed through the fill at 45° or 30° depending on the transportation route construction, their influence on the pipes decreases with fill height and when greater than 2.5 m, these loads are generally 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 Equation 6 as this covers the most severe conditions. The earth load, on a rigid pipe under embankment loading condition where the fill height exceeds 1,7 times the outside diameter of the pipe is conservatively given by Equation 6.

$$We = Ce \ \gamma \ Bc \ H \qquad [6]$$

Where We is the installed earth load on the pipe
Ce is the embankment load coefficient with maximum values of 1,69 for sandy and 1,54 for clayey soils
Bc is outside diameter of the pipe
γ is material density of the soil
H is fill height over the pipe

When a pipeline has been installed on yielding founding conditions it may settle into this material, the earth around it can consolidate giving it more support than the bedding originally provided. If this does occur, although unlikely, the earth load reduces to a geostatic load which is equal to Equation 6 with Ce value equal to 1,0.

As the total load on an installed pipeline is the sum of traffic and earth loads, this value is used in Equation 5.

6.2 Problems that arise

The structural problems that arise on sewers are either due to a change in the loading conditions, such as the loss of bedding support, the loss of strength due to corrosion losses of pipe walls, or a combination of the two. Doing a MSI will generally visually identify these problems and by locating them on the sewer profile and an indication of the underlying causes can usually be obtained.

If there has been a loss of bedding support along a pipeline the bedding factor given in Equation 5 is reduced and higher strength pipes would be required. If the pipes are not strong enough, they will develop longitudinal bending cracks along both crown and invert. As the bedding factor deteriorates further the stresses along the invert increase more than those along the crown resulting in larger invert cracks. A severe loss of bedding support changes the load distribution around the bottom of the pipes to a concentrated load. This can result in a shear failure indicated by off centre cracks along the invert. The bottom of the pipe then flattens and this affects both the pipeline's hydraulic performance and structural integrity.

When an internal MSI is done and the sewer still has some flow through it the cracks along the crown will be visible, but the more severe cracking along the invert may not be seen. However if profiling shows a flat bottom, it is essential that the pipeline be drained and reinspected to determine the cracking severity along the invert.

If there has been a loss of bedding support at short sections along the length of a pipeline, as happens when there are defective joints and there is infiltration bringing bedding material into the pipeline, the pipeline sags and circumferential cracks can occur. This frequently occurs on the pipes next to manholes as after installation the manholes do not settle, but the pipes into and out of them may settle when they are backfilled.

Should the founding conditions along the trench bottom between manholes be variable and the necessary measures were not taken to ensure that the bedding foundation provided uniform support along trench bottom before the placing bedding and pipes sections of the pipeline could sag causing ponding. The impact of this and the resulting sequence of events can lead to serious capacity and structural problems as covered in the section that follows dealing with water-tightness.

When there are corrosion losses the wall thickness varies around the pipe circumference and will reduce the load carrying capacity of the pipe. The impact of this is covered under the section of paper dealing with corrosion.

7. WATER-TIGHTNESS

Pipelines should be installed so that they are water-tight and will remain so, to ensure that the hydraulic performance and structural integrity are not compromised. When a pressure pipeline leaks there are usually indications that this is happening. However, when a gravity pipeline leaks this may continue unnoticed for years until there is a serious problem like a sinkhole forming in the middle of a freeway.

Pipelines consist of pipes that are jointed and installed in excavated trenches that are then backfilled, so their performance is dependent upon the pipes, the joints, the material through which the trench is dug, the bedding and the backfill material. As bedding material is generally cohesionless for easy placing and compaction it is more permeable than the material through which the excavation was made. This means that any groundwater in the vicinity as is usual with large diameter sewers it will flow into and follow route of the backfilled excavations. Provided the sewer is water tight this will not cause a problem as the flow through this material will be slow.

7.1 Problems that arise

Sewers generally flow partly full with flow depths varying depending on the time of day and of year. If there any defective joints during low flow periods groundwater can flow into the pipeline and during high flow periods sewage could flow out of the sewer causing groundwater contamination. During wet weather the infiltration problem is more serious and the extra flows can result in overloading the capacity of the treatment works.

A serious problem arises when the infiltration carries solid material through the joints into the sewer. This can be initiated when there are poor and variable founding conditions and the sewer settles. This sagging can result in the joints between the pipes opening and no longer effectively sealed. This will not be indicated on the pipeline profile based on the levels taken, but will be shown on the MSI. When the MSI indicates ponding due to sagging and on investigation it is found that the joints between the pipes have been damaged or opened so wide that they no longer seal measures will be needed to effectively seal these joints before doing any rehabilitation.

This sagging of the pipes leading into and out of manholes can be serious resulting in circumferential cracks around these pipes and the damming of water either side of the manholes.

In addition to causing a pollution problem the exfiltration of effluent through defective joints during high flows may soften and loosen the bedding and backfill materials, thus accelerating the rate at which infiltration of ground water during low flows washes this fine material into the sewer. This movement of material into the sewer increases the siltation within the sewer and the loss of bedding support under it. This problem is progressive as the flow path developed either side of the sewer results in both bedding and backfill material being washed into the sewer increases the amount of siltation and the size of cavities either side of it over time. Eventually the size of a cavity becomes so large that it can daylight as a sinkhole. In an urban area this has very serious consequences as it means that transportation routes have to be closed and buildings evacuated.

