DESIGN APPROACH FOR FLEXIBLE PIPES INSTALLED AS NEW PIPELINES OR AS LININGS

When installing buried pipelines one must understand that one deals with the pipes and the surrounding soil that together form the basic structural unit. Hence there needs to be an understanding of the interaction between the two.

Flexible pipes are used in open trench and trenchless installations, and linings to rehabilitate deteriorated pipelines. Their stiffness defines the inherent strength of flexible pipes. This is measured by doing a parallel plate test, which is the external load when the pipe has deformed by 5 % or another deflection as specified for the material type. The output from this test is adjusted to model installed conditions. Equation [1] covered in ASTM D2412 is applied to the test results.

$$PS = F/\Delta Y \qquad [1]$$

Where PS is pipe stiffness expressed as kN/m/m or kPa
F is the force necessary to deflect the pipe by the specified amount in N/mm
ΔY is the vertical deflection of the pipe at a specified % deflection in mm

It is essential to appreciate that this test gives the physical properties of the pipe and the output in the format of equation [1] does not include any pipe material or dimensional properties.

The pipe ring stiffness used in the ISO standards, which is also used to model installations, is a calculated value that is determined from both the pipe material properties and the pipe geometry as given in equation [2].

$$PRS = EI/Dm^3 = E\,(t/Dm)^3/12 \qquad [2]$$

Where PRS is the pipe ring stiffness expressed as kN/m/m or kPa
E is the short term modulus of elasticity for pipe material in MPa
I is the moment of inertia of the pipe wall in mm^3
t is the wall thickness
Dm is the mean pipe diameter ((ID + OD)/2) in mm

An approximate relationship between equations [1] and [2] is given by equation [3].

$$PS = 53.69\ PRS \qquad [3]$$

This is a valuable relationship when dealing with the profiled wall pipes where the calculation of I is involved. When a more accurate value of PRS is required a more detailed calculation is needed.

When flexible pipes are installed, several performance limits must be established to ensure their performance is not compromised. These are, stress, fatigue, deformation, longitudinal bending, buckling, wall crushing and strain.

There are severe shortcomings in the currently used approach in the design of the pipe/soil system. The performance limit that generally governs the design of flexible pipes under various loading conditions is based on the unrestrained buckling pressure that Timoshenko has defined. This can be expressed similarly to equation [2] as equation [4].

$$Pcr = 24EI/Dm^3 \quad (24\ PRS) \qquad [4]$$

Where Pcr is the critical buckling pressure in kPa.

When a pipe, irrespective of the material used, is subject to internal pressure the relationship between the various parameters is given by equation [5].

$$Pi = 2\,\sigma_s\,(t/Dm) \qquad [5]$$

Where Pi is the internal pressure in MPa
σ_s is the tensile hoop stress across the pipe wall in MPa
t and Dm are as described above in mm

The same equation is applicable if a pipeline is empty and subject to a vacuum or negative internal pressure the same equation is applicable, but the components are different as shown in equation [6].

$$Pv = 2\,\sigma_s\,(t/Dm) \qquad [6]$$

Where Pv is the negative internal pressure in MPa

σ_s is the compressive hoop stress across the pipe wall in MPa

t and Dm are as described above in mm

It is important to appreciate the significance between the (t/Dm) ratio to the power of 3 for external loading as given in equation [2] and later equations [7] to [10] and that shown in equations [5] and [6] which is to the power of 1 for internal pressure or vacuum.

For a flexible pipe with no lateral support the critical buckling pressure can be calculated from equation [4] which is modified to handle the lateral deformation due to vertical load as defined by the Poisson's ratio and is taken into account in equation [7]. However, this is an unstable failure mode, because the more the pipe buckles, the less resistance it has, hence total collapse occurs at the Pcr.

$$Pcr = 24\,EI\,x10^3/((1-\vartheta^2)\,Dm^3) = 24\,PRS\,/(1-\vartheta^2) \qquad [7]$$

Where Pcr is the critical buckling pressure in kPa

E, I and Dm are as given below equation [2]

ϑ is the Poisson's ratio of the pipe material

Although flexible pipes are usually used for pressure applications, an understanding of what happens due to the loading other than internal pressure is needed when evaluating the performance of flexible pipes under various installation conditions. This includes the loading on pressure pipelines when they are empty and there is no internal pressure to counter the external loading.

