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STABILITY OF DETERIORATED METAL CULVERTS INCLUDING THE EFFECT OF SOIL EROSION

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ABSTRACT: Ministries and departments of transportation everywhere are working to undertake assessments of deteriorated metal culverts. To assist with these assessments, the effects of metal corrosion and backfill erosion are being studied as part of a project to develop rational methods of classifying culverts requiring replacement or repair. This paper uses finite element calculations to explain how stability is reduced by these two forms of deterioration. Both material failure (yield in the steel) and geometrical nonlinearity (buckling failure) are examined. The stability assessments are presented in the context of the limit states design procedures in the Canadian Highway Bridge Design Code and the LRFD Bridge Design Code of the American Association of State Highway and Transportation Officials.

1. INTRODUCTION

Figure.1 shows the normal outcome of the problem of corrosion which is the forming of erosion voids around locations of severe corrosion due to the ingress of water. Erosion voids that spread can have enormous effects on the stability of buried corrugated metal culverts as well as influence their hydraulic efficiency. This problem needs to be stated clearly and quantified in terms of its hydraulic and structural impact. The current study emphasizes the effect of deterioration of culvert material and supporting soil on the structural stability.

Figure.1 shows that erosion can eventually extend to the ground surface. While the structure shown is shallow buried and erosion occurred at the median (between the Eastern and Western lanes of the 401), erosion voids extending to the surface under pavements can have catastrophic effects. In the current study, non uniform erosion patterns are considered. The erosion voids are located adjacent to the most severe zones of corrosion, corresponding to the water line.



Figure 1. Erosion takes place due to water percolation through corroded zones (culvert in South Eastern Ontario).

2. GEOMETRICAL AND MATERIAL PROPERTIES

2.1. Design Case

One design case has been chosen for assessment, an 152×51 mm corrugated steel plate, with 4m span and 3m burial depth (Figure.2). The objective is to study the effect of backfill soil erosion on thrust and moment distributions around the structure circumference and on the stability of metal culverts against elastic buckling. The void geometries considered are shown in Figure.3. This study of the stability of deteriorated buried culverts focuses on circular structures, though future studies should consider noncircular, arch and box culvert structures.

