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Comparison of Required CIPP Liner Thickness with ASTM F1216, WRc Type II and ASCE MOP 145 Design Method

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1.0 ABSTRACT

A new method for design of cured in place liners in gravity flow pipes has been introduced in the ASCE Manual of Practice 145 (2021), challenging WRc type II and ASTM F1216 design methods on safety and cost-effectiveness. The design method in the MOP 145 is commonly referred to as the MOP 145 method and this name will be used in this paper as well. This paper will review selected equations and design approaches associated with the different methods. Calculations will be made for selected pipe shapes, loading conditions and liner materials to show the difference in results obtained with different methods. It will be shown that the MOP 145 method accounts for safety where the WRc type II design is deficient. Comparisons with the ASTM F1216 method will show that the use of realistic annular gap in the MOP 145 method makes it possible to significantly reduce the liner thickness, for as much as 30% in case of reinforced liners installed in large diameter pipes. In this paper, FEA method will be used as a reference method to confirm the validity of some calculations.

2.0 INTRODUCTION

The ASCE Manual of Practice (MOP) 145 (ASCE 2021) design method is a calculation method used for design of close-fit liners installed in gravity flow pipelines – see the note at the end of this section for clarification of close fit and the annular gap. The MOP 145 design method complies with the Load and Resistance Factor Design (LRFD) format, which is currently the standard for structural calculations used in concrete, steel, wood, and bridge design specifications. The LRFD method, when applied to close-fit liners, takes into account the exact geometry of the liner (i.e., the radii of curvature and the opening angles of arcs which comprise the liner profile). Further, it is applicable to both circular shapes and a wide range of non-circular shapes including eggs, arches, ovals, boxes, horseshoe shapes, elliptical shapes, etc. The method explicitly takes into account the residual annular gap between the liner and the host pipe after the liner installation.

The MOP 145 method derives from the 3R2014 calculation recommendations in France (ASTEE 2017). There, the 3R2014 method completely replaced the WRc type II method (WRc 2001) due to important shortcomings of the latter, such as not taking buckling under groundwater pressure into account for egg shapes (Braun A. and Macey C. 2017) and seriously underestimating deflections for oval shapes.

In North America, the circular liner design, and more specifically Cured in Place Pipe (CIPP) design, is covered by the method published in the Nonmandatory Appendix X1 of the ASTM F126 standard (ASTM 2021). The ASTM F126 method is also considered empirical because it is based on results of laboratory tests, but it should be noted that it was calibrated by tests only for the resistance to buckling (Eq.X1.1), and only for common diameters (10-12 in). Other calculations (stresses under the effect of the groundwater pressure, Eq.X1.2, and especially the calculation under the addition of all the loads, Eq. X1.3) have not been the subject of tests, whereas this last equation is generally the one which gives the final thickness. Regardless, this method generally satisfies the profession because it is very simple to apply, and it gives “acceptable” thicknesses for common diameters.

It should be noted that, like for any empirical method when used outside of its calibration range (e.g., large diameter CIPPs), it is not clear whether the thickness calculated with ASTM F126 is excessive or, on the contrary, insufficient. If the calculated thickness is excessive, then more safety is built into the liner than is actually required, but this advantage quickly becomes a disadvantage because the extra thickness induces higher than necessary cost for the utility owner, increases difficulty of installation due to the increase in the liner weight, increases the risk of curing defects, etc. It should also be noted that the ASTM F126 method does not explicitly take into account the residual annular gap between the liner and the host pipe (NASTT 2015), which plays a fundamental role in the resistance to buckling (MOP 145). This paper shows that significant reduction in liner thickness (30% to 40%) is possible if, instead of ASTM F126, the MOP 145 method with realistic values for the annular gap is used, while maintaining the same level of safety.

The formulas in the MOP 145 method were widely validated with finite element analysis (FEA) calculations outside of this paper (Thépot 2000b, 2001, 2021). In this paper, FEA is used as a reference method to confirm the validity of some calculations.

The CIPP design for external groundwater pressure, which is the most fundamental loading in liner design, typically determines the liner thickness in the MOP 145. Two design approaches used in the MOP 145 for this design are briefly outlined in this paper. Design for other loads (traffic and other surface loads, soil overburden pressure) that may act on the liner is also included in the MOP 145 (Design for State III). Although this design is not specifically discussed in this paper, it is used in one example (see 4.4.2).

Note: Close-fit liners for gravity flow pipes are the liners installed in defective sewer or culvert pipes with the trenchless cured-in-place installation method which leaves a very small residual annular gap between the host pipe and the liner after the resin cure. Today it is possible to install CIPPs with dimension ratio (DR) greater than 100, with practically perfect contact. Indeed, a tight fit is premised in most CIPP liner installations, with the outside surface of the finished liner required to be in contact with the inside surface of the host pipe. A fit tolerance is typically 1.0 mm or 0.04 in and an annular gap exceeding 1.0 mm is (with some exceptions) indication of deficient fit (NASTT 2015). Additional explanation about determining the value of annular gap in liner design is in section 4.4.1.

3.0 NON-CIRCULAR DESIGN

3.1 OVERVIEW OF NON-CIRCULAR DESIGN SECTION

The WRc type II design is an empirical design method calibrated for one particular egg shape (normalized 3x2 egg). However, the method has been used for many years for other non-circular shapes, including other egg shapes, ovals, arches, boxes, horseshoe shapes, etc. The

use for non-circular shapes has proven unreliable due to two specific shortcomings which will be explained in this section.

But first, the MOP 145 method applied for non-circular shapes will be briefly outlined and some formulas specifically related to the egg-shaped liner design will be shown which will be useful for better understanding of the WRC type II design of egg-shaped liners.

Two examples will follow to show the difference in calculations with the WRC type II method and the MOP 156 method:

- The first example will present calculations for a liner in a 2x1 egg shape pipe, 1,200 mm height by 600 mm width. It will be shown that the WRC type II method gives greater allowable groundwater height than the groundwater height which leads to buckling (critical buckling height) calculated with the MOP 145 method.
- The second example will present calculations for a liner in an oval shape pipe, 1,200 mm height by 600 mm width. It will be shown that the WRC method gives an admissible groundwater depth which is four (4) times greater than that calculated with the MOP 145 method and the FEA method (used here as a reference method).

3.2 MOP 145 DESIGN FOR NON-CIRCULAR SHAPES

The MOP 145 method for non-circular liners includes two calculation approaches in design for external groundwater pressure based on the spreading of the deformation blister which develops under the loading (ASCE 2021): the critical approach, where the blister remains confined on one pipe arc, and the subcritical approach, where the blister spreads over one pipe arc completely and extends further into the connecting arcs (see Figure 1).

