MODELLING TIME DEPENDENT BEHAVIOR OF BURIED POLYETHYLENE PIPES USING ABAQUS

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ABSTRACT
Buried polyethylene pipes are increasingly used for their various advantages over the metal pipes including light-weights, ease of installation and corrosion resistance. The polymer pipe material possesses time-dependent behavior that influence the pipe-soil interaction over time. The current industry practice to account for the time-dependent effect is to use secant modulii to calculate the short-term and long-term responses. A short-term and a long-term modulus of the pipe materials are used to calculate the pipe responses independently. This method is unable to predict the continuous time -depended pipe-soil interaction and the resulting pipe responses over time. To address this limitation, researchers are working toward developing time dependent material models for the pipe materials to conduct pipe-soil interaction analysis. A number of different visco-elastic and visco-plastic models were developed for polymer materials over the last few decades. However, these models are not extensively used in soil-pipe interaction analysis since these are not incorporated in commercially available finite element software. In this research, time-dependent modelling approach using the features available in a commercial software, Abaqus, is developed. Strain rate dependent test data from published literature are used to develop the model. The model is incorporated in Abaqus using its USDFLD subroutine and simplified modelling techniques for time-dependent behavior. The proposed model successfully simulates the test results of a pipe material and the behavior of a buried pipe.

RÉSUMÉ
Buried polyéthylène est plus utilisés pour leurs différents avantages sur les tuyaux en métal y compris lumière-poids, facilité d'installation et la corrosion de la résistance. Le matériel de tuyauterie de polymère possède des comportement dépendant du temps qui influent sur l'interaction de la conduite-sol au fil du temps. La pratique actuelle de l'industrie pour tenir compte de l'effet dépendant du temps est d'utiliser la sécante filamentaire pour calculer les réponses à court et à long terme. Un à court terme et un module à long terme des matériaux tuyaux sont utilisés pour calculer les réponses de conduite indépendamment. Cette méthode est incapable d'anticiper la continu temps - interaction dépendait conduite-sol et les réponses de tuyau qui en résulte au fil du temps. Pour combler cette lacune, les chercheurs travaillent à l'élaboration de temps matériel dépendant des modèles pour les matériaux de tuyaux mener l'analyse des interactions conduite-sol. Un certain nombre de modèles différents de visco-élastique et visco-plastique ont été développé pour les matériaux polymères dans les dernières décennies. Cependant, ces modèles.

1 INTRODUCTION

Polyethylene is increasingly used for civil engineering applications including water and gas distribution pipes, drainage and sewer pipes, and geomembranes. Polyethylene pipes possess various advantages over the metal pipes including light-weights, ease of installation and corrosion resistance. However, long term performance of buried polyethylene pipes is not well-known due lack of data available for an understanding of the time-dependent pipe-soil interaction. Polymer material possesses time, temperature and strain rate dependent mechanical behavior. Analysis of buried pipe accounting for the time, temperature and strain rate dependent behavior requires complex algorithms. A simple secant modulus is often used in the analysis of polymer pipes to capture the time dependent effects (Katona 1990, Moser 1997, Suleiman et al. 2003). Existing design codes (i.e., AASHTO 2010) recommend using short-term and long-term values of the modulus of elasticity of pipe material for calculating the short-term and long-term responses, respectively. However, the approach is too simple and is unable to account for the non-linear stress-strain behavior of the material, which is commonly observed for polymer (Zhang and Moore 1997). Another limitation of this approach is the estimation of the short-term and long-term values of the elastic modulus. AASHTO (2010) recommends the short term and long term values of the elastic moduli for High Density Polyethylene (HDPE) pipe material as 758 MPa and 152 MPa, respectively. The basis employed for the estimation of the long-term modulus without specific long-term data requires validation.

