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EFFECT OF WALL CORROSION AND BACKFILL EROSION ON THE STRENGTH OF DETERIORATED METAL CULVERTS

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ABSTRACT: While inspection technologies and assessment methods are being developed for corrugated metal culverts and sewers by researchers and specialized contractors, there is a dearth of information on how the level of corrosion influences culvert stability, and the possible consequences of backfill erosion. Therefore, work is needed to make the connection between an assessment of pipe condition and structural stability. This manuscript outlines recent findings from two and three dimensional computer studies of corroded metal culvert stability. First the article explains and quantifies how wall loss by corrosion across the invert of the pipe influences the thrusts and moments that occur in the structure, how this changes stability against yield, and how it changes resistance to global buckling. Next it examines the impact of backfill erosion resulting from groundwater inflow through wall perforations. This loss of soil support influences expected thrust and moment, and resistance to yield and global buckling. Lastly, the impact of wall thinning on resistance of the corrugated plates to local buckling is examined. The study indicates that wall loss has little influence on the hoop thrusts in culvert wall, so that reductions in stability against crushing are a linear function of the percentage of wall area that remains to support the thrust. Three dimensional analysis reveals that average rather than minimum wall thickness controls stability at any circumferential position, and buckling calculations indicate that wall thinning has little effect on global buckling strength until almost all the wall has been removed. Erosion can actually reduce thrust levels, but global buckling resistance is dramatically reduced. Furthermore, local buckling can occur for corrugated plates where thickness reduces below 3mm.

1. INTRODUCTION

Following the development of corrugated metal pipes late in the nineteenth century, many millions of these pipes have been used as culvert structures across North America and beyond. Many have now reached their design life.

a. Invert corrosion. b. Loss of backfill due to erosion through perforation

Figure 1. Deteriorated metal culvert in Eastern Ontario; invert corrosion

Figure 1 shows two views of one particular culvert in Eastern Ontario, Canada. In the first, the corrosion across the invert is visible, stretching from haunch to haunch, and developing in the zone of regular or permanent water flow. Once the steel is perforated (corrosion extends through the pipe wall in certain locations), ingress of groundwater through these perforations during storm events or when external water pressures develop due to other causes, and the backfill surrounding the structure can erode; an extreme version of this erosion is seen in the second image. Since Ministries and Departments of Transportation have an excess of structures requiring repair or replacement, it is important to identify which have or are close to reaching their stability limits. While a number of qualitative assessment systems have been developed for these structures (e.g. FHWA, 2010), these do not provide clear measures of stability.

Now, corrugated metal pipe design is inherently conservative, since it is usual to design to provide a factor of safety against wall crushing (mobilization of yield stresses through the full thickness of the culvert wall at the springline), and these shell structures with external ground support are highly redundant structures. Design is intended to prevent the development of yield at the springlines, but that yield does not mean collapse, since that requires development of multiple yield zones (plastic hinges) to form a mechanism. Furthermore, surface live loads are treated in highly approximate fashion, including simplified pressure distribution patterns, or, at best, two dimensional (rather than three dimensional) finite element calculations. All this is reasonable, since the choice of pipe structures that are somewhat stronger than they might otherwise be has little effect on cost (pipe cost is small compared to earthworks, pavement construction and so on). However, conservative strength calculations are undesirable when highway authorities have vast inventories of deteriorated structures, and only those really needing work can be repaired.

For these reasons, El Taher (2009) has undertaken work to characterize the strength of deteriorated metal culverts. That study employed two and three dimensional finite element analysis to determine:

- how uniform wall loss across the invert of the structure influences thrust and moment in the structure, and the effect of wall loss on stability limits associated with wall crushing and global buckling strength
- how erosion voids influence thrust and moment in the structure, and the effect of erosion voids on stability limits associated with wall crushing and global buckling strength

The results of these assessments are summarized in the sections that follow.

