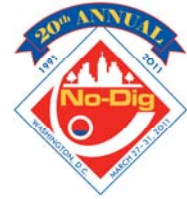




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A THREE-DIMENSIONAL STUDY OF THE EFFECT OF SOIL EROSION ON RIGID PIPES

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ABSTRACT: As sewer pipes age, they experience different signs of deterioration including cracks, open joints and loss of pipe wall material. Such defects in the pipe system can result in soil loosening and erosion void development around the pipe. This study employs three-dimensional numerical analysis to evaluate the effects of void size and location on the changes in radial earth pressure acting on the pipe and pipe wall stresses. A series of simplified voids half-circular in shape are introduced at two critical locations around the pipe, namely, springline and invert. Three-dimensional elasto-plastic finite element analyses are then performed to study how the void size and location influence the radial earth pressure and the stresses in the pipe wall. The results of the numerical analysis are summarized for each investigated case and the critical locations and void sizes are then identified. The results revealed significant changes in soil pressure and pipe wall stresses particularly near the boundaries of the introduced voids.

1. INTRODUCTION

Rigid pipes are commonly used in sewer and drainage networks. The design of these pipes has been the focus of many researchers since the early 1900's. This has resulted in several methods that are presently being employed to design buried pipes used in different applications. These design methods include empirical (Marston & Anderson, 1913), analytical (Burns & Richards, 1964 and Hoeg, 1968) and numerical approaches (Katona & Smith, 1976 and Heger et al., 1985).

As pipes approach their service life and regular maintenance plans are delayed, they become prone to different sources of deterioration including cracks, open joints and loss of pipe wall material. Davies et al. (2001) reported three different stages that a sewer pipe undergoes before it collapses. The first stage is the onset of small defects in the pipe system. The second stage is the growth of this defect as the pipe deteriorates allowing the migration and wash-out of the backfill material. The final stage is the loss of ground support resulting in excessive pipe deformation and collapse. The backfill material surrounding the sewer pipe can be either cohesionless or cohesive material. For cohesionless material (e.g. sand), the loss of support around a deteriorated section of a sewer pipe is generally caused by water infiltration

and the migration of soil particles through the pipe defect. For cohesive material (e.g. clay), voids may be formed around buried pipes due to exfiltration or surge in the system. The support loss around sewers and the accelerated deterioration of rigid pipes has been a problem of growing concern among municipal engineers, in several cases; it has caused complete pipe failure. The damaging effect of erosion voids is not limited to old aging sewer systems- the two case studies discussed below highlight how support loss can cause damage to newly constructed pipes that were never put into service.

Helfrich (1997) reported the failure of 0.3 m diameter sewer pipe made of vitrified clay buried at depths that range from 3 to 6 m. Inadequate subsurface investigation was the main reason resulting in the settlement of the subgrade soil under the pipe invert by about 50 mm. The costs associated with the detailed geotechnical investigation and the addition of more bedding material would have saved 30 times the replacement costs. Talesnick and Baker (1999) reported the failure of a 1.2 m diameter concrete-lined steel sewage pipe buried in clayey soils. Field investigations revealed the formation of a physical gap of approximately 20 mm between the invert and the bedding layer supporting the pipe. Severe cracking developed at the crown and springline along a 300 m segment of the pipeline. Although the loss of soil support in the above examples may not have been due to erosion void formation, these case studies illustrate the possible consequences of ground loss around and under buried pipes.

Tan and Moore (2007) investigated numerically the effect of void formation on the performance of buried rigid pipes. The influence of both the void size and location (e.g. springline and invert) on the stresses and bending moments developed in the pipe wall was investigated. Results of an elastic model showed that the presence of a void at springline leads to an increase in the extreme fiber stresses and the bending moments at all critical locations: crown, springline and invert. The rate of increase is controlled by the growth of the void in contact with the rigid pipe. Extending the model to include shear failure resulted in stresses and moments higher than those reported in the elastic analysis. Changing the location of the void from springline to invert resulted in reduction in bending moment values followed by sign reversion of the moments at crown, springline and invert.