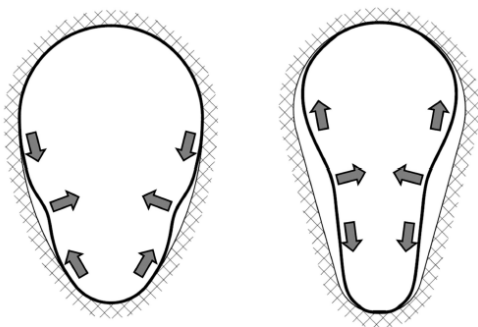


Figure 1. (a) Critical Shape with Localized Blisters, (b) Subcritical Shape with Blisters Extending Over Entire Length

The critical design approach is based on the calculation of the critical buckling pressure, the critical bending moment, and the critical hoop force for given liner thickness, see Tables 5-14 and 5-25 in (ASCE 2021). But first, the critical angle of the blister, α_{cr} , which is the angular extension of the deformation blister at the time of buckling, must be calculated and compared with the angle of pipe arc where the blister develops, α (see Figure 2). The solution in the critical approach was developed for condition $\alpha_{cr}/\alpha \leq 1.0$. However, comparisons with the FEA show that the critical approach can be applied for $\alpha_{cr}/\alpha \leq 1.3$, and with some conservative results until $\alpha_{cr}/\alpha = 1.5$. The calculations in critical design are simple and straightforward.

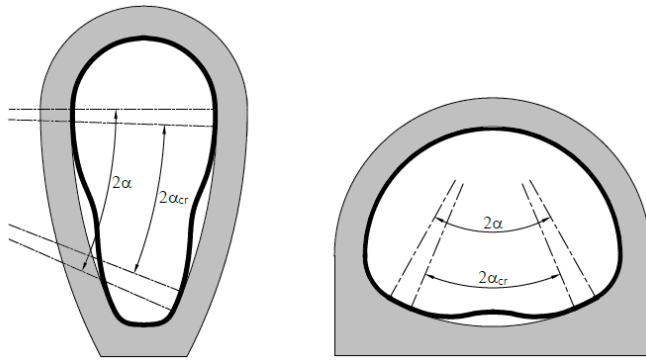


Figure 2. Critical Angle of the Blister (α_{cr}) and Angle of the Pipe Arc (α).

The sub-critical design approach is very different because, unlike the critical approach, it is based on calculation of the pressure as a function of liner deflection (Thépot 2001), see Tables 5-34, 5-35, 5-38 and 5-40 in the MOP 145 (ASCE 2021). The calculations in sub-critical design are not quite simple and straightforward. First, the extension angles of the deformation blister, α_1 and α_2 , must be calculated for the maximum allowable deflection at the center of the blister (see Figure 7 on the right). This calculation requires iterative procedure to solve a polynomial equation of degree 5. Once solved, the corresponding pressure, the bending moment, and the hoop force are calculated as functions of α_1 and α_2 .

Egg shape design typically involves critical design approach (although sub-critical design approach is sometimes required). The formulas for design buckling pressure in two different egg shapes developed for critical design approach are presented and commented here.

The design buckling pressure for the normalized 3x2 egg shape of height H (Figure 4 left), where the radius of the sides R is equal to the height H, calculated with the Glock-Thépot formula is given by (see ASCE 2021, Table 5-24):

$$p_{cr,w,d} = 0.407 \cdot \frac{E_{50,d}}{1-\nu^2} \cdot \frac{t^{2.2}}{H^{2.2}} \cdot \kappa_p \quad [1]$$

For the 2x1 egg shape, where the radius of the sides equals 1.75 times the height H (Figure 4 right), the buckling pressure calculated with the Glock-Thépot formula is given by:

$$p_{cr,w,d} = 0.153 \cdot \frac{E_{50,d}}{1-\nu^2} \cdot \frac{t^{2.2}}{H^{2.2}} \cdot \kappa_p \quad [2]$$

By comparing Eq. [1] and [2], the MOP 145 method shows that for the two different egg shapes of the same height, the critical buckling pressure of the 2x1 profile is 2.66 times lower (more critical) than that of the 3x2 profile. The calculations with WRc type II method are quite different which is presented and explained in 3.3.

3.3 WRc TYPE II DESIGN

The mechanical model in WRc type II design is based on first order beam formulas that have been calibrated to the results of tests on a 3x2 normalized egg GRP liner (Glennie 1982).

The experimental device consisted of two GRP shell elements, 850 mm high by 550 mm wide by 7 mm thick, placed in a rigid frame (see Figure 3). This formed shell was subjected to an internal depression (with the net pressure limited to 100 kPa). It should be noted that the rigid frame restrained the shell only vertically and horizontally at the springs level, which is not comparable to the restraint caused by the continuous contact with a host pipe. The comparison of the test results with those of a simple numerical model made up of beams and nodes had made it possible to establish the following (empirical) expressions for the maximum bending moment and the maximum displacement of the shell:

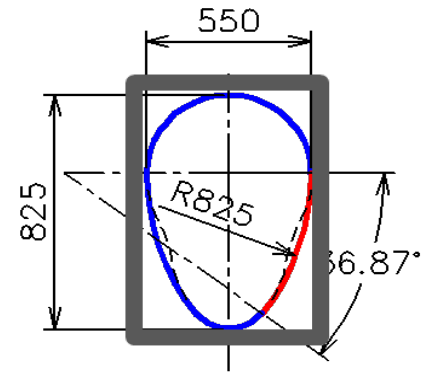


Figure 3. Experimental Device in WRc Tvee II Design

$$M = \frac{p \cdot l^2}{20} \quad [3]$$

$$d = \frac{p \cdot l^4}{927EI} \quad [4]$$

Where:

M	Maximum bending moment
p	Pressure of the water table counted from the invert (kPa)
l	"Critical length" (mm)
d	Maximum displacement of the shell (mm)
EI	Product of inertia of the liner's wall

The critical length, l, is equal, in case of an egg-shaped liner, to Max (2/3 H, W), where H and W are the height and the width of the egg, respectively. For an oval-shaped liner, l is equal to Max (W, H-W).