2. METHODOLOGY OF THE STUDY AND ANALYSIS CASES

The approach taken in the study is to use ABAQUS Version 6.7 (Hibbitt et al., 2002) to model development of wall thinning due to corrosion, and loss of backfill support associated with soil erosion. Table 1 defines the geometry of five corrugated steel pipes that have been considered, all composed of 152 mm by 51 mm corrugated steel plate. Plate thickness for the intact structure was selected using design calculations based on CHBDC (2006), and the section properties I and A are recorded in Table 1. These structures were selected to provide a range of pipe diameters at a burial depth of 3m, and a range of burial depths for a pipe with diameter of 4m.

Table 1. Five design cases

Case	D m	H m	I mm^4/mm	A mm^2/mm
1	2	3	1057	3.52
2	4	3	1057	3.52
3	6	3	1057	3.52
4	4	1.5	1057	3.52
5	4	10	1867	6.15

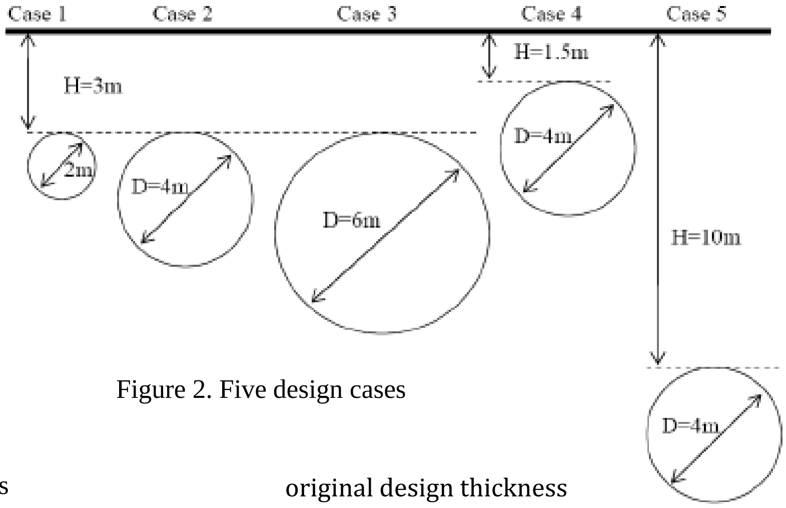
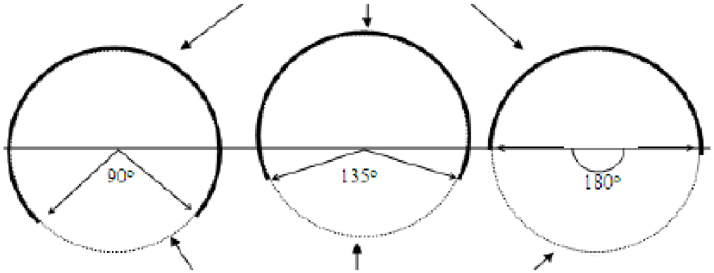


Figure 2. Five design cases

original design thickness



reduced wall thickness

Figure 3. Invert corrosion angles (El Taher and Moore, 2008)

Figure 3 shows the three corrosion patterns examined in the study – where the invert is modeled with reduced wall thickness across three different angles $\alpha = 90^o$, 135^o and 180^o (from springline to springline). These are based on observations in the field (Figure 1) where corrosion is accelerated in the zone where water accumulates for extensive time periods. If corrosion extends to the springlines (corrosion angle α=180^o), then wall loss is developing at the location where wall thrust typically reaches its highest value. One of the issues investigated therefore has been the effect of corrosion away from this location (cases $\alpha=90^o$ and 135^o) since the critical location in the pipe wall may continue to be at the springline until the wall loss away from that location becomes very significant. The structure was modeled using layers of solid elements, with inner elements removed to represent the effect of wall loss. Full details of the modeling approach are provided by El Taher and Moore (2008) and El Taher (2009).