Meguid and Dang (2009) studied numerically the effect of erosion void formation around an existing tunnel on the circumferential stresses in the lining. A series of elastic-plastic finite element analysis was carried to investigate the effect of different controlling parameters (e.g., flexibility ratio, coefficient of earth pressure at rest and void size) on thrust forces and bending moments in the lining. When the void was located at the springline, bending moment significantly increased. Similar results were reported for the thrust forces under the same conditions regardless of the flexibility ratio. The presence of erosion void at the lining invert was found to reduce the bending moments causing reversal in the sign of the moment as the void size increased. The above studies illustrate the significant changes associated with backfill erosion around buried infrastructure. However, these studies were limited to two-dimensional analyses of one transverse cross section of the pipe-soil system assuming that the erosion void extends along a significantly large section of the pipe.

In this study, a three-dimensional nonlinear finite element analysis has been conducted using ABAQUS software to investigate the 3D effect of erosion voids induced around a concrete pipe wall on the earth pressure distribution as well as the circumferential stresses in the pipe. The size and location of the induced voids have been varied and the changes in earth pressure and pipe stresses have been investigated.

2. MODEL DESCRIPTION

The investigated problem involves a concrete pipe 600 mm in inner diameter and 70 mm in thickness installed using the embankment installation condition with 3 m cover above the crown. The pipe is first placed in a large trapezoidal shaped trench on a layer of bedding material and backfilled in layers and covered by an embankment. The problem geometry and material properties used in this investigation were based on those reported by Liedberg (1991) in full scale experiments. The problem geometry showing the pipe location is shown in Figure 1.