Researchers employed a power law relation to account for the reduction of elastic modulus with time for HDPE (Chua and Lytton 1989). This model is applicable for a particular level of strain for which the power law equation is developed. Hashash and Selig (1990) revealed that an explicit time-dependent model would be necessary to successfully characterize the long-term behavior of buried pipe. Moore (1994) developed a linear viscoelastic model for a HDPE pipe material based on conventional rheological parameters, which was found applicable for small deflection problems. Zhang and Moore (1997) then developed nonlinear viscoelastic and viscoplastic models for problems involving large deflections. Several other constitutive models are also developed for polymer materials with a goal to simulate the time-dependent behavior (Chehab and Moore 2007, Suleiman and Coree 2004, Siddiquee and Dhar 2015). However, none of these models are implemented in commercially available finite element (FE) software and therefore not used widely.

The objective of the current study is to employ the features available in commercially available FE software, Abaqus (Dassault Systemes 2014), to simulate the time dependent behavior of buried pipe. The uniaxial compression test data in Zhang and Moore (1997) is used to develop input parameters for the model. The capability of the modelling approach is evaluated through simulation of selected time-dependent stress-strain response reported in Zhang and Moore (1997). The developed model is then used for simulation of a buried pipe problem reported in Dhar and Moore (2000).

2 TIME-DEPENDENT MODELING USING ABAQUS

For investigating the time dependent response of material, tensile and/or compression tests are generally performed with application of different rates of loading. Strain rate dependent stress-strain responses are then used to develop the constitutive model. Strain rate dependent stress-strain data are implemented here using user subroutine, USDFLD, in Abaqus to simulate the time-dependent material behavior. USDFLD allows defining field variables at material points including time and solution dependent material properties. It allows access to material point quantities at the start of the load step and therefore provides explicit solution (Dassault Systemes 2013). A utility routine, GETVRM, is used to access the material point quantities (at the start of the increment). The values of the material point quantities (e.g., strain) are obtained using the appropriate output variable keys (i.e., 'E' for strains). The values of the material point data are recovered using arrays ARRAY, JARRAY, FLGRAY for floating point, integer and character data, respectively. The values can be stored in user–defined state variables (i.e., STATEV) for using in the next increments, which can be recalled using variable key 'SDV' in the utility routine, GETVRM.

In this study, GETVRM is used with output variable "E" to access all strain components. Current strain component, time increment and calculated strain rate are stored in user-defined state variables for using in subsequent time steps. At each time step, the strain rate is calculated based on the current strain (accessed by GETVRM), previous strain (stored in user defined variables) and time increment (accessed by USDFLD). The strain rate is checked with strain rate from last increment (which is stored and accessed by user defined variable) to ensure stable continuous numerical solution.

The strain rate is then assigned to the FIELD variable which is an array containing the field variables at the current material point. ABAQUS interpolates the material parameters based on these FIELD variables from the information in the input file. Strain-rate dependent stress-stress relations are included in the Abaqus input file, which are used for the interpolation.

Strain rate dependent stress-strain relations for HDPE were developed in Zhang and Moore (1997). These stress-strain data are used in Abaqus input file for modelling of time-dependent behavior of buried polyethylene pipes using the feature in Abaqus.

3 FE SIMULATION OF ELEMENT TESTS

Finite element analysis was performed for numerical simulations of the uniaxial compression tests presented in Zhang and Moore (1997). Siddique and Dhar (2015) used the results to validate an isotach based constitutive model developed for HDPE. Zhang and Moore (1997) performed uniaxial compression tests on a HDPE pipe material using cylindrical specimens of 12.7 mm diameter and 25.4 mm height. Tests were conducted under different loading conditions including application of constant strain rates ranging from 10^{-5}/s to 10^{-1}/s. These strain-rate dependent stress-strain relations are used in the input file and were simulated using FE modelling using Abaqus. Same size of the specimen (i.e. 12.7 mm diameter and 25.4m height) is modelled in the FE analysis. Figure 1 shows the FE mesh developed. Both horizontal and vertical boundaries at bottom and left side were modeled as smooth rigid. Top and bottom surfaces of the test specimens were maintained smooth during the tests, Zhang and Moore (1997). At the corner node, the horizontal and vertical translations were restrained. A uniform strain was applied from top of the mesh at the same rate as those applied during the tests.