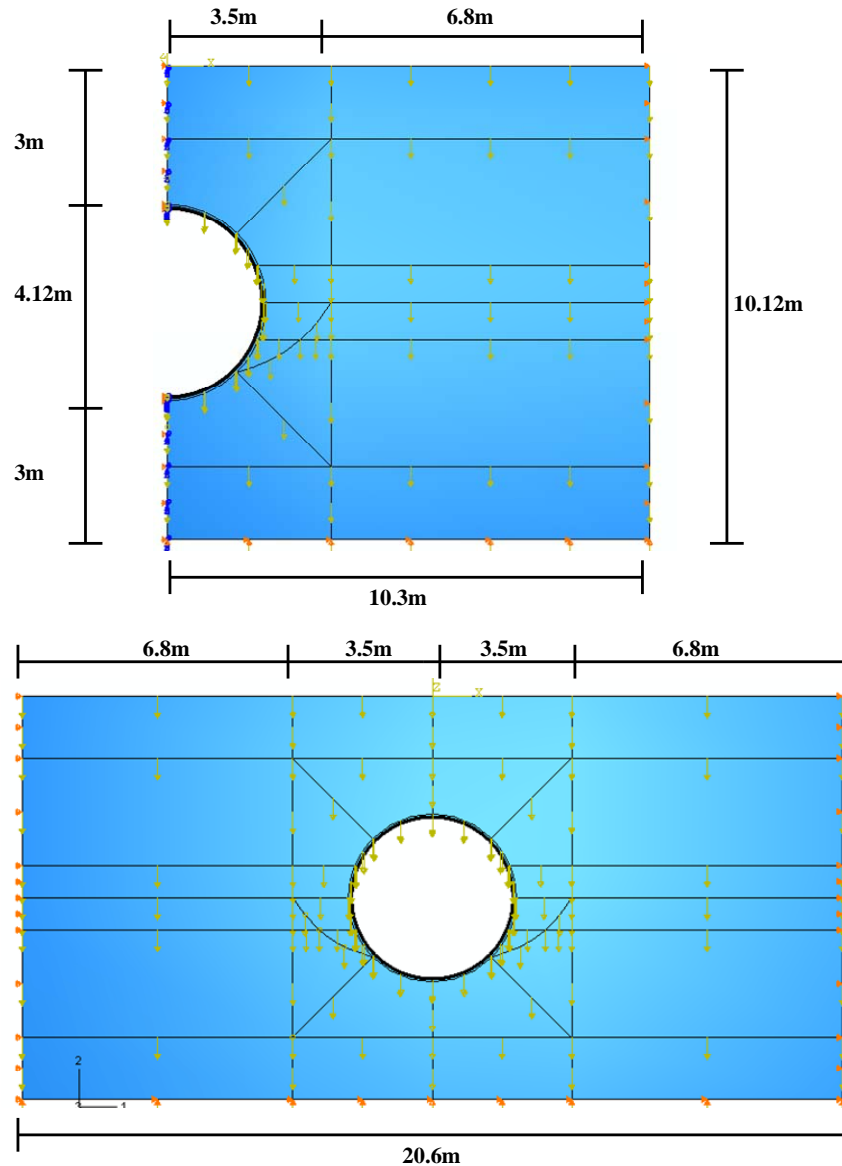


Figure 2. Typical dimensions and boundary conditions used in the analyses.

2.2. Soil Conditions

Well-graded granular soil (SW in the Unified Classification System) of 22 kN/m^3 unit weight is considered as the backfill material. It is modelled as an elastoplastic solid to include the influence of shear failure around the void. Soil properties used are friction angle ϕ of 40° and dilation angle ψ of 25° with a small value of cohesion of 5kPa. Poisson's ratio is set to 0.25 and elastic soil modulus is varied between 19MPa and 56MPa as a function of minor principal stresses according to Janbu's (3) elastic modulus relationship. The Janbu parameters for SW95 reported by Webb et al. (5) were employed in a manner like that described by Taleb and Moore (4). A constant soil modulus value of 32 MPa, corresponding to minor principal stress value just above the culvert crown, is used for all buckling analyses in the current study.

