Finite Element Analyses of Buried Pipeline Subjected to Live Load Using ABAQUS

Ahdyeh Mosadegh and Hamid Nikraz
Curtin University, Perth, Western Australia, Australia

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
This paper shows the methodology used for modelling the behaviour of a buried pipeline subjected to traffic load using the finite element method (FEM). Soil behaviour is represented by the elasto-plastic Drucker-Prager model and the pipe material is assumed to be isotropic and linear elastic using FEM software ABAQUS 6.13. For the whole system, the effect of surface pressure (magnitude of 200 and 550 kPa) on pipe-soil displacement and stress distribution is investigated at different pipe burial depths of 1–5 times the pipe diameter. In addition, the influence of pipe-soil interaction properties, boundary conditions at pipeline ends, pipe material properties and internal pressure are taken into consideration. For all cases, the results are compared with predictions obtained through numerical and experimental research, which shows satisfactory agreement with results from the literature.

RÉSUMÉ
Cet article montre la méthodologie utilisée pour modéliser le comportement d'un pipeline enfoui soumis à une charge de trafic en utilisant la méthode des éléments finis (MÉF). Le comportement du sol est représenté par le modèle élastoplastique de Drucker-Prager et le matériau du tuyau est censé être isotrope, élastique, et linéaire en utilisant le logiciel ABAQUS 6.13 de FÉM. Pour l'ensemble du système, l'effet de l'amplitude de la pression de surface (magnitude de 200 et 550 kPa) sur le déplacement tuyau-sol et sur la distribution des contraintes est étudié à différentes profondeurs d'enfouissement de 1-5 fois le diamètre du tuyau. De plus, les influences des propriétés d'interaction tuyau-sol, des conditions aux limites aux extrémités des pipelines, des propriétés du matériau du tuyau, et de la pression interne sont prises en considération. Pour tous les cas, les résultats obtenus ont été comparés avec ceux des prédictions obtenues par la recherche numérique et expérimentale, ce qui montre un accord satisfaisant avec les résultats de la littérature.

1. INTRODUCTION

Pipelines are essential infrastructure for providing water and gas to urban areas. They are typically buried in onshore and offshore applications for protection. In many cases, pipelines are buried in shallow foundations under highways or railways. Any damage due to traffic load, ground movement or any other reason can cause failure in the pipeline or malfunctioning of the system.

In recent decades, many numerical and experimental studies have investigated the response of buried pipes subjected to different conditions focusing on pipe-soil interaction. In the 1970s, pipe-soil interaction analysis received attention from many researchers. For numerical studies, the American Concrete Pipe Association made a serious study of buried concrete pipe behaviour using a finite element method (FEM) computer programme. The use of FEM to simulate problems was introduced by Culvert in 1976, and in 1984 ASCE introduced the Winkler model, an elasto-plastic soil spring model based on the model developed by Audibert (Audibert and Nyman 1977). Since then, many numerical and experimental analyses have been performed to investigate buried pipe response under various conditions such as moisture change, cyclic load, installation procedure effects and so on (Abo-Elnor et al. 2004; Calvetti et al. 2004; Chatterjee et al. 2013; Farhadi Hikooei 2013; Kang et al. 2008; Liu et al. 2010; Rajeev and Kodikara 2011; Trautmann 1985; Zaman M M et al. 1984). Various numerical and experimental researches have investigated the effect of various parameters on pipeline behaviour using different approaches. In a numerical study the effect of interaction properties, backfill geometry and material properties on pipe-soil interaction was investigated using the FEM software ABAQUS (Kararam 2006). It was found that increasing the friction coefficient leads to a reduction in pipe deflection and the effect of bedding material is more significant than the effect of bedding thickness on induced stress. In another study, the behaviour of an HDPE pipe buried in a sandy soil under cyclic load was analysed through an experimental approach (Tafreshi and Khalaj 2011). A formulation was developed to calculate soil surface settlement and pipe crown displacement based on soil density, burial depth variation and stress. It was found that burial depth, amplitude of surface pressure and soil density dramatically affects pipe behaviour. The results from this research showed that increasing the burial depth leads to an increase in soil settlement and a decrease in pipe displacement. Also increasing the burial depth leads to a considerable reduction in the rate of pipe displacement conducted another investigation in which a steel pipe was subjected to a repeated load up to 100 kPa(Mir Mohammad Hosseini and Moghaddas Tafreshi 2002). It was found that pipe embedment depth and soil density were the most significant parameters, amongst others. Another study considered the effect of various conditions on pipe-soil interaction subjected to a surface surcharge load. Soil and pipe were modelled as a continuous area with two different nodes and their interaction modelled as a surface to node. The researchers found that the impact of bedding stiffness and compaction levels on the induced stresses were more important than the effect of bedding thickness (Abolmaali and Kararam 2010). In another research carried out using Plaxis, the effect of different parameters including pipe burial depth, surface pressure, internal pressure, pipe diameter and thickness were taken into consideration (Shaalan 2014).

The objective of this paper is to determine the performance of a buried pipeline subjected to traffic load, taking into consideration the effect of internal pressure. The computations are done using the commercial finite element software ABAQUS, version 6.13 (ABAQUS-6.13 2013). For the whole system, the study investigates the effect of pressure magnitude of 200 and 550 kPa at different pipe burial depths, varying between 1, 1.5, 2, 2.5, 3.5 and 5 times the pipe diameter, on pipe-soil interaction, on soil surface settlement and on stress distribution. In addition to this, the effect of pipe-soil interaction properties, pipe material, boundary conditions at the pipeline ends and the internal pressure of different fluids are investigated. All results will be presented in the following sections and verified against predictions published in the existing literature.