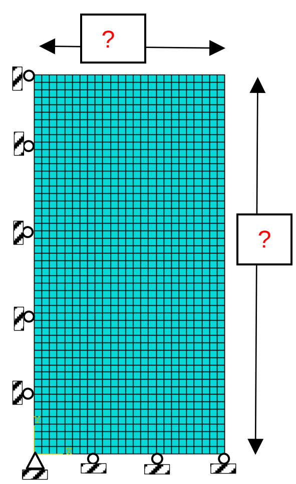

Figure 1. FE model

3.1 Comparison of results

Figure 2 compares the stress-strain relations from the finite element analysis with those obtained from the measurements. The comparison shows a reasonable agreement between the measured response and the finite element simulation. The proposed method is thus capable of simulating the time dependent behavior of the HDPE material while avoiding the need for implementing complex models in FE codes.

This approach was also found to simulate successfully a loading-unloading-reloading response and a jump in the strain rate measured in Zhang and Moore (1997). Figure 3 compares the results of FE simulation with the test results where a test with load-reload cycle was conducted. A uniaxial compression test was conducted with a strain rate of 10^{-3}/sec for loading (and reloading) and 10^{-4}/sec for unloading. In Figure 3, the results of finite element analysis match reasonably with the measured responses.

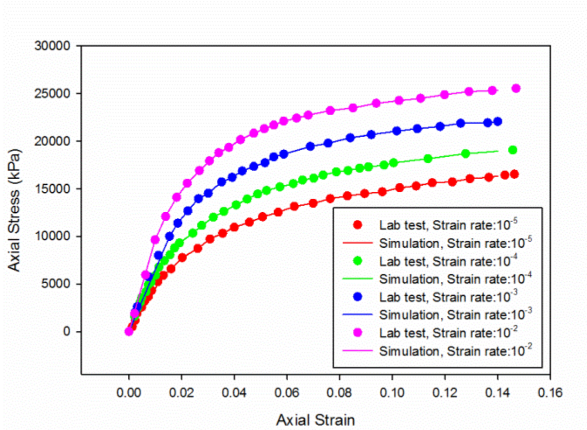

Figure 2. Comparison with stress-strain response

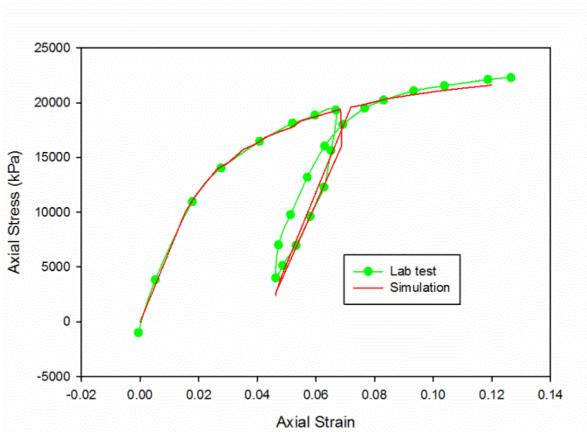

Figure 3. Simulation of loading-unloading-reloading response

The method of analysis was also successful in simulating a jump in the strain rate during the test. Zhang and Moore (1997) performed a test with a change in strain rate from 10^{-3}/s to 10^{-2}/s and then back to 10^{-3}/s. FE analysis using the proposed method is performed to simulate these jumps in the strain rate. Figure 4 compares the result of the FE analysis with the measurements. The comparison shows that the method of analysis successfully captured the observed behavior during the change in strain rate.

