Influence of HDD installation on the stress-strain response of HDPE pipe

Cholewa, J.A.[1], Brachman, R.W.I.[1], Moore, I.D.[1]

[1]*GeoEngineering Centre at Queen's – RMC, Queen's University, Kingston, Canada*

Abstract

Horizontal directional drilling (HDD) involves pulling a new pipeline through a horizontal borehole. When installing a high density polyethylene (HDPE) pipe, axial stresses and strains develop as it is pulled into place. The potential service life of an HDPE pipe is likely controlled by these stresses and strains. Currently, pulling force equations are used to calculate maximum pulling force during an HDD installation. To better understand how axial stresses and strains developed in the pipe during and after installation, a pipe specimen was tested under a cyclic pulling force history. This simplified loading history involves a square wave with maximum axial stresses of 3.8 MPa and minimum axial stresses of 0.6 MPa. Axial strain accumulation during the experiment reached a peak of 0.75% at the end of the 60 minute simulation. The laboratory measurements were then compared with numerical simulations using both linear and nonlinear rheological models. Axial strain accumulation was best estimated using a nonlinear viscoelastic model. Subsequent to the simulated installation, the pipe samples were subjected to a constant axial strain condition while monitoring the development of axial tensions. After four days the axial tensions rose to 0.94 MPa. Strain levels developed during this simulation of a typical HDD installation fall within performance limits used for conventional buried pipes.

Introduction

Horizontal directional drilling (HDD) is a trenchless technology that has been adapted from the oil industry. It creates a pathway underground with a drill bit and a series of reamers to enable a product pipe to be pulled in place. HDD makes it possible to install underground services with minimal surface disruption and disturbance. This technology is fast becoming the primary method for crossing water courses, wetlands, utility corridors, roadways, railways, shorelines, environmentally sensitive areas, and congested urban areas.

There are three essential stages to the horizontal directional drilling process: pilot bore, pre-ream, and pull back. During the pull back stage, the pipe being installed is subjected to a complex loading history. The drill rig pulls the pipe through the ground in a series of steps, as each successive rod in the drill string is pulled up into the drilling machine and then removed. This action generates cyclic axial loads on the pipe.

However, during installation of high density polyethylene (HDPE) pipes, the cyclic pulling force history produces stresses and strains which are not well understood. The long term performance of an HDD installed pipe is linked to the stresses and strains that develop during and after installation. The state of industry practice is to use pulling force equations to calculate the maximum pulling force to ensure that this is less than some set fraction of the ultimate axial load capacity of the pipe, Baumert and Allouche (2002). A more detailed investigation of the response of HDPE pipe requires evaluation of axial strains and stresses during and after installation as a result of the axial force history imposed during pull back. The objective of this paper, therefore, is to quantify those axial stresses and strains.

Axial force histories measured during installation, Baumert et al. (2004), are used to generate an idealized loading history. Those loads are then applied to an isolated pipe sample to obtain laboratory measurements of stresses and strains during installation. Two computer models are then studied, to determine their ability to estimate HDPE pipe response to the cyclic pulling force history. Post-installation pipe response is then studied by imposing a zero strain condition on the pipe specimen, and observing the stresses that result.

Development of idealized loading history

Baumert and Allouche (2003) have developed a number of load cells to monitor pulling forces during pipe installation. The load cell is attached in front of the pullhead so that pulling force is recorded during commercial HDD installations. Figure 1 provides typical field data obtained by Baumert (2003) for an HDPE pipe with an inside diameter of 200 mm pulled 115 meter through clay.

