

Pulling rate effects on the pullout force of buried small diameter MDPE pipe in loose sand

Auchib Reza¹, Ashutosh Sutra Dhar¹, Mujib Rahman² & Lalinda Weerasesekara³

¹*Department of Civil Engineering – Memorial University of Newfoundland, St. John's, NL, Canada*

²*FortisBC Energy Inc., Surrey, BC, Canada*

³*WSP Canada Inc., Vancouver, BC, Canada*



ABSTRACT

Buried pipelines have been operated worldwide since for decades as the most convenient means of transporting natural gas and liquid. Polyethylene pipes came into extensive use during the latter half of the twentieth century. These pipelines are sometimes impacted by ground movements triggered by landslides, earthquake fault rupture as well as other natural hazard and human-induced sources. Owing to the lack of alternative approaches, soil-pipe interaction models developed for steel pipes are often used for assessing the PE pipe subjected to ground movement. However, the difference between the behaviours of PE and steel pipes subjected to ground loads are well recognized. PE pipe materials are flexible compared to steel and show nonlinear time and temperature dependent stress-strain responses. As a result, stress or strain developing in the pipe due to ground movement is influenced by the rate of loading and the temperature. However, limited studies have been performed to examine the impact of temperature and ground movement rates. In the current research, a series of full-scale laboratory tests were performed at Memorial University of Newfoundland to investigate the effects of loading rates on buried medium density polyethylene (MDPE) pipes subjected to axial movements relative to the soil. Although pipes with different diameters buried in dense and loose sand are being investigated as a part of the research project, tests completed for small diameter MDPE pipes in loose sand are discussed in this paper. The study reveals that a relatively higher loading rate offered a higher axial pullout resistance from the soil and induced higher axial strains on the pipe.

RÉSUMÉ

Les conduites enterrées sont exploitées dans le monde entier depuis des décennies et constituent le moyen de transport le plus pratique pour le gaz naturel et les liquides. Les tuyaux en polyéthylène ont été largement utilisés au cours de la seconde moitié du vingtième siècle. Les mouvements de terrain provoqués par des glissements de terrain, la rupture d'une faille sismique, ainsi que par d'autres dangers naturels ou d'origine anthropique, sont parfois à l'origine de ces pipelines. Faute d'approches alternatives, les modèles d'interaction sol-tuyau développés pour les tubes en acier sont souvent utilisés pour évaluer le tube en PE soumis au mouvement du sol. Cependant, la différence entre les comportements des tubes en PE et des tubes en acier soumis à des charges au sol est bien reconnue. Les matériaux des tuyaux en PE sont flexibles par rapport à l'acier et présentent des réponses contrainte-déformation non linéaires en fonction du temps et de la température. En conséquence, les contraintes ou les déformations dans la conduite dues au mouvement du sol sont influencées par la vitesse de chargement et la température. Cependant, des études limitées ont été réalisées pour examiner l'impact de la température et des taux de mouvement du sol. Dans les recherches actuelles, une série d'essais en laboratoire à grande échelle a été réalisée à l'Université Memorial de Newfoundland pour étudier les effets des taux de charge sur les canalisations enterrées en polyéthylène à moyenne densité (MDPE) soumises à des mouvements axiaux par rapport au sol. Bien que des recherches sur des tuyaux de différents diamètres enfouis dans du sable dense et en vrac fassent partie du projet de recherche, les essais réalisés pour les tuyaux en MDPE de petit diamètre dans du sable en vrac sont discutés dans le présent document. L'étude révèle qu'un taux de charge relativement élevé offre une résistance à l'arrachement axial plus élevée du sol et induit des contraintes axiales plus élevées sur le tuyau.

1 INTRODUCTION

Buried pipelines are extensively used as a dependable mode of transportation of oil and gas. About 2 million km of transmission pipelines are operated worldwide (CIA 2009). About half a million km of local distribution pipelines are operated in Canada (NRC 2016). Failure of transmission and/or distribution pipes can have adverse effects on the associated utility, economy and public health. Among the various causes of pipeline failure, ground deformation has been responsible for 15% of the total incidents of onshore pipelines over the last ten years, as reported in the 10th

report of European Gas Pipeline Incident Data Group (EGIG, 2018).

Ground deformation may occur from hazards including landslide, mining, erosion, liquefaction, and differential soil movement at the fault lines. Landslides are by far the most typical types of ground movements encountered by the pipelines. Ideally, the routing of a buried pipe is selected to avoid these natural hazards. Where this is not possible, the effects of postulated ground motions are considered.