From formulas [3] and [4], two "allowable" heights, H_1 and H_2 (in meters) are directly derived and used in the WRc type II calculation method:

$$M = \frac{p \cdot l^2}{20} \Rightarrow \sigma = \frac{6M}{t^2} = \frac{6}{20} p \left(\frac{l}{t}\right)^2 \Rightarrow \sigma \leq s_L \Rightarrow p \leq \frac{20}{6} s_L (t/l)^2 \Rightarrow H_1 \leq 340 s_L (t/l)^2 \quad [5]$$

$$d = \frac{p \cdot l^4}{927EI} \Rightarrow \frac{d}{l} = \frac{12}{927E_L} p \left(\frac{l}{t}\right)^3 \Rightarrow \frac{d}{l} \leq 3\% \Rightarrow p \leq \frac{0.03 \cdot 927}{12} E_L (t/l)^3 \Rightarrow H_2 \leq 236 E_L (t/l)^3 \quad [6]$$

Where:

t	Thickness of the liner's wall (mm)
E_L	Long-term (time corrected) flexural modulus of the liner's material (MPa)
s_L	Long-term flexural strength (permissible long-term bending stress) (MPa)
H_1	Head of water limited by the permissible long-term bending stress (m)
H_2	Head of water limited by the permissible long-term deflection (3% of the critical length) (m)

Besides the liner thickness, the only geometrical parameter considered here is the critical length. The curvature of the sides is not taken into account, which is concerning because the curvature plays the fundamental role in the resistance to buckling under external pressure. The WRc method indeed does not consider buckling which is the primary failure mode for egg shapes according to both the FEA and the MOP 145 methods.

Note that equations like [3] or [4] can be calibrated with experimental results for a particular shape, but this does not imply that such equations are universally valid and may be used for other shapes.

3.4 EGG SHAPED LINERS

To illustrate the importance of buckling in the design of egg-shaped liners, the results obtained with the WRc type II method and the MOP 145 method will be compared for a normalized 3x2 egg shape and a 2x1 egg shape (Figure 4).

The two shapes used in this comparison have the same height, H . The radius of the sides is H and $1.75 \times H$ for 3x2 egg and 2x1 egg, respectively. Their critical length, l , is equal ($l = 2/3H$) which can be easily verified.

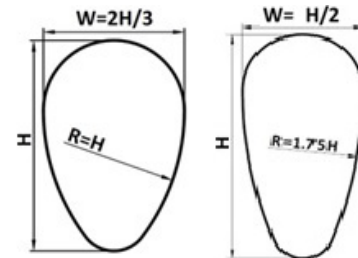


Figure 4. Eggs Shapes in Examples, 3x2 (left) and 2x1 (right)

With WRc type II method, these two shape designs give exactly the same result (the same admissible heads of water), which may immediately seem odd because one might expect that the liner would behave differently in different pipe shapes.

The liner material used in the calculations is the reinforced material, with properties listed in Table 1 (see section 4.2). The admissible heads of water, H_1 and H_2 calculated with the WRc type II method (see section 3.3) are shown in Figure 5 (green and blue lines) for a 3x2 egg (left) and for a 2x1 egg (right). The critical buckling head calculated with the MOP 145 method is added for comparison (red line).

In figure 5 it can be seen that in the case of a 2x1 egg, the WRc type II method gives allowable heads of water greater than the critical buckling head. This is due to the radius of curvature of the sides, which is greater for a 2x1 egg than for a 3x2 egg. In conclusion, the WRc type II method may be unsafe for egg-shaped liners different than the normalized 3x2.

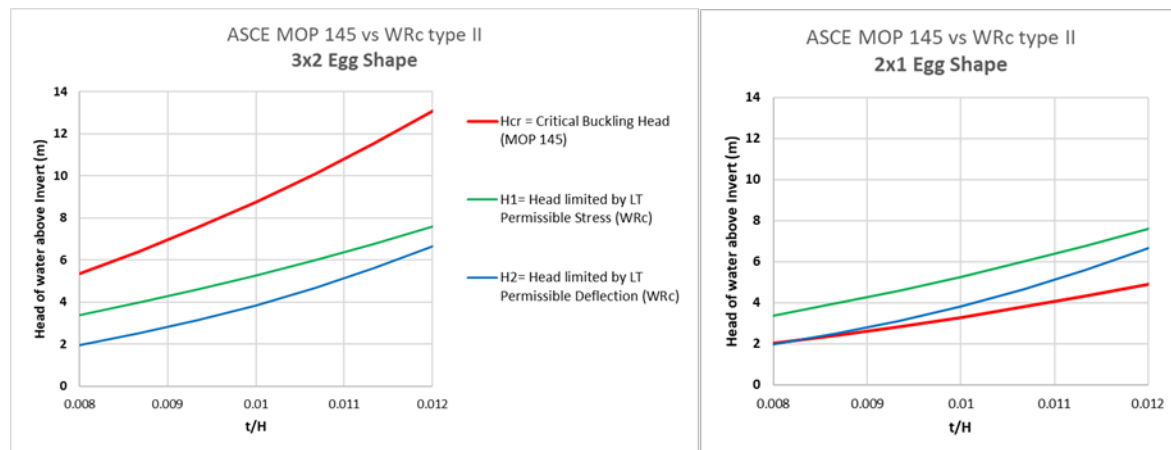


Figure 5. Comparisons of the “Allowable” Heads of Groundwater Calculated with WRc Type II and the Critical Buckling Head of Water Calculated with MOP 145

3.5 OVAL SHAPED LINERS

The oval shape has flat (straight) side sections (see Figure 7) that considerably increase deformability of this shape under external groundwater pressure compared to an egg shape. While true ovals are rarely found, designers using the WRc type II method often use oval shape design to calculate other shapes with flat sections (see Figure 6).

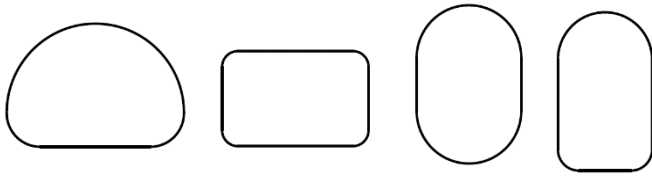


Figure 6. Some Common Pipe Shapes with Flat Sections

For the oval shape calculation, the WRc type II method simply divides the head of water limited by the permissible long-term deflection of 3% by 2, by introducing a coefficient 0.5 in Equation [6]. This assumes that the maximum deflection of the deformation blister at the level of the flat section (see Figure 7 left) is two (2) times greater than that of a curved section (egg shape). In reality, the deflection is at least 5 to 10 times greater as shown in the following example.