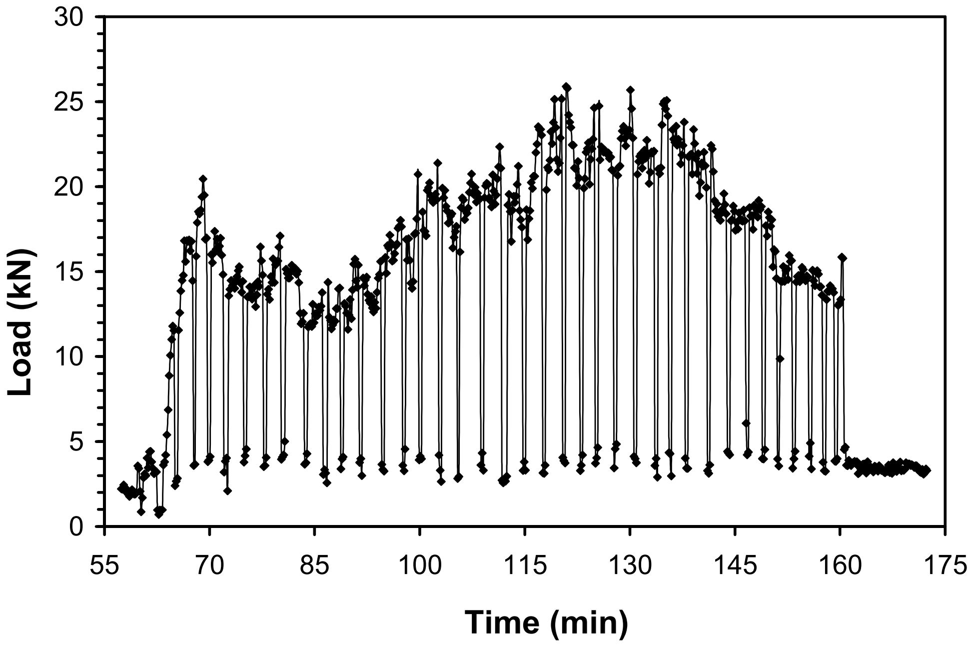


Figure 1: Pulling force measured from a commercial drilling rig (Baumert, 2003).

As the new HDPE pipe is installed it is subjected to a cyclic axial load history. Peaks occur when the pipe is being actively pulled through the borehole. Troughs in the axial force history occur when the drill string is released to remove a drill rod. An idealized loading history is needed for the 150 mm diameter HDPE pipe samples to be used in the laboratory experiments. This involves scaling the load measurements obtained in the field, Figure 1, to account for the difference in pipe size. Assuming that external drag forces are proportional to the external circumference of the pipe, a 75% scaling factor has been applied. The scaled data over a ten minute time interval is shown in Figure 2.

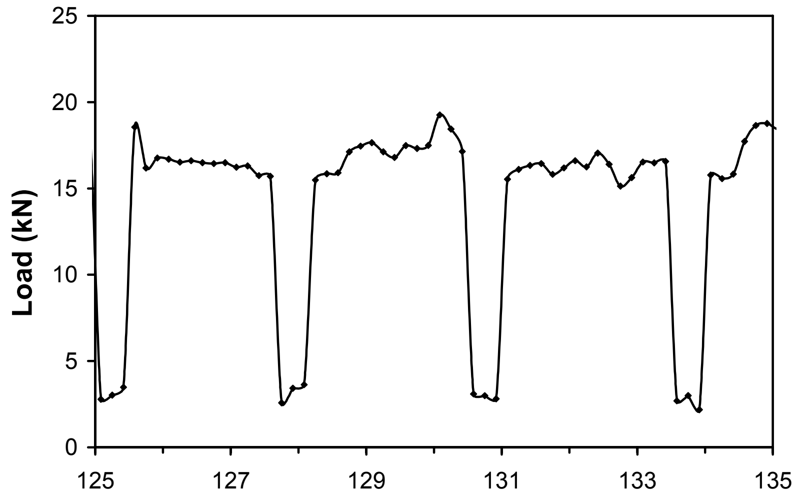


Figure 2: Scaled pulling forces over a ten minute time interval.

The loading and unloading of the HDPE pipe during installation is clearly shown. Approximately every 2 minutes the drill string is released to remove a drill rod. This process takes approximately 30 seconds, where after the pipe is reloaded as it is being pulled through the borehole. This process continues until the pipeline has been installed.

From this loading history, a simplified installation sequence is generated for use in the laboratory. Peak force values of 20 kN are applied over a time interval of two minutes, to represent the pulling force applied at the leading end of the pipe as one drill rod is pulled up into the drill rig (and the HDPE pipe advances through the borehole a corresponding distance). Force is then decreased to 3 kN and held at this level for 30 seconds, to represent the axial force applied as a rod is recovered. The frequency of force measurements reported by Baumert (2003) was insufficient to define the loading rate as forces increase or decrease during this cyclic loading history. A decision was made to apply changes in axial force very quickly in the laboratory. The consequences of the loading rate were examined using numerical models (described in more detail in a subsequent section). The pipe response was found to be largely insensitive to loading rate once that loading rate becomes rapid.