Pipelines crossing active landslide areas are subjected to additional loads due to ground movements. Longitudinal load on the pipeline is expected when the direction of the ground movement is parallel to the pipe axis. The regions,

where ground movement can occur, have the potential to cause significant strain on the pipelines in a network. With the development of modern technologies (e.g., Global Positioning System (GPS) surveys, in-place slope inclinometer (IPSI) string) ground movements and its variations over time can be detected reasonably precisely in the field. However, estimating the strains in a buried pipe is difficult, even with available ground deformation data. It is essential to understand the response of the pipe to those induced strains to define a safe operating window.

Over the years, numerous studies have been conducted to understand the soil-pipe interaction mechanisms of pipes subjected to ground movements (Wijewickreme et al. 2009; Meidani et al. 2017; Bilgin and Stewart, 2009ab; Liu et al. 2011; Gerlach and Achmus, 2018; Sheil et al., 2016). However, most of these studies focused on understanding the behaviour of steel pipe. PE pipe materials are flexible compared to steel and show nonlinear time and temperature dependent stress-strain responses. As a result, stresses or strains developing in the pipe due to ground movement are influenced by the rate of loading and the temperature. However, limited studies have been performed on evaluating the temperature and rate-dependent responses of the soil-pipe interaction. Weerasekara and Wijewickreme (2008) and Wijewickreme and Weerasekara (2015) experimentally observed the effects of loading rate on the axial strain development on a buried MDPE pipe. They proposed an analytical method to calculate the pipe strain observed in their experiments. Bilgin and Stewart (2009b) revealed that the diameter of polyethylene pipe changes with temperature that affects the pullout force. As mentioned earlier, the loads on the pipelines due to landslides may depend on the rate of ground movement, the effects of different rates of landslide on the pipeline integrity have not been investigated extensively. Thus, the objective of the current research is to develop an improved understanding of the rate-dependent effect of buried MDPE pipes using full-scale tests. While pipes buried in dense and loose sand are investigated in this research, the results of pipe tests in loose sand are presented in this paper.

2 AXIAL PULLOUT FORCE

The maximum axial soil load on a pipe subjected to axial ground movements can be calculated using the formula recommended in ASCE (1984) and ALA (2001) guidelines. These guidelines use a simplified method to calculate the maximum pullout force due to axial landslide without proper consideration of soil-pipe interaction. As the general form of the equations was not varied significantly over the past 30 years, it is a common practice to determine the axial loads for the onshore buried pipeline in cohesionless soil using the following expression as in Eq. 1:

$$F_A = \gamma \times H \times (\pi D L) \times \left(\frac{1+k_0}{2}\right) \times \tan \delta \quad [1]$$

Where, F_A = the maximum axial soil resistance; γ = average effective unit weight of the soil; H = depth from the ground

surface to pipe springline; L = pipe length; D = pipe outer diameter; k_0 = coefficient of lateral earth pressure at rest and δ = interface friction angle between the pipe and the surrounding soil. This equation employs the average of the estimated vertical and lateral stresses at the springline of the pipe as the normal stress on pipe wall. It is assumed that the normal stresses on the pipe remain the same even after shear displacements occur at the soil-pipe interface, and the pipe is rigid so that an uniform shearing stress occurs over the entire length of the pipe. However, (Muntakim and Dhar 2018) revealed through finite element analysis that the axial pullout force on pipeline depends on relative rigidity of pipe with respect to surrounding soil. It is reported that the interface normal stresses during axial pullout was higher for the pipe with higher rigidity (i.e., the steel pipe). Thus, the recommended equation in current guidelines may not be applicable for flexible MDPE pipelines. To validate these findings experimentally, full-scale tests are conducted using a new laboratory testing facility developed at Memorial University of Newfoundland. Tests conducted with a 42.2 mm diameter MDPE pipe in loose sand subjected to relative axial movements are discussed in the current paper.

3 TEST MATERIAL, EQUIPMENT, AND METHODS

A new full-scale pipe test facility has been designed and constructed at Memorial University of Newfoundland at St. John's, NL, to investigate the behaviour of flexible pipes subjected to axial pullout. The pipe test facility is a steel box with inside dimensions of 2 m in width, 4 m in length, and 1.5 m in depth. The test pipe is backfilled with sand found locally. The pipe is protruded out of the test box from two ends through two circular openings which are adjustable to accommodate pipes of different diameters. The openings are somewhat larger than the pipe diameter, which is filled using a rubber gasket with lubrication to minimize friction between the pipe and the tank wall at the openings. The profile view of the test box is given in Figure 1. The test sand is directly in contact with the inside walls of the steel box. No step has been taken to reduce the sidewall friction. Weerasekara and Wijewickreme (2008) revealed that the effect of sidewall friction on axial pullout test is insignificant during the axial pullout. Researchers commonly employ sidewall treatment to reduce the effects of arching under vertical loads (Dhar and Moore 2006).