2. MODEL DESCRIPTION

The following section presents the definition of the problem, as shown in Figure 1. Due to the long length of the pipe compared to its width, the problem can be modelled assuming plane strain conditions. The size of the model should be sufficient to keep the boundary conditions from affecting the soil movements due to traffic loading. It should be noted that in this study, the X-Y plane is the area in which the soil is subjected to various loads, e.g. positive direction for Y is opposite direction of the weight. For boundary conditions, as shown in Figure 1, both vertical sides of the model are fixed in a horizontal direction with vertical displacement, and the bottom of the model is fixed in both vertical and horizontal directions. In all models, the mesh has been refined in areas with stress concentration around the pipe. Pipe and soil elements were modelled as CPE4R or 4-node bilinear plane strain quadrilateral, with reduced integration. To calculate thickness of pipe, based on the hoop stress formula for a pipe with an internal pressure of σ_p, with a tensile pressure of P and an outside diameter of D_0, a minimum thickness of $t_0=PD_0/2\sigma_p$ is required (Whidden 2009). For this study the internal pressure of water and gas have been applied on the steel pipeline wall with the internal pressure of 414 and 7500 kPa, respectively. The pipe has the yield stress of 490 MPa and tensile strength of 690-840 MPa. This means that widely used steel pipe of 1 m diameter with the thickness of 5 cm is satisfactory for this study. The width of the trench should not be less than the greater of 1.5 times of the pipe outside diameter (1 m) plus 305 mm or the pipe outside diameter plus 406 mm (AASHTO 1998). The chosen trench width is therefore 2 m with material properties being a well-graded or gravelly sand with a 90% compaction (SW90) based on ASTM recommendations (ASCE 2001). To predict live load effects on pipe-soil behaviour, the best constitutive soil model is elasto-plastic. In this study, the soil is modelled as an isotropic elasto-plastic material satisfying the Drucker-Prager failure criterion. Since the pipe is stiffer than its surrounding soil, the plastic behaviour of the pipe is not investigated here and the pipe is classified as linear elastic. Two types of pipe are selected due to investigate the impact of pipe properties on pipe-soil behaviour: steel pipe and high density polyethylene, referred to hereafter as HDPE. Soil and pipe properties are illustrated in Table 1. The properties of the soil, steel pipe and HDPE pipe are adapted from (NCHRP 2009; Tafreshi and Khalaj 2011)

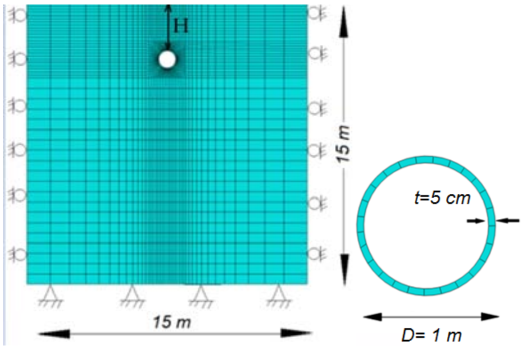


Figure1. Finite element discretization and boundary condition selection of the model

Table 1 Material property of sandy soil and pipes

Type of soil	Term	Value
Trench Soil	Density, ϒ (kg/m³)	1920
	Young's Modulus, E' (MPa)	18
	Poisson's Ratio, ϑ	0.3
	Cohesive strength, d′ (kPa)	<1
	Friction angle, β′ (plane strain), (deg)	48.5°
	Dilation angle, ψ (deg)	12°
	Flow stress ratio, K	1

Parameters	Steel pipe	HDPE pipe
Density, ϒ (kg/m³)	7850	955
Young's Modulus, E (GPa)	200	0.816
Poisson's Ratio, ϑ	0.3	0.46

From the different contact models in ABAQUS, surface-to-surface interaction is chosen to model the interaction of soil and pipe as two deformable parts. It is worth noting that the interaction between pipe and soil has two components, of which one is perpendicular to the surface and the other is tangential to the surface. The friction coefficient between the pipe and soil is assumed to vary from 0.1 to 1. It should be noted that for this case or for tangential contact, separation is allowed after contact and slipping is allowed during analysis. Hard contact is chosen for the normal direction, means there is pressure just only when there is contact. To define the interaction in ABAQUS, the pipe element is chosen as the master surface with a stiffer body, and the soil as a slave surface with more refined meshes (King and Richards 2013). The model is created in four steps. In the first step, which is the initial condition, all boundary conditions are defined as described previously. In the next step, a geostatic step a gravity load is applied to the model. In the third step, pipe and pipe-soil interaction are activated and the pipe weight is applied to the model. Pipe elements are reactivated during this step allowing movement in a vertical direction. In the last step, traffic load is applied to the soil surface at the trench width, exactly on top of the pipe. In addition, when considering the effect of internal pressure, fluid pressure is applied to the pipe's internal walls. It should be noted it is assumed that relative movement between the soil and pipe is impossible.

3. RESULTS AND DISCUSSION

The following sections present the results of numerical analysis along with discussions highlighting the effect of different factors on buried pipeline behaviour. Pipe behaviour and deformation depend on the geometry and properties of the surrounding soil, pipe properties, pipe-soil interaction and pressure values. In this study, the effect of some of parameters, which are summarised in Table 2, on pipe-soil behaviour will be investigated. It is noted that pipe diameter, trench width and properties remain unchanged.