8. DURABILITY

8.1 Corrosion mechanism and corrosion rate

Although structural, leakage and hydraulic problems usually occur where caused, corrosion problems do not necessarily occur where expected. They are influenced by the effluent properties and frequently due to upstream hydraulic conditions where there are flat sections of sewer, siphons and rising mains fed by pump stations. H_2S gas is generated in these sections and then released downstream when the velocity increases. The rate at which H_2S gas is released increases with velocity increases especially when there is supercritical flow. When there is corrosion it may be necesssary to inspect the upstream section of the sewer to determine the problem source.

The factors contributing to the corrosion phenomenon are the H_2S generation in the effluent, its release from the effluent, and the biogenic formation of sulphuric acid (H_2SO_4) on the sewer walls. If there is insufficient oxygen in the effluent 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. When there is an imbalance of H_2S in the sewage and the sewer atmosphere, the gas comes out of solution until the gas concentrations in the sewage and the sewer atmosphere are in equilibrium. The released H_2S is absorbed into the moisture on the sewer walls and is oxidised by another set of bacteria to H_2SO_4.

The alkaline component of the concrete reacts with the acid formed, resulting in corrosion above the flow level. As the corrosion products are about five times the volume of the original material, and porous they absorb moisture. These saturated products of corrosion having little strength fall away from the pipe wall at 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 1. With both types of pipe, the loss of sound material results in the loss of pipe strength.

If inert coarse aggregate 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 is attacked by the acid and the process continues.

The deterioration of the pipe wall can be rapid. If made with concrete using a calcareous aggregate, such as limestone or dolomite which is acid soluble, the attack is spread over both binder and aggregate. It takes much longer for it to loosen and fall out. The aggregate fallout problem is minimised reducing the rate of sewer wall loss. CCTV images taken inside sewers clearly show the differences between FC and RCP pipes using either inert or acid soluble aggregate as shown in Figure 1.


Figure 1: Corroded RCP (front) and FC (back)

The corrosion rate is determined by the rate at which the H_2S flux to the pipe wall is oxidised to H_2SO_4. The EPA design manual (1985), 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 is predicted by Equation 7.

$$C_{avg} = 11.5\ (k/A)\ \phi_{sw} \qquad [7]$$

Where C_{avg} is average corrosion rate, mm/year
k is the efficiency coefficient for acid reaction and ranges from 0.3 to 1.0.
A is alkalinity of concrete expressed as calcium carbonate ($CaCO_3$) equivalent.
ϕ_{sw} is flux of H_2S to the pipe wall in g/m^2/h
11.5 is the conversion rate of 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 8 is used in conjunction with the design life to determine the additional cover over reinforcement needed to ensure serviceability for this period. The Life Factor Method (LFM) (McLaren, 1984) given by Equation 8 is used.

$$Az = 11.5\ k\ \phi_{sw}\ L \qquad [8]$$

Where Az is called the life factor
L is the required design life
z is the additional cover over reinforcement needed to ensure serviceability for the period L.

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 cover and alkalinity. The right-hand side describes the conditions within the sewer in terms of effluent properties, flow characteristics, sewer atmosphere and the required life.

With slow flow velocities the products of corrosion may remain intact on the pipe wall around the whole circumference of the sewer and can 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 water level. Under these circumstances the material lost just above the average daily water level can be far greater (5 times or more) than that on the sewer crown due to the combination of corrosion and erosion. This results in a longitudinal horizontal sill either side of the sewer below which there is little or no corrosion and above which it 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 2.

8.2 The problems that arise

The above does not address the problem with an existing sewer that has already deteriorated and will at some time need rehabilitation. It needs to be determined when rehabilitation should take place and what technique to be used.

The moments generated in the pipe wall during testing or under installed conditions are dependent upon the loads and reactions on the pipe. As sewers are installed on bedding to enhance their load carrying capacity, the critical positions for moments are at the crown and invert provided the wall thickness around the circumference is the same. The invert moment given by Equation 9 is slightly higher than the crown moment due to pipe self-weight.

$$M = C_i\ W_I\ D + C_i\ W_p\ D \qquad [9]$$

Where M is the moment at the pipe invert

C_i is the moment coefficient at the pipe invert for the particular loading condition
D is the mid-wall diameter of the pipe
Wp is the pipe mass
W_I is the total installed load

The values of C_i are dependent upon actual loading conditions. When corrosion has occurred the wall thickness around the pipe circumference will vary and determining the remaining pipe strength means checking the strength at various locations around the circumference. With NR pipes failure occurs when the material's flexural stress, is exceeded. The flexural stress at any point around the pipe circumference will be calculated using Equation 10.

$$\sigma_t = 6\ M / t^2 \quad \text{or} \quad M = 0.167\ t^2\ \sigma_t \qquad [10]$$

Where σ_t is the ultimate flexural tensile of the material
M is moment at a location on the pipe circumference
t is wall thickness at location on the pipe circumference

When backfill material has some cohesion in it even though the pipe walls have corroded through the pipes may not actually collapse. This is shown in Figure 2. When these pipes were exposed the tops of some pipes collapsed. Several features discussed above are shown, corrosion at spring line more severe than at crown forming longitudinal horizontal sills, reinforcement that had corroded through was masked by corrosion products and there was no corrosion below the low flow level. These pipes were made from inert aggregate, flow velocity was about 2,5 m/s and the 70 mm walls were corroded through after 10 years. This 900 mm ID pipe was fed from a rising main with long retention times.