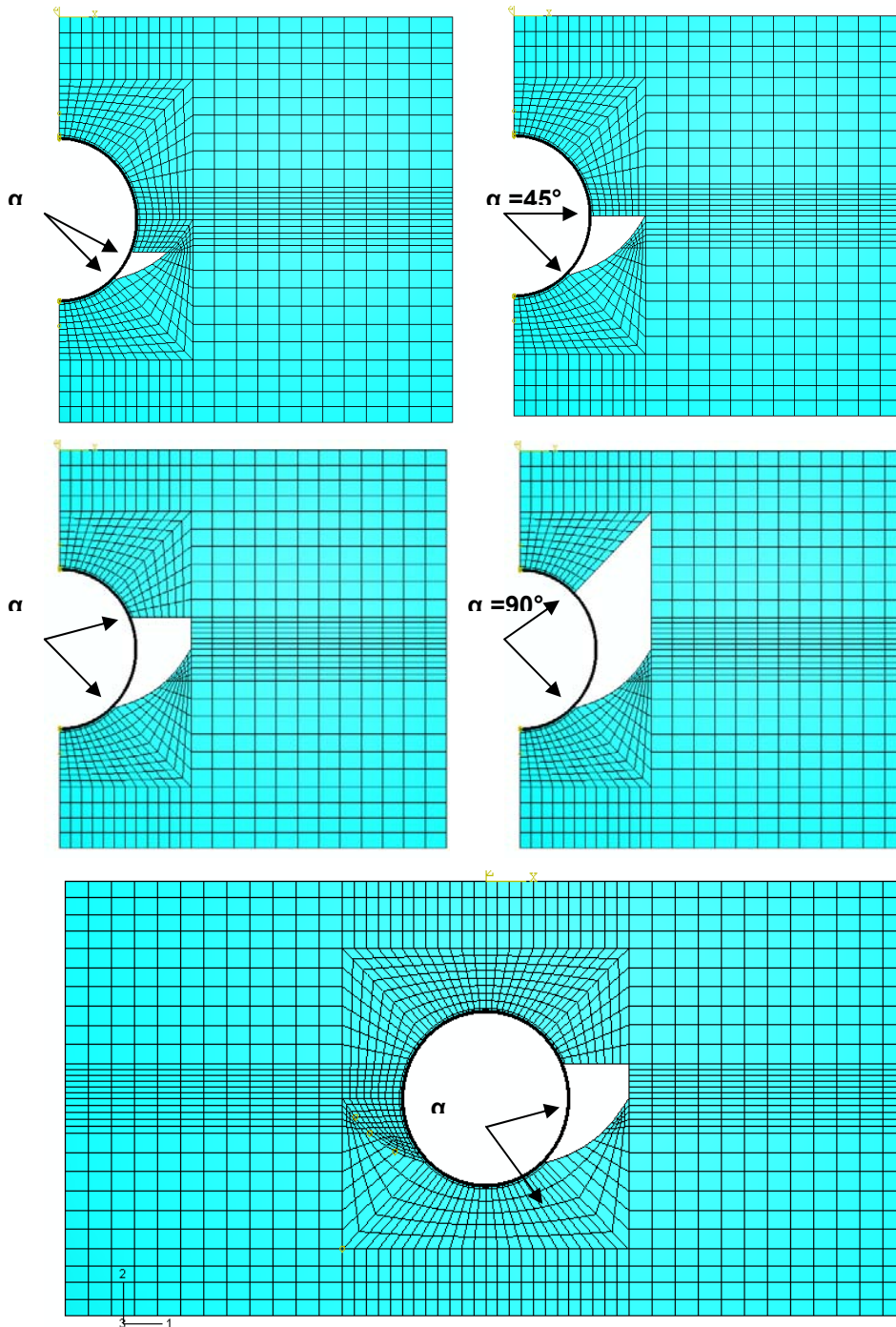


Figure 3. Typical finite element meshes used in the analyses with lateral void extent; erosion void angles α of 22.5°, 45°, 67.5°, and 90°.

2.3. Structural Properties

For a 152×51×3 mm corrugated steel section, $E_p = 2E+8$ kPa ($2.9E+7$ lbf/in²), $I_p = 1057.25$ mm⁴/mm (0.0645 in⁴/in), and $A_p = 3.522$ mm²/mm (0.1387 in²/in). An equivalent thickness of 60mm (2.3622 in) and an equivalent Young's Modulus of 11.74 GPa ($1.7E+6$ lbf/in²) are considered to take the effect of the corrugation into consideration as proposed by El-Taher and Moore (1).

3. NUMERICAL MODELLING

3.1. Finite element program

All the analyses in the current study are performed using the general purpose finite element code ABAQUS version 6.5. Unsymmetrical backfill soil erosion patterns are considered in a full model, but only half the problem geometry is studied for the symmetrical backfill soil erosion case, given the line of symmetry about the vertical pipe diameter, Figure 2. The soil and the pipe are modeled using CPE8 elements which are available in the ABAQUS element library. These elements are two dimensional, eight-node quadrilaterals, based on bi-quadratic shape functions and full-integration (9 integration points). The use of full integration eliminates the possibility of the 'hour-glassing' problem associated with the use of under-integrated elements in relatively coarse meshes, Hibbitt et al. (2).

3.2. Numerical modeling of pipe corrosion and backfill soil erosion

Culvert corrosion, only in the buckling analyses, and backfill soil erosion are simulated by excavating elements where elements are deactivated so they no longer contribute to the stiffness and loading of the system. The culvert structure was modeled with four rings of elements, so that reductions of three layers of elements, for the [152×51×3 mm] corrugated steel section used in the study, produced a corresponding amount of remaining thickness for the equivalent plain structure of 1.5% of the original thickness, as proposed by El-Taher and Moore (1).

As the effectiveness of corrosion modeling based on removing rings of elements was checked by El-Taher and Moore (1), the accuracy of analysis founded on element excavation for elastic backfill soil near the structure was tested by analysing models that were already excavated before starting the analysis; for the special case of elastic soil these produced the same deformations and stress resultants (thrust and moment).

3.3. Description of buckling analyses

Assessment of stability against elastic buckling and evaluation of the likely failure mode were performed using eigenvalue buckling analyses. In ABAQUS, an incremental loading pattern, denoted QN, was defined in the eigenvalue calculation step. The loading magnitude is not important (the self-weight of the backfill soil was used in all the eigenvalue buckling analyses in this study), since the static culvert response (distribution of thrust and moment) for this unit value of vertical pressure is scaled by the critical load multiplier found in the eigenvalue calculation. The critical thrusts are scaled from QN by using the lowest critical load multiplier. The critical thrust corresponding to elastic buckling is therefore obtained by multiplying the eigenvalue of interest by the thrust value from the static finite element analysis for that specific problem geometry (diameter, depth and so on).

