Field investigation to study the response of buried polyethylene natural gas pipelines installed in a landslide zone in British Columbia

Jeremy Groves & Dharma Wijewickreme
Department of Civil Engineering – University of British Columbia, Vancouver, BC, Canada
Bassam Saad
FortisBC Energy Inc., Surrey, BC, Canada

ABSTRACT
The performance of buried pipelines in areas subject to ground deformations is a major concern for utility owners since the failures of such pipeline systems could cause property damage and even human losses, in addition to business disruption. With increasing use of plastic pipes, such as MDPE pipes, in most utility distribution systems, understanding the response of extensible piping during ground movement has become an important consideration. A new analytical model has been developed to account for the soil-pipe interaction mechanisms in buried MDPE pipes through previous research work conducted at the University of British Columbia (UBC). In order to assess the applicability and validity of this analytical model to buried pipeline systems in the field, a testing program was undertaken involving the installation of five buried MDPE pipe alignments, each 24 m in length, in a very slow-moving landslide located in Chilliwack, BC. The installed pipes are instrumented with over 200 strain gauges for periodic measurement of pipe strains during ground displacements, along with monitoring of the system for overall pipe and land movements. The overall purpose is to develop a reliable data base of ground movement and associated pipe strain to provide further validation for the new analytical model for buried MDPE pipes subjected to ground movements.

RÉSUMÉ
Grâce à un travail de recherche menée à l'Université de la Colombie-Britannique (UBC) précédemment sur le thème des gazoducs extensibles soumis à des mouvements de terrain, une nouvelle solution analytique a été développé afin de rendre compte des mécanismes d'interaction du tuyau de renvois dans l'enfouis à densité moyenne polyéthylène (MDPE). La nouvelle approche peut être utilisée pour estimer les mouvements de la surface par rapport au sol nécessaires pour mener à la défaillance des conduites, ce qui est une considération importante dans l'évaluation de la performance des systèmes de tuyauterie du terrain. Les derniers travaux de recherche qui ont été menées à l'UBC sur ce sujet consistent en un programme à grande échelle de vérifications sur le terrain, un examen composé de cinq alignements de tuyaux PEMD chacun d'une longueur de 24 m, enterré sous un terrain à glissement lent situé à Chilliwack, en Colombie-Britannique. Le but de l'expérience est de fournir une base de données fiable des mouvements de terrain et les données de déformation des tuyaux associés afin de valider davantage la nouvelle solution analytique pour les tuyaux de MDPE enterrés sous terre soumis à des mouvements de terrain.

1 INTRODUCTION

The performance of buried natural gas pipelines located in areas prone to ground movement is a major concern for utility owners since the failures of such pipeline systems due to the potential for loss of life, as well as the associated environmental and economical impacts. With extensible plastic pipes now becoming the industry standard for most utility distribution systems (e.g., medium density polyethylene (MDPE) pipes for natural gas distribution), understanding the response of these piping when subjected to ground movements is an important consideration.

Over the past 13 years, an extensive research study has been conducted at the University of British Columbia (UBC) in collaboration with FortisBC Energy Inc., of Surrey, BC, to study the performance of buried MDPE pipes subjected to relative axial and lateral ground movements. As part of this research, a full-scale pipe testing chamber was designed and constructed at UBC in which a series of pipe pullout tests were performed on straight and branched MDPE pipe configurations in both loose and dense Fraser River Sand (Anderson 2004). The test results indicated that the peak axial pullout resistance predicted using published design equations (ASCE 1984; ALA 2001) tend to over-predict axial pullout resistance of MDPE pipes in uncompacted sand and to underestimate pullout resistance in dense sand. Additionally, the results showed that the anchoring effects of branched pipes generate significant strain concentrations in both the trunk line and the branch pipes in gas distribution systems.

Weerasekara (2007) carried out further pipe pullout tests on various MDPE pipe configurations using the same soil chamber, and the results from these works further indicated that buried MDPE pipes subjected to relative soil movements in the axial direction cannot be predicted using the simplified design equations, primarily due to the complex soil-pipe interaction arising from the flexibility and the non-linear material response of PE pipe. These mechanisms were further complicated by the arching and shear-induced dilation and effects from the soil around the pipe. The test results also provided a reliable database for calibrating and/or validating numerical and analytical models for potential future studies. This work led to a new analytical model to account for the nonlinear material response of MDPE pipes allowing the user to obtain the response of the pipe (strain, force and the mobilized frictional length along the pipe) for a known relative displacement of the pipe. The new analytical solution incorporates the influence of soil dilation and frictional degradation.

