

# Assessment of Stress Intensity Factor for buried cast iron pipeline using finite element analysis

Suborno Debnath, & Ashutosh Sutra Dhar

Department of Civil Engineering – Memorial University of Newfoundland, St. John's, NL, Canada



## ABSTRACT

Cast iron pipelines were widely used as water mains that were installed in the early last century. Most of the cast iron water mains are on the verge of their service life. Replacement of these old pipelines all at once is not an economically viable solution for the municipalities. It is preferred to utilize the pipes that are still in the workable condition and prepare a replacement/repair plan based on the remaining strength of the pipes. However, an acceptable method is currently not available for the remaining strength assessment of cast iron water mains subjected to corrosion and/or stress corrosion cracking. The commonly applied method of continuum modelling of soil-pipe interaction was not successful in predicting the failure mechanism observed in the field. Researchers are now focusing on applying fracture mechanics in the failure assessment of water mains. However, a method for the assessment of stress intensity factor (SIF) for fracture mechanics-based assessment is currently not available for buried pipes subjected to corrosion and/or stress corrosion cracking. In this paper, finite element modelling using Abaqus is performed for assessment of SIF for buried cast iron water mains considering soil-structure interaction. Computational challenges and the numerical techniques employed in the FE analysis are discussed in the paper. The numerical analysis reveals that the defect shapes and the location of defects significantly affect the SIF of buried water mains.

## RÉSUMÉ

Les conduites en fonte étaient largement utilisées comme conduites d'eau installées au début du siècle dernier. La plupart des conduites d'eau en fonte sont sur le point de vivre. Le remplacement simultané de ces anciens pipelines n'est pas une solution économiquement viable pour les municipalités. Il est préférable d'utiliser les tuyaux encore en état de marche et d'élaborer un plan de remplacement / réparation en fonction de la résistance restante des tuyaux. Cependant, aucune méthode acceptable n'est actuellement disponible pour l'évaluation de la résistance restante des conduites d'eau principales en fonte soumises à la corrosion et / ou à la fissuration par corrosion sous contrainte. La méthode couramment appliquée de modélisation du continuum de l'interaction sol-tuyau n'a pas permis de prédire le mécanisme de défaillance observé sur le terrain. Les chercheurs se concentrent maintenant sur l'application de la mécanique de la rupture dans l'évaluation de la défaillance des conduites d'eau. Cependant, aucune méthode d'évaluation du facteur d'intensité de contrainte (SIF) pour une évaluation basée sur la mécanique de la rupture n'est actuellement disponible pour les tuyaux enterrés soumis à la corrosion et / ou à la fissuration par corrosion sous contrainte. Dans cet article, la modélisation par éléments finis à l'aide d'Abaqus est réalisée pour l'évaluation de la SIF des conduites d'eau principales en fonte enterrée, en tenant compte de l'interaction sol-structure. Le document traite des problèmes de calcul et des techniques numériques utilisées dans l'analyse FE. L'analyse numérique révèle que les formes et l'emplacement des défauts affectent de manière significative le SIF des conduites d'eau enterrées.

## 1 INTRODUCTION

A sustainable water supply network plays a vital role for the development of a city. Cast iron pipelines were one of the main components in this system in the past few decades and are still functioning but show deterioration with passes of time. As a result, cast iron pipe failure increases day by day that causes huge economical loss and affects public safety. Internal and external corrosions occur in buried pipelines which are the most predominant causes of pipe incidents (Mohebbi et al. 2011). Corrosive soil is mainly responsible for the corrosion of buried pipes. Folkman (2018) reported that cast iron pipeline breaks 20 times more in highly corrosive soils than in low corrosive soils. Among the several types of corrosions identified in water mains, pitting corrosion is considered as the most dangerous types. Irregular soil contact and non-uniformities in the metal structure cause pitting corrosion

when the pipes are in a hostile soil environment. It is difficult to detect pitting corrosions, which may initiate stress corrosion cracking and lead to failure.

Pipeline failure occurs either due to loss of strength or loss of toughness. Cast iron is a brittle material and may fail due to loss of strength through cracking rather than yielding. Fracture mechanics can be applied in failure (cracking) assessment of the pipe. For brittle material, stress intensity factor (SIF) is used for the assessment of crack initiation and crack propagation in fracture mechanics. Several works have been conducted analytically and numerically to calculate the SIFs for pipes with internal and external cracks. Raju and Newman (1982) determined different influence coefficients and provided an empirical equation to calculate the SIFs for semi-elliptical surface cracks in cylindrical pressure vessels with aspect ratios of defects ranging from 0.2 to 1.0. Lambert et al. (1994) extended the work of Raju and

Newman (1982) by conducting three-dimensional finite element analysis (FEA) considering low aspect ratios (0.05 to 0.1) to calculate the SIFs for semi-elliptical cracks. Lin and Smith (1998) worked with crack growth in pressure vessels and revealed that after some cycles the crack forms a semi-elliptical shape. Li et al. (2012) further conducted FEA to find SIFs with high aspect ratio for semi-elliptical cracks in pipes. Similar research has been presented by Diamantoudis and Labeas (2005), Moulick and Sahu (2012), Predan et al. (2013) and Li et al. (2016b). Li et al. (2016a) studies the effect of inclined surface crack in pressurized pipes and determine SIF with mixed modes failure. Most of the studies focused on the crack-only defect of the pipes. Randeniya et al. (2016) considered surface crack along with corrosion for the determination of the influence coefficients. The SIFs reported to date were developed for in-air pipe only. No study is available on the SIF considering the soil effect for buried pipe. In this paper, a three-dimensional FE analysis analyses are performed to investigate the SIF of buried cast iron pipe, subjected to cracking or 'corrosion with cracking'.