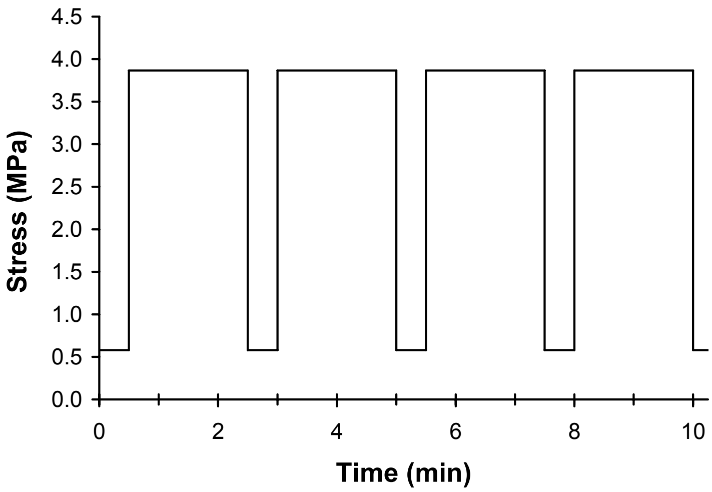


Figure 3: Idealized axial stress history used in the laboratory tests.

Figure 3 shows the corresponding axial stress history. It is a square wave with 3.8 MPa peaks and 0.58 MPa troughs. This cyclic loading history is used throughout the simulated pipe installation, since it is much easier to define and apply than the more complex and variable loading history seen in Figure 1. The idealization captures the key elements of the cyclic pulling force history, so that the consequences for the HDPE pipe can be investigated both during and after the cyclic loading.

Test apparatus

The HDPE pipe samples were 500 mm long with a diameter of 150 mm and a wall thickness of 10 mm. HDPE is a thermoplastic material, and differential cooling at the inner and the outer surfaces of the pipe during production leads to the generation of residual stresses in the HDPE pipe (Boot and Guan, 2004). The decision was therefore made to employ complete pipe samples in each of the experiments, rather than applying the axial stress history to small samples cut from those pipes (residual stresses are released when small specimens are cut).

The pipe is gripped through steel flanges bolted onto standard stub-end fittings welded to the ends of the pipe samples, Figure 4. The idealized stress history shown in Figure 3 was applied over a time period of one hour.

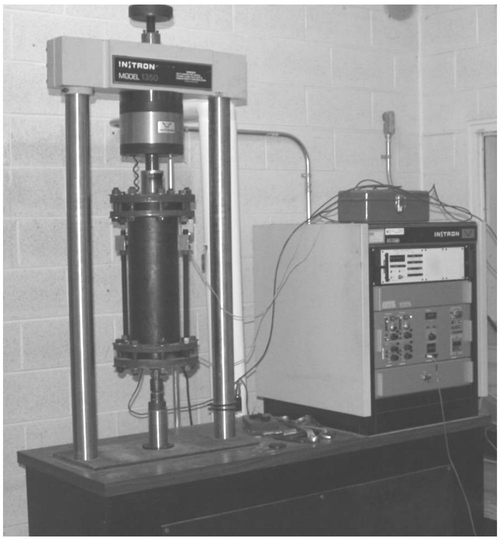
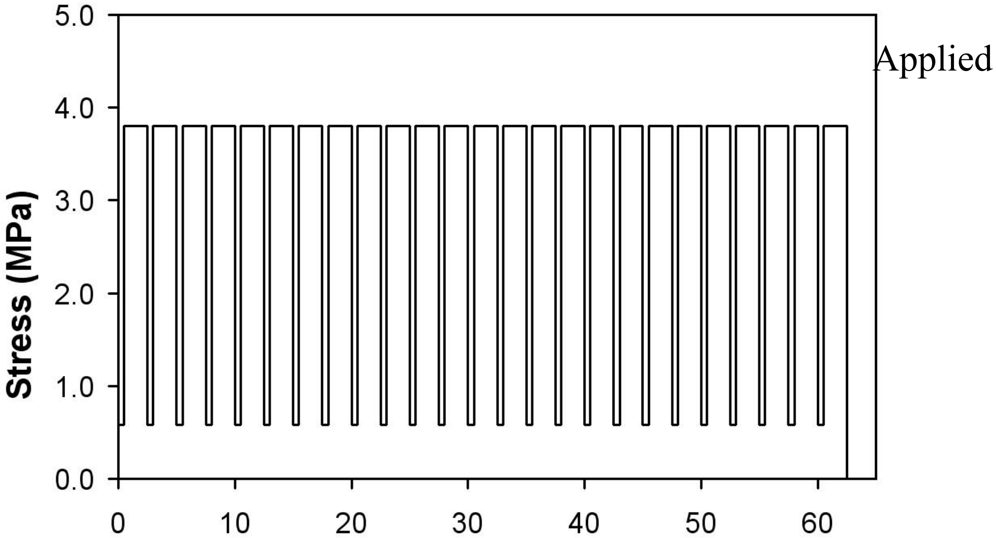