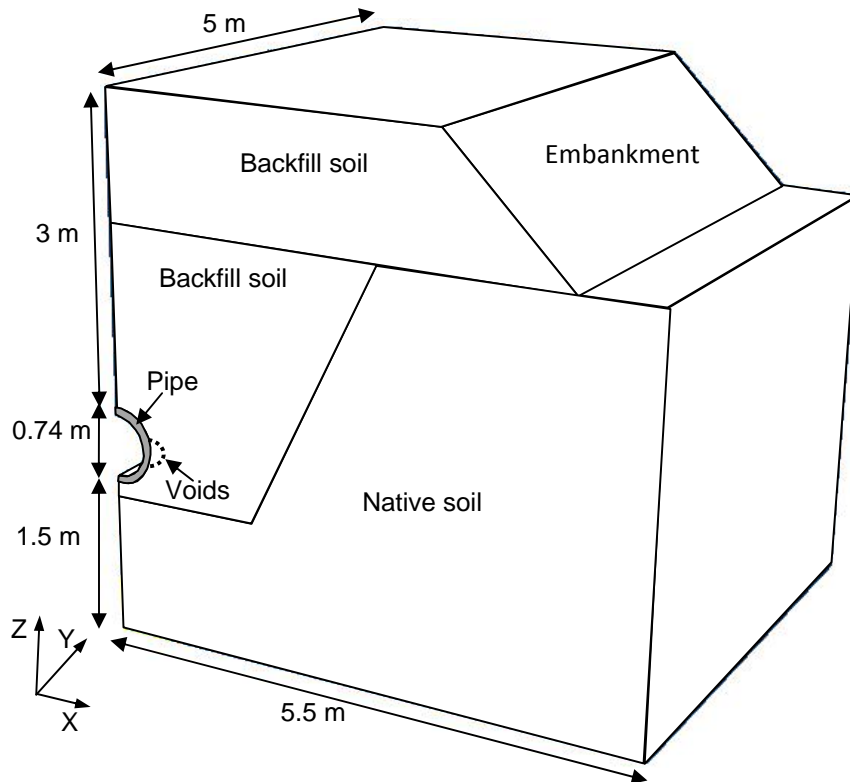


Figure 1: Model geometry

To simulate the presence of erosion voids around the existing pipe in 3D space, semi-cylindrical zones were predefined at specific locations next to the pipe wall. The sizes of these zones have been controlled such that their diameter and length along the pipe axis can be varied to reflect the growth of the void in the radial and/or longitudinal directions. The dimensions of the void in both directions have been normalized with respect to the circumference of the pipe cross section and the pipe length, respectively. In the radial direction, the void radius was incrementally increased in three steps to represent unsupported lengths of 3%, 7% and 11% of the pipe circumference. The extent of the void in the longitudinal direction was also varied in three steps to represent 2%, 5% and 10% of the pipe length. Two critical void locations are examined in this study, namely, springline and invert and the changes in earth pressures and stresses in the pipe wall are then calculated. In order to illustrate the void location and geometry with respect to the pipe, a 3D schematic of the pipe with partial backfill is shown in Figure 2.

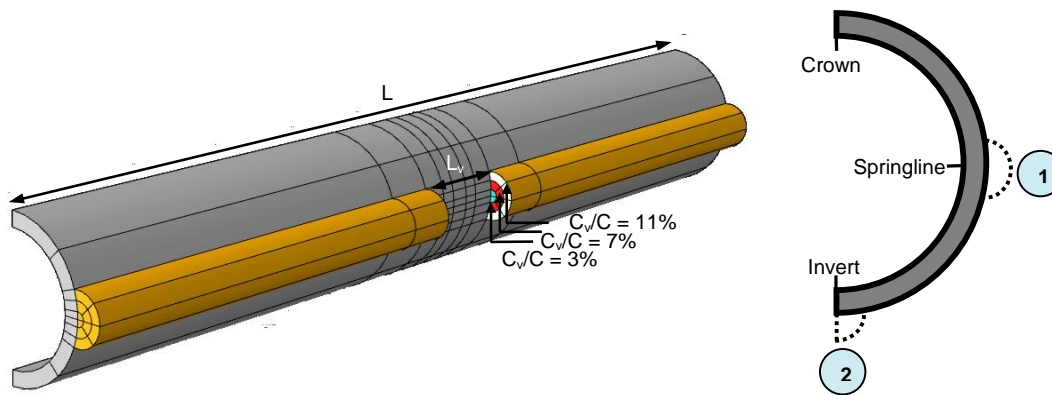


Figure 2: Size and length of voids and their orientation around the pipe

3. NUMERICAL DETAILS

All the analyses reported in this study are performed using the finite element code ABAQUS version 6.8-3. Only half of the geometry is investigated due to the symmetry of the problem. Both the pipe and the soil are modeled using solid elements C3D20 available in ABAQUS element library. These elements are general purpose quadratic brick elements with 20 nodes and 27 integration points under full integration condition. The used second order interpolation elements provide higher accuracy, to capture the stress concentration more effectively and to model complex curved surfaces (ABAQUS, 2009).

The properties of the native soil located below the pipe and outside the trench as well as the backfill material (embankment and trench) were based on those reported by Liedberg (1991). The parameters used in modeling the different soil materials and the rigid concrete pipe are summarized in Table 1.

Table 1: Soil and pipe Parameters

	ρ (t/m ³)	E (MPa)	ν	ϕ (°)	ψ (°)	c (kPa)	ϵ_p
Native Soil	2.0	138	0.2	42.5	29.8	5	0
Backfill material	1.7	2.274	0.34	39	27.5	5	0
Concrete pipe	2.6	34,000	0.2	-	-	-	-

A total of six different numerical models were built in this study including three models for each void location (springline and invert). For each of the six models, the void size was increased in the radial direction to represent support loss (C_v/C) of 3%, 7% and 11% of the pipe circumference. Similarly, the void length was incrementally increased in the longitudinal direction corresponding to unsupported length (L_v/L) of 2%, 5% and 10% of the total pipe length.

The model is restrained in the horizontal direction (smooth rigid) at the vertical boundaries with symmetry condition about the Y-Z axis and is restrained in all directions (rough rigid) at the lower boundary.