## 2 FINITE ELEMENT (FE) MODELLING

The Abaqus/Standard module (Dassault Systemes Systemes 2014) is used in this study for calculating the fracture parameters for pipelines containing a crack defect (no metal loss) and a 'cracks with corrosion' defect.

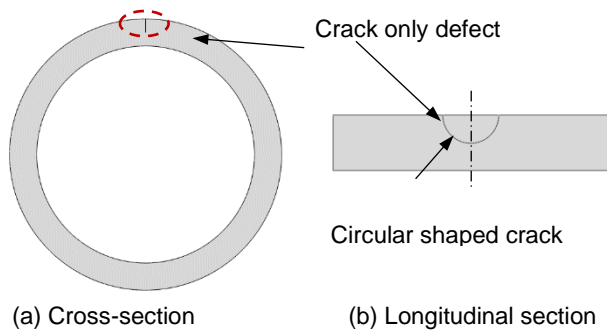


Figure 1. Crack only defect

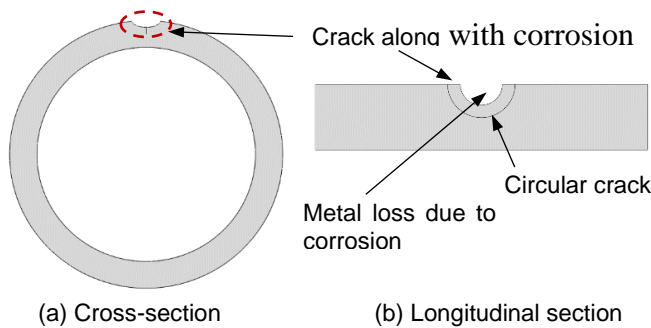


Figure 2. Crack in corrosion defect

Abaqus/Standard employs static implicit and dynamic implicit algorithms, which are suitable for smooth nonlinear problems. Static implicit method with small strain analysis is considered in the present study. For the development of FE model, the solution for the SIFs reported in Raju and Newman (1982) is first simulated for validation. Pipelines are then analyzed under buried condition subjected to either crack (Figure 1) or crack along with corrosion (Figure 2).

### 2.1 FE model development

Using extensive FE analyses, Raju and Newman (1982) developed a simplified equation (Eq. 1) for the calculation of SIF at any point along an elliptical crack of a pipe subjected to an internal pressure.

$$K = PR/t \sqrt{\pi a/Q} F_e (a/c, a/t, t/R, \phi) \quad [1]$$

Where,  $PR/t$  is the average hoop stress of an uncracked pipe subjected to internal pressure,  $a$  is the depth of crack,  $Q$  is the crack shape parameter,  $F_e$  is the boundary-correction factor,  $t$  is the pipe wall thickness,  $c$  is the half-length of surface crack,  $R$  is the inner radius of the pipe and  $\phi$  is the parametric angle locating a point on the crack (Figure 3).

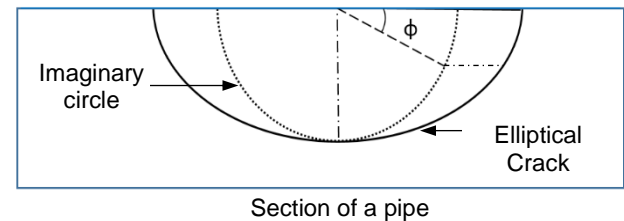


Figure 3. Parametric angle ( $\phi$ ) of an elliptical crack

The boundary-correction factor,  $F_e$  is expressed using influence coefficients of a polynomial function of the crack depth,  $a$ . For  $j^{\text{th}}$  order polynomial ( $j = 0, 1, 2, 3$ ) with influence coefficients  $G_j$ , the  $F_e$  is given by

$$F_e = \frac{t}{R} \left( \frac{R^2}{R_0^2 - R^2} \right) \left[ 2 G_0 + 2 \left( \frac{a}{R_0} \right) G_1 + 3 \left( \frac{a}{R_0} \right)^2 G_2 + 4 \left( \frac{a}{R_0} \right)^3 G_3 \right] \quad [2]$$

Where  $R_0$  is the outer radius of the pipe and  $G_0, G_1, G_2, G_3$  are the influence factors for four polynomial terms for uniform, linear, quadratic and cubic distributions, respectively. The influence coefficients are obtained from FEA. Crack shape parameter,  $Q$  in Eq. 1 can be found from Eq. 3, Raju and Newman (1982):

$$Q = 1 + 1.464 \left( \frac{a}{c} \right)^{1.65} \quad \text{for } a \leq c \quad [3]$$

In this study, an elliptical external surface crack ( $a/c = 1$ ) on a pipe in the longitudinal direction is considered for validation of the FE model developed using Abaqus. The

outer diameter of the cast iron is considered as 220 mm and the thickness is 10 mm to satisfy the relative wall thickness ( $t/R$ ) and relative crack depth ( $a/t$ ) mentioned in Raju and Newman (1982). The depth of crack ( $a$ ) is considered as 5 mm. During the analysis, an internal pressure of 600 kPa is applied. Although cast iron shows nonlinear stress–strain behavior, it is assumed as a linear elastic material. A Young’s modulus of 125 GPa and Poisson’s ratio of 0.25 are considered based on the test results of a cast iron pipe material conducted at Memorial University (Debnath 2019). The pipe is defined as 3D deformable solid bodies. For modelling of the crack, a partition is applied on the pipe’s crack face. The crack is then defined using Abaqus command along the partition.

Calculation of SIF along a crack in pressure tube requires fine meshes around the crack tip that result in a large number of elements in the FE model. This large number of elements increases the computational time and the memory requirement of the computer. To overcome the problem, a sub-model technique available in Abaqus is applied. In this approach, a global model is first run with larger element sizes to calculate the stress and displacement fields. A sub-model with fine mesh around the crack is then reanalyzed under the stress and displacement fields from the global model.