4. RESULTS

4.1 Initial stresses and elastic modulus

Figure 4 shows contours of elastic soil modulus and vertical stresses in the backfill soil for the symmetric models prior to erosion and corrosion. Patterns for the unsymmetrical analysis are identical at this stage before the onset of the deterioration processes. Shear failure in the backfill soil due to the development of erosion voids is shown in Figure 5.

4.2 Deflections

For the most severe erosion case, change in horizontal diameter $\Delta D_h = 99.56$ mm and change in vertical diameter $\Delta D_v = -95.5$. The magnitudes of these are both less than 100mm or 2.5% of culvert span.

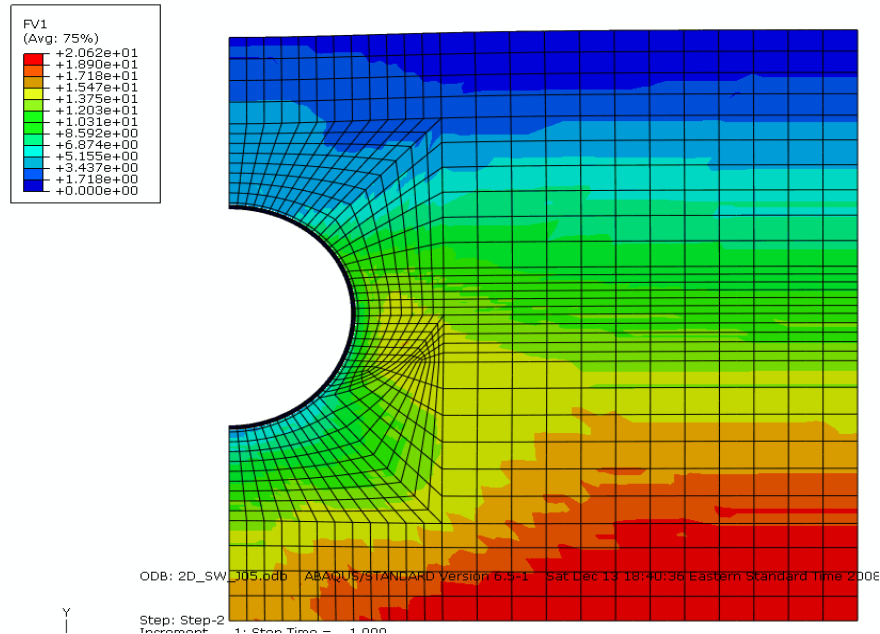


Figure 4. Distribution of elastic modulus (specified for ABAQUS as field variables between 1 and 20 dependent on minor principal stress, giving 19MPa at the surface and a maximum value of 56MPa).

4.3 Stability against yield and distributions of thrust and moment

Reductions in wall thickness due to corrosion were found to produce reductions in factor of safety in proportion to the amount of wall loss, El-Taher and Moore (1). To explore backfill soil erosion effect on the stability against yield and to avoid any noise from culvert wall corrosion on the results, only erosion of backfill soil is considered without corroding the structure. The same is done for calculating thrust and moment distributions, because the low flexural stiffness and high hoop stiffness of typical corrugated metal culverts relative to the good granular backfill that surrounds them mean that the changes in thrust and moment with corrosion are negligible, El-Taher and Moore (1).

Factor of safety against wall crushing (i.e. yield) is given by

$$[1] \quad F \text{ of } S = \sigma_y A_p / N_{sp}$$

Figures 6 and 7 show that the effect of erosion on stability against wall crushing due to excessive thrust is small. The effect is dominated by the position of the erosion void rather than its volume.

The dramatic effect of the position of the backfill soil void and its volume on the moment distribution can be seen in Figure 8. An unsymmetrical erosion pattern yields significant moments in the structure on the eroded side alone.

4.4 Stability against elastic buckling

While the investigation by El-Taher and Moore [1] of the effect of culvert wall corrosion on elastic buckling strength produced interesting results, they did not threaten the structure, since the critical design condition for corroded (not eroded) structures was found to be yield. Buckling was only found to be of importance for structures buried in poor quality backfill soil.