The study also examined the influence of erosion in the backfill, and Figure 4 shows the idealized patterns of erosion that were modeled. These represent erosion on one side of the structure where the size of the contact between the erosion void and the external surface of the pipe is quantified as an ‘erosion angle’, with magnitudes 11.25^o, 22.5^o, 45^o, 67.5^o and 90^o all examined. While there are many different void shapes that could be studied, these are representative of what has been seen in the field by the second author and will enable the study to examine the effect of void size. They characterize the progress of erosion which generally initiates adjacent to the haunch and the develops up past the springline to the shoulder.

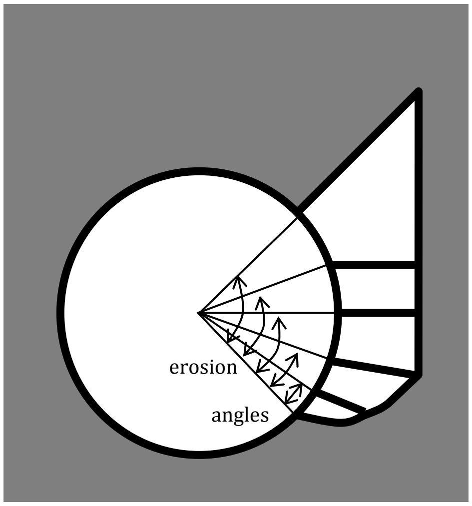


Figure 4. Soil voids modeled to study erosion.

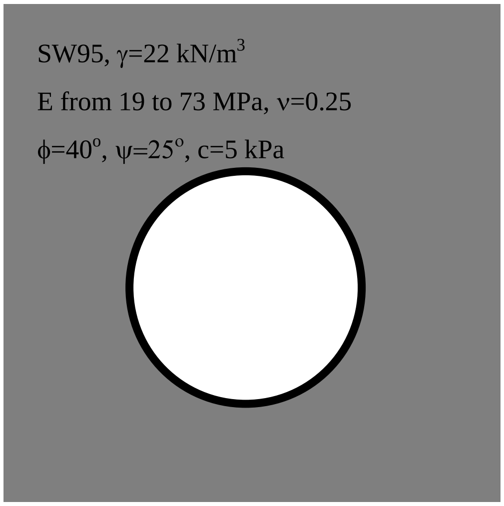


Figure 5. Soil properties.

Well-graded granular backfill (SW in the Unified Classification System) is considered, with strength and modulus at different levels of vertical effective stress based on compaction to 95% of the peak values obtained from a Standard Proctor test, as specified by McGrath et al. (1999). Unit weight of 22 kN/m^3 is considered, and the elasto-plastic response is characterized using the Mohr-Coulomb failure criterion with friction angle ϕ of 40^o (since the soil near the void may be loosened due to soil erosion, this value corresponds to the lower end of the range for granular materials), a dilation angle ψ of 25^o (this value is at the high end of expected values, but is chosen to limit numerical problems; since soil near the erosion void is in a state of low confinement, the effect of dilation angle is small, El Taher, 2009) and a cohesion value of 5kPa to limit numerical problems. Poisson’s ratio is set to 0.25 and the stress-dependent elastic modulus ranges from 19 MPa and 73 MPa as a function of minor principal stresses in accordance with Janbu's (1963) relationship.

3. UNIFORM WALL CORROSION ACROSS THE INVERT

The effect of wall thinning due to corrosion on the stability of these structures is summarized in Figures 6 and 7. In each case, the factor of safety has been quantified as a function of remaining wall thickness “t left”, as a percentage. To represent stability of the corrugated steel pipe against wall crushing, the factor of safety has been calculated using the maximum thrust per unit length in the corroded zone $N_{corroded}$, and the remaining wall area per unit length in this zone, $A_{corroded}$ as follows:

$$FOS_{Yielding} = \frac{A_{corroded}\sigma_y}{N_{corroded}} \tag{1}$$

where the yield strength of the steel σ_y is assumed to equal 230 MPa. These values are then normalized against the value for 100% of thickness left (the intact structure). The reduction in stability in the corroded section is essentially a linear function of wall thickness. This occurs because the effect of wall loss on the pattern and magnitude of thrust in the structure is negligible. Since the corrugated steel pipes are flexible compared to the surrounding ground, the changes in pipe stiffness associated with wall loss do not significantly influence the soil-pipe interaction and therefore the distribution of external earth pressures around the outside of the pipe structure. Furthermore, while pipe deflections are not reported here, the soil modulus controls the deformations that occur in buried flexible metal pipes, so the loss of wall thickness does not have a significant effect on culvert deformations until commencement of backfill erosion (to be examined in the next section).