The soil is modeled using ABAQUS Mohr-Coulomb with surface-to-surface contact interaction between the backfill soil and the buried pipe. To simulate the bonding interaction between the pipe and the soil, both the tangential and normal stresses are defined in each model.

The model is first subjected to geostatic stresses followed by the placement of the pipe and the soil to reach the target height of the embankment. To simulate the erosion void around the pipe, the elements located within a predefined zone are deactivated. This is followed by further void expansion in the radial and longitudinal direction.

3.1. MODEL VALIDATION

Liedberg (1991) conducted full-scale experiments to measure the earth pressure distribution around a concrete pipe underlain by different bedding conditions. Field measurements were compared with closed form and numerical solutions. To validate the numerical model used in this study, the geometry and material properties reported by Liedberg (1991) were adopted and the earth pressure acting on the lining was calculated. The earth pressure results calculated using different methods are presented in Figure 3 along with the field measurements. The calculated results using ABAQUS was found to agree with Hoeg's analytical solution as well as the numerically calculated pressure using CANDE software as shown in Figure 3. It was reported that earth pressure at the pipe invert ($\theta = 180^\circ$) is sensitive to the backfilling procedure particularly under the haunches.

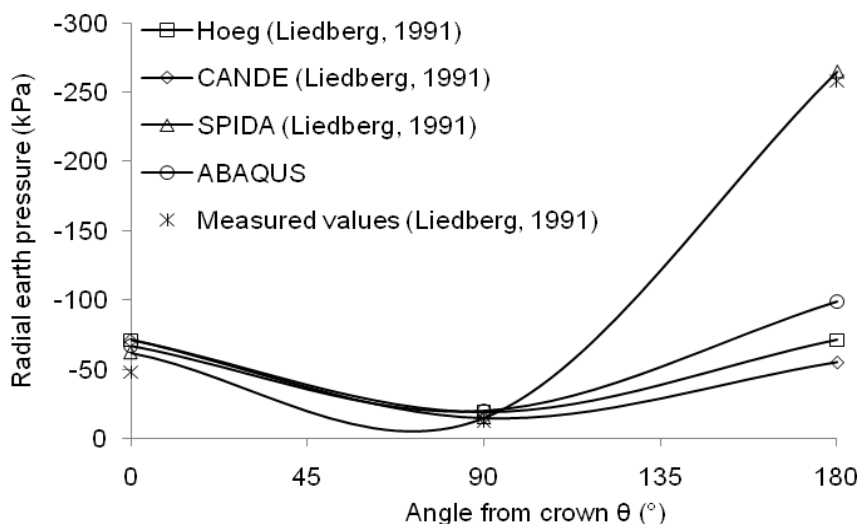


Figure 3: Measured and calculated earth pressure distribution using different methods