A flexible pipe installed in an open trench and backfilled has support against buckling from the soil surrounding. Similarly it has support from the host pipe if used as a lining. However, if it has deformed into an elliptical shape due to external loading or an internal vacuum, it will have less bucking resistance than before deflection occurred, hence a correction factor must be applied depending on the application.

When placed in the soil the most commonly used approach is using the Iowa formula which in its basic form is

Deflection = external load / (pipe stiffness + soil stiffness)

The Modified Iowa Formula given in equation [8] for deflection calculations is the most commonly used format.

$$\frac{\delta}{ND} = \frac{T_f\;B_f\,W}{8 \times PRS + 0{,}061 \times F_d \times E'} \qquad [8]$$

Where : δ is the deflection in mm

ND is the nominal diameter in mm

T_f is the time lag factor

Bf is the bedding factor

W is the total load in kN/m

PRS is the pipe ring stiffness in kN/m/m

F_d is a design factor

E´ is the modulus of soil reaction in kPa (kN/m^2)

Both the pipe ring stiffness (PRS) and the soil stiffness (E') must be expressed in the same units even though their orders of magnitude are different. It is important to understand that these units must be compatible, even though the former applies to the pipe strength and the latter to the soil stiffness.

When flexible pipes are used as linings to rehabilitate existing pipelines that have deteriorated the critical structural parameter is also the bucking due to the water pressure that accumulates between the liner and the host pipe. Therefore, when a lining is designed, the equation is adjusted by adding factors to prevent buckling as shown in equation [9].

$$Pw = \frac{2KE_L}{(1-\vartheta^2)} \times \frac{1}{(SDR-1)^3} \times \frac{C}{N} \qquad [9]$$

Where Pw is ground water pressure in MPa

K is an enhancement factor from the existing pipe with a recommended minimum value of 7,0

E_L is the long term (time corrected) modulus of elasticity for the lining material in MPa

ϑ is the Poisson's ratio of the lining material

SDR is the standard dimension ratio = outside diameter / wall thickness

C is the ovality reduction factor

N is the factor of safety

When a pipe is placed in soil ovality is induced by the deflection due to the soil loading and this reduces the resistance of the pipe due to buckling due to the soil support.

As SDR = (Dm + t)/t = (Dm/t) +1, so $1/(SDR-1)^3 = (t/Dm)^3$ and $EI/(Dm)^3 = PRS$ so equation [9] could be rewritten as equation [10].

$$Pw = \frac{24PRS}{(1-\vartheta^2)} \times K \times \frac{C}{N} \qquad [10]$$

Where the various factors have already been defined. The factor 'K' covers the interaction between the lining and the host pipe and its value will depend upon how tightly the liner fits into the host pipe.

When a lining deforms at a certain stage it will 'snap through' and buckle. So for most cured-in-place and other tight fit liners a 'K' value of 7, although considered conservative, is used. However with linings pulled through, or spirally wound into the host pipeline a lower value of 'K' is applicable.

The difference between, the pipe placed in the soil and the pipe used as a lining is due to the difference in the external support provided by the soil or the host pipe and the critical loading condition. For a pipe placed directly in the soil the critical loading is due to the vertical earth and traffic loads resulting in buckling at the crown. When used as a lining the loading will be due to the water pressure between the host pipeline and the lining, resulting in buckling at the invert as the water pressure at the invert will be greater than elsewhere.

In conclusion, irrespective of the application of the flexible pipe, whether for a pressure pipeline, or a gravity pipeline through the soil, or pipeline rehabilitation the pipe/soil interaction should be considered. The various criteria for the structural performance that should be considered are deflection, buckling and yielding of the pipe wall material and how these relate to the particular application.