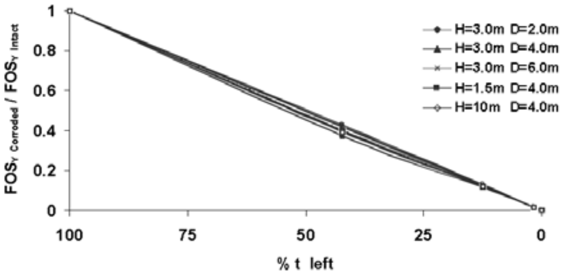


Figure 6. Reductions in factor of safety against yield as a function of wall loss; five design cases and three corrosion angles; from El Taher and Moore (2008).

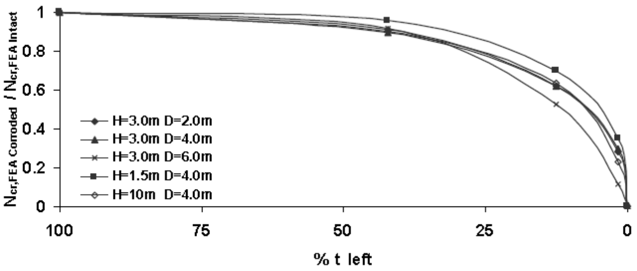
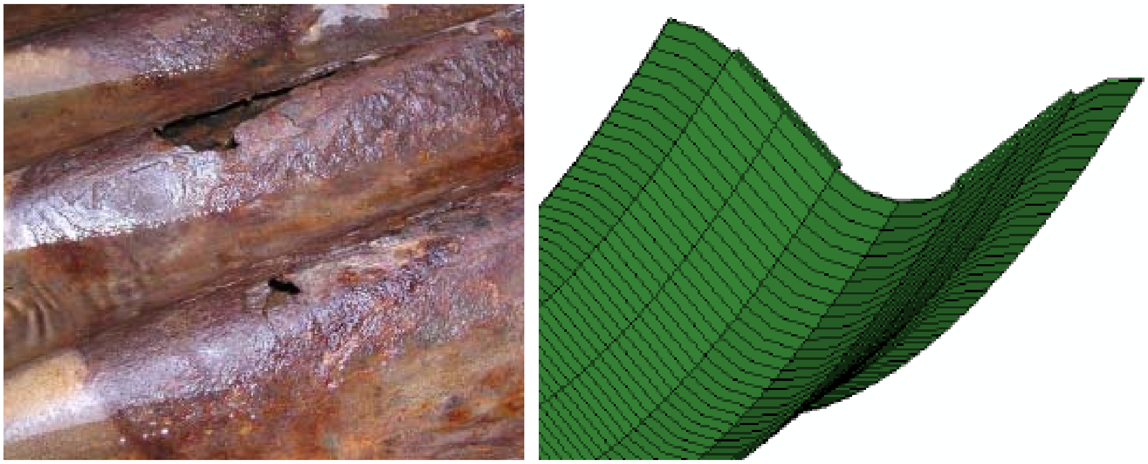


Figure 7. Reductions in factor of safety against global buckling as a function of wall loss; five design cases; and corrosion angle of 135^o; El Taher & Moore (2008).