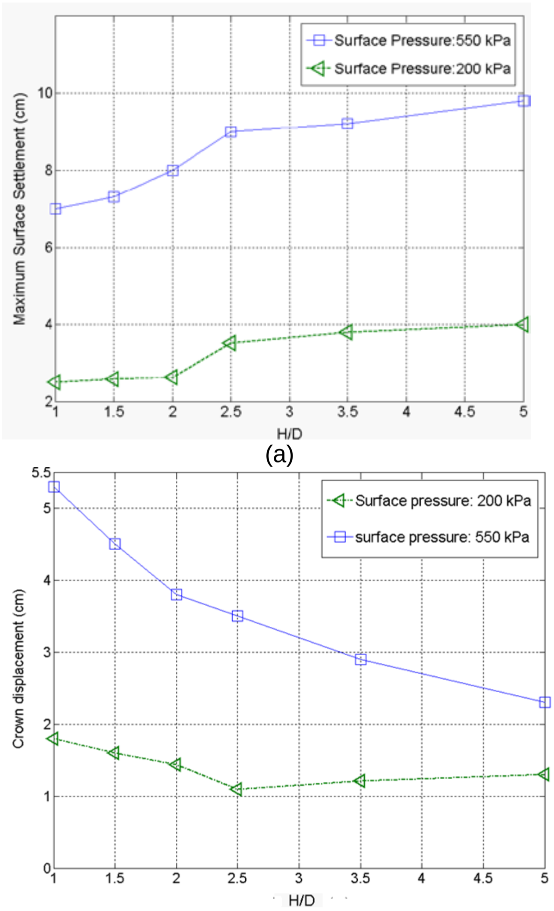
Table 2 Scheme of different cases for buried pipe behaviour investigation

$\frac{H}{D}$	Surface load (kPa)	Pipe type	Internal Pressure (kPa)			Interaction (friction coefficient)	Boundary condition
			Without fluid	Water	Gas		
1 1.5 2 2.5 3.5 5	200 550	Steel HDPE	---	414	7500	0.1 0.3 0.5 0.7 0.9 1	Hinged **Roller**

$\frac{H}{D}$ = embedded depth of pipe (the ratio of soil cover height; H to pipe diameter; D)

3.1 Effect of Burial Depth and Surface Pressure on Displacement at Soil Surface and Pipe Crown

Figures 2(a) and 2(b) show the displacement on the soil surface and at the pipe crown versus the burial depth of a pipeline subjected to pressure of 200 and 550 kPa to simulate a variety of vehicles (Huang 1993). Figure 2(a) describes the vertical displacement at the soil surface for six different burial depths $1 \le H/D \le 5$ under a surface pressure of 200 and 550 kPa. The reason of selecting 550 kPa surface pressure is described in section 3.2. It can be seen that under a surface pressure of 200 kPa, at H/D=1, the soil surface displacement is about 2 cm and with an increase in H/D from 1 to 5, the soil surface displacement increases to 4 cm. For a surface pressure of 550 kPa, with increasing depth of embedment from 1 to 5, the soil surface settlement increases from 7 to 10 cm. It should be noted that both graphs display the same pattern and the gap between these graphs is almost consistent. Displacement rate varies significantly on the soil surface for shallower burial depths compared to deeper burial depths. Overall, for a burial depth of H/D=1, surface displacement is at its minimum, and increasing the H/D leads to greater displacement at the soil surface.



(a)

(b)

Figure2. Vertical displacement as a function of depth and surface pressure (a) on soil surface (b) on pipe crown

Figure 2(b) illustrates the crown displacement of the pipe at six different burial depths under surface pressures of 200 and 550 kPa. It can be seen that the crown displacement of a steel pipe is a function of burial depth and surface pressure, and it is more sensitive to surface pressure variation rather than burial depth changes. Under a surface pressure of 200 kPa with a burial depth increasing from H/D=1 to H/D=5, the pipe crown displacement decreases from 2 cm to 1 cm. For a surface pressure of 550 kPa, crown displacement is 5.5 cm at H/D=1 and with a burial depth increasing to H/D=5, crown displacement goes down to 2.5. In addition, the gap between the two graphs is more significant at shallower depths and this gap tends to become narrower with an increasing H/D. In other words, surface pressure value tends to have less effect on pipe displacement at deeper embedment depths.

Another study analysed the behaviour of a buried pipe under cyclic load through an experimental approach (Tafreshi and Khalaj 2011). The result of this research shows that increasing burial depth leads to increased settlement on the soil surface and decreased crown displacement. It was found as well that increasing the surface pressure leads to more displacement in both the soil surface and pipe crown. The results found in the abovementioned research were in good agreement with the results of the current research.