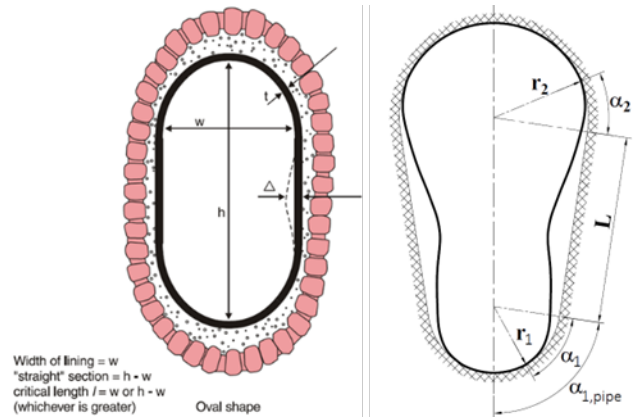


Figure 7. Oval shape. WRc Parametrization (left), MOP 145 Parametrization (right)

Calculations were carried out with WRc type II, FEA and MOP 145 methods, for a liner in the oval pipe, 1,200 mm height by 600 mm width, subjected to an external hydrostatic pressure. The liner thickness used in the calculations is 15 mm. The “critical length” (the length of the straight side) is equal to 600 mm. The material long-term modulus is $E_L=5000$ MPa (Reinforced GRP from Table 1, see section 4.2) and long-term flexural strength is $70 S_L =$ MPa. Calculations with the MOP 145 were performed using CLinT software.

In Figure 8, the admissible height of water is depicted for WRc type II method for deflection 3% (red dot), and relative deflections for different heights of groundwater above invert for other two methods, MOP 145 (black line) and FEA (white symbols).

It can be seen that the WRc method gives an admissible height of water for a deflection of 3% that is four (4) times greater than the results of the FEA and MOP 145. The origin of this error can be understood by looking at Figure 7: The profile on the left, which is extracted from the WRc manual, has a deformation blister confined to the straight side. The profile on the right, which is extracted from the MOP 145, has a deformation blister that extend over the adjacent arcs (at the obvert and invert), which is the mechanical reality (Thepot, 2001).

The length of deformation blister in the MOP 145 is therefore greater (about 30 to 50%) than that of the straight side. Because the deflection varies to the power of 4 of this length, the deflection is much greater than that of the (double-clamped) beam of length equal to that of the straight side (the dotted black line on the graph in 8). So, the WRc type II method introduced a factor of 0.5 to take into account the absence of curvature, but in fact, a coefficient of about 0.1 should have been used in this case. (This factor is not a constant as it depends on the liner thickness used in calculations.)

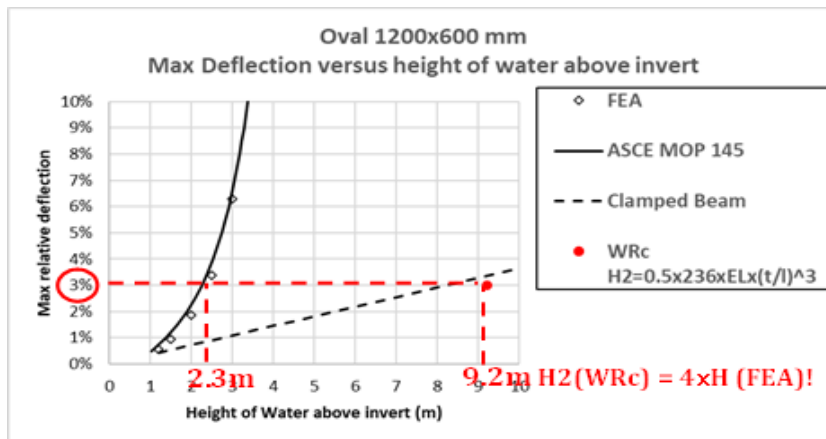


Figure 8. Comparisons of Maximal Deflections for an Oval Shape

It should also be noted that the factor of 0.5 was simply assumed rather than calibrated based on the test results like in case of the egg shape. This demonstrates once again that empirical formulas calibrated or otherwise proposed for a particular shape cannot be extrapolated to other shapes without risk.

4.0 CIRCULAR DESIGN

4.1 OVERVIEW OF CIRCULAR DESIGN SECTION

The ASTM F1216 design method has been used for design of circular liners for many years. The use of this method has some issues which will be explained in this section. But first, the MOP 145 method applied for circular shapes will be briefly outlined and some formulas will be shown which will be useful for better understanding of the comparison between the two methods.

The ASTM F1216 method is an empirical design method that was calibrated in laboratory testing. It should be noted that the tests were done only for resistance to buckling (Eq. X1.1) and only for common diameters (10-12 in). The other two equations, stresses under the effect of groundwater pressure (Eq. X1.2) and stresses under the addition of all the loads (Eq. X1.3) were not the subject of tests. However, the last equation (Eq. X1.3) is generally the one which gives the final thickness.

The design for external groundwater pressure brings into play two limit states: buckling and material failure. Both the ASTM F1216 and MOP 145 methods take into account these two limit states, however, the former is the Allowable Stress Design (ASD) and the latter Load and Resistance Factor Design (LRFD). In this section, the design equations for ASTM F1216 and MOP 145 methods will be shown first. The methods will be compared based on the experimental enhancement factor, K, which plays a very important role in the ASTM F1216 method. This factor does not exist in the MOP 145 method, and for the purpose of comparing the methods, an analytical formula for K was derived from the MOP 145 method.

The issues with the ASTM F1216 design that will be brought to light include:

- The method does not explicitly take into account the residual annular gap between the liner and the host pipe which plays a fundamental role in the resistance to buckling.
- The ovality reduction factor used in this method is strictly applicable only to elliptically (flexible) ovalized pipe.
- The use of the formula Eq. X1.2 is not applicable for close-fit liners.

Three examples of liner design in large diameter pipes will follow to show the difference in methods calculations. All examples include cracked rigid pipe, but the extent of ovality at the time of lining, soil conditions and material properties differ. The material properties of the liner are shown in Table 1. Calculations with the MOP 145 were performed using CLinT software.

- The first example is the reinforced (GRP) CIPP liner installed in the pipe with low ovality (3%) in average soil conditions.
- The second example is the reinforced (GRP) CIPP liner installed in the pipe with high ovality (10%) in poor soil conditions.
- The third example is the non-reinforced CIPP liner installed in the pipe with low ovality (3%) in average soil conditions.

These examples will show that significant reduction in required thickness (on the order of 30% to 40%) is possible if, instead of using the F1216 design method, the MOP 145 method with the realistic values for the annular gap is used, while maintaining the same level of safety.