Stability against buckling is calculated by first determining the expected distribution of thrust around the structure, and then formulating the global buckling solution as an eigenvalue problem, where those thrusts are scaled until the determinant of the stiffness equations becomes zero. A critical thrust resulting from that finite element analysis $N_{cr,FEA}$ is then calculated, which is the maximum value of thrust for that unstable state, and this is used to represent load resistance to buckling. Figure 7 shows how global buckling resistance changes with wall loss, where critical thrust for the corroded structure $N_{cr,FEA\ corroded}$ is normalized using critical thrust for the intact culvert, $N_{cr,FEA\ intact}$. These results are for the specific case of corrosion across an angle of 135^o at the invert, but the results for other corrosion angles are similar. What is seen is that wall loss has little effect on buckling strength, until more than 80% of the original wall thickness is removed. All of the design cases considered in the study have high resistance to global buckling and are controlled by wall crushing, so despite the substantial reductions in buckling strength that finally occur when remaining thickness becomes small, global buckling never controls stability for any of these deteriorated structures. Global buckling strength is strongly dependent on the modulus of the backfill (see Moore et al. 1988), so this performance limit can control design when low stiffness backfill is employed. Furthermore, deterioration of the backfill will reduce resistance to global buckling, as examined in a subsequent section.

3. NONUNIFORM WALL CORROSION

The geometry of wall thinning due to corrosion seen in Figure 1a and in Figure 8a, is not uniform. Therefore three dimensional analysis has been performed with explicit modeling of the corrugations for Design Case 2 (Figure 2), to represent variable thickness, such as where corrosion is higher at the crest and valley of the corrugation, Figure 8b. The results of stability calculations for two and three-dimensional analyses are presented in Figure 9, where factor of safety around the culvert circumference is represented. Solutions are given for intact structures, and those with 75%, 50% and 25% of the wall area remaining. Each result is for the case where corrosion occurs across a 90^o angle (45^o on either side of the invert). These solutions show that in each case the two dimensional analysis based on equivalent section properties provides the same results as the three dimensional analysis with explicit modeling of the corrugations. These plots also show that factor of safety is lowest at the springline (angle of 90^o from the crown) until more than 25% of the wall is lost. The minimum factor of safety then occurs at the haunch where thrust in the corroded section has its largest value. Figure 10 presents the three dimensional solutions for both uniform and non-uniform wall loss across the corrugation. The non-uniform solution corresponds to 25% of thickness remaining at the crest and valley, and intact structure elsewhere, an average of about 62% wall area remaining. Interpolation would give this answer based on analysis of uniform corrosion (midway between 50% and 75% results).



a. Non-uniform wall loss in culvert. b. Finite element idealization

Figure 8. Non-uniform wall loss for corrugated metal culvert; from El Taher (2009).

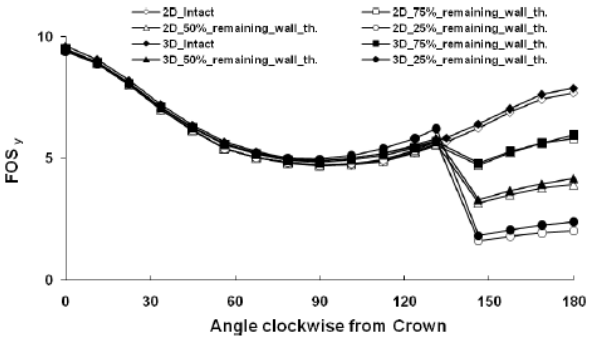


Figure 9. Factor of safety against crushing; comparison comparison of 2D and 3D analyses; from El Taher (2009).

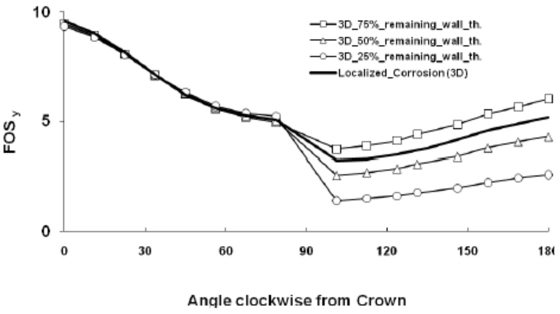


Figure 10. Stability results for nonuniform wall loss compared to uniform wall loss; from El Taher (2009).