4. RESULTS AND DISCUSSION

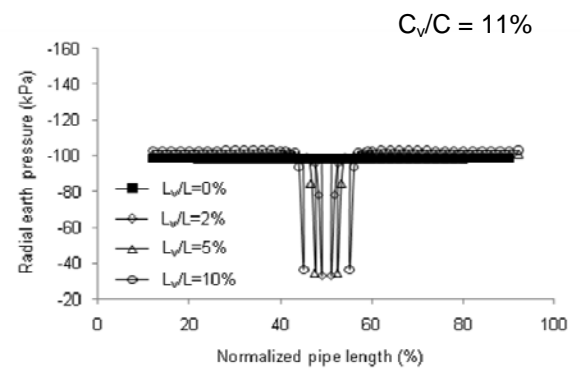
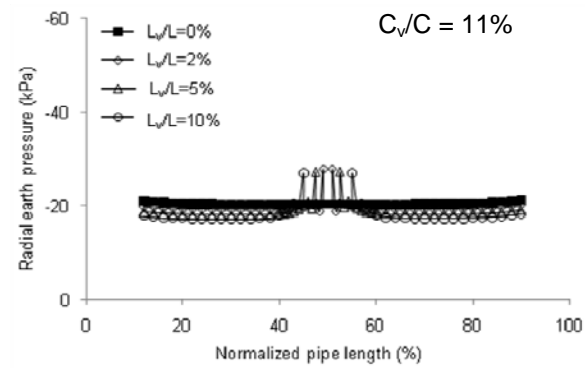
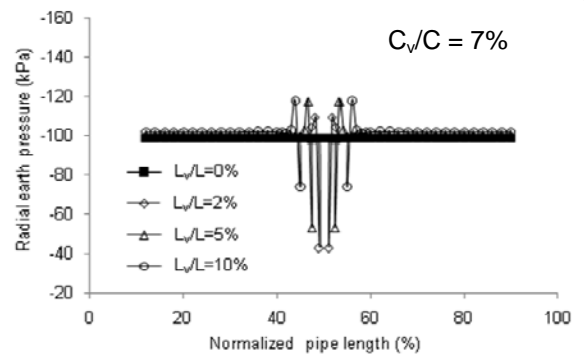
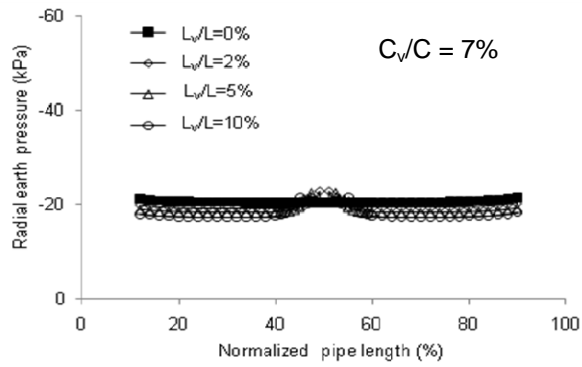
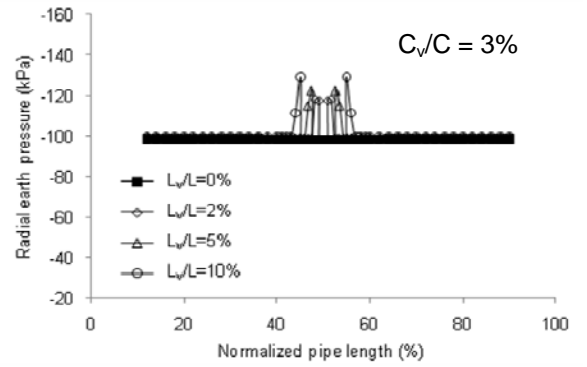
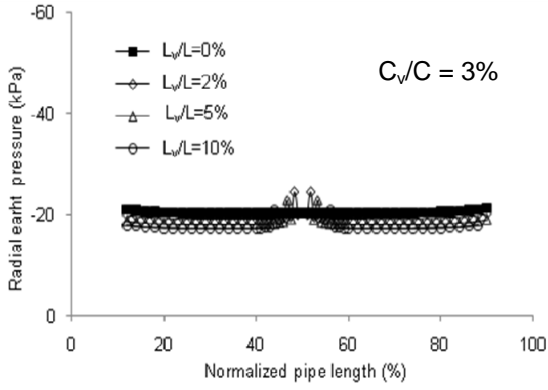
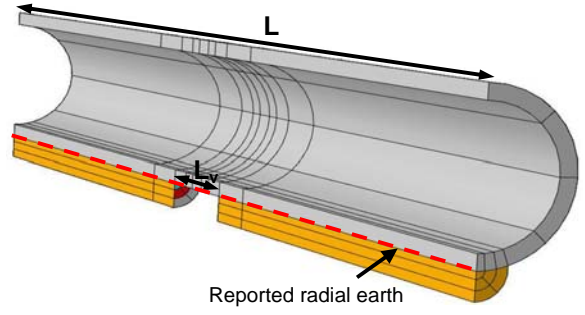
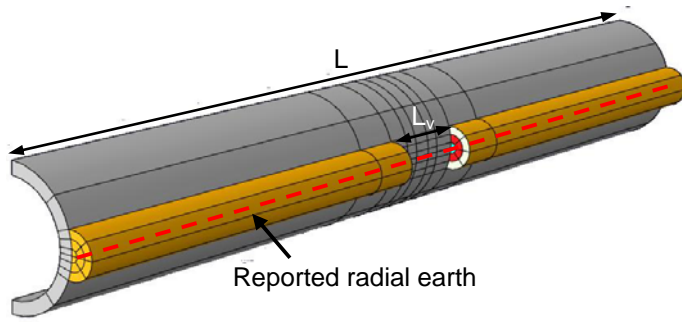
The introduction of the erosion voids at the pipe wall generally affected the initial earth pressure distribution and the stresses in the pipe wall. These changes are found to depend on the size and location of the void with respect to the pipe circumference.