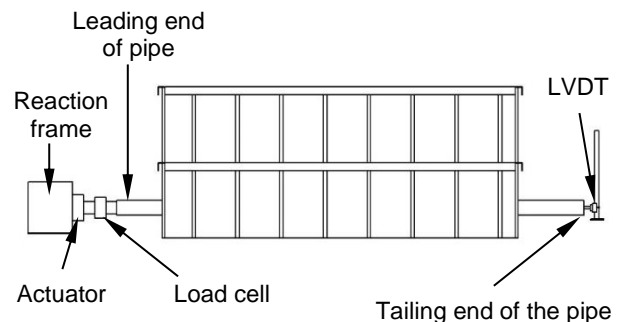


Figure 1. Profile view of the test box along with pipe instrumentations

3.1 Test Pipe

Four 4.6 m long 42.2 mm nominal diameter, with a standard dimension ratio (SDR, a ratio of the pipe outside diameter to wall thickness) of 10, MDPE pipe segments are used for the tests. These gas distribution pipes are CSA B137.4 certified and mostly used for the gas utilities across Canada. The pipe once used for pullout test is never used in subsequent tests to avoid the effects of residual stresses.

3.2 Sand Backfill

A locally available well-graded sand (USCS classification = SW) is used as the backfill material for the pipe. The soil contains, by weight, approximately 1.30% of fines and 98.70% of sand. The coefficient of uniformity (C_u) and the coefficient of curvature (C_c) were 6.5 and 0.75 respectively. The particle size distribution is given in Figure 2. The maximum dry density is obtained as 18.9 kN/m^3 from Standard Proctor Compaction tests (ASTM D698 2003) (Saha et al. 2019).

The strength parameters of the sand have been determined using direct shear tests at normal stress ranging from 25 kPa to 50 kPa representing the typical field soil stress conditions of oil and gas distribution network using polyethylene (PE) pipelines. An internal friction angle of 33° is obtained from the direct shear test of this sand at the loosest state at a unit weight of 12 kN/m^3 (nearly 2% of moisture content) at these stress levels (Saha et al. 2019).

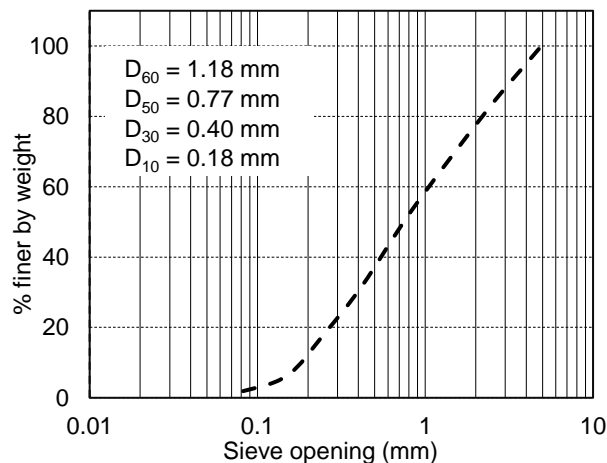


Figure 2. Particle size distribution of test sand (After Saha et al. 2019)

3.3 Pipe Installation

Test cell is first backfilled up to a depth of five times the pipe diameter below the pipe center to represent native soil. Soil is then placed at 100 mm thick lifts which are spread over the test box using a wooden spreader. Extra precautions have been taken while spreading the sand to prepare the backfill in loose conditions. When the pipe invert level is reached, the soil surface is uniformly levelled

to minimize stress concentrations at potential localized hard spots. Then the pipe is placed straight on the levelled soil surface. Placing of soil is then continued consistently until the desired burial depth for the pipe is achieved. Density measurements are taken at three different locations inside the testing tank. Note that the flexible MDPE pipe may not always be straight, particularly in uneven ground, which may affect the pullout force. The effect of out-of-straightness on the pullout force has not been investigated here.

Density of the backfill sand plays a vital role in the pullout resistance because interface friction angle between the pipe and sand increases with increasing density of sand. More importantly, the densities of soil influence the normal stresses on the pipe during the axial pullout. After the completion of axial pullout test, density measurements are taken at different locations, which yielded an average unit weight of 12 kN/m^3 from the top surface to the pipe springline level. Thus, the average relative compaction of the backfill material is roughly 60% of the Standard Proctor Maximum dry density. Air-dry condition of sand with the water content of around 1.5% for Test 1 and less than 1% for Test 2-4 is confirmed during the tests through measurements of water content.