4 FE SIMULATION OF BURIED PIPE RESPONSES

The applicability of the modelling approach for simulating the buried pipe response is examined through simulation of test results reported in Dhar and Moore (2000). Dhar and Moore (2000) examined a test conducted on buried HDPE pipe using FE analysis with different material modeling choices including stress dependent response of granular materials, shear failure of the soil surrounding the flexible compressible pipe products, and the materially nonlinear response of the polyethylene. Elastic, visco-elastic and viscoplastic models were employed to characterize the thermoplastic pipe material. In that study, the viscoelastic material model was found to provide the best representation of the mechanical response of the polyethylene. In the current study, FE modelling using Abaqus is performed to simulate the buried pipe responses in the test. The test was conducted on plain HDPE pipe in a biaxial pipe cell (Dhar and Moore 2000). The plain HDPE pipe specimen had 320 mm internal diameter and wall thickness of 15 mm. The cell was devised to model the biaxial field stresses experienced by deeply buried pipes (Moore et al. 1996). The apparatus is a high strength steel box with dimensions 2m×2m in plan and 1.6m in height. The stiff sides of the box restrain lateral soil deformation and axial pipe deformation, and hence, close to plane strain K_o conditions are attained. Pipes tested within the cell were placed horizontally on a bed of soil and backfilled within a rectangular prism of soil. Uniform pressures are applied on the top of the soil using an air bladder placed beneath the stiff lid of the cell. More detail on the test procedure and instrumentation is available in Dhar and Moore (2000).

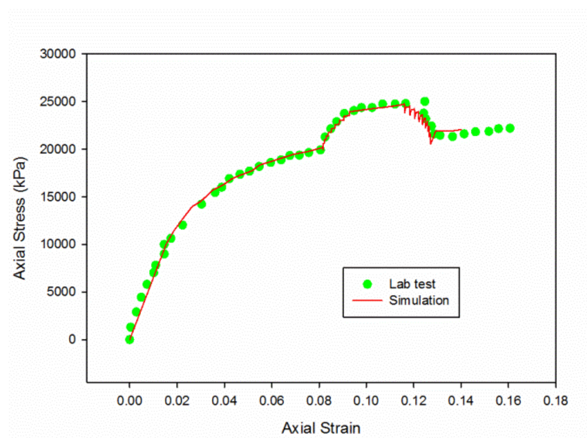

Figure 4. Simulation of a jump in the strain rate

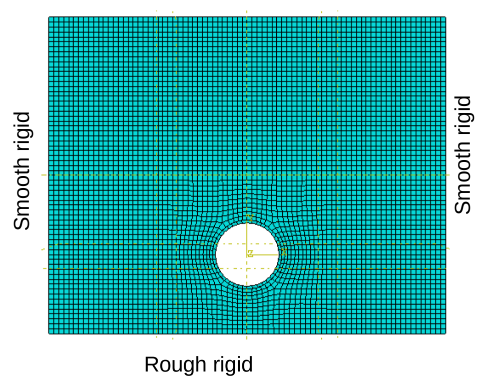

Figure 5: Finite element representation of the test cell

FE model is developed to simulate the pipe and soil conditions in the test cell. A vertical cross-section of the test cell is analyzed as shown in Figure 5. Six noded continuum elements were used for plane strain representation of the pipe and the surrounding backfill. The sidewall treatment was assumed to provide smooth side boundaries. The nodal points along the bottom boundary were fixed in both horizontal and vertical directions.

4.1 Soil Model

Soil parameters used in Dhar and Moore (2000) are employed to represent the soil condition in the test cell. Dhar and Moore (2000) estimated the angle of internal friction for the cohesionless backfill soil based on Selig (1990) as 42°. Poisson ratio was calculated from measured Ko value, where Ko is given by 1-sinø, and $\nu = K/(1+K) = 0.25$. Soil was modelled as elasto-plastic with constant modulus of elasticity estimated from the measured stresses and settlements of the soil in the test cell. Modulus of elasticity of the soil was estimated to be 35 MPa. Although nonlinearity in the stress-strain relation of the soil is often observed (Dancan and Chang 1970), the effect of nonlinearity was insignificant for this particular case (Dhar and Moore 2000). Soil response measured during the test was linear.