Furthermore, Weerasekara (2011) performed large-scale field tests, in which good agreement between axial pullout mechanisms measured during pullout testing and estimates from the new analytical model were observed. The tests conducted included different soil and burial conditions, displacement rates and pipe properties Additionally, as a part of Weerasekara’s (2011) research, the analytical model was further developed to account for the case of extensible pipes that are subjected to combined loading from axial tension and bending when initial soil loading is acting perpendicular to the pipe axis.

Using the pullout test results obtained from the above listed studies for validation, more realistic performance behaviour has been observed using the new analytical solution compared to the results obtained from traditional design equations.

The purpose of this paper is to present the current research work that is being initiated at UBC in succession to the previous studies on this topic. The current work consists of a large-scale field testing program, comprised of five MDPE pipe alignments, each 24 m in length, buried in a very slow moving landslide located in Chilliwack, BC. Each of the buried pipes has been instrumented with an array of strain gauges from which measurements are recorded regularly in order to monitor any relative changes of the pipe strain occurring due to the continued ground movement at the site. Several survey monuments have also been installed across the site in order to closely monitor the ground movements that occur over time.

2 DESCRIPTION OF THE GEOHAZARD AT THE SELECTED RESEARCH LOCATION

The selected site for this research study is located within a residential development just east of Chilliwack, BC, situated on the toe of a 4,000-year-old, very slow moving (Cruden and Varnes 1996) landslide. Ground movements have been observed at the site since the property development in the early 1990’s. The site location is depicted by the red balloon in the plan-view area map below in Figure 1, and a photo taken facing the toe of the landslide mass is shown in

Figure 2.

Figure 1 Research study location map (Google Maps 2014)

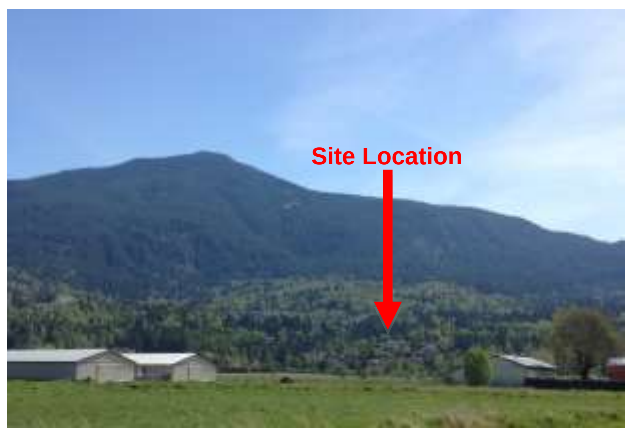

Figure 2 Photo of the site with the research location shown by the red arrow (photo taken facing south)

Based on the available geotechnical information extracted from the 2010 Association of Professional Engineers and Geoscientists of BC (APEGBC) Annual Conference (Watts 2010) and several engineering reports available from local municipal authorities that outline the preliminary investigation into the cause of the ground movements at the selected research location, it is understood that the site is underlain by an upper colluvium (geo-materials at the foot of a slope brought there by gravity; including landslide material), including surficial fill about 5 m thick and comprising mostly of sand and gravel, with trace to some silt. Underlying the upper colluvium is a distinctively black weathered shale-derived landslide mass comprising mostly of silt and clay mixed with some sand and gravel, and occasional cobbles and boulders. The mass is generally stiff and moist, but contains discrete softer wet and harder dry zones. The shale-derived mass overlies Fraser River floodplain deposits consisting of organic silts and fine sand. Generally, the ground surface at the site slopes in the Northeastern direction at an angle of about 8° to 12°.

Detailed investigations carried out by consultants retained by the local stakeholders suggest that the ground movements are within the shale-derived landslide mass and that the observed ground movements are promoted by high water pressures in the network of water-filled cracks within this landslide mass. The high groundwater pressures most likely resulted from water infiltration due to land clearing and subdivision development. It should be noted that the mechanisms of ground movement within the shale-derived mass at this location are not fully understood and the cause of the original landslide has not been established.

In addition to the geotechnical reports outlining the preliminary assessment of the cause of the slope movements at the site, several reports summarizing survey field monitoring data for the site dating back to February 2004 were reviewed. These survey monitoring data suggest that throughout a seven year period, from February 2004 to February 2011, ground movement as much as 450 mm in magnitude has occurred at the site. This suggests that on average, about 5 mm of ground surface movement is occurring at the site each month. The ground movements are occurring in the North-eastern direction, approximately parallel to the slope of the ground surface.

Figure 3 and Figure 4 below illustrate some of the damage that has occurred to the existing residences and paved roadways at this location caused by the perpetual ground movement.