Figure 3. Bedding for MDPE pipe in loose sand inside the testing cell

The tested MDPE pipe and sand are removed from the tank after each test, and the pipe installation procedure is repeated in a consistent manner for the next tests (Figure 3).

There different pipe pullout tests were conducted with pulling rates of 0.5 mm/min, 1 mm/min and 2 mm/min (termed herein as Test 1, Test 2 and Test 3, respectively)

3.4 Instrumentation

Four different types of instrumentation were used including piezoresistive tactile pressure sensor (Tekscan 2009), linear variable differential transducer (LVDT), load cell and strain gauges. Pressure sensors are used to measure the changes of vertical and lateral soil pressures near to the pipe during axial pullout (not discussed in this paper). LVDTs are needed to measure the axial movement during

the pullout tests. Load cell is used to measure the resisting force of the soil to the pipe movements, which is equal to the pullout forces applied to the pipe. Also, pipe wall strains are monitored using an array of electrical resistivity strain gauges. A pipe without strain gauge is also tested to examine if the surface roughness caused by the strain gauge placement may affect the pullout force. However, no significant effect on the pullout force due to strain gauge placement was found. The data from the load cell, LVDT and strain gauges are monitored using a computer-controlled data acquisition system. There was a total of seven channels for reading measurements in the data acquisition system: one for the load cell, five for the strain gauges and one for the LVDT. For the selected range of displacement rates, all measurements were recorded at two samples per second.

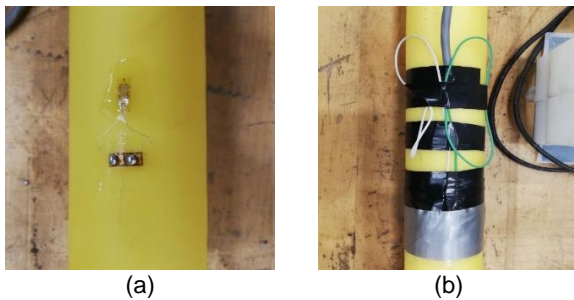


Figure 4. Strain gauge installation techniques (a) before wrapping (b) after wrapping using duct tape and electrical tape.

The capacity of the load cell used is 22.25 kN with a system accuracy of ± 4.45 N. The stroke and piston area of the load cell are 150 mm and 32,390 mm² respectively. A LVDT was attached to the opposite end of the load cell, called herein as the tailing end. The LVDT has a total travel capacity of 110 mm with an accuracy of about 0.50 mm. Three uniaxial strain gauges were installed: at one-fourth, half and three-fourths of the pipe length within the box. The uniaxial strain gauges were placed at the pipe crown. One biaxial strain gauge was attached to the pipe invert at the mid-length of pipe within the test box to monitor longitudinal and circumferential strains. Strain gauge installation techniques are shown in Figure 4. A further detailed description of the testing facility with instrumentation is available in Reza et al. (2019).

4 EXPERIMENTAL RESULTS

4.1 Axial Load Versus Displacement Response

The pullout forces measured during the tests are presented in Figure 5. As seen in Figure 5, the pullout resistance increases nonlinearly with the displacement of the leading end of the pipes. The soil resistances reach its first peak and then slightly decrease with displacement. Afterwards, the axial soil force starts to increase again that continues up to the end of the experiment. The experiments were terminated when the leading end displacement reached 120 mm. The initial part of the load-displacement response

is associated with the elongation of the pipe under the axial pullout force. No movement of the tailing end of the pipe is observed during this period. The axial force in the pipe increases with the increase of pullout displacement at the leading end and reaches the peak value when the tailing end starts to move. The tailing end of the pipe starts to move when the shear strength at the soil-pipe interface is mobilized over the entire length of the pipe. Immediately after mobilization of the shear strength over the entire pipe, the pullout force slightly reduces. Then, the pullout force increases again at a much slower rate, which is potentially due to the densification of the loose soil with rigid body movement of the pipes. The increase of the pullout force due to this effect is significant, particularly at large displacement. However, the magnitudes of axial force for the pipes are less (<1.5 kN). The effect of the post-peak increase of pullout force may not be observed in the field since the soil is not confined within a boundary as in the case of the laboratory test box.