4.2 HDPE model

HDPE pipe material is modelled using test data of Zhang and Moore (1997) as discussed above in Section 2. Poisson's ratio of the HDPE is assumed to be 0.46. FE simulation was conducted for the duration of the tests (i.e., 5 hours).

4.3 Comparison of results

Figure 6 plots the calculated and measure pipe deflections against the applied pressures. The results of FE analysis reasonably match with the observed pipe responses in the figure. In Figure 6, FE calculation overestimate the diameter changes of the pipe. Similar observation was reported in the analysis presented in Dhar and Moore (2000). The overestimation of the diameter change was attributed to the modelling of the sidewall as smooth. Although an extensive sidewall treatment was carried out to limit wall friction, the wall still possesses some frictional resistance (Brachman, 1999). In addition, the walls were assumed to be perfectly rigid, which may not be true in reality. Most of the discrepancies for vertical diameter changes occurred in the first 200 kPa of surface loading. This may be the loading required to mobilize shear on the lateral boundaries. The comparison however reveals that FE analysis using the time-depended modelling approach in Abaqus reasonably simulates the response of the buried pipe.

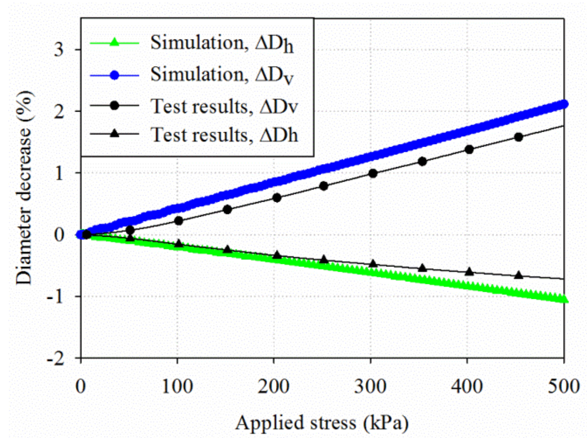

Figure 6. Comparison of pipe deflection

The soil stresses and soil settlements measured during the tests are also compared with the FE simulation. Figure 7 compares the measure horizontal and vertical soil stresses with the FE calculations. Figure 8 compares the measure soil settlements with the FE calculation. The FE calculations match well with the measured soil stresses and soil settlements in the figures.

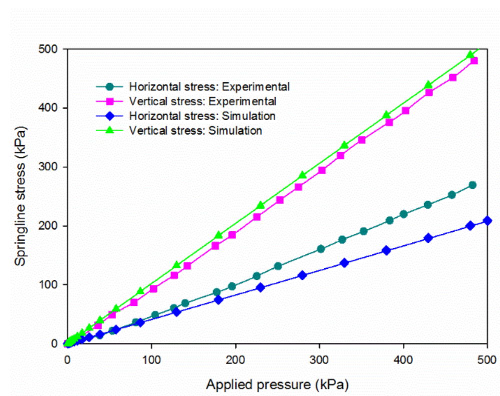

Figure 7. Measured and predicted soil stress

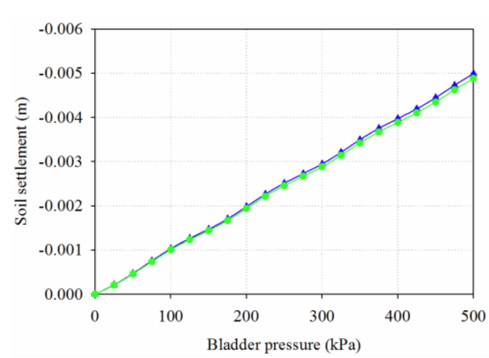

Figure 8. Comparison of soil settlements

5 CONCLUSION

This paper presents a FE modeling approach for simulating the time behavior of a polymer pipe material. The modeling approach employs existing features available in a commercially available FE software, Abaqus, without the development and implementation of complex constitutive model to FE code. The finite element model could successfully simulate the strain-rate dependent stress-strain relations observed in laboratory tests available in published literature. A loading-unloading-reloading response and a jump in the strain rate in the stress-strain response are also successfully simulated. Using the modelling approach, the responses of a buried HDPE pipe are simulated. Finite element calculations pipe deflections and soil responses matched reasonably with the observed responses in a full-scale pipe test, indicating the strength of the proposed modelling for simulation of time-dependent behavior of buried polymer pipes.