Table 1. Mechanical Properties of CIPP Liners Used and Referenced in Various Examples in this Paper (Sections 3 and 4)

CIPP	Flexural Modulus, E	Flexural Strength, σ_{Rf}	50 Year Retention for E	50 Year Retention for σ_{Rf}	Poisson's Ratio
Nonreinforced	400,000 psi (2758 MPa)	4,500 psi (31.0 MPa)	50%	50%	0.3
Reinforced (GRP)	1,400,000 psi (9653 MPa)	20,000 psi (137.9 MPa)	50%	50%	0.3

4.2 ASTM F1216 DESIGN

4.2.1 Buckling Limit State

In ASTM F1216, the buckling stability is handled by Eq. X1.1 (see Equation 7), which makes it possible to directly calculate the maximum dimension ratio (DR) and the minimum thickness compatible with the buckling stability of the liner.

The equation is based on the Timoshenko Formula, which calculates the critical buckling pressure of a free-standing tube subjected to a uniform external pressure, and it is modified by an enhancement factor K that takes into account the restraining effect of the host pipe.

$$P = \frac{2KE_L}{(1-\nu^2)} \cdot \frac{1}{(DR-1)^3} \cdot \frac{C}{N} \quad \text{Eq. X1.1} \quad [7]$$

Where:

$$C = \left(\left(1 - \frac{\Delta}{100} \right) / \left(1 + \frac{\Delta}{100} \right)^2 \right)^3 \quad [8]$$

- P Groundwater load measured from the invert of the pipe (MPa)
- K Enhancement factor, minimum value of 7.0 (unitless)
- E_L Long-term (time corrected) flexural modulus of the liner's material (psi, MPa)
- C Ovality reduction factor (unitless)
- DR Dimension ratio of CIPP, DR = D/t (unitless)
- t Liner thickness (mm)

ν	Poisson's ratio, 0.3 average (unitless)
N	Safety factor = 2.0 (unitless)
Δ	Percentage ovality of original pipe (unitless)

It can be seen that annular gap is not included in Eq. X1.1, which is a serious drawback. For instance, if the annular gap is not 1 mm (0.04 in) but is instead 5 mm (0.2 in), the consequence on the resistance to buckling is not considered. Annular gap is further discussed in section 4.3.1.

The enhancement factor, K , is an empirical coefficient that was calibrated in tests carried out by Aggarwal and Cooper (Aggarwal 1984) on 49 CIPP liners with DRs ranging from 30 to 90. They found the enhancement factors to vary from 6.5 to 25.8 and concluded that because 46 of 49 tests gave a value of K greater than 7.0, the value of 7.0 should be the lower 90% confidence limit (equivalent to the 5% fractile) of K and used for design purposes. The validity of the calibration will not be discussed in this paper and it will only be noted that an empirical equation is generally only usable around the values (DR values) for which it was calibrated.

One issue with Eq.X1.1 is related to the use of ovality reduction factor, C . This factor is based on the maximum radius of curvature of an ellipse (see Equation 8), and as such should be applied only to pipes with elliptical ovality, i.e. to flexible pipes. However, it is also applied to cracked rigid pipes, for which it was not designed: the reduction of buckling pressure (which is based on the curvature in the middle of a deformation blister) in a cracked rigid pipe is fundamentally different than in an elliptically deformed flexible pipe. To elaborate, ovality of rigid pipes is mainly due to cracks. The classic cracking pattern is separation into four hinge segments with cracks at the crown, springlines, and invert (4H ovality). The curvature of cracked pipe segments does not change. In contrast, in elliptically deformed flexible pipes, the radius of curvature at invert is increased. (Thépot 2021)

4.2.2 Material Failure Limit State

In ASTM F1216, the calculation of stress is handled by equation X1.2 (see Equation 9). This equation gives the first order maximum tensile stress in a free-standing tube with some initial ovality, subjected to a uniform external pressure. Two initial observations can be made:

- Eq. X1.2 does not include any experimental coefficient to take into account the constraining effect of the pipe (unlike Eq. X1.1), thus revealing that it was not validated experimentally.
- The ovality used in the equation is of the elliptical type and not from the development of cracks.

$$1.5 \frac{\Delta}{100} \left(1 + \frac{\Delta}{100}\right) DR^2 - 0.5 \left(1 + \frac{\Delta}{100}\right) DR = \frac{\sigma_L}{PN} \quad \text{Eq. X1.2} \quad [9]$$

Where:

σ_L	Long-term (time corrected) flexural strength for CIPP (psi or MPa)
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Further analysis of Equation 9 reveals that the first term on the left side represents the bending stress and the second term the axial stress (both are divided by the pressure). Also, the bending stress depends significantly on the ovality, whereas the axial stress depends very little on the ovality. The bending stress is significantly (5 to 30 times) greater than the axial stress. This equation is not quite correct because the bending term should have been multiplied by an amplification factor due to buckling. However, the main problem with using this equation is that bending stresses that develop in the deformation blister of a constrained liner (with or

without initial ovality) under external pressure are not the same as those which develop in a free-standing tube with initial ovality. In conclusion, the use of equation X1.2 for a close-fit liner is incorrect.

4.3 MOP 145 DESIGN FOR CIRCULAR SHAPES

4.3.1 Buckling Limit State – Equations, Enhancement Factor

In the MOP 145 method, the buckling stability verification is handled by Equations 10 and 11 (MOP 145: Table 5-23, 5-24 and 5-30). Note that because MOP 145 design is LRFD, critical buckling pressure and groundwater pressure are factored by applying the resistance factor to the liner’s long-term flexural modulus and the load factor to the groundwater pressure.

One important factor in the MOP 145 is the reduction factor for imperfections, κ_p , which is for different liner imperfections (annular gap, 4-hinge ovality, or elliptical ovality; see Figure 9) given in Equations 12, 13 and 14.

Note that MOP 145 method distinguishes the effect of ovality of a cracked rigid pipe (4H ovality) from that of a flexible pipe (elliptical ovality) on the reduction in critical pressure: the reduction is greater in a rigid pipe than in a flexible pipe of the same ovality.

$$p_{cr,w,d} = 0.218 \cdot \frac{E_{50,d}}{1-\nu^2} \cdot \frac{t^{2.2}}{R^{2.2}} \cdot \kappa_p \quad [10]$$

$$p_{cr,w,d} \geq p_{w,u} \quad [11]$$

Where:

- $p_{cr,w,d}$ Factored critical buckling pressure (psi)
- $p_{w,u}$ Factored groundwater pressure (psi)
- $E_{50,d}$ Factored long-term flexural modulus of the liner’s material (psi)
- ν Poisson’s ratio
- t Liner’s thickness (inch)
- R Liner’s mean radius (inch)
- κ_p Reduction factor for imperfection (gap, ovality, etc.)