The effect of the erosion voids being considered in the present study is much more dramatic. Figure 9a presents factors of safety against elastic buckling of buried structures with backfill and structural deterioration. Figure.9.b shows factors of safety against elastic buckling normalized relative to the initial factors of safety calculated for the undeteriorated buried structure system.

Both figures show that stability reductions are substantial even at the onset of erosion and it is also significant when erosion voids develop alone (without corrosion). However, it is not likely that erosion will occur without corrosion, because erosion of the backfill soil adjacent to the structure only commences after the wall is perforated. Symmetrical corrosion patterns like those that generally occur in the field are also examined, both from springline to springline and from haunch to haunch (not surprisingly, the latter results in lower reductions in buckling strength).

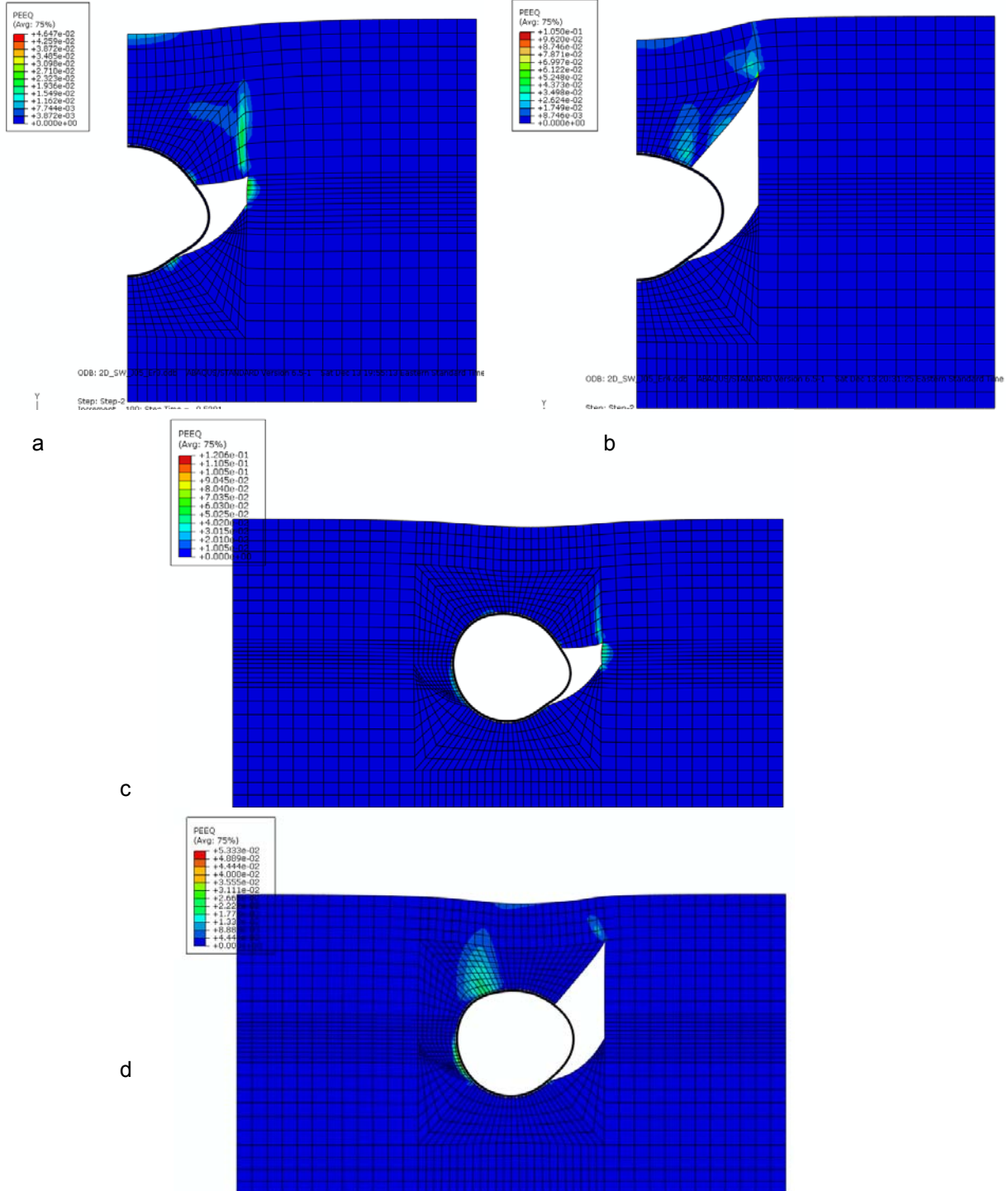
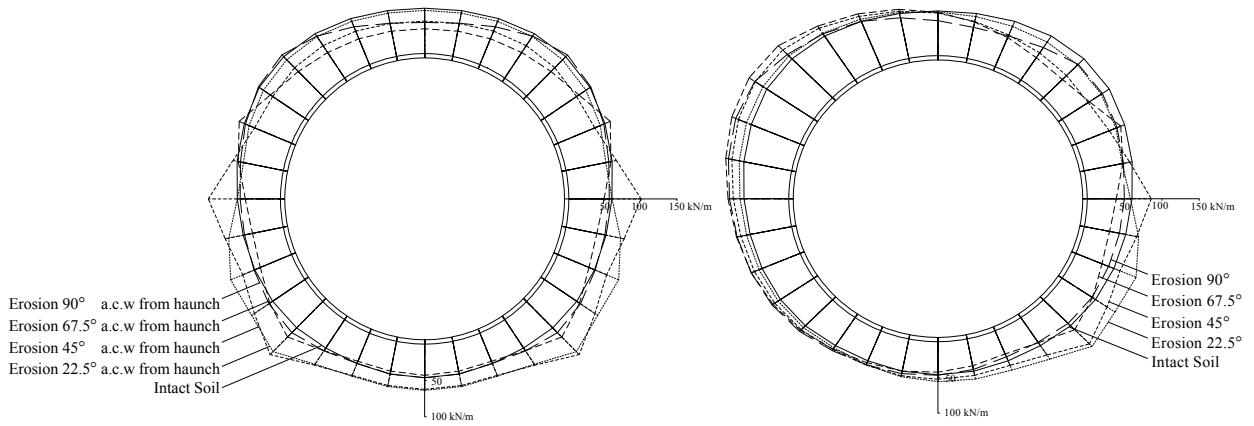