6 ACKNOWLEDGEMENT

The financial support of this research was provided by National Science and Engineering Research Council of Canada through its Collaborative Research and Development Grants and FortisBC Energy Inc.

7 REFERENCES

AASHTO (2010) “LRFD Bridge Design Specifications”, 2nd ed., AASHTO, Washington, D.C., 1997.

Brachman, R.W.I. (1999). “Structural performance of leachete collection pipes” Ph.D. Thesis, Department of Civil and Environmental Engineering. University of “Western Ontario. London. Canada.

Chehab, A.G., and Moore, I.D., 2006. Constitutive Model for High Density Polyethylene to Capture strain Reversal, ASCE Pipelines, 2006. 15419.

Chua, K.M. and Lytton, R.L. (1989) “Viscoelastic approach to modeling performance of buried pipes”, Journal of Transportation Engineering, ASCE, Vol. 115, No. 3, pp. 253-269, 1989.

Duncan, J.M and Chang, C.-Y. (1970) “Nonlinear analysis of stress and strain in soils”, J. Soil Mech. Found. Div. 96(5), 1629-1653.

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

Dassault Systemes (2013) Abaqus User Subroutines Reference Guide, Dassault Systemes Simulia Corp. Providence, RI, USA.

Dhar, A.S. and Moore, I.D. (2000) “Non-linear analysis of buried hdpe pipe by the finite element method: comparison with laboratory test”, Proceedings of the International conference of Geotechnical and Geological Engineering (GEOENG2000), Melbourne, Australia, November 19 – 24, 2000.

Hashash, N.M.A. and Selig, E.T. (1990) “Analysis of the performance of a buried High Density Polyethylene pipe”, Structural Performance of Flexible Pipe, Sergand, Mitchell and Hurd edition, Balkema, Rotterdam, pp. 95-102.

Katona M.G. (1990) “Minimum cover height for corrugated plastic pipe under vehicle loading”, Transportation Research Record 1288, 127-135.

Moore, I.D (1994) “Three dimensional time dependent model for buried HDPE pipe”, Computer Methods and Advances in Geomechanics, Siriwardane & Zaman (eds), 8th International Conf. On Computer Methods and Advances in Geomechanics, pp. 1515-1520.

Moore, I.D., Laidlaw, T.C. and Brachman, R.W.I. (1996). “Test cells for static pipe response under deep burial”, 49th Canadian Geotechnical Conference, pp. 738-744.

Moser, A.P. (1997) “Analytical methods for predicting performance of buried flexible pipes”, Pre-print (CD-ROM), Transportation Research Board, Washington, D.C.

Siddique, M.S.A. and Dhar, A.S. (2015) “A Novel Elasto-Viscoplasticmodel of High Density Polyethylene Material”, Geosynthetics International, Vol. 22, No. 2, pp: 173-182.

Suleiman, M.T. and Coree, B.J. (2004) “Constitutive model for high density polyethylene material: systematic approach”, Journal of Material in Civil Engineering, ASCE, Vol. 16, No. 6, pp. 511-515.

Suleiman, M.T., Lohnes, R., Wipf, T., and Klaiber. W. (2003) “Analysis of deeply buried flexible pipes” Transportation Research Record 1849, pp.

Zhang, C. and Moore, I.D. (1997) “Nonlinear mechanical response of High Density Polyethylene. Part II: uniaxial constitutive modeling”, Polymer Engineering and Science, Vol. 37, No. 2, pp. 414-420.