3.2 Effect of Burial Depth on Vartical Stress Variations on Pipe Crown

This section presents how to analyse the stress distribution transmitted to a shallow buried pipe. In the early 1900s, Anson Marston developed a method of calculating earth load on a buried pipe subjected to a service load. The Marston load theory, serves to predict the supporting strength of pipe in which vertical load transmitted to the pipe is the sum of the dead load due to the weight of the soil cover on top of the pipe(Moser 1990). Then, Boussinesq and Newmark introduced pyramid/cone method to calculate the the pressure on a buried pipe in a semi-infinite elastic medium due to concentrated load at soil surface as shown in "Eq.1"

$$P_{total} = P_d + P_l = YH + \frac{W}{(B+H)(L+H)} \quad [1]$$

Where P_{total} is the sum of the dead load pressure and live load pressure as shown in Figure 3.a. Dead load pressure, P_d, is a function of the density of the soil and H or soil depth. Live load pressure or P_l is a function of W representing wheel load, H representing soil depth cover and B & L a rectangular area as the tyre print (Moser 2001). A standard HS-20 truck is assumed to apply a uniform contact pressure of 750 kPa on the road surface to simulate a highway load of a 20-ton truck (Austroads 2012). If a 5 cm layer of asphalt was taken into consideration, the maximum applied stress on the soil surface would be reduced to 550 kPa. W in "Eq.1" is a concentrated load due to soil surface pressure of 550 kPa over the length of B=60 cm considering each wheel has imprint length of 50 cm or 20 inch (AASHTO 1998). A comparison of two methods, the empirical and FEM solution is presented in Figure 3.b. In both methods, the pressure on the pipe crown is calculated for different burial depths under a pressure of 550 kPa at soil surface over the area located exactly on top of pipe. In addition, truck travel is transverse to the centreline of the pipe.

It can be seen in Figure 3.b that the pressure values on pipeline obtained by FEM and through the empirical method show almost the same pattern. In the empirical method, increasing the H/D from 1 to 2.5 causes the stresses on the pipe to drop dramatically from 210 kPa to less than 100 kPa. When the H/D increases from 2.5 to 3.5 the graph remains almost steady at 88 kPa, and increasing the H/D to 5 causes a slight increase in the stress value up to 105 kPa. In the FEM method, increasing the embedment depth from 1 to 3.5 causes the stress on the pipe to fall from 260 kPa to less than 80 kPa. After this point the graph begins to rise reaching 90 kPa at H/D=5. Overall, the stress on the pipe is higher using the FEM method for shallower depths, compared to the empirical solution in shallower depths. It is worth noting that the stress on the pipe is at its maximum when the burial depth is at its minimum. This difference can be due to the different assumptions made in the two methods. For example, in the empirical method or Boussinesq solution soil is supposed to be elastic while in the FEM method, soil shows elasto-plastic behaviour. In addition, the effect of lateral earth pressure is not considered in the empirical method, while in nature and in the FEM solution, soil is not classified as an isotropic and homogenous material. It is noted that a lateral pressure coefficient of K_0 is calculated based on Jaky's formula in which K_0=1-sinΦ for the sand and is chosen as 0.4. (Jaky. J 1944)

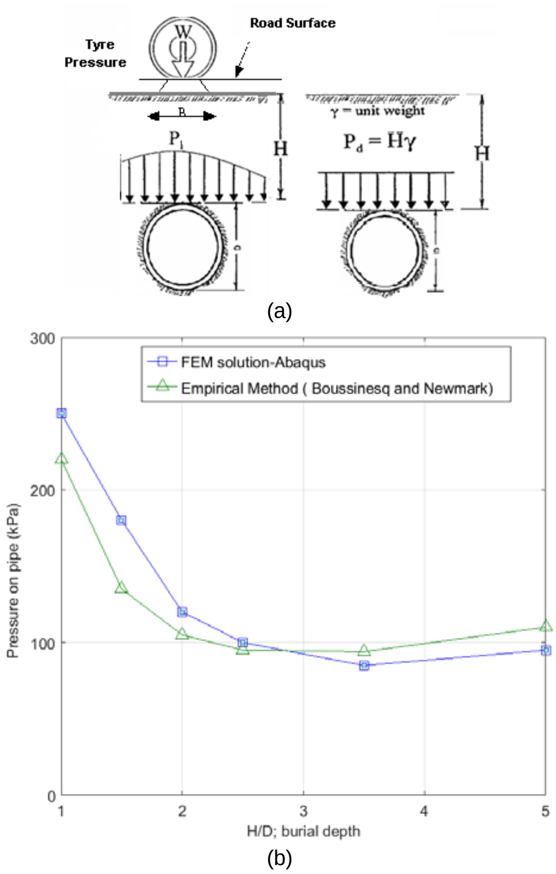


Figure3. (a) Graphic of pipe and soil subjected to live and dead load (b) Pressure on the pipe crown at various burial depths

3.3 Effect of Internal Pressure on Steel Pipe

This section investigates the performance of buried pipelines subjected to a surface load with regard to the internal pressure effect. The influence of internal fluid pressure is investigated under a surface pressure of 550 kPa at two different burial depths of H/D=1, 2.5. It is assumed that the fluids in the pipe are water and gas, which induce internal pressures of 414 and 7500 kPa, respectively. Figure 4 illustrates the effect of liquid pressure on pipe displacement for two burial depths of 1 and 2.5. For H/D=1 when there is no fluid pipe crown displacement is 5.3, and with the application of water pressure, the crown displacement drops to 5 cm as shown in Figure 4. However, applying higher pressure leads to a lower crown displacement for both burial depths although this change is negligible. Figure 5 illustrates the effect of internal pressure on the maximum stress on a pipe wall for two burial depths of H/D=1 and 2.5. It can be seen that applying internal pressure causes an increase in the maximum stress value. The higher the internal pressure is, the greater is the stress on the pipe. It should be emphasised that stress on pipe for high pressure liquids or gas is highly affected by the burial depth.

In another study, the effect of three fluid pressures on steel pipeline was investigated (Shaalan 2014) using PLAXIS 2D program software. It was concluded that increasing the internal pressure leads to a decrease in pipe crown displacement for shallower burial depths ≤3H/D although this decrease is not remarkable. This shows a good agreement between the two studies.