4. BACKFILL EROSION

Backfill erosion can have serious effects on highway safety if the void is allowed to extend up under the road pavement, and vehicle loading leads to void collapse. This is particularly serious for shallow buried structures, and highway authorities need to be very careful to remedy such developments, or they risk hazardous conditions that can readily lead to fatalities.

Now, the current study is focused on the culvert, so it continues with calculations to see how erosion influences culvert stability. Backfill erosion modeling starts with calculations for the initial intact condition of the soil and the culvert, and then progress of the erosion is represented by removing soil from beside the structure. Figure 11 shows five of the finite element meshes considered in the study, tracking growth of erosion staring with a small zone of the external boundary of the structure where soil support is lost (over an angle of 11.25^{o}), then growth through the different void sizes defined earlier in Figure 4 (22.5^{o}, 45^{o}, 67.5^{o} and finally 90^{o}). Analyses considered two erosion cases: those were soil loss was symmetry about the vertical diameter of the culvert (Figures 11a to 11d), and those where erosion of soil occurred on one side only (Figure 11e). All analyses focused on Case 2 from Figure 2.

In all cases, the loss of soil adjacent to the structure lead to reductions in thrust distribution around the culvert circumference. This is because the soil void promotes positive soil arching, just as bales of hay placed in a void above the crown of the culvert (so called ‘induced trench construction’) reduces the earth pressures that develop on the external surface of the structure. Neglecting for the moment the effect of wall loss (corrosion) on the culvert’s ability to resist hoop thrust, all such cases featuring erosion modeling had factors of safety against yield that actually increased (since expected thrust is reduced).

The other failure mode of concern during evaluations of culvert stability is global buckling. Calculations like those described in section 3 were therefore performed, but this time where soil loss due to erosion was also modeled.