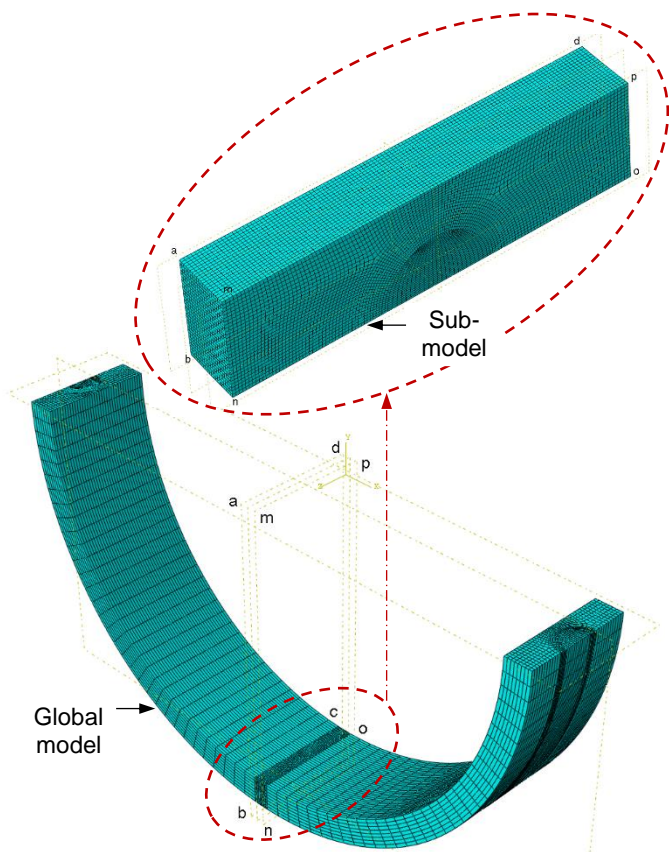


Figure 4. Global model and sub-model

To develop the global model, a quarter of the pipe cross-section is first developed and then a model of half cross-section is obtained using mirror tools, available in Abaqus. To take the advantage of symmetry for saving computational time, the pipe cross-section is assumed as symmetric about a diametric plane passing perpendicular to the crack surface. This assumption corresponds to a pipe with two cracks on diametrically opposite locations. Since the SIF for a particular crack is not affected by any other crack located at sufficient distance, it is expected that the calculated SIF will not be affected by the assumption of the symmetric condition. Symmetric boundary conditions are used on the planes of symmetry. Longitudinal displacements of the pipe are restrained at the end planes by using roller supports. Figure 4 shows the global model where the volume defined by  $abcd$  and  $mnop$  planes in the close vicinity of the crack is used for developing the sub-model. In the global model, within the volume (defined by  $abcd$  and  $mnop$  planes) there are 6,720 elements. In the sub-model, the number of elements is increased to 81,840 through re-meshing to ensure higher degree of accuracy in the results.

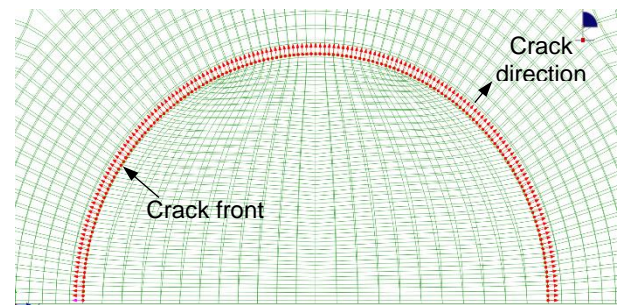


Figure 5. Crack extension direction of a semi-elliptical crack ( $a/c = 1$ )

For the sub model, the boundary condition option of sub-model, available in Abaqus, is applied at the faces  $abcd$  and  $mnop$  and thus the stress and displacement fields from the global model are transferred to these faces. Axially restrained boundary conditions are applied on faces  $abmn$  and  $cdpo$ .

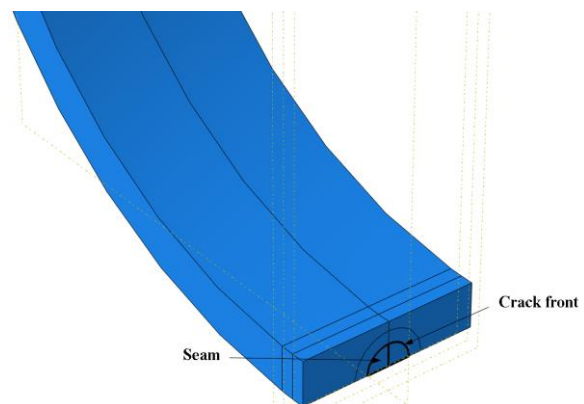


Figure 6. Crack front and seam locations

The contour integral method is used for calculating the SIFs along the crack tip. The contour integral method requires defining the crack front, and specifying the virtual crack extension direction. The crack extension direction is assigned orthogonal to the crack front (perpendicular to the ellipse) which varies along the elliptical crack front. To specify the crack extension direction in Abaqus, a single  $q$  vector is first defined. The input file data is then edited to correct the  $q$  vectors at each node to make orthogonal to the crack front (Figure 5). A seam is assigned that creates overlapping nodes and allows the crack to open when loaded (Figure 6).

In the contour integral method, five contours are specified using Abaqus commands. Abaqus automatically selects the elements that form each ring of contour from the crack line. Each contour provides an evaluation of the contour integral that is path-independent and has same energy. The first contour usually shows abrupt results as it is defined by specifying the nodes at the crack tip and is ignored (Figure 7) (Dassault ~~systemes~~ Systemes 2014). Figure 7 shows one half portions of the contours, which are symmetric about the crack plane.