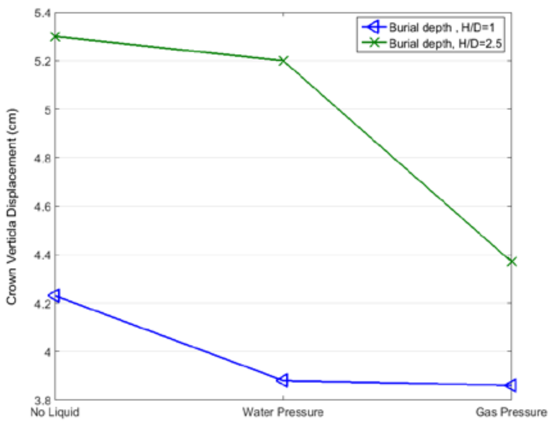


Figure4. Effect of internal pressure on vertical crown displacement-steel pipe

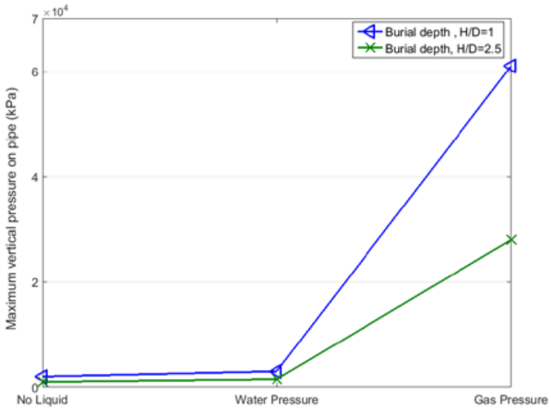


Figure5. Effect of internal pressure on the maximum stress - steel pipe

3.4 Pipe Material Properties Effect

This section investigates the effect of pipe material properties on crown deflection by considering two types of pipe, HDPE and steel, whose properties are based on those listed in Table 1. The effect of interaction property is not taken into consideration for this analysis and it is supposed that the contact pairs are a tied surface to surface. Figure 6 shows the ring deflection of the pipe represented as a function of E. Ring deflection is a function of different parameters including pipe stiffness, geometry and soil parameters(Whidden 2009). In this case, as the properties and geometry of the pipe and the soil properties remain unchanging, deflection is only a function of the ratio of E/E' in which the E of steel is almost 250 times greater than the E' of HDPE pipe. In addition, the results presented are for the case in which surface pressure is 550 KPa and H/D=2.5.

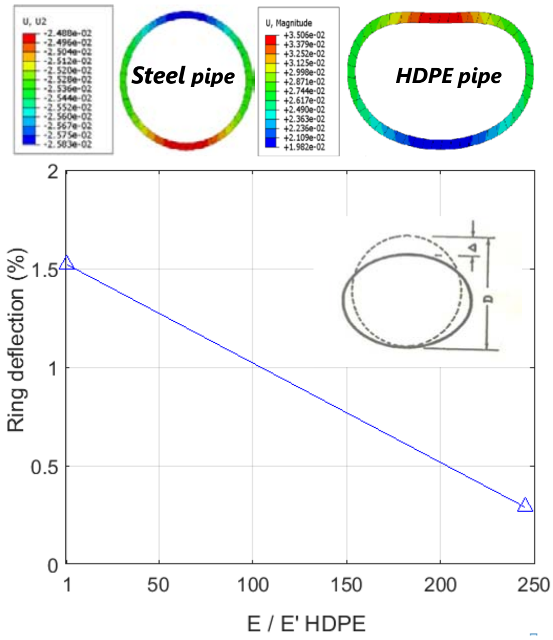


Figure6. Ring deflections of HDPE and steel pipe as function of E

It is clear that the ring deflection,*d*, plunged from 1.5% for HDPE to 0.2% for steel. Looking closely at the figure reveals that for the steel pipe, the crown and bottom have almost the same value of displacement, while for the HDPE pipe these values are different. For example, the bottom of the HDPE pipe has a displacement of 2 cm while its crown has a displacement of 3.56 cm; this difference leads to a higher value of ring deflection for the HDPE pipe.

3.5. Effect of Friction on Pipe-Soil Interaction

In ABAQUS, the interface can be used to simulate the interaction between the steel pipe and its surrounding soil using surface-to-surface contact. As the pipe is stiffer, it is simulated as a master surface and its surrounding soil as a slave surface, based on the FEM recommendation. To avoid convergence difficulties, an unsymmetric solver matrix is used to solve the problem, and to avoid the penetration of the master surface nodes into the slave surface, the master surface mesh is refined. It is noted that in previous sections, it was assumed that pipe was full-bonded to the soil or the interaction between pipe and soil was tied. However, in this section the interaction properties of the model are created by defining both tangential and normal behaviour. To assess the effect of the friction coefficient on pipe-soil behaviour, different friction coefficient values were selected, varying from 0.1 to 0.9 and value of 1 is presenting full-bonded situation.The effects of the friction coefficient on the displacement of steel pipe at a depth of H/D=1 and under a surface pressure of 550 kPa are investigated and results are shown in Figure 7.