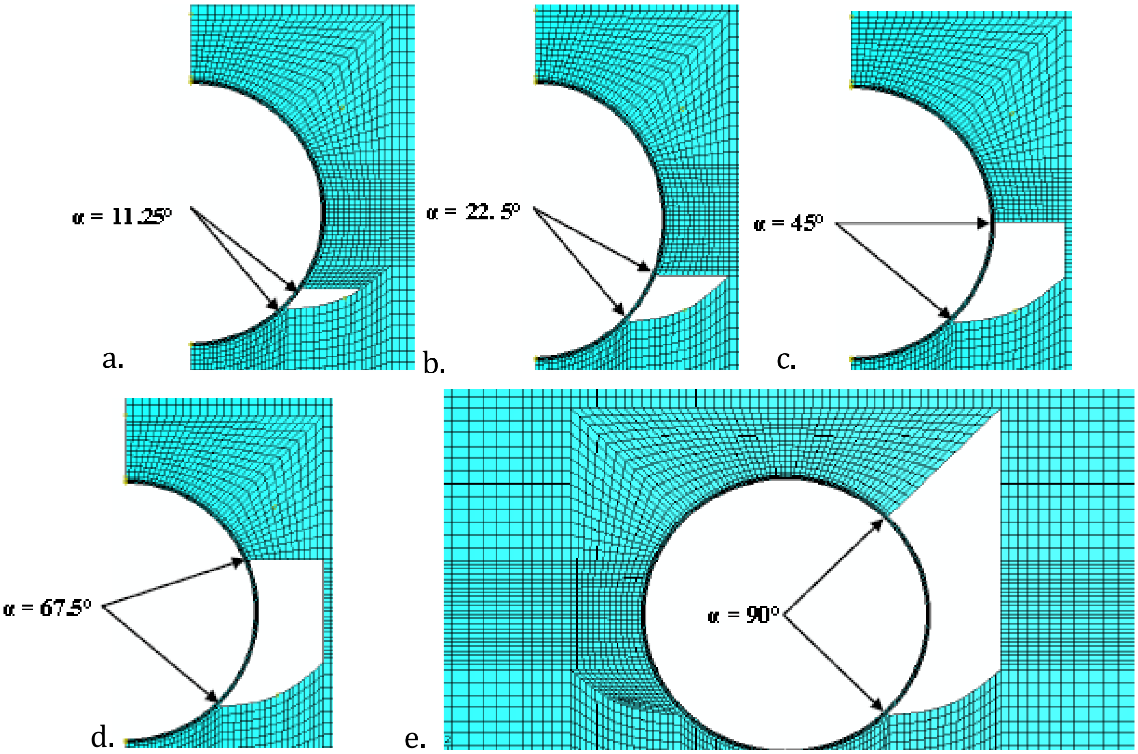


Figure 11. Erosion voids considered; five examples featuring angles from 11.25° to 90°; from El Taher (2009).

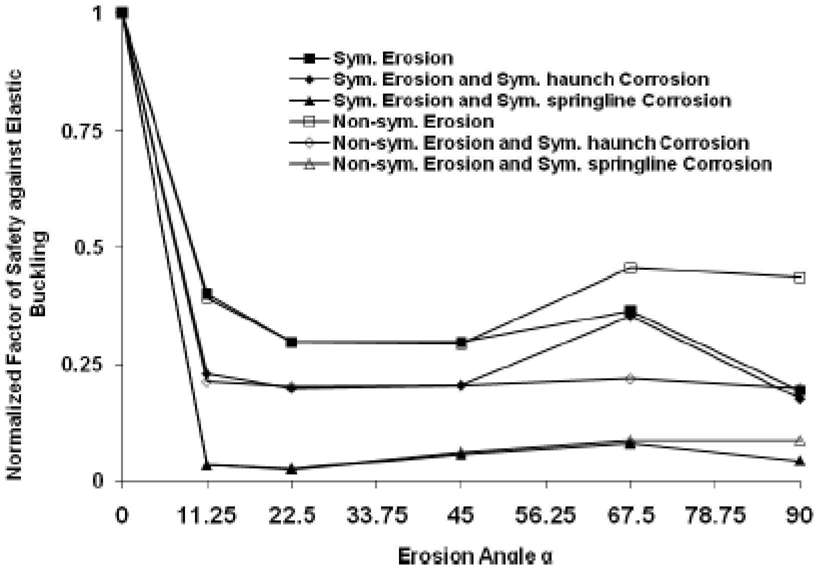


Figure 12. Reductions in factor of safety against buckling resulting from backfill erosion; results shown for different angles over which erosion leads to loss of soil support above the haunch; results for erosion on both sides (Symmetric erosion) and one side only (Non-Symmetric only); three steel culvert conditions – intact, and where 25% of wall thickness remains from haunch to haunch (45° on either side of the invert), and from springline to springline (90° on either side of the invert); from El Taher (2009).

Figure 12 shows how factor of safety against buckling is reduced as soil erosion develops. Stability drops dramatically as a small erosion void featuring loss of soil support over just 11¼°. Factor of safety against buckling reduces to 40% of its value for intact ground if the plate is not corroded, to 22% of its ‘intact’ value if the plate is corroded from haunch to haunch, and to less than 5% of its ‘intact’ value of corrosion stretches from springline to springline. This means that buckling can now control stability. If the culvert survives and the void continues to grow, the stability then appears to increase, likely because the magnitude of thrust decreases due to positive arching. The sensitivity to the very small zone losing ground support results because the critical buckles for these culverts buried in well compacted granular material have short wavelengths – fitting within the zone of lost ground support.

For all the analyses shown in Figure 12, the results for symmetric and non-symmetric erosion voids were essentially the same. Therefore the analysis can be simplified by modeling symmetric at the vertical diameter.