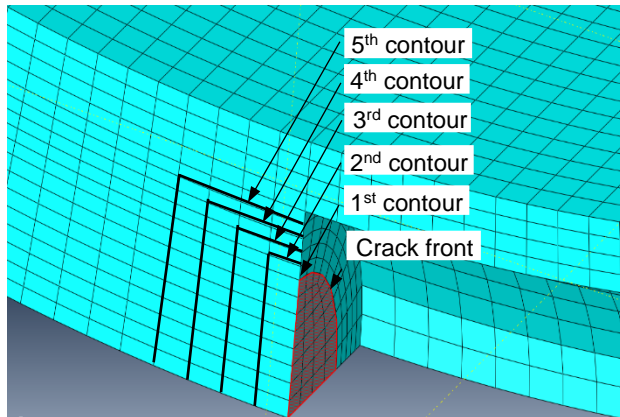


Figure 7. Five contours and crack location

Twenty-noded brick elements with reduced integration (C3D20R) and eight-noded linear brick elements (C3D8R) are used in the FE analysis to examine the suitability of elements to be used in the analysis. Element size is determined through a mesh sensitivity analysis. The SIFs at the location  $\phi = 0$  along the crack calculated using C3D20R elements are plotted in Figure 8 for four contours (except the first one). In Figure 8, the SIFs calculated from each of the contours are the same. The FE analysis with C3D20R elements thus simulated successfully the path-independent contour integrals. However, the use of C3D20R elements requires higher calculation effort and sometimes it is not possible to perform analysis due to lack of computational capacity for complex problems involving a large number of

elements. On the other hand, the use of C3D8R elements provide constant strain in the elements and requires less computational effort. The SIFs calculated using C3D8R elements is found to vary from contour to contour as shown in figure 9, which is potentially due to the errors in the calculated stress field in the vicinity of the crack tip. However, the variation of SIFs in figure 9 is not significant. Recognizing the limitations of FE analysis in accurately calculating the stress field in the vicinity of crack tip, Fisher-Cripps (2007) proposed to plot the SIF obtained for different contours located at various distances from the crack tip against the distance from the tip and extrapolate the best fit curve backward to the tip (distance = 0) to estimate the SIF.

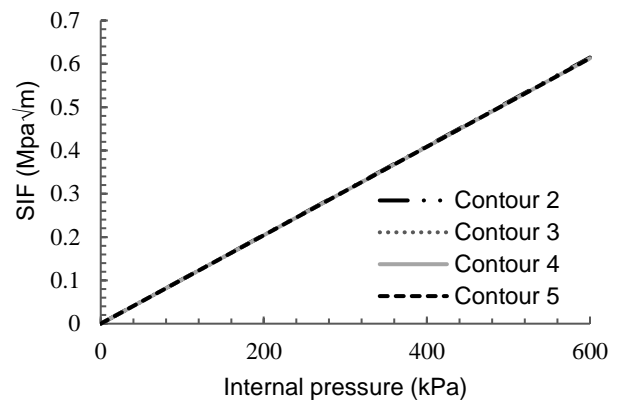


Figure 8. SIFs of four contour around the crack front (when  $\phi = 0^\circ$  OR  $180^\circ$ )

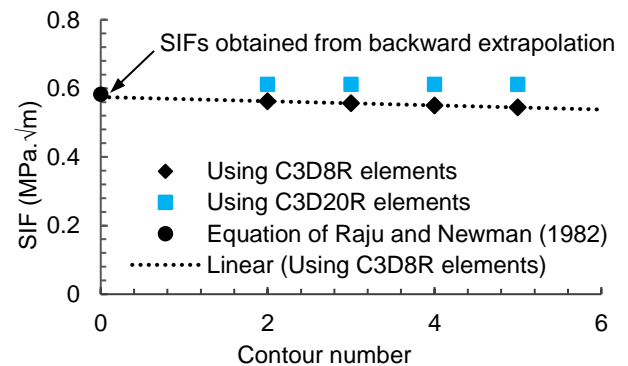


Figure 9. SIF at various contours ( $\phi = 0$ )

The SIF is obtained using the method proposed in Fisher-Cripps (2007) as shown in Figure 9 from FE analysis with C3D8R elements. This SIF is around 4% less than the SIF calculated using C3D20R elements and matched with the value calculated using the equation of Raju and Newman (1982). The SIFs estimated from FE analysis using this method throughout the crack length are compared with those calculated using the equation of

Raju and Newman (1982) in Figure 10. The comparison shows good agreement (<5% error) of the results of FE analysis with those from the equation of Raju and Newman (1982). Randeniya et al. (2016) also found FE calculations of SIFs within 5% of the values calculated using the equation of Raju and Newman (1982). FE analysis with C3D8R elements is therefore used for buried pipes where the method proposed in Fisher-Cripps (2007) is used for estimating the SIFs.

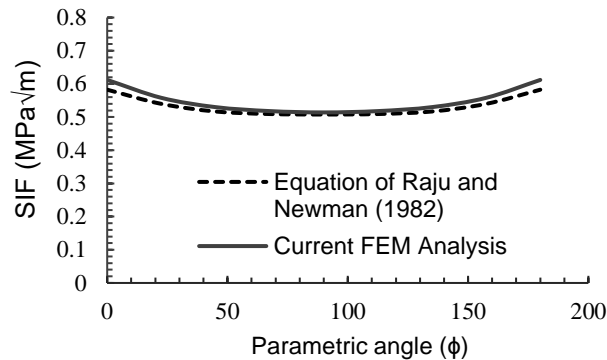


Figure 10. Comparison of SIFs

## 2.2 SIF calculation for buried pipeline

Three-dimensional pipeline-soil interaction analysis is performed using Abaqus to assess the SIFs for buried pipes with a wall crack. The soil and pipe are modelled as a 3D deformable solid body. The pipeline and crack geometries similar to those discussed above for in-air pipe are considered. Soil is assumed as an elasto-plastic material and defined by the Mohr–Coulomb failure criteria. Material parameters typical for medium dense sand are used, as shown in Table 1.