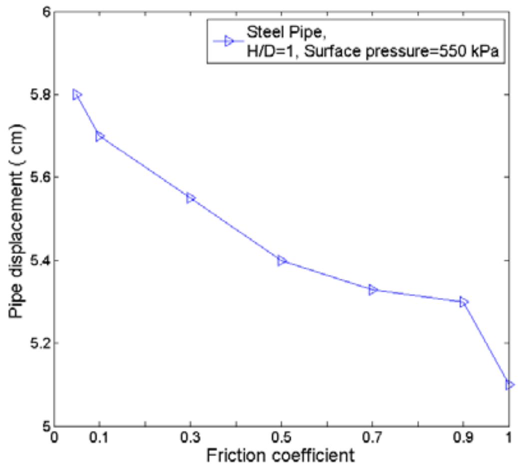


Figure7. Effect of friction coefficient on pipe-soil displacement at pipe crown

It can be seen that friction coefficient variation has a small effect on pipe displacement. Pipe displacement under a surface pressure of 550 kPa drops from 5.8 cm for friction coefiicient of 0.1 to 5.1cm for a full-bondad case. In another study the effect of interaction on deflection of a concrete pipe was investigated using ABAQUS(Kararam 2010). It is shown in that study that increasing friction coefficient from 0.1 to 0.9 leads to decrease in pipe deflection although this decrease is too small changing which is in a good agreement with results of current study.

To compare the effect of interface conditions along pipe boundaris, the influence of the friction coefficient of 0.5 are compared with those for full-bonded conditions and results are presented in Figures 8 and 9. In Figure 8 the effect of two interface conditions on pipe displacement under a surface pressure of 550 kPa for two burial depths of H/D=1 and 3.5 are illustrated. As is illustrated by the graph, for H/D=1 and friction coefficient of 0.5 pipe displacements drops from 5.5 cm to 3.0 cm when angel is increasing. Similarly for a full-bonded case, pipe displacement drops from 5.1 cm to 4 cm when angel increases from 0^o to 60^o. After this point with inceasing angel from 60^o to $120^{o.}$ pipe displacement remains steady at 4 cm. Then with increasing angel to 180^o pipe displacement declines to 3.0 cm. Almost the same pattern is obtained for deeper burial depth for both interaction conditions . Overall the pipe displacement decrease with increasing angel and the effect of friction coefficient value is higher at pipe crown and with increasing the angle along pipe circumference the gap between two graphs, full-bonded and friction coefficien=0.5, decreases. The effect of interaction properties on stress distribution of pipe as a funtion of angel from crown is illustrated in Figure 9. As can be seen three different sections exist in the graph. Left and right parts for which stress of full-bonded interaction is bigger than those with friction coefficient of 0.5. While in the third or in the middle area full-bonded interaction has a lower stress along pipe. It should be noted at crown and invert interaction propertis almost has no impact on stress. Results presented here had a good agreement with those presented by (Kang 2007)

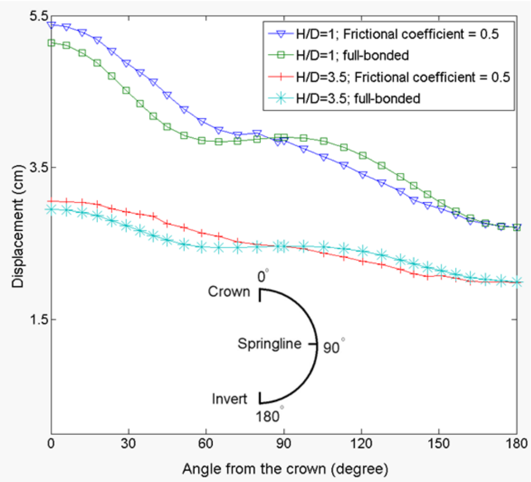


Figure8 Effect of interface conditions on pipe displacement along pipe circumference

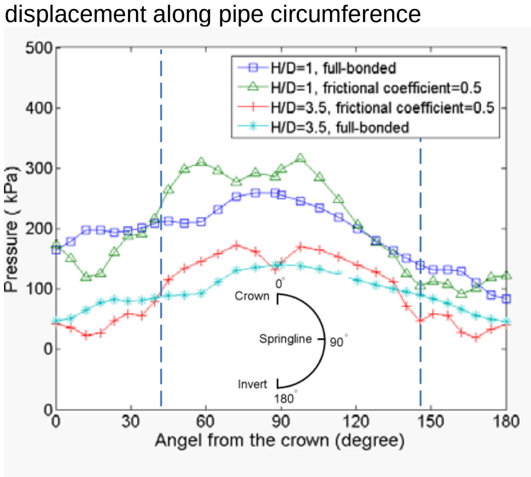


Figure9 Effect of interface conditions on stress distribution along pipe circumference

3.6 Effect of Boundary Conditions

So far, all of the results presented here have been analysed in a 2D plane strain model. Under the plane strain condition, it is assumed that the length of the pipe compared to its width is sufficient. However, boundary conditions can be changed for any infrastructure existing through the pipe length. To compare the effect of boundary conditions, a 3D model is built to analyse how boundary conditions can affect the stress and displacement distribution along the steel pipeline. Two types of boundary conditions at the end of pipeline are selected, roller and hinge representing infinite and finite length of the buried pipeline, respectively. As suggested in many standards for three-dimensional analysis, it is better to model pipe elements as a series of shell elements. Three-dimensional brick elements are used to simulate the surrounding soil (C3D8R) and four-node reduced-integration shell elements (type S4R) are used for the pipe, as shown in Figure 10.