Figure 2: Severely corroded mushroom shaped

When the silt level in a sewer is deep it may flow full most of the time and the only location where the H_2S can escape is at the manholes. The H_2S concentration can be very high causing severe corrosion of the manhole walls. Due to this access into such manholes is hazardous both from a toxic and structural perspective and it may be necessary to rehabilitate or replace these manholes before cleaning the sewer in preparation for its assessment.

9. COMBINING THE OUTPUT

The digitized output of the MSI from above and below water level scanning provides internal pipe profiles along the whole sewer. This gives actual dimensions showing siltation levels reducing capacity and corrosion losses that reduce strength. It is recommended that the details from the MSI are complemented by measurements at a few locations as shown in Figure 3. This means sections of sewer where severe corrosion is anticipated and which can be easily exposed from the surface are identified, and inspection windows cut to do physical inspections and take measurements, photographs and material samples. These physical measurements can verify the digitized data and confirm the sewer's condition.

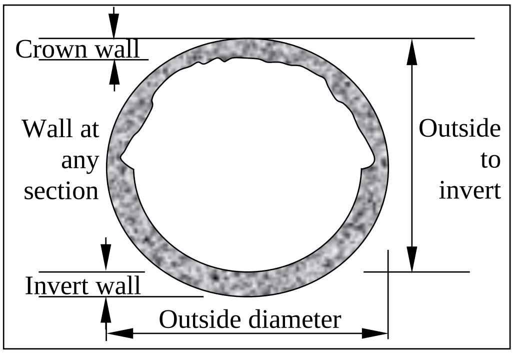

Figure 3: Physical dimensions to check

Combining the observations made from the MSI with the sewer profile identifies the problem areas. By then applying the theoretical principles the underlying causes of these problems can be established and if necessary, ways of addressing them investigated and applied before sewer rehabilitation is undertaken. There will be certain problems which cannot be completely rectified and others that can be eliminated. The rehabilitated sewer may actually operate more effectively and efficiently than when it was originally installed and its rehabilitated life span can be considerably longer than that planned for the original sewer.

From the utility owner's perspective the critical issue 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 to minimize its maintenance.

9.1 Calculating the remaining life

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 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. If some of the material surrounding the pipeline has infiltrated through leaking joints, cavities will probably form around the sewer resulting in a loss of bedding support. The load-carrying capacity of the pipe/soil system will then deteriorate, and collapses can be expected.

The major factor determining the life of a sewer is its durability which depends on the hydraulics and effluent composition. When the pipe wall has corroded, this must be considered in determining the residual strength. As corrosion just above the average flow level is frequently greater than at the pipe crown, the residual strength has to be calculated for 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 measurements provided by the MSI.

The calculations for determining the pipe strength around its circumference depending on the actual wall thickness are covered in the paper "Determining the remaining life of concrete sewers" (AM Goyns 2018). From these the remaining life along the whole sewer length, showing the critical sections, can be obtained. This is a critical input for risk analysis, as it will indicate whether the sewer has sufficient strength to be rehabilitated as a partially deteriorated conduit, when structural rehabilitated is needed to prevent it collapsing in the near future, as described in ASTM F 1276 (ASTM, 1999) or whether 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.

10. CONCLUDING COMMENT

Performance and 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 in addition to the MSI. This data is used to determine the sewer performance and the condition of pipes, manholes, joints and the soil around them.

Assessing the hydraulic performance and pipe condition shows the impact of various factors and how these may or may not for various reasons correspond with what was anticipated during the system design. By investigating the differences between the anticipated and actual performance there is a good chance of identifying the underlying causes to problems found and what preventative measures should be taken when designing new pipelines as well as preventative measures to take during their operation to avoid these past mistakes.

The two most serious underlying causes of the problems observed are variable gradients along a sewer's length causing H_2S formation, its release and the corrosion of cementitious pipes, and the settlement of founding material under the pipe bedding causing the opening of joints, resulting in exfiltration, infiltration and sedimentation.

However the problems that arise with sewer health are not just due to design defects, but also their misuse due to ignorance. The combination of these two factors causes serious operational problems. The utility owners should address this latter issue with users to ensure that there are healthy wastewater systems for future generations.

REFERENCES

ASTM F 1216. (1999) 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.

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. (2018) Determining the remaining life of concrete sewers. Proceedings of International No-Dig 2018, Cape Town, South Africa, October 8 - 9, 2018.