Figure 5 reveals that the rate of loading significantly affects the maximum pullout forces of the pipes. The pullout force is the highest for the test conducted at the loading rate of 2 mm/min (Test 3). However, the maximum pullout force in Test 2 conducted at 1 mm/min of loading rate is less than the pullout force in Test 1 conducted at a loading rate of 0.5 mm/min in Figure 5. To confirm the results of Test 2, an additional test with a loading rate of 1 mm/min (Test 4) was conducted, and almost identical results were observed (Figure 5). An additional test for Test 1 has not been conducted. The higher pullout force in Test 1 is likely due to a different level of compaction of the backfill soil, which was challenging to maintain at the loose condition. Besides, the water content of the backfill in Test 1 was higher than the water content of the backfill in other tests.

The peak axial force is also calculated using the current design guidelines (ASCE 1984, ALA 2001) that provided the maximum pullout resistance of 0.5 kN (shown in Figure 5). Here the k_0 value (from Jaky's formula, $k_0 = 1 - \sin \phi$) is calculated using ϕ of 33°, corresponding to the peak friction angle of the local sand at the test density, the interface friction angle (δ) between the MDPE pipe surface and sand is assumed to be 18° and effective unit weight of sand used (γ) of 12 kN/m³ which is in loose condition. The calculated pullout force from the design equation is less than the maximum pullout force observed during the tests. From the comparison of peak pullout resistances, it reveals that the maximum pullout resistance for the MDPE pipes depends on the pulling rate of the pipes, which is not considered in the current design guidelines. As a result, the equation in the design guidelines underestimated the axial force for the pipes. As may be noted, the current design guidelines developed for steel pipes are the only resource available for assessing the pipelines subjected to ground movement. The study reveals that the existing design guidelines are not applicable for calculation of pullout force for MDPE pipes.

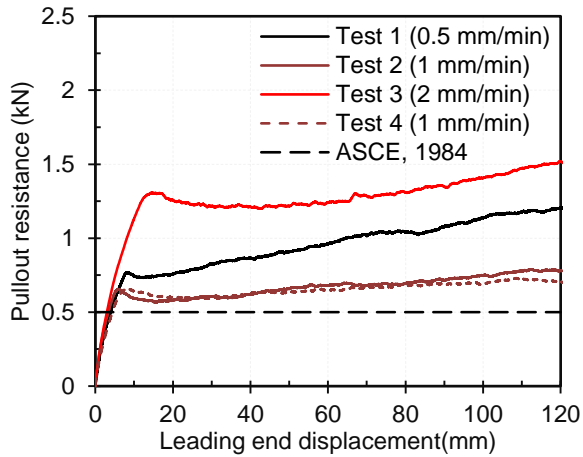


Figure 5. Pullout resistance with leading end displacement of the pipe

4.2 Pipe Deformation

The elongation of the pipes obtained during the tests is presented in Figure 6. The figure plots pipe elongations, calculated from the difference between the leading end displacements and tailing end displacements, against the leading end displacements. In the figure, the pipe elongation increases linearly up to leading end displacement of 8 mm, 6 mm and 12 mm in Tests 1, 2 and 3, respectively where mobilization of interface shear stress occurs over the entire pipe length. After that, the pipe elongation is stabilized or increased at a slower rate. The increase in pipe elongation beyond the first peak load is associated with the increase of soil resistance to the axial pipe movement. It also shows that the tailing end begins to move at the leading end displacement of 8 mm, 6 mm and 12 mm in Tests 1, 2 and 3, respectively. Thus, the leading end displacement is initially due to the elongation of the pipes only. Therefore, the interface shear strength is not mobilized over the entire length of the pipes up to these displacements.