Figure 4: Test apparatus

The axial strains induced during the simulated installation sequence were measured using two linear potentiometers mounted on the outside of the sample, Figure 4. The load cell associated with the universal test machine was used to ensure the correct stress history was applied.

Results

Figure 5 illustrates the applied stress history as well as the measured strain history obtained during one laboratory experiment.



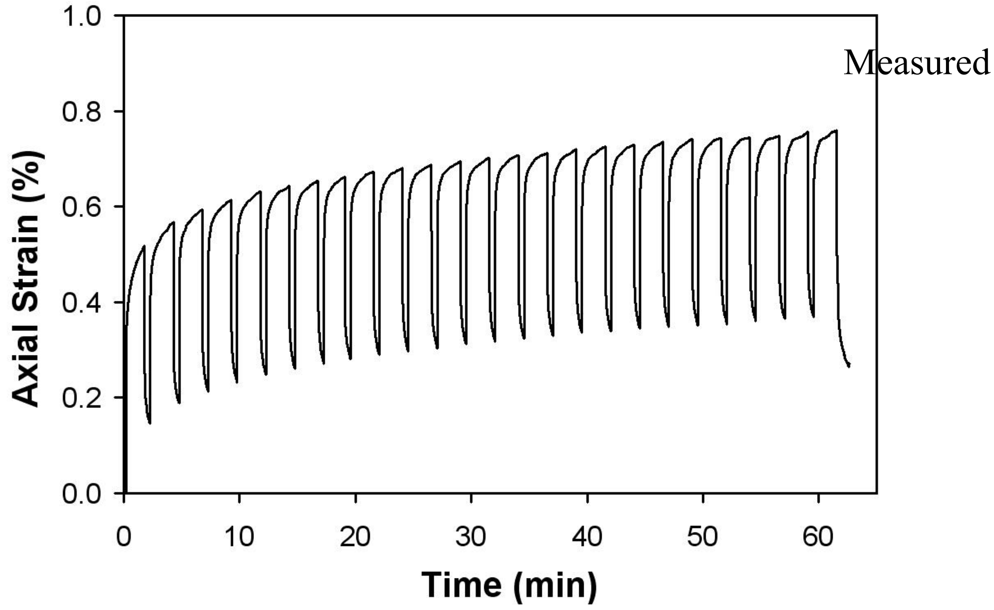


Figure 5: Axial stress and strain histories for the simulated installation sequence

During the cyclic loading history the axial strains progressively accumulate. At the end of the first load cycle, a peak strain of 0.52% is obtained. At the end of the second load cycle, this has risen to 0.57%. After 5, 10, and 25 cycles, this rises to 0.63%, 0.68% and 0.76%, respectively. Figure 6 provides a more detailed picture of the axial strain history over a 10 minute interval.