5. LOCAL BUCKLING STRENGTH

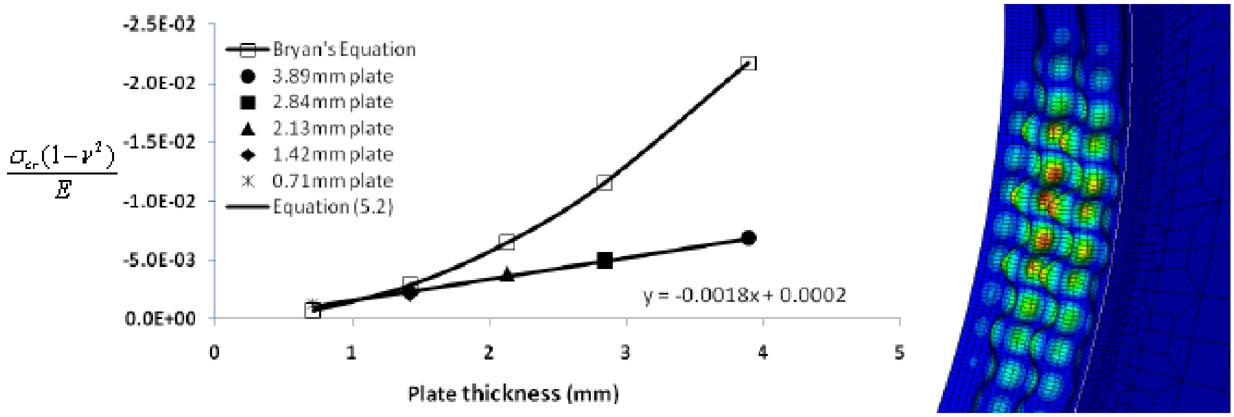
ABAQUS has also been used to undertake three dimensional and geometrically nonlinear analysis of the 152 mm by 51 mm corrugated steel plate with various thickness values. The analysis features explicit modeling of the corrugations, and has been performed using plate thickness values of 3.89, 2.84, 2.13, 1.42, and 0.71 mm to estimate how wall thickness influences resistance to local buckling. This range of plate thicknesses provides guidance on the potential effects of corrosion that reduces plate thickness to very small values. Design case 2 from Figure 2 is studied.

Now, the simplified equation of Bryan (1891) is generally used to represent the critical stress σ_{cr} that produces local buckling in stiffened plate structures,

$$\frac{\sigma_{cr}(1-\nu^2)}{E} = \frac{k\pi^2}{12(W/t)^2} \qquad [1]$$

where critical stress is normalized by elastic modulus *E* and Poisson ratio ν, and stability is influenced by plate width *W*, thickness *t*, and the amount of edge restraint represented by factor *k*. Figure 13 presents the results of these finite element calculations, as well as the Bryan equation with a plate width W=47.9 mm, and an assumption of simple supports along the edges of this plate (for which k=4). These assumptions produce local buckling stress for thinnest plates (thicknesses of 0.71 and 1.42 mm) that almost match the finite element calculations. However, where thickness remains above 1.5 mm, the Bryan equation provides unconservative values. Instead of the quadratic relationship seen in equation (1), the finite element results appear to be linear function of thickness given by

$$\frac{\sigma_{cr}(1-\nu^2)}{E} = 0.0002 - 0.0018t_{remaining} \qquad [2]$$



a. Critical stress versus plate thickness b. Typical local buckling mode

Figure 13. In-plane buckling stress σ_{cr} normalized by modulus E and Poisson ratio ν, versus plate thickness; the Bryan equation and the best fit equation numbered (5.2) in El Taher (2009) (equation 2 above) are also shown.

where thickness is given in mm.. For cases where wall loss is substantial, the stability against local buckling can control, rather than yield or global buckling. However, while physical evidence exists covering considerations of yield (wall crushing) and global buckling (see Moore, 1989), local buckling has not been studied in the laboratory, and work to undertake experiments is warranted. Furthermore, this equation is for 152 mm by 51 mm corrugated plates, and additional effort will be needed to investigate other corrugation dimensions (pitch and depth).

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