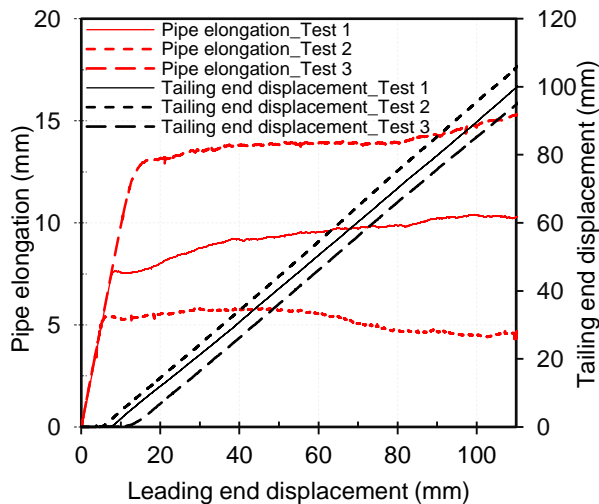
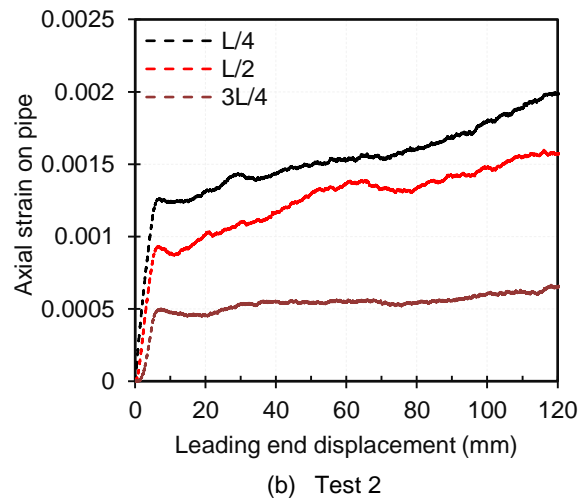
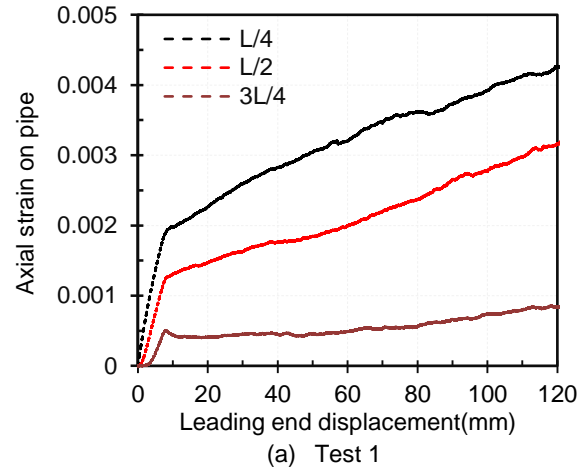


Figure 6. Pipe elongation and tailing end displacement with leading end displacement of the pipe

4.3 Axial Strain

During the tests, pipe wall strains are measured at three locations along the length of the pipes. Strain gauges are placed on the pipe crown at the distances of a quarter ($L/4$), half ($L/2$) and a three-quarter ($3L/4$) of the pipe length within the test cell measured from the pulling end. Figure 7 shows that the axial strains increase linearly with the increase of the leading end displacement and reach its first peak values at the point where the interface shear strength is fully mobilized, and the first peak pullout resistance is reached. Beyond this point, the tailing end of the pipe moves, and the axial strain continues to increase at a very slow rate. The rate of increase of axial strain is higher in Test 3 up to its first peak, which is consistent with higher pullout resistance discussed earlier.



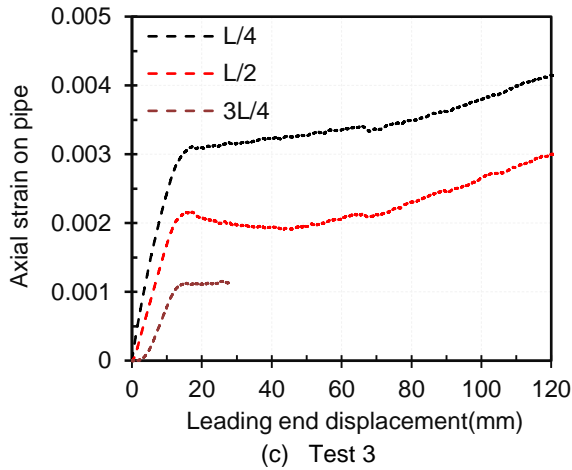


Figure 7. Axial strains at different locations of the pipes

The mobilization of axial force along the length of the pipe can be examined from the axial strains along the pipe length. The strain distribution along the MDPE pipe length for different leading end displacement of the pipe in Test 1 is shown in Figure 8. It shows that with leading end displacement, axial strain propagates progressively from the leading end towards the tailing end of the pipe (such as higher toward the leading end and less toward the tailing end). For example, in Test 1, the point at $L/4$ (i.e., at 1 m from the leading end within the test box) experiences axial strain almost immediately after application of leading end displacement, while the points at the distances of $L/2$ (i.e., at 2 m length) and $3L/4$ (i.e., at 3 m length) experience axial strains at around 2.5 mm and 5 mm of leading end displacements, respectively. Therefore, soil resistance is developed over 50% of pipe length at ~ 2.5 mm leading end displacement and over 75% of pipe length at ~ 5 mm leading end displacement. Initially, the soil resistance increases almost linearly that reach the peak below when the interface shear strength is fully mobilized. After mobilization of shear strength over the entire pipe length unit shearing resistance is expected to be constant, which can be examined from the distribution of axial strains along the pipe length. The distributions of the axial strain are almost linear along the pipe length until higher leading end displacement is reached (Figure 8). This implies that unit shear resistance at the pipe-soil interface is constant along the pipe length, after full mobilization of the shear strength. Thus, the maximum pullout resistance may be calculated through prediction of the unit interface shear resistance. The maximum axial strains experienced by the pipe is 0.5% at the leading end displacement of 100 mm of the pipe, which is not significant for the MDPE pipe.