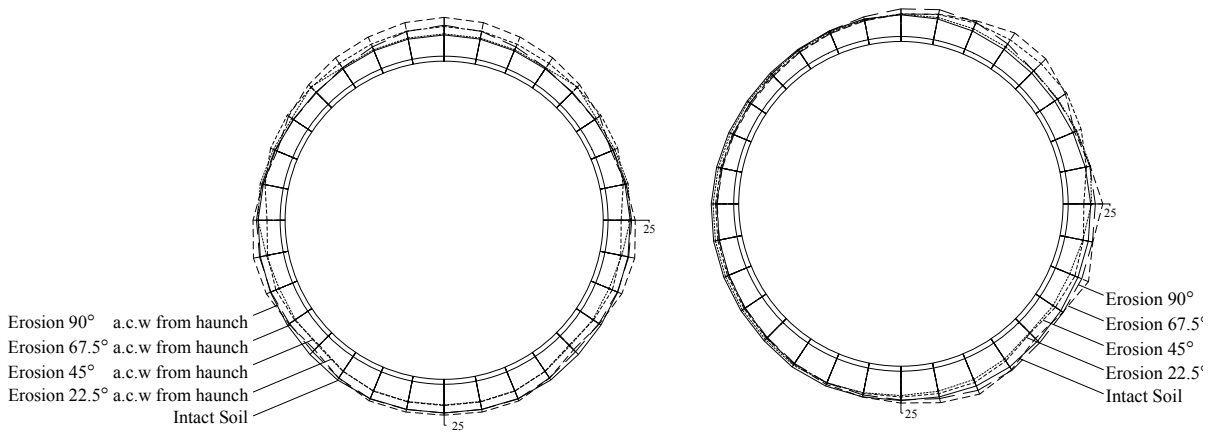
Figure 5. Distributions of plastic strain (indication of yield zone) for symmetric (a and b) and unsymmetric (c and d) erosion patterns.