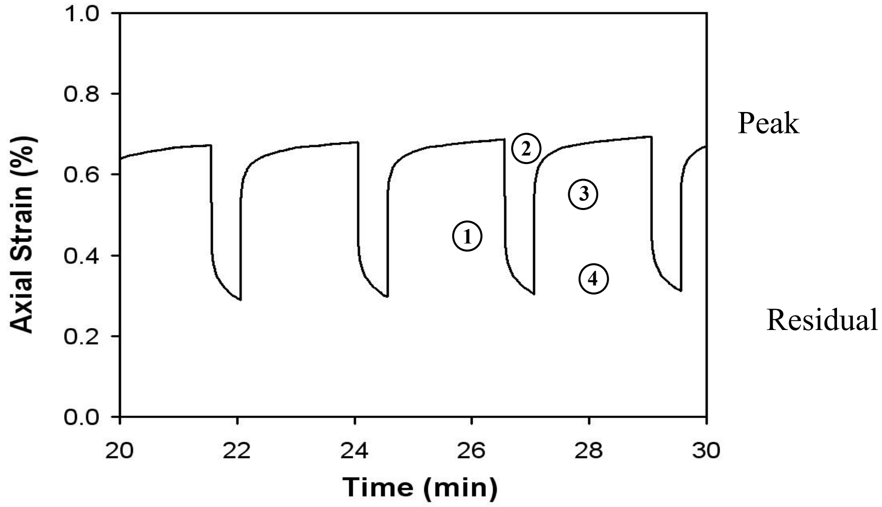


Figure 6: Axial strain history during a ten minute time interval.

A typical cycle occurs in 4 stages. During the first stage the axial stress is applied rapidly, and this induces a large increase in axial strain (corresponding to the initial pipe response as pulling commences). The second stage involves pipe response as the peak stress of 3.8 MPa is held constant. This creates a creep condition, with strains accumulating over time. The third stage occurs when the drill string is released by the drill rig. The pipe sample unloads rapidly, and instantaneously recovers some strain. The fourth stage occurs over the time period that the drill string is broken, to remove a drill rod. Strain recovery continues over that period until the beginning of the next load cycle.

The peak axial strain occurs at the end of the second stage of the load cycle, and the minimum or residual strain occurs at the end of the fourth stage of the load cycle. Figure 7 shows the measured values of peak and residual strain for each of the 25 loading cycles. The axial strain levels generated using the idealized loading history were consistently within conventional strain limits used in industry for buried HDPE pipes subjected to conventional earth loading.