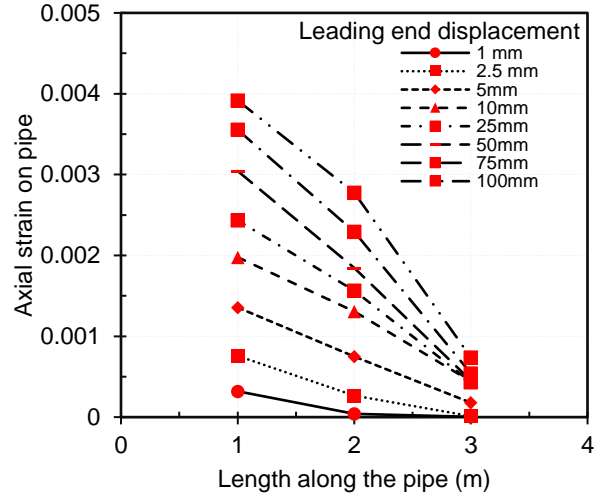


Figure 8. Axial strain distribution along pipe length (Test 1)

A biaxial strain gauge is attached in Test 1 and Test 3 at the $1/2$ length of pipe at the invert level to monitor axial and circumferential strains, as shown in Figure 9. Figure 9 shows circumferential compressive strain develops at the invert, which is associated with the change in the pipe diameter during the test. This diameter change is also not accounted in the current design method for calculation of the maximum pullout force. However, the effect of the change in diameter may be insignificant for pipes with high internal pressures. The circumferential compression and the change in pipe diameter are likely due to the Poisson's effect under the axial load. The ratio of the circumferential strain to the longitudinal strain is 0.45, which is the Poisson's ratio of the pipe material.

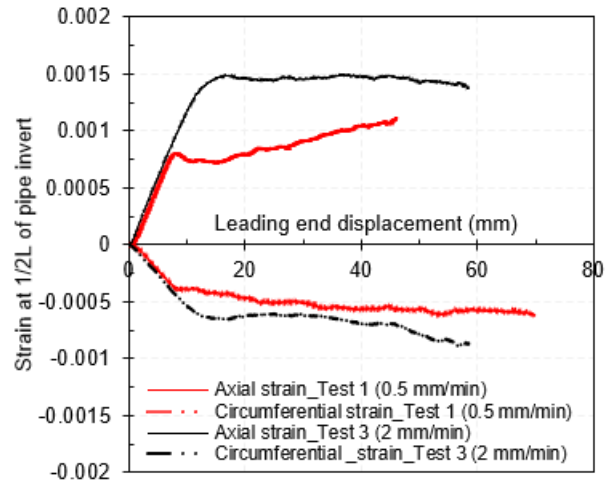


Figure 9. Axial and circumferential strains at pipe invert level

4.4 Strain Rate on Pipe during Pullout

Since MDPE pipes are viscoelastic, it responds to induced strain in a time-dependent manner. The response to the pullout forces applied to the pipe not only depends upon the resistance offered by the surrounding soil but also on the strain rate of the pipe, since stress is not only a function of strain but also a function of strain rate for MDPE.

The strain rates during the tests are examined from the measured axial strains as shown in Figure 10. Figure 10 shows that initial high strain rates reduce with the leading end displacement. The strain rates significantly drop beyond the full mobilization of shear strength over the entire pipe length (i.e., peak pullout force). After full mobilization of shear strength pipe movements as rigid body contributes, and therefore the strain rate is decreased and reaches closed to zero. The computed strain rate at the distances of $L/4$ starts to decrease immediately after application of leading end displacement, while the strain rates at the distances of $L/2$ and $3L/4$ increase up to 6 to 8 mm leading end displacements, and then begins to decrease. Beyond the leading end displacement of about 20 mm, the rate of strains stabilizes (reaches to a constant value) at different points (e.g., $L/4$, $L/2$, $3L/4$ distances along the pipe length) on the pipe wall.