a. Symmetrical erosion

b. Unsymmetrical erosion

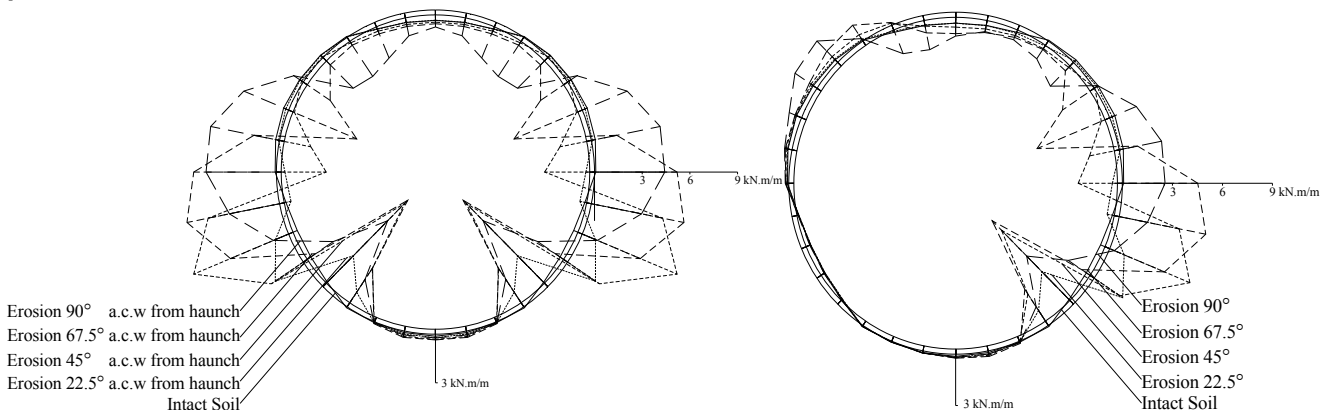
Figure 6. Thrust distributions for symmetrical and unsymmetrical erosion patterns



a. Symmetrical erosion

b. Unsymmetrical erosion

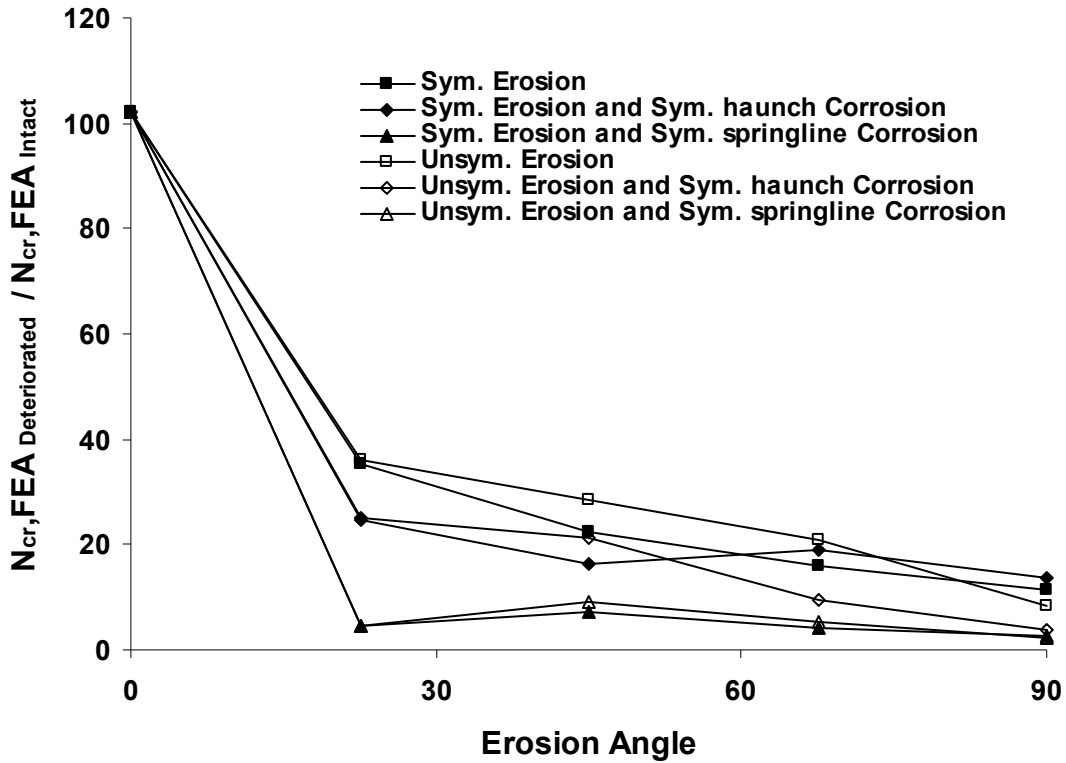
Figure 7. Factor of safety against yield for symmetrical and unsymmetrical erosion patterns