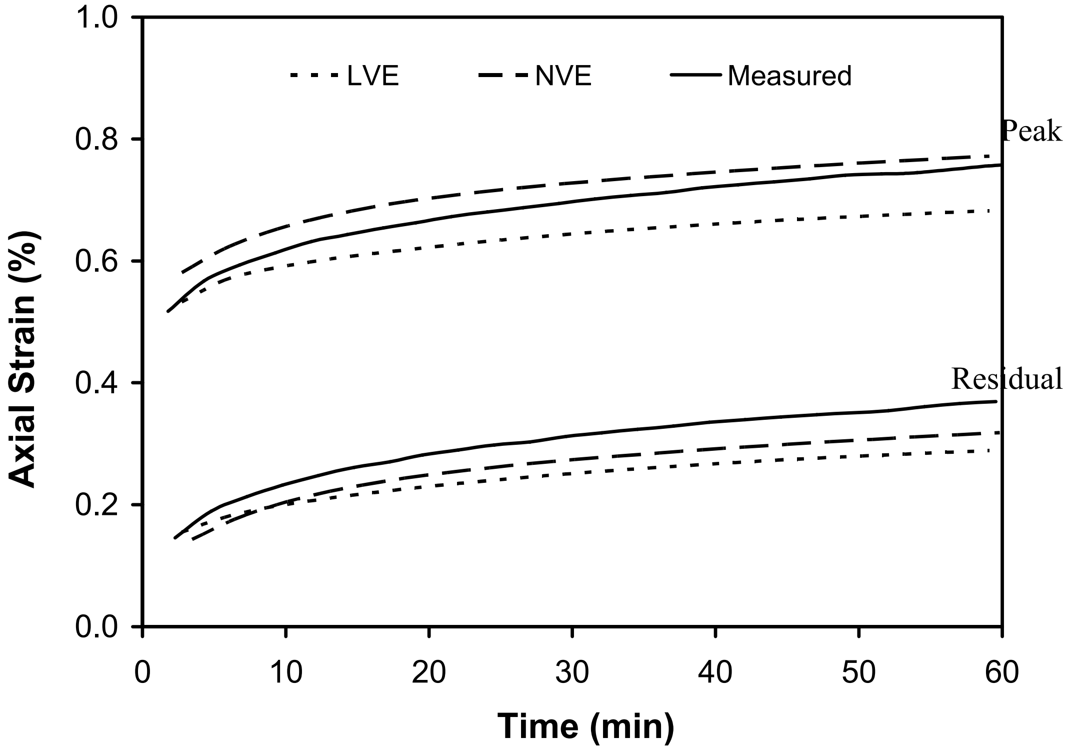


Figure 7: Comparison between numerical models and laboratory results

Comparison of laboratory results with numerical models

The axial response of the HDPE pipe was calculated for the idealized loading history using two numerical models. Comparisons were then made to the laboratory measurements, to evaluate the potential use of those models to determine pipe response during pullback.

The linear viscoelastic (LVE) model of Moore and Hu (1996) features an independent spring and nine Kelvin elements. This linear model has spring stiffness and the dashpot viscosity defined as constants. The peak and residual strain values obtained from this calculation are included in Figure 7.

The performance of the nonlinear viscoelastic model (NVE) of Zhang and Moore (1997b) was also investigated. This model features an independent spring and six Kelvin elements, where the spring stiffnesses and the dashpot viscosities are defined as functions of stress.

These models have been found to perform well for loading histories that do not feature strain reversal, e.g. Zhang and Moore (1997a, 1998). Figure 7 illustrates the performance of these models for the idealized pulling force history that does involve strain reversal.

The peak strain measurements fall between the calculations obtained using the LVE and the NVE models, though the NVE calculations are somewhat closer. Each of the calculations for residual axial strain overestimates the amount of strain recovery (i.e. the observed strains are greater that the calculated values). None of the axial strain levels exceed 1%, and this likely explains why the LVE and NVE calculations are generally reasonable, Moore and Hu (1996).

Pipe response after installation

After a HDPE pipe is installed, the pipe is released from the drill string and is free to experience axial strain recovery. The pipe is then fastened to a fixed object (manhole, fire hydrant), so that subsequent strain recovery is prevented. One of the objectives of the current project is to study how axial tensions redevelop over time.

After application of the simulated pulling force history, axial load was released and the pipe was left free to experience axial strain recovery for a predetermined time period. The ends of the pipe specimen were then restrained, so that axial length (i.e. axial strain) was held constant. The redevelopment of axial tensions was then monitored, Figure 8.