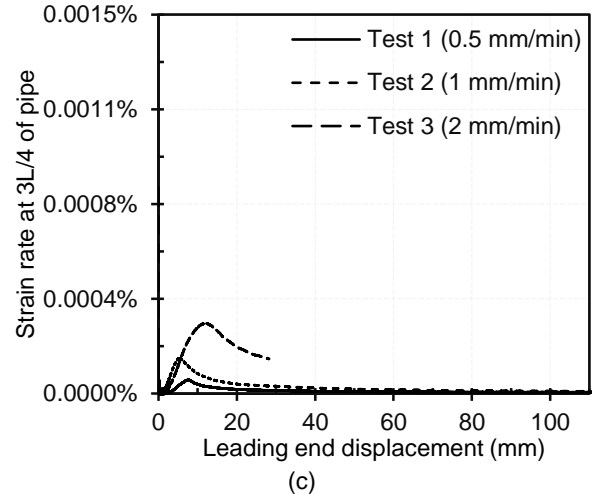
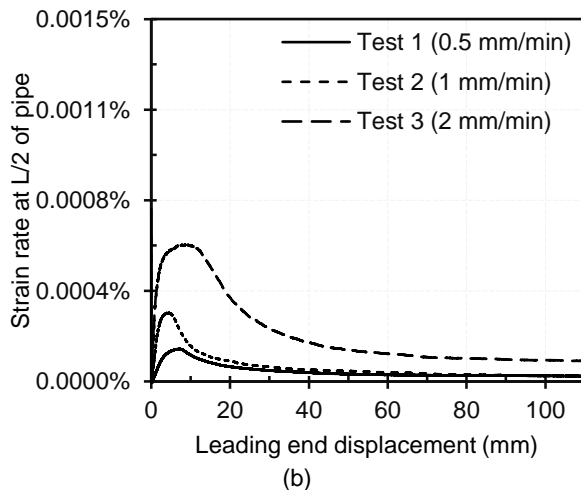
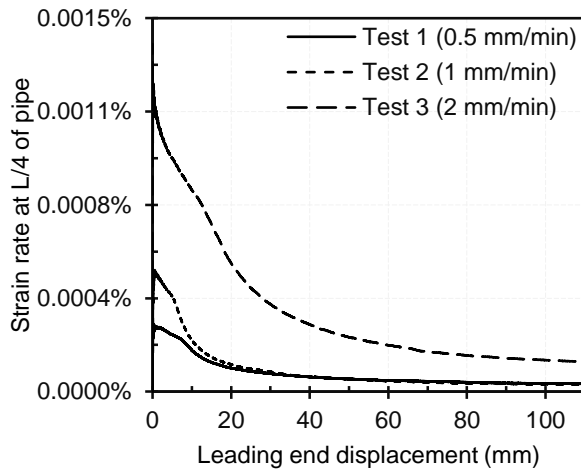


Figure 10. Strain rate responses to pipe movements at (a) $L/4$ (b) $L/2$ (c) $3L/4$ distances along the pipe length

5 CONCLUSION

A full-scale testing facility at Memorial University of Newfoundland is used to investigate the behaviour of the flexible 42.2 mm diameter MDPE pipes buried in loose sand subjected to axial ground movements. The measurements of axial pullout resistance, pipe movements and axial pipe strains mounted at different circumferential locations on the pipe wall were monitored during the tests. The test results reveal that the existing design guidelines (ASCE 1984, ALA 2001) may not be applicable for predicting the maximum axial force on MDPE pipelines due to ground movement. The main conclusions are:

- The maximum pullout force on MDPE pipes depends on the rate of relative ground movement. The peak pullout force is higher in the tests with higher displacement rates. ASCE (1984) and ALA (2001) design guidelines do not account for the effect of the rate of ground movement.
- MDPE pipes elongate during application of pullout force, and axial force is not mobilized over the entire length of the pipe at the same time. Pipe-soil interface shear strength is also not mobilized at the same time.
- The distribution of axial strain along the pipe length is almost linear after full mobilization of the interface shear strength at leading end displacement beyond 10 mm. Thus, the distribution of the axial force can be assumed to be linear along the pipe length. A maximum of 0.5% axial strain is attained after the leading end of the pipe has reached over 100 mm of relative movements (in Test 1), which is not significant.
- The strain rate is not the same along the pipe length during axial pullout. The variation of strain rates may affect the soil-pipe interaction for buried MDPE pipe.

6 ACKNOWLEDGEMENTS

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