Table 1. Material Parameters

Material Properties	Soil	Cast Iron
Density (gm/cm <sup>3</sup> )	1.77	7.88
Young's modulus (MPa)	24	125,000
Poisson's Ratio	0.25	0.25
Friction Angle in (°)	38	-
Dilation Angle in (°)	8	-
Cohesion Yield Stress (kPa)	0.1	-

General contact algorithm that automatically select master and slave surface is used for soil-pipe interaction. For the interface, the Coulomb's friction model is used that defines the critical shear stress at which sliding of the surfaces occurs. The friction coefficient ( $\mu$ ) depends on interface characteristics and the slip rate between the soil and the pipe. Larger value of  $\mu$  indicates rough surface and lower value represents a smooth surface. In this study,  $\mu$  is assumed to be 0.30. The locations of the bottom and side boundaries of the problem with respect to

the location of the pipe are sufficiently large in order to avoid the boundary effects. As the pipe is lying on uniform soil, the bending of the pipe due to vertical load is expected to be negligible. The length of the model (L) is thus selected as 100 mm so that  $L/c > 20$ , which is small to reduce computational time, yet sufficient to minimize the length effect on SIFs (Randeniya et al. 2016). Crack locations at the crown, springline and invert of the pipe are considered for the calculation of the SIFs. For analysis, horizontal and vertical movements are restrained at the bottom boundary, while the lateral movement of soil is restrained at side boundaries using roller supports. A typical FE model used for the determination of SIFs for a crown or invert crack is shown in Figure 11.

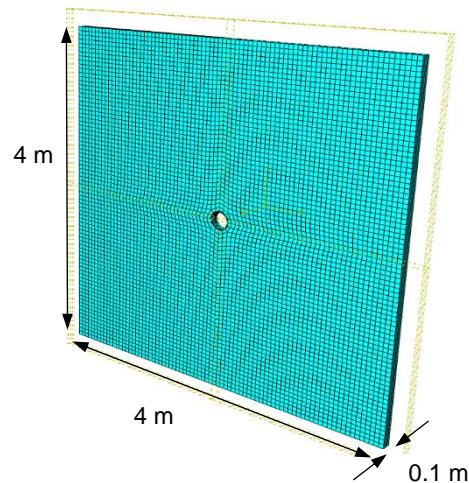


Figure 11. Global model of a buried pipeline for the determination of SIFs for a crown or invert crack

Springline SIFs are calculated by taking the advantage of symmetry. Therefore, half of the soil-pipe system is considered for the analysis where the symmetric boundary condition is applied at the plane of symmetry. Figure 12 shows a typical FE model used for the determination of SIFs for springline crack.

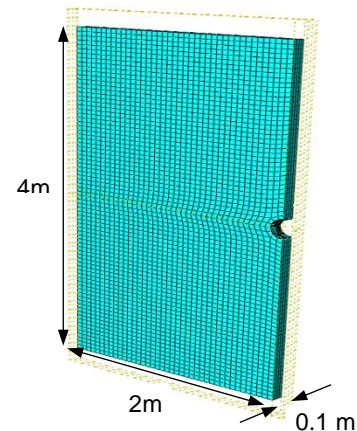


Figure 12. Global model of a buried pipeline for calculation of SIFs for a springline crack

The global model and sub-model approach is again applied to save computational time. Figure 13 shows the sub-model considered for SIFs calculation of a springline crack.

Numerical analysis is carried out in two main steps. In the first step, 600 kPa internal pressure is applied to obtain SIFs and compared with the analytical solution of Raju and Newman (1982). In the second step, a surface load is applied at the top boundary to account for the surface load including gravity load. A surface pressure of 34.73 kPa, equivalent to the weight of 2 m of soil is applied.

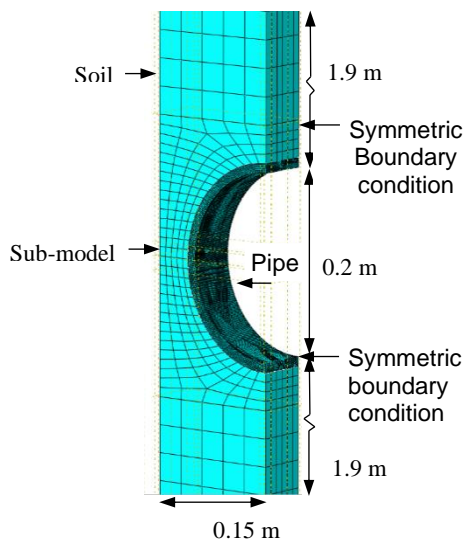


Figure 13. Sub-model boundary condition

It is to be noted that SIFs for pipelines subjected to surface load has not been extensively investigated earlier. Existing literature focused on calculating SIFs for pipelines subjected to internal pressure only. In the current study, the SIFs of buried pipes under internal pressure and surface load are examined at various locations of an elliptical crack. SIFs for a 'crack in corrosion defect' for a buried water main is also calculated considering half ellipsoidal shape of corrosion (Figure 14).