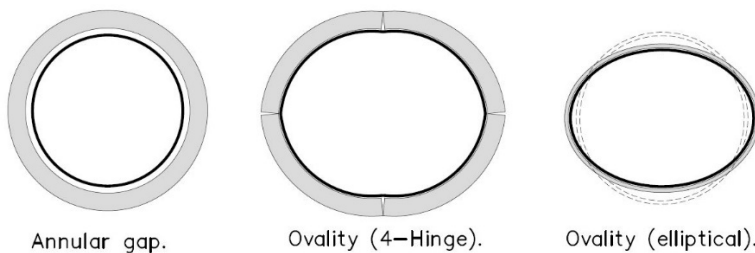


Figure 9. Liner Imperfections

For a perfect circular host pipe (annular gap only):

$$\kappa_p = \kappa_{p,g} = \frac{1}{1+0.38 \cdot \delta_g} \quad \text{where} \quad \delta_g = 3.87 \cdot \frac{g}{R} \cdot \left(\frac{R}{t}\right)^{1.2} \quad [12]$$

For a rigid cracked circular host pipe (annular gap + 4H ovality):

$$\kappa_p = \kappa_{p,g-4H} = \frac{1}{1+0.38 \cdot \delta_g + 1.3 \cdot \delta_g \cdot \delta_{4H} + 3.23 \cdot \delta_{4H} + 21.2 \cdot \delta_{4H}^2} \quad \text{where} \quad \delta_{4H} = 0.448 \cdot \theta \cdot \left(\frac{R}{t}\right)^{0.4} \quad [13]$$

For a flexible circular host pipe (annular gap + elliptical ovality):

$$\kappa_p = \kappa_{p,g-el} = \kappa_{p,g} \cdot \kappa_{p,el} \quad \text{where} \quad \kappa_{p,el} = \left[\frac{1 - Ov_{el}}{(1 + Ov_{el})^2} \right]^{1.8} \quad [14]$$

Where:

$\kappa_{p,g}$	Reduction factor for annular gap (see MOP 145 Table 5-22)
$\kappa_{p,g-4H}$	Reduction factor for annular gap and 4H ovality (see MOP 145 Table 5-23)
$\kappa_{p,g-el}$	Reduction factor for annular gap and elliptical ovality (see MOP 145 Table 5-23)
g	Mean gap calculated over the perimeter, recommended maximum value: 0.04 in
θ	4H ovality, maximum value: 0.2 (20%)
Ov_{el}	Elliptical ovality, maximum value: 0.02 (20%)

Equations 10 and 11 are not directly comparable with Equation 7 because Equation 7 includes an overall safety factor of 2, whereas Equations 10 and 11 have the safety distributed between the loads and the resistances in accordance with the LRFD design. Here, the service groundwater pressure is multiplied by a load factor, γ_{GW} , of 1.6, and the long-term modulus (which is here the resistance) is multiplied by a resistance factor, Φ_{LM} , of 0.8 (see Equations 15 and 16). It will be shown next that with these LRFD factors, the level of safety “globally” (global safety factor) built into equation 10 (and therefore into the result of the MOP 145 design calculations) equals 2.

$$p_{w,u} = \gamma_{GW} \cdot p_w \quad \text{where} \quad \gamma_{GW} = 1.6 \quad [15]$$

$$E_{50,d} = \Phi_{LM} \cdot E_{50} \quad \text{where} \quad \Phi_{LM} = 0.8 \quad [16]$$

Where:

E_{50}	Long-term (50 years) flexural modulus of the liner’s material (psi)
p_w	Service groundwater pressure (psi)

Enhancement Factor in MOP 145

E_{50} and p_w in MOP 145 are equivalent to E_L and P in F1216 Eq. X1.1. To derive enhancement factor K for the MOP 145 method, Equation 10 is rewritten into Equation 17 after setting $p_{cr,w,d} = p_{w,u}$. Equation 17 is directly comparable to Equation 7. It can be seen that $\gamma_{GW} / \Phi_{LM} = 2.0$, which corresponds to the global safety factor of 2.0 of Eq. X1.1. In other words, the global safety factor of 2 is built into the MOP 145 method calculations.

$$p_w = 0.218 \cdot \frac{E_{50}}{1 - \nu^2} \cdot \frac{t^{2.2}}{R^{2.2}} \cdot \frac{\kappa_p}{(\gamma_{GW} / \Phi_{LM})} \quad [17]$$

Next, by comparing Equations 7 and 17, the enhancement factor K is derived (see Equation 18). Note that the K factor is not constant: it increases almost linearly with the DR and decreases rapidly with the gap.

$$K = 0.5 \cdot (DR - 1)^{0.8} \cdot \kappa_{p,g} \quad [18]$$

In Figure 10, the enhancement factor K is depicted for ASTM F1216 method as a dashed line (a constant of 7.0) and for the MOP 145 method as a function of g/R for several different DR

values (30, 50, 100, 150), which are shown as black, blue, green and red lines. For a full contact (where $g = 0$), the enhancement factor K equals 7.2, 11.3, 19.8, and 27.4 for listed DR values.

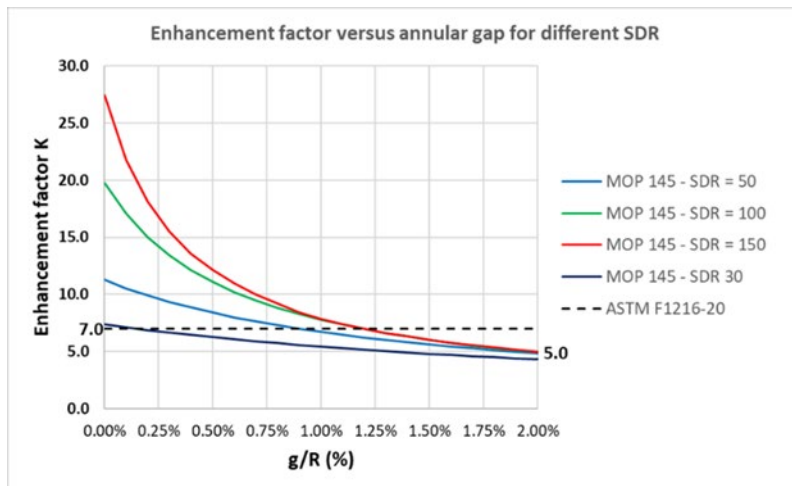


Figure 10. Enhancement Factor vs. Annular Gap for Different Standard Dimension Ratios (SDRs)

The K value of 7.0 determined in the ASCE calibration process corresponds approximately to g/R value of 0.9% for a DR of 50.