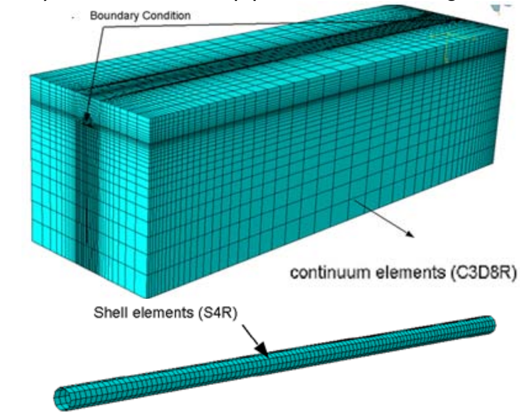
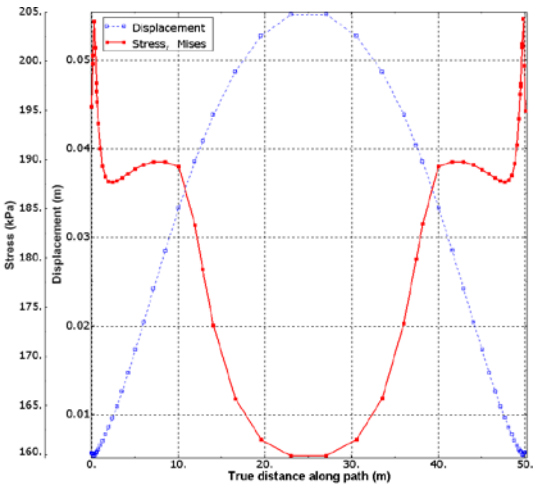
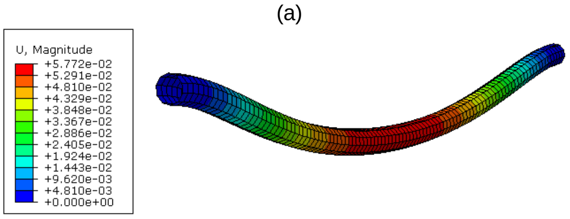


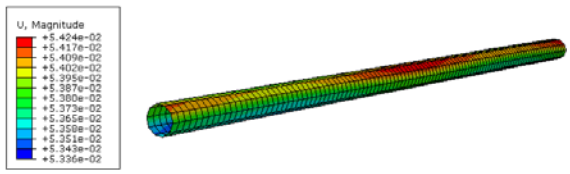
Figure10. Finite element discretization and boundary condition



(a)



(b)



(c)

Figure11. (a) Displacement and stress on the pipe-soil interaction along the whole length of a pipe with a hing boundary at the pipeline ends (b) & (c) Pipeline settlement according to two boundary conditions at pipeline ends hinge boundary and roller boundary.

For the hinge boundary the left and right hand parts of the graph are restricted in movement due to these points while for the roller end there is no restriction in movement. As can be seen from the results in Figure 11(a), moving towards the middle of the pipe, there is a downward deformation of 5 cm which is the maximum in the middle of pipe. At the ends of the pipeline and for hinge boundary condition there is no displacement, while maximum stress occurs at these points as shown in Figure 11 (a). In addition, from the sides of the pipe to the middle, there is a decrease in the stress of the pipe from 204 to 160 kPa, while displacement increases from 0 to 5 cm in the middle. The results of stress and displacement of pipe with a roller boundary is not illustrated in a graph as there is not any significant change of stress and displacement along pipeline path. In Figures 11(b) and 11(c) schematic displacement of pipeline for two boundary conditions are illustrated. As described before for a hinge boundary condition, Figure 11(b), displacement at the pipeline ends is zero and moving toward the middle of pipe this value increase to 5.7 cm. However, as shown in Figure 11 (c) for the roller boundary the displacement along the pipeline varies just between 5.3 and 5.4 cm. It is concluded that analysing pipe soil behaviour using plane strain conditions should be carried out with carefulness. Existing of any infrastructure along the pipeline path can change the boundary conditions from roller to the hinge with restrained ends which cause significant variation of both stress and displacement along the pipeline.

4. SUMMARY AND CONCLUSIONS

In this research, a numerical analysis was carried out to investigate the influence of different parameters on pipe-soil behaviour under live load using the FEM software ABAQUS. The soil model was elasto-plastic and the pipe was elastic linear. The effect of surface pressure of 200 and 550 kPa at different pipe burial depths, H/D= 1, 1.5, 2, 2.5, 3.5 and 5 on settlement and stress distribution at the pipe-soil interaction and soil surface were investigated. In addition, the influence of pipe-soil interaction properties, pipe material, boundary conditions at pipeline ends and internal pressure from different fluids were taken into consideration. All results obtained through this research were verified with predictions published in the existing literature.

The effect of burial depth and surface pressure for different burial depths under a surface pressure of 200 and 550 kPa on soil settlement at the soil surface and on the pipe crown was investigated. It was demonstrated that when H/D is at a minimum, surface displacement is also at a minimum, and an increasing H/D leads to more displacement at the soil surface, especially for H/D<2.5. However, displacement at the crown decreases with increasing H/D. This rate of change for H/D <2.5 is more significant. In other words, live load tends to have less effect on pipe displacement for deeper embedment depths. In addition, pressure on the pipe is at a maximum when H/D is at a minimum showing the impact of live load under shallower deeps. Increasing the H/D leads to a decrease in the stress on the pipe, and for H/D>2.5, increasing the depth does not significantly affect the stress on the pipe. Variations in internal pressure and interaction properties affect pipe displacement, although these changes are not remarkable. Increasing the friction coefficient leads to a decrease in pipe displacement at its crown. Effect of friction coefficient on pipe displacement along pipe circumference is investigated and results shows that moving from crown toward invert of pipe along pipe circumference leads to a lower displacement. Analysing the effect of boundary conditions shows that hinged boundary condition affects stress and displacement distribution along the pipe length, showing that at the ends of the pipeline, when there is no displacement, maximum stress occurs at these points and maximum displacement occurs along pipeline path when the stress is minimum. It is worth noting that one of the limitations in this research was that the pipe installation procedure was not simulated. In addition, it was assumed that the pipe did not deform during construction, and the relative movement of the pipe and soil was not taken into consideration which are recommended to be investigated in future. Considering traffic load as a cyclic load to assess pipe-soil interaction behaviour and degradation effect is another area of interest.