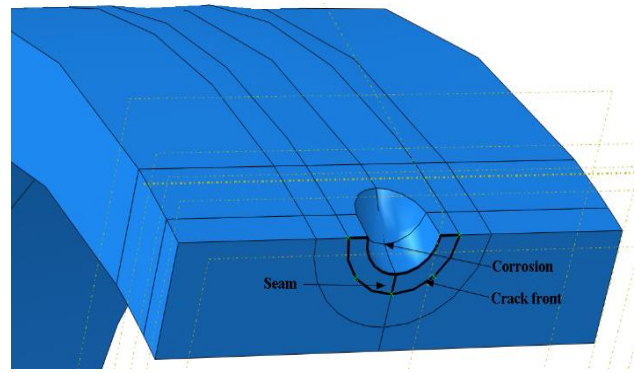


Figure 14. Crack front and corrosion location for crack in corrosion defect

To identify the crack propagation direction for assigning during application of contour integral method, analyses with extended finite element method (XFEM), available in Abaqus, are first performed. Figure 15 shows a crack predicted using the XFEM analysis, which is essentially in the longitudinal direction. Therefore, longitudinal crack is assigned at the location determined from XFEM in the SIF calculation using the contour integral method. Table 2 shows the pipe dimensions and defect geometries considered.

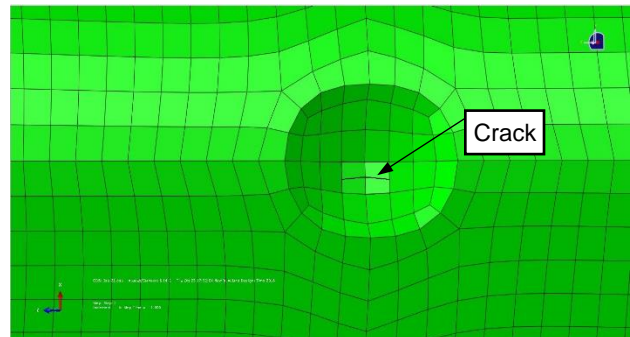


Figure 15. Crack location using XFEM analysis

Table 2. Pipe dimensions and defect geometries

Geometries	Values
Pipe diameter, $D$ (mm)	220
Wall thickness, $t$ (mm)	10
Corrosion depth, $d$ (mm)	3.3
Corrosion length, $l$ (mm)	13
Corrosion width, $w$ (mm)	6.5
Crack depth, $d_c$ (mm)	1.7
Crack length, $l_c$ (mm)	10

### 3 RESULTS-SIF FOR BURIED PIPES

Numerical analysis is first performed to investigate the critical SIFs for longitudinal and circumferential cracks of

a buried cast iron pipeline. Figure 16 shows that SIFs is much higher for longitudinal crack than the circumferential crack. As a result, longitudinal crack is considered for further analysis.

The SIFs calculated for a longitudinal crack located at the springline and crown/invert of a buried pipeline are compared in Figure 17. Figure 17 shows that the SIF is higher for the springline crack than for a crown or invert crack. The SIFs calculated using the equation of Raju and Newman (1982) are also included in the figure. It is to be noted that the equation of Raju and Newman (1982) is only applicable under the loading of internal pressure. Due to the application of surface load, the SIFs at the springline is increased and SIFs at the crown/springline is decreased from the values under the internal pressure only (calculated using the equation of Raju and Newman 1982).

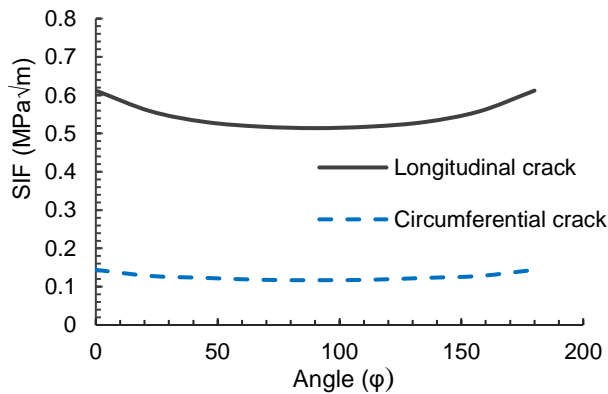
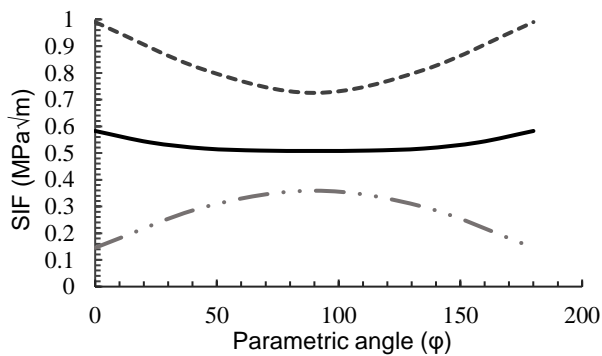


Figure 16. SIFs for a longitudinal and circumferential crack



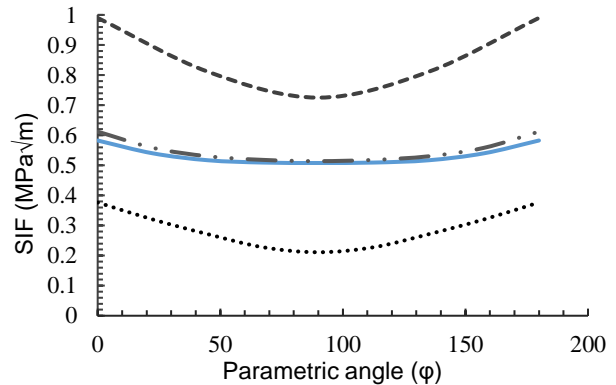
- Equation of Raju and Newman (1982) (considering only internal pressure)
- - - Springline SIFs (considering internal pressure & surface load)
- · · · Invert SIFs (considering internal pressure & surface load)

Figure 17. SIFs in springline and invert position, considering combined loading condition

The Contribution of the internal pressure and external load independently on the SIFs are also obtained from FE calculations, as plotted in Figure 18. Figure 18 shows that FE calculation of SIFs under internal pressure matches reasonably with the values calculated using the equation of Raju and Newman (1982), which was developed for the in-air pipe. This implies that the surrounding soil does not have a significant effect on the SIFs due to the internal pressure. The equation of Raju and Newman (1982) can be used for calculation of SIFs under internal pressure of buried pipe. The SIFs under the surface load can be separately calculated and added to the SIFs under the internal pressure to obtain the total SIFs. The SIFs for a buried pipe can be expressed as:

$$K = K_{\text{pressure}} + K_{\text{surface}} \quad [4]$$

Where,  $K_{\text{pressure}}$  corresponds to the SIF due to internal pressure and  $K_{\text{surface}}$  corresponds to the SIFs due to surface load.  $K_{\text{pressure}}$  can be calculated using the equation of Raju and Newman (1982).