Annular Gap

As already mentioned in the Introduction (section 2.0), a fit tolerance in CIPP installations is typically 1 mm (0.04 in). It should be noted that annular gap is never uniform around the perimeter. The max values are generally localized and the calculated mean value over the perimeter is typically 2 to 6 times lower than the maximum value (EPA 2012). So, a mean value of 1.0 mm (0.04 in), which is the fit tolerance, corresponds to a max gap value of about 2 to 6 mm observed somewhere around the perimeter.

Enhancement Factor for 0.04 in (Mean) Annular Gap

In Figure 11, the enhancement factor K is depicted for a (mean) annular gap of 0.04 in (1 mm), as a function of pipe diameter (inside diameter, ID) for several different DR values (50, 100, 150) shown as yellow, blue, and green lines. It can be seen that the K value increases quickly with the DR and ID. For instance:

- The K factor equals to 15.6 for DR 100 and ID 48 in, which is more than 2 times the value recommended in ASTM F1216.
- The K factor equals to 21.3 for DR 150 and ID 72 in, which is more than 3 times the value recommended in ASTM F1216.

With a recommended (mean) annular gap of 0.04 in, the MOP 145 design is significantly more favorable than ASTM F1216 design for liners with high DRs (greater than 100) that are installed in large diameter pipes. On the other hand, the results are close to ASTM F1216 design values for the usual DRs (50) and small diameters (8 to 15 in).

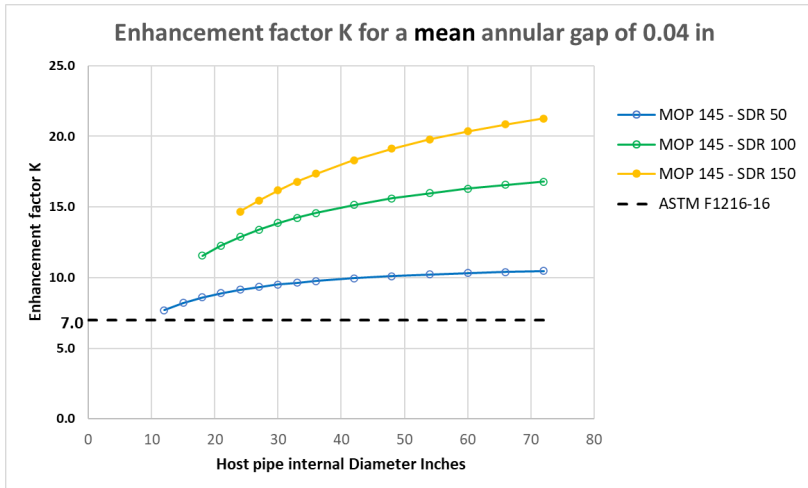


Figure 11. Enhancement Factor vs. Internal Diameter (ID) for a Mean Annular Gap of 0.04 in

4.3.2. Material Failure Limit State

In the MOP 145 method, the material failure checking is handled by equations given in Table 5-25, 5-28 and 5-29 (ASCE 2021). The details of these equations are not given here.

The MOP 145 equation gives higher stresses than Eq. X1.2. for a 3% ovality. However, because Eq. X1.2 is not applicable to a close-fit liner (as explained in 4.2.2), the two equations are not really comparable.

4.4 EXAMPLES

4.4.1 Reinforced (GRP) CIPP, Low Ovality, and Average Soil

In this example, a reinforced CIPP is installed in a cracked-ovalized pipe of 48 in diameter. The ovality is set to 3%, the soil modulus is 1,000 psi and the water table is at ground level. The host pipe state is fully deteriorated according to F1216, and State II (cracked rigid pipe with ovality less than 10%) according to MOP 145.

In Figure 12, the required liner thickness is shown as a function of groundwater pressure as calculated with MOP 145 (blue line) and with F1216 (black line).

The calculations showed that:

- In F1216 Fully Deteriorated design, the governing limit state is buckling under earth loads (Eq. X1.3). But this limit state, which completely neglects the host pipe presence, is not realistic.
- In MOP 145 State II design, the governing limit state is buckling under groundwater pressure. The MOP 145 design thickness is approximately 30% less than that the ASTM F1216 thickness.

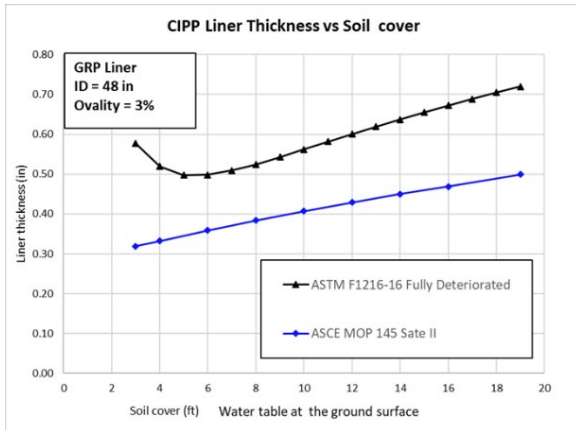


Figure 12. MOP 145 vs. ASTM F1216 - Reinforced CIPP, Low Ovality (%)

4.4.2 Reinforced (GRP) CIPP, High Ovality and Poor Soil

In this example, a reinforced CIPP is installed in a cracked-ovalized pipe of 48 in diameter (same as in previous example). The ovality is set to 10%, and the surrounding soil is soft (density of 85%, soil modulus of 400 psi). The host pipe state is fully deteriorated according to F1216, and State III (cracked rigid pipe with ovality greater than or equal to 10%) according to MOP 145.

In Figure 13, the required liner thickness is shown as a function of groundwater pressure as calculated with MOP 145 (blue line) and with F1216 (black line).

The calculations showed that:

- In F1216 Fully Deteriorated design, the governing limit state is again buckling under earth loads and again this limit state is non-realistic unlikely and leads to very high thicknesses.
- In MOP 145 State III design, the governing state is now flexural strength under groundwater pressure and no longer buckling. It is due to the 10% ovality which increases the bending stress under groundwater pressure.

In this example, the MOP 145 thickness is approximately 42% less than that the F1216 thickness.