4.1. Radial earth pressure: Figure 4 shows the changes in radial earth pressure acting on the pipe for the investigated range of parameters. The initial earth pressure is calculated to be approximately 21 kPa and 100 kPa at the springline and invert, respectively and is presented in Figure 4 for comparison purposes. As the void is introduced at the springline of the pipe, the initial earth pressure slightly increased at the void boundaries. No change in pressure is calculated away from the void and pressures

dropped slightly below the initial values. As C_v/C increased from 3% to 11%, the calculated earth pressure slightly increased from the initial values with a maximum increase of about 25% for $C_v/C = 11\%$. Increasing the void length from 2% to 10% of the original pipe length at the springline had less significant effects on the earth pressure distribution acting on the pipe. The above results are summarized and presented in Figure 4.

At the pipe invert, the earth pressure slightly increased for $C_v/C = 3\%$. As the void size increased the earth pressure decreased. With further increase in C_v/C to 11% the pressure redistributed such that earth pressure decrease is calculated as shown in Figure 4. This behavior is consistent with the beam bending of a pipe supported at both ends and allowed to deflect downwards. This will be further confirmed in the next section.

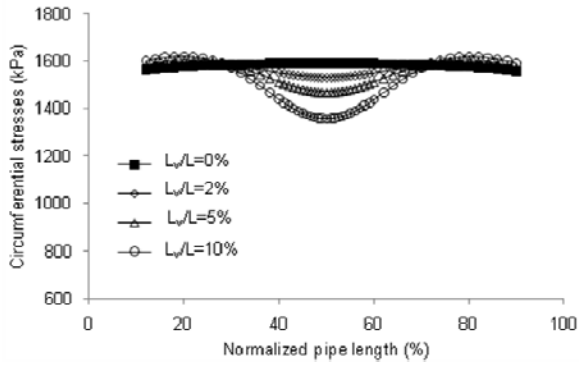
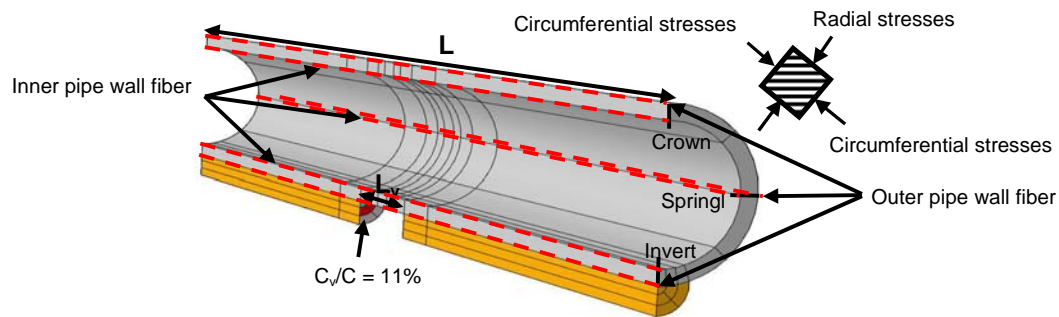
4.2. Stresses in the pipe wall: Circumferential stresses are calculated at the inner and outer fibers of the pipe before and after the introduction of the erosion voids as described in section 2. It was observed that the introduction of an erosion void at the pipe invert resulted in changes in changes in stress at the invert, springline and crown. The calculated stresses at the crown, springline and invert are presented in Figure 5. As C_v/C increased, the circumferential stresses changed as compared to the initial stresses and reached a maximum change of 45% at the centre of the void. For a given void length ($L_v/L = 10\%$), the increase in C_v/C ratio by 11% led to a change in the pipe stresses by about 45% of the initial values.