5. REFERENCES

AASHTO. 1998. American Association of State Highway and Transportation Officials (AASHTO). Washington DC USA.

ABAQUS-6.13. 2013. *ABAQUS/CAE User's Manual*. Dassault Systèmes, USA.

Abo-Elnor, M., Hamilton, R., and Boyle, J.T. 2004. Simulation of soil–blade interaction for sandy soil using advanced 3D finite element analysis. *Soil and Tillage Research* 75(1): 61-73.

Abolmaali, A., and Kararam, A. 2010. Nonlinear Finite-Element-Based Investigation of the Effect of Bedding Thickness on Buried Concrete Pipe. *Journal of Transportation Engineering* 136(9): 793-799.

ASCE. 2001. *Guidelines for the Design of Buried Steel Pipe*. americanlifelinesalliance.

Audibert, J.M.E., and Nyman, K.J. 1977. Soil Restraint against Horizontal Motion of Pipe

1142. ASCE, *Journal of Geotechnical Engineering* Division 103(GT10): 1119-1142.

Austroads. 2012. Part 2: *Pavement Structural Design*. Sydney

Calvetti, F., di Prisco, C., and Nova, R. 2004. Experimental and Numerical Analysis of Soil–Pipe Interaction. *Journal of Geotechnical and Geoenvironmental Engineering* 130(12):

Chatterjee, S., White, D.J., and Randolph, M.F. 2013. Coupled consolidation analysis of pipe–soil interactions. *Canadian Geotechnical Journal* 50(6): 609-619. doi: 10.1139/cgj-2012-0307.

Farhadi Hikooei, B. 2013. Numerical Modeling of Pipe-Soil Interaction under Transverse Direction. *In* DEPARTMENT OF CIVIL ENGINEERING. University of Calgary, Canada. p. 71.

Huang, Y.H. 1993. *Pavement Analysis and Design*. Prentice Hall Inc., Englrwood Cliffs, NJ.

Jaky. J. 1944. The coefficient of earth pressure at rest. Society of Hungarian Architects and Engineers 355-358.

Kang, C.H.Y.J. 2007. Soil-structure Interaction for Deeply Buried Corrugated PVC and Steel Pipes. *In* IR-07-01. *Highway Research Center* , Aubrun University. p. 110.

Kang, J., Parker, F., and Yoo, C.H. 2008. Soil–structure interaction for deeply buried corrugated steel pipes Part I: Embankment installation. *Engineering Structures* 30(2): 384-392.

Kararam, A. 2006. Nonlinear Finite Element-based Investigation Of The Effect Of Bedding Thickness On Underground Pipe. The University of Texas. p. 107.

Kararam, A. 2010. Nonlinear Finite-Element-Based Investigation of the Effect of Bedding Thickness on Buried Concrete Pipe. *Journal of Transportation Engineering* 136(9): 793-799.

King, S., and Richards, T. 2013. Solving Contact Problems with Abaqus.

Liu, P.F., Zheng, J.Y., Zhang, B.J., and Shi, P. 2010. Failure analysis of natural gas buried X65 steel pipeline under deflection load using finite element method. *Materials & Design* 31(3): 1384-1391.

Mir Mohammad Hosseini, S.M., and Moghaddas Tafreshi, S.N. 2002. Soil-Structure Interaction of Embedded Pipes Under Cyclic Loading Conditions. *International Journal of Engineering* 15(2): 117-124.

Moser, A.P. 1990. *Buried Pipe Design*. McGraw-Hill.

Moser, A.P. 2001. *Buried Pipe Design*, 2nd Edition. Mcgraw-hill.

NCHRP. 2009. Investigation of Suitable Soil Constitutive Models for 3-D Finite Element Studies of Live Load Distribution Through Fills Onto Culverts.

Rajeev, P., and Kodikara, J. 2011. Numerical analysis of an experimental pipe buried in swelling soil. Computers and Geotechnics 38(7): 897-904.

Shaalan, H.H. 2014.]parametric study of oil and gas internal pressures in buried pipes. *In* The department of Civil Engineering. ATILIM University, Graduate School Of Natural And Applied Sciences. p. 124.

Tafreshi, S.N.M., and Khalaj, O. 2011. Analysis of repeated-load laboratory tests on buried plastic pipes in sand. *Soil Dynamics and Earthquake Engineering* 31(1): 1–15.

Trautmann, C.a.T.O.R. 1985. Lateral Force-Displacement Response of Buried Pipe. Journal of Geotechnical Engineering 111(9): 1077-1092.

Whidden, W.R. 2009. Buried flexible steel pipe : design and structural analysis /. Reston, VA : *American Society of Civil Engineers*, Reston, VA.

Zaman M M, Desa Ch., and Drumm E.C. 1984. Interface Model for Dynamic Soil-Structure Interaction. *Journal of Geotechnical Engineering* 110: 1257-1273.