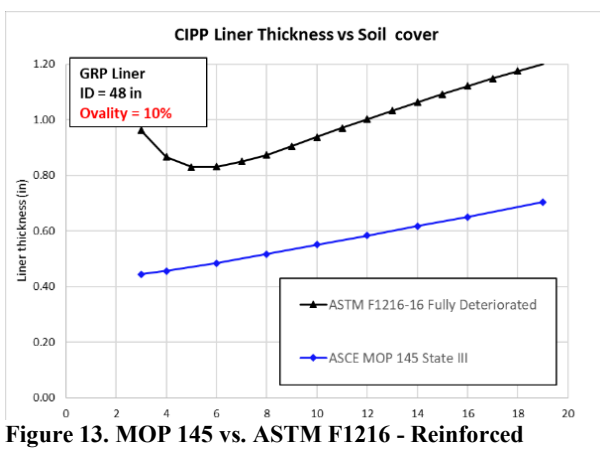


Figure 13. MOP 145 vs. ASTM F1216 - Reinforced CIPP, High Ovality (10%)

4.4.3 Nonreinforced CIPP, Low Ovality, Average Soil

In this example, a CIPP liner is installed in a cracked-ovalized pipe of 48 in diameter, the ovality is set to 3%, the soil modulus is 1,000 psi and the water table is at ground level (same as in the first examples). However, the liner material is the unreinforced CIPP.

The host pipe state is fully deteriorated according to F1216, and State II (cracked rigid pipe with ovality less than 10%) according to MOP 145.

The calculations showed that:

- In F1216 Fully Deteriorated design, the governing limit state is definitely again buckling under earth loads.
- In the MOP 145 design, the governing limit state is now flexural strength under groundwater pressure and not buckling as for the reinforced CIPP because the bending strength of non-reinforced CIPP is lower.

The thickness calculated with the MOP is here again lower than that of the F1216 but to a lesser extent. The maximum decrease is observed for ground covers less than 6 ft.

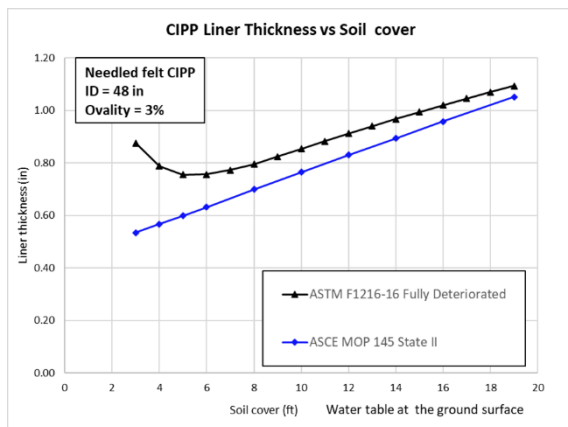


Figure 14. MOP 145 vs. ASTM F1216 – Non-Reinforced CIPP, Low Ovality (3%)

4.4.4 Summary of Results

The reduction in liner thickness calculated with the MOP 145 vs. the F1216 method in previous examples is shown in Figure 15. It can be seen that:

- Significant reduction (~ 25% to 45%) is observed for reinforced (GRP) CIPP liners.
- Significant reductions is observed for non-reinforced CIPP for soil cover less than 6 ft.

Apart from the obvious cost reduction, the decrease in required thickness is very useful for large diameters because it reduces the weight of the liner to be installed and resin curing problems.

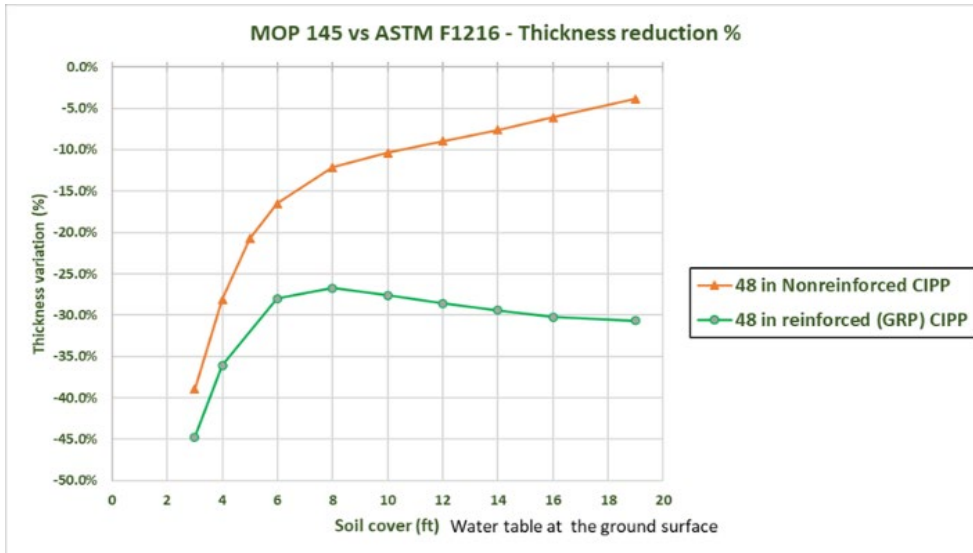


Figure 15. Reduction in Liner Thickness Calculated with MOP 145 vs. ASTM F1216 Method, for Reinforced and Non-Reinforced CIPP

5.0 CONCLUSIONS

The ASCE MOP 145 design method of close-fit liners for the rehabilitation of gravity pipes is based on a mechanical model that takes into account the interaction between the liner and the host pipe and in particular the exact geometry of the liner (the radii of curvature) and the initial annular gap, which has a strong influence on the critical buckling pressure.

With regard to non-circular liners and the WRc type II method, comparisons show that when the WRc method is used for cross sections different than the standard 3x2 egg shape, it may give unconservative results, in particular an admissible groundwater height higher than the critical buckling head. Indeed, the WRc type II method does not consider buckling which is the prime failure mode for egg shapes according with the FEA and the MOP 145. Regarding oval shapes or shapes with straight sides, the WRc type 2 method considerably underestimates the deflections and gives admissible heights of groundwater which can be 4 times higher than those calculated with MOP 145 or FEA.

Comparisons with the ASTM F1216 method show that the use of realistic annular gaps makes it possible to achieve significant thickness reduction of around 30% for reinforced liners installed in large diameter pipes. Also, significant thickness reduction can be achieved for ground cover less than 6 ft due to the lack of earth buckling (replaced by bending).

6.0 REFERENCES

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