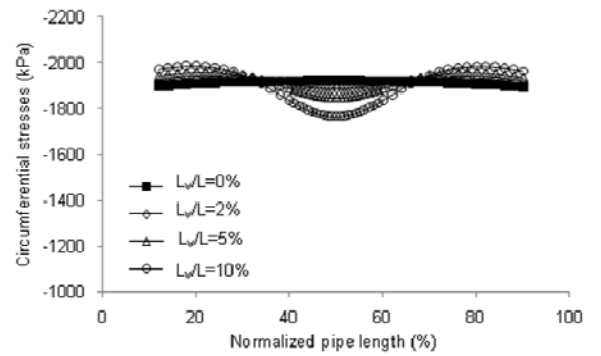
(a) Springline

(b) Invert

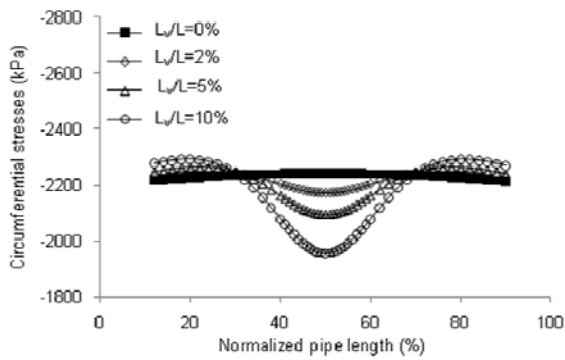
Figure 4: Earth pressure distribution around the voids at (a) springline (b) invert