- Equation of Raju and Newman (1982) (considering only internal pressure)
- - - Springline SIFs (considering internal pressure & 2 m soil cover pressure)
- · · Springline SIFs (considering only internal pressure)
- Springline SIFs (considering only 2 m soil pressure)

Figure 18. SIF for 'crack only defect' for a springline crack

For  $K_{\text{surface}}$ , the results of FE analysis are used to develop a simplified equation as shown in Eq. 5.

$$K_{\text{surface}} = q \sqrt{\pi \frac{a}{Q}} F_s (a/c, a/t, t/R, \phi) \quad [5]$$

Where,  $q$  is the surface load and  $F_s$  is the influence coefficient. The crack shape parameter,  $Q$  is recommended in Ichsan (1994) is assumed to be applicable for this case. The parameter can be accurately approximated by Eq. 6 & 7 (Ichsan 1994).

$$Q = 1 + 1.464 \left(\frac{a}{c}\right)^{1.65} \quad \text{for } a \leq c \quad [6]$$

$$Q = 1 + 1.464 \left(\frac{c}{a}\right)^{1.65} \quad \text{for } c \leq a \quad [7]$$

To simulate the gravity load, the surface load can be estimated as  $q = \rho gh$ , where  $\rho$ ,  $g$ ,  $h$  is the density, specific gravity, depth of soil cover, respectively.

The influence coefficients along the surface crack are determined using the results of FE analysis and listed in Table 3 for the particular crack considered ( $a/c=1$ ,  $t/R=1$ ).

SIFs for corroded pipe subjected to crack ('crack in corrosion defect') are also calculated and are presented in Figure 19. In this study, a total 5 mm defect depth is considered by assigning 3.3 mm of corrosion depth and 1.7 mm of crack depth. SIFs in Figure 19 are similar to those obtained for the crack only defect (presented in Figure 18). SIFs for internal pressure calculated using the equation of Raju and Newman (1982) with the crack depth as 5 mm (total of the corrosion and crack depths) is included in Figure 19. The equation with  $a$  total depth of defect can therefore, be used to calculate the SIFs for 'crack in corrosion defect' using the simplified equations.

Table 3. Influence coefficient for external surface crack ( $t/R=1$ )

$a/c$	parametric angle ( $\phi$ )	Springline influence coefficient, $F_s$	Crown or Invert influence coefficient, $F_s$
0	0	135.783	- 168.209
	$\pi/8$	115.350	- 120.583
1	$\pi/4$	97.711	- 83.598
	$3\pi/8$	82.078	- 62.318
	$\pi/2$	76.120	- 55.732

Figure 20 compares the SIFs for 'crack only defect' and 'crack in corrosion defect' obtained from FE analysis. The calculated SIFs for the 'crack only defect' and the 'crack in corrosion defect' are almost same in the figure. This reveals that the solution developed for crack only defect (presented in Table 3) can be used for 'crack in corrosion defect' using total depth of defect as the crack depth.

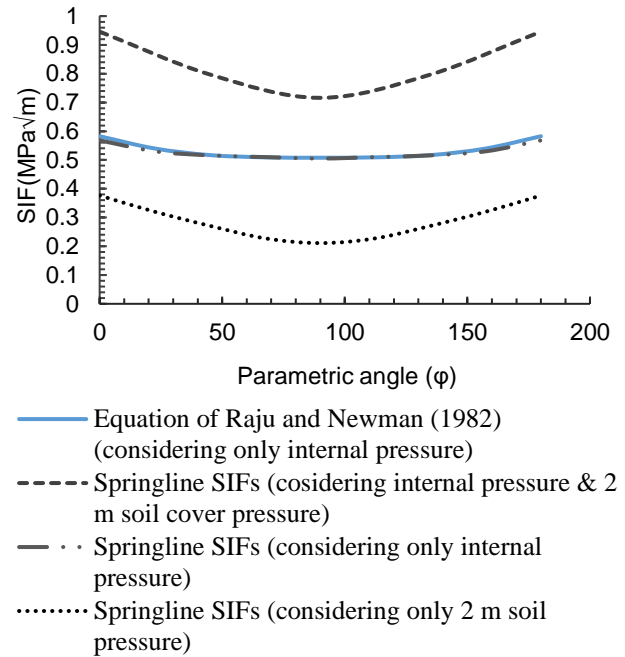


Figure 19. SIF for 'crack in corrosion defect' for a springline crack

#### 4 CONCLUSIONS

In this study, FEA is used to investigate SIFs for a buried pipeline subjected to wall crack and 'crack in corrosion defects'. The analysis is performed using the contour integral method available in Abaqus FE software. Major numerical issues for the application of the contour integral method in calculating SIFs includes assignment of crack location, defining crack propagation direction and the computational requirements to deal with fine mesh requirements. XFEM analysis is performed to identify the crack location to assign during the analysis for calculation of SIFs. A sub-model technique is used to deal with the computational requirement to use fine mesh in a smaller region around the crack. The key finding from this study is presented below:

- The proposed FE modelling technique can be used to calculate SIF for buried pipeline. However, for properly calculating SIFs, one should be careful in assigning crack propagation direction which must be perpendicular to the crack face. The FE analysis with C3D8R elements successfully simulated the SIFs obtained from the equation of Raju and Newman (1982) for the in-air pipe.
- The SIFs due to internal pressure is not affected by the surrounding soil and therefore can be calculated using the equation of Raju and Newman (1982).
- A new equation is developed for calculating the SIFs due to the effect of surface load, which can be added

to the SIFs due to the internal pressure to calculate the total SIFs.