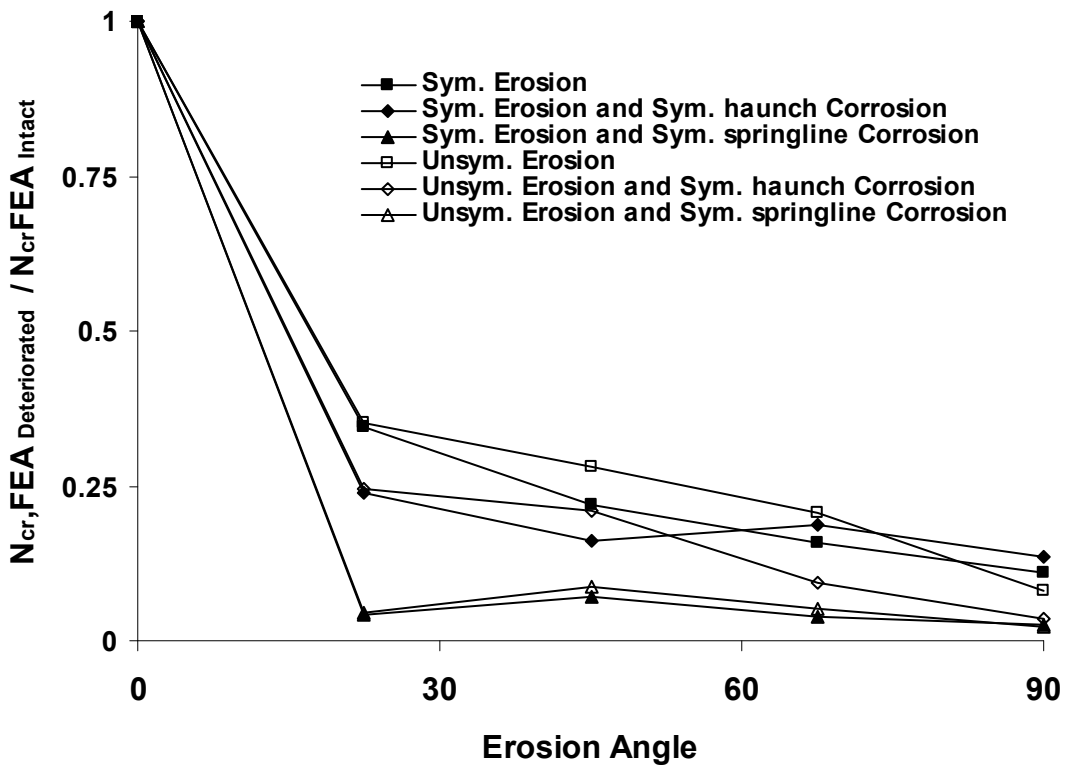
a. Symmetrical erosion

b. Unsymmetrical erosion

Figure 8. Moment distributions for symmetrical and unsymmetrical erosion patterns



a. Factor of safety against elastic buckling versus void size (contact angle of erosion).



b. Factor of safety against elastic buckling normalized using initial stability versus void size.

Figure.9 Effect of erosion on the culvert buckling strength.

CONCLUSIONS

For the shallow-buried culvert studied in this investigation the following conclusions are drawn.

1. Development of erosion voids adjacent to the culvert has a modest effect on the thrust distribution as well as on the factor of safety against yield (calculated without considering bending moments).
2. Any effects of erosion on thrust and the factor of safety against yield are dominated by the position of the erosion void, not by its volume.
3. Symmetrical and unsymmetrical erosion patterns had almost the same effect on the thrust distribution and on the factor of safety against yield.
4. The moments in the metal culvert were greatly influenced by the erosion void.
5. Both position and volume of the erosion pattern affect the moments in the culvert.
6. Moment distribution is un-symmetric for unsymmetrical erosion patterns.
7. The elastic buckling analyses demonstrate that the development of erosion voids, either symmetrical or unsymmetrical, is sufficient to destabilize an intact (uncorroded) structure.
8. Stability against elastic buckling is jeopardized more severely when erosion patterns are symmetric.
9. Increases in the volume of erosion void and the extent of invert corrosion leads to greater decreases in elastic buckling strength.
10. Deflections in the eroded structure increased, but were still reasonable (less than 100mm or 2.5% of diameter).

REFERENCES

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