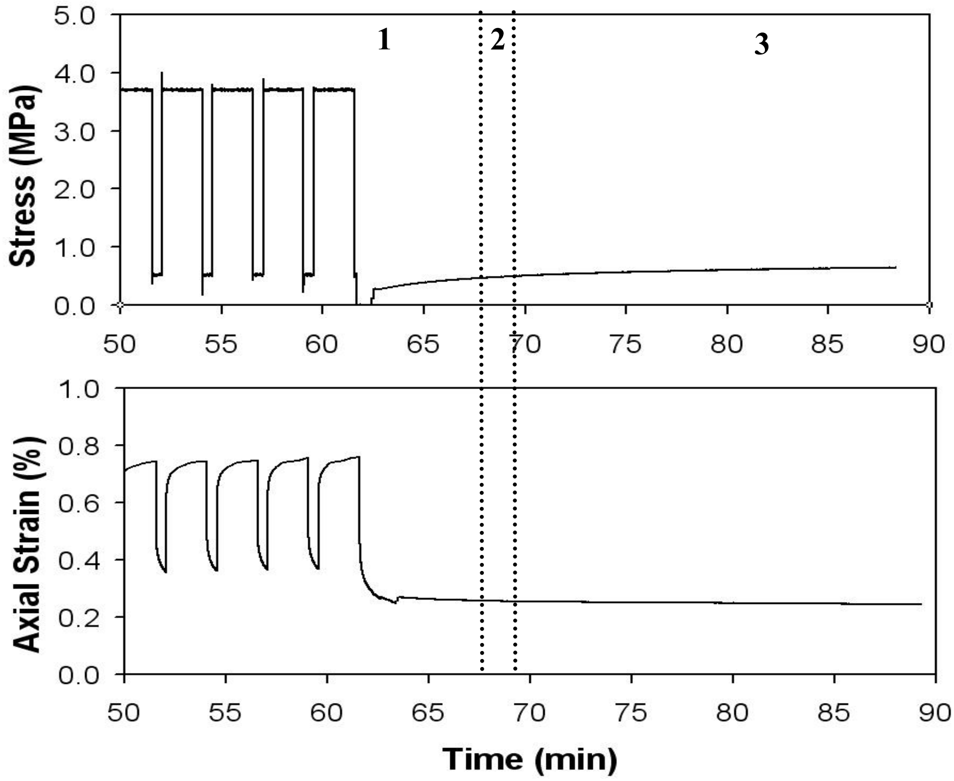


Figure 8: Development of axial tensions subsequent to installation

Figure 8 is divided into 3 stages. The first stage involves the application of the idealized cyclic loading history. Stage 2 features axial strain recovery for a period of 2 minutes. Stage 3 involved axial restraint to ensure axial strain was held constant. The development of axial tensile stresses during stage three is evident. After four days these axial tensions reached a level of 0.94 MPa. Work is ongoing to investigate the effect of loading history variables, such as the time period for stage 2, and the effect of maximum and minimum stresses used during cyclic loading, on the axial tensions that occur during stage 3. Of particular interest are the long term stresses that the pipe experiences during stage 3, since these are expected to control the service life of the buried HDPE pipe.

Conclusions

During a typical HDD installation of an HDPE pipe, it experiences a complex stress and strain history, featuring periods of loading, creep, unloading, and strain recovery. Throughout the course of the installation, axial strains progressively accumulate.

Laboratory tests were used to study the axial response of a sample of HDPE pipe subjected to an idealized pulling force history. Axial strain levels generated from the idealized loading history were within accepted performance limits for HDPE under monotonic loading.

The laboratory measurements of axial strain were compared with calculations obtained with linear and nonlinear viscoelastic computer models. Both models provide reasonable estimates of the maximum strain levels that occur during installation, though the performance of the nonlinear viscoelastic model was superior. Both models over predicted the amount of strain recovery while the drill string is broken to remove each drilling rod. This study examines the response of the leading section of the HDPE pipe where it is attached to the drill string. Further work is required to study the soil-pipe interaction along the full length of the HDPE pipe.

References

Baumert, M E and Allouche, E N 2002, 'Methods for estimating pipe pullback loads for horizontal directional drilling crossings', *Journal of Infrastructure Systems*, ASCE, 8(1): 12-19.

Baumert, M E and Allouche, E N 2003, 'Real-time monitoring for quality delivery of directional drilling installations', *Journal of Infrastructure Systems*, ASCE, 9(1): 35-43.

Baumert, M E 2003. *Experimental investigation of pulling loads and mud pressures during horizontal directional drilling installations*. Ph.D, The University of Western Ontario, London, Ontario.

Baumert M E, Allouche, E.N. and Moore, I.D 2004, 'Experimental investigation of pull loads and borehole pressures during horizontal directional drilling installations', *Canadian Geotechnical Journal*, 41: 672-685.

Boot, J C and Guan, Z W 2004, 'A method to predict triaxial residual stresses in plastic pipes', *Polymer Engineering and Science*, 44(10): 1828-1838.

Moore, I D and Hu, F, 1996, 'Linear viscoelastic modeling of profiled high density polyethylene pipe', *Canadian Journal of Civil Engineering*, 23: 395-407.

Zhang, C and Moore, I D, 1997a, 'Nonlinear mechanical response of high density polyethylene. Part I: Experimental investigation and model evaluation', *Polymer Engineering and Science*, 37(2): 404-413.

Zhang, C and Moore, I D, 1997b, 'Nonlinear mechanical response of high density polyethylene. Part II: Uniaxial constitutive modeling', *Polymer Engineering and Science*, 37(2): 414-420.

Zhang, C and Moore, I D, 1998, 'Nonlinear finite element analysis for thermoplastic pipes' *Transportation Research Record*, No. 1624, Structural Analysis and Design – Bridges, Culverts and Pipes. National Research Council, Washington, 225-230.