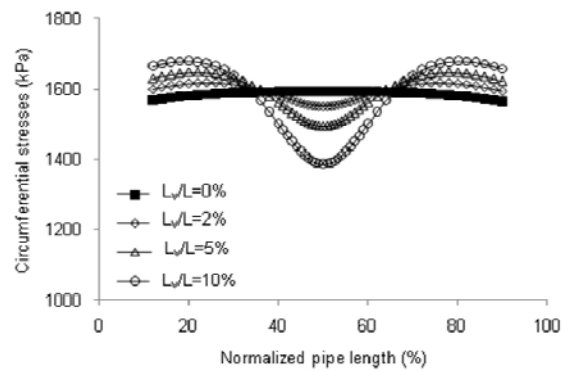
(a) Inner pipe wall fiber at Crown



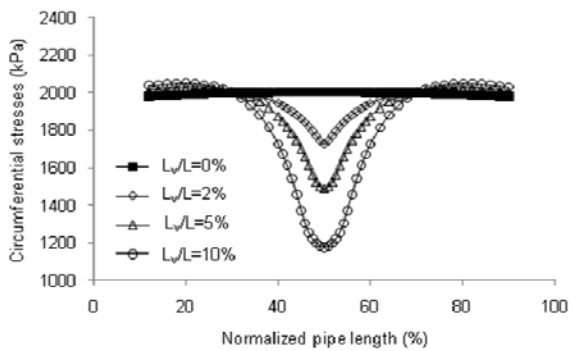
(b) Outer pipe wall fiber at Crown



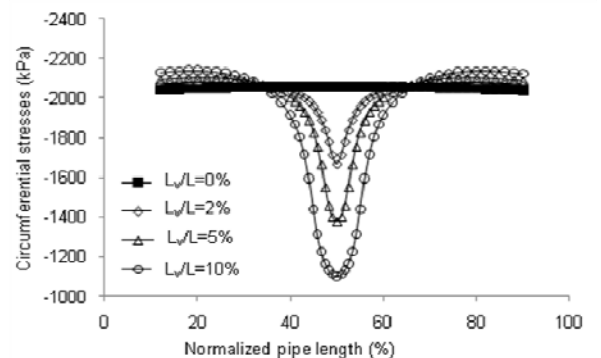
(c) Inner pipe wall fiber at Springline



(d) Outer pipe wall fiber at Springline



(e) Inner pipe wall fiber at Invert



(f) Outer pipe wall fiber at Invert

Figure 5: Circumferential stresses at the inner and outer fiber of the pipe wall

5. SUMMARY AND CONCLUSIONS

A three-dimensional nonlinear finite element analysis has been conducted in this study to investigate the effects of erosion void on buried rigid pipes. The changes in earth pressure and stresses in the pipe wall were calculated and compared with the initial conditions. Results indicated that both earth pressure and stresses in the pipe have significantly changed due to the introduction of the void.

The void size was found to have a substantial effect on magnitude of stress changes in the pipe. The presence of a large void at the invert can lead to the bending of the entire pipe causing compressive stresses in the upper fibers and tensile stresses in the lower fibers of the pipe. This study highlights that erosion voids around rigid pipes are detrimental to the structural integrity of the pipe and can lead to pipe failure.

6. ACKNOWLEDGEMENT

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7. REFERENCES

ABAQUS documentation, 2009.

Burns, J. Q., and Richard, R. M. (1964). Attenuation of Stresses for Buried Cylinders, Symposium of Soil-Structure Interaction Proceedings, Arizona University, pp.378-392.

Davies, B. A., Whiter, J. T., and Cunningham, R. J. (2001). Factors Influencing the Structural Deterioration and Collapse of Rigid Sewer Pipes, Urban Water, Volume 3, No. 1-2, pp.73-89.

Heger, F.J., Liepins, A. A., and Selig, E. T. (1985). SPIDA: An Analysis and Design System for Buried Concrete Pipe, Advances in Underground Pipeline Engineering, Proceedings of the International Conference, Madison, WI, USA, pp.143-154.

Helfrich, S. C. (1997). Investigation of Sewer-Line Failure. Journal of Performance of Constructed Facilities, ASCE, Volume 11, No. 1, pp. 42-44

Hoeg, K. (1968). Stresses against Underground Structural Cylinders, Journal of the Soil Mechanics and Foundation Division, ASCE, Volume 94, No. SM4, pp.833-858.

Katona, M. G., and Smith, J. M. (1976). Modern Approach for Structural Design of Pipe Culverts, CAD 76 2nd International Conference on Computers in Engineering and Building Design, London, UK, 23-25 March, 1976, pp.128-140.

Liedberg, S. (1991). Earth Pressure Distribution against Rigid Pipes under Various Bedding Conditions. Full-Scale Field Tests in Sand, Chalmers Tekniska Hogskola, Doktorsavhandlingar, No. 796, pp1-223.

Marston, A., and Anderson, A. O. (1913). The Theory of Loads on Pipes in Ditches and Tests of Cement and Clay Drain Tile and Sewer Pipe, Iowa State College of Agriculture , No. 31, 181pp.

Meguid, M. A., and Dang, H. K. (2009). The effect of erosion voids on existing tunnel linings, *Tunnelling and Underground Space Technology*, Volume 24, No. 3, pp. 278-286.

Talesnick, M., and Baker, R. (1999). Investigation of the failure of a concrete-lined steel pipe, *Geotechnical and Geological Engineering*, Volume 17, No. 2, pp. 99-121.

Tan, Z., and Moore, I. D. (2007). Effect of backfill erosion on moments in buried rigid pipes, *Transportation Research Board Annual Conference*, Washington, D.C.