- For the pipe with 'crack in corrosion defect', the simplified equation for SIFs can be used using the total depth of the defect (including corrosion depth and crack depth) in the equation.

The study shows that for properly calculating SIFs, one should be careful in assigning crack propagation direction which must be perpendicular to the crack face. The FE analysis with C3D8R elements successfully simulated the SIFs obtained from the equation of Raju and Newman (1982) for in-air pipe. The FE analysis is then performed for buried pipe. The study reveals that the SIFs due to internal pressure is not affected by the surrounding soil and therefore can be calculated using the equation of Raju and Newman (1982). A new equation is developed for calculating the SIFs due to the effect of surface load, which can be added to the SIFs due to the internal pressure to calculate the total SIFs. For the pipe with 'crack in corrosion defect', the simplified equation for SIFs can be used using the total depth of the defect (including corrosion depth and crack depth) in the equation.

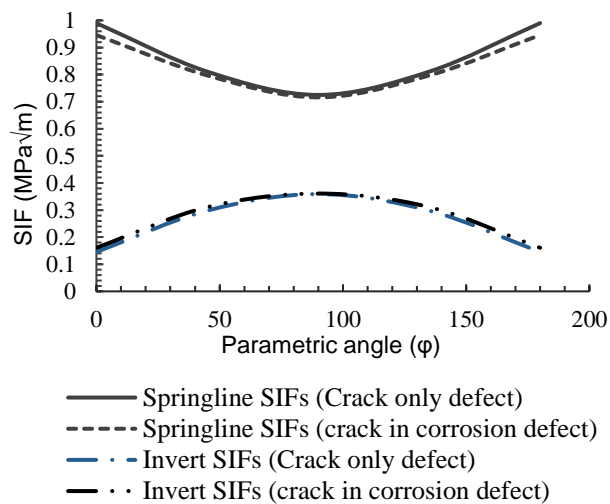


Figure 20. Comparison of 'crack only defect' and 'crack in corrosion defect'

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## 6 REFERENCES

Dassault Systemes. (2014). ABAQUS/CAE user's guide. Dassault Systemes Simulia Corp. Providence, RI, USA.

Debnath, S. (2019). Failure Assessment of Cast Iron Water Mains Using Fracture Mechanics. M. Eng.

Thesis, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, NL.

Diamantoudis, A.T. & Labeas, G.N. (2005). "Stress intensity factors of semi-elliptical surface cracks in pressure vessels by global-local finite element methodology." *Engineering Fracture Mechanics*, vol. 72, no. 9, pp. 1299-312.

Fisher-Cripps, C.A. (2007). "Introduction to Contact Mechanics", 2<sup>nd</sup> Ed., New South Wales, Australia.

Ichsan S.P. (1994). "Fatigue crack growth predictions of surface cracks under constant amplitude and variable amplitude loading". Faculty of Aerospace Engineering. Delft University of Technology.

Folkman, S. (2018) "Water Main Break Rates in the USA and Canada: A Comprehensive Study". *Mechanical and Aerospace Engineering Faculty Publications*. Paper 174.

Li, C.Q., & Yang, S.T. (2012). "Stress intensity factors for high aspect ratio semi-elliptical internal surface cracks in pipes". *International Journal of Pressure Vessels and Piping*, vol. 96–97, pp. 13-23.

Li, C.Q., Fu, G., & Yang, W. (2016a). "Stress intensity factors for inclined external surface cracks in pressurised pipes". *Engineering Fracture Mechanics*, 165, 72–86. doi:10.1016/j.engfracmech.2016.08.014

Li, Y., Hasegawa, K., & Udagawa, M. (2016b). "Development of Stress Intensity Factors for Cracks with Large Aspect Ratios in Pipes and Plates". *Journal of Pressure Vessel Technology*, 139(2), 021202.

Lin, X.B. and Smith, R.A. (1998). "Fatigue growth prediction of internal surface cracks in pressure vessels." *Journal of Pressure Vessel Technology-Transactions of the ASME*, Vol. 120, pp. 17–23, 1998

Mohebbi, H., & Li, C. Q. (2011). "Experimental Investigation on Corrosion of Cast Iron Pipes". *International Journal of Corrosion*, 2011, 1–17. doi:10.1155/2011/506501

Moullick, S.K. & Sahu, Y.K. (2012). "Stress Intensity Factor for Cracks in Thick Pressure Vessels using Weight Function Technique". *National Conference on Innovative Paradigms in Engineering and Technology (NCIPET 2012)*

Predan, J., Močilnik, V., & Gubeljak, N. (2013). "Stress intensity factors for circumferential semi-elliptical surface cracks in a hollow cylinder subjected to pure torsion". *Engineering Fracture Mechanics*, vol. 105, pp. 152-68.

Raju, I. S., & Newman, J. C. (1982). "Stress-Intensity Factors for Internal and External Surface Cracks in Cylindrical Vessels". *Journal of Pressure Vessel Technology*, 104(4), 293. doi:10.1115/1.3264220

Randeniya, C., Robert, D., Fu, G., and Li, C. (2016). "The effect of corrosion patch geometry on stress intensity factors for external surface cracks in cast iron water mains". *Proceedings of the 4th International Conference on Sustainable Construction Materials and Technologies (SCMT4)*, Nevada, United States, 7-11 August 2016, pp. 1673-1680.