Figure 3 Example of damage to existing residences caused by ground movement (Watts 2010)

Figure 4 Example of damage to pavement caused by ground movement

In general, the above described landslide setting provided an ideal environment to study the performance of buried polyethylene natural gas distribution pipelines subjected to permanent ground deformation. After consultation with local authorities, provisions to two residential lots located at this site were granted where the field study described herein and currently underway has been conducted. Figure 5 below provides an overview of the subject research site, where the small black arrows indicate the approximate direction of the ground surface movement.

The engineering reports from local municipal authorities that were reviewed for this publication are confidential and cannot be released herein. Limited information describing this landslide is available to the public domain, but some information can be obtained from Watts 2010.

Figure 5 Overview of the subject research site

3 LARGE-SCALE FIELD TEST PROGRAM DETAILS

A total of five pipeline alignments, each approximately 24 m in length, were installed during this research to investigate the performance of straight and branched natural gas pipeline configurations when subjected to ground movements in both the axial and lateral directions of pipe alignment.

Alignments 1 through 4 were installed such that the alignments of the pipelines are parallel to the anticipated direction of the predominant ground movements occurring at the site. The intent is that the soil loads developed from the relative axial soil movement will extend the pipes in axial direction. In contrast, Alignment 5 was installed with the axial length of the pipeline perpendicular to the ground movement in order to develop tensile forces in the pipe resulting from relative lateral pipe movement.

Two, 3-m long branch pipes, each having 26.7 mm outside diameter, were attached to the trunk line of Alignment 1 using tapping tee connections and butt fusion joining techniques at 2.0 m and 4.0 m from the top, or uphill end, of the alignment. The purpose of the branch connections is to replicate pipe configurations typical of local natural gas pipeline distribution networks. Figure 6 below shows the general pipeline alignment configurations installed at the site. The angles provided in the figure indicate the orientation of the alignments with respect to North.

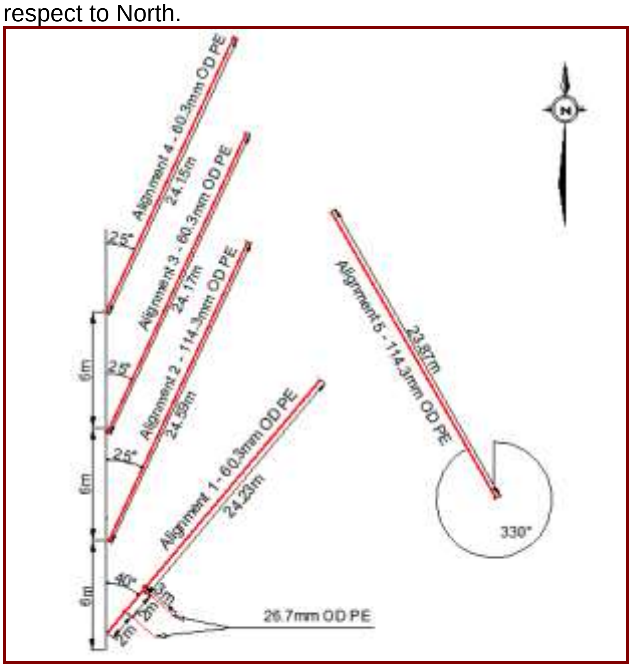

Figure 6 Installed pipeline alignment configuration and layout

For all five pipeline installations, locally available Fraser River Sand (FRS) was used as the soil backfill. For typical buried natural gas distribution pipeline installations, it is customary to reuse the excavated trench material as pipe backfill, however FRS was chosen for this project in order to protect the pipe instrumentation throughout installation and compaction as well as for its well known material properties. Additionally, FRS has been used extensively in previous full-scale natural gas pipeline testing at UBC.

The uphill ends of Alignments 1, 2, 3 and 4 are anchored using buried lock-blocks acting as dead-man anchors. The primary objective of the anchors is to create boundary constraints that can be implemented in subsequent analyses. The downhill ends of these four alignments are left free. The south end of Alignment 5 has also been attached to a buried lock-block to restrict movement in the lateral and the axial direction at this end. The north end of this pipe has been left free.

Since the stress-strain response of polyethylene pipes depends on the in-situ operating temperature, the temperatures of the pipelines at their respective burial depths are monitored using six resistive temperature devices (RTDs), which have been installed across the site. Obtaining the temperature measurements at the time of the strain gauge data collection is also important in order to be able to normalize the gauge measurements for temperature changes so that any relative strain induced in the pipe caused by relative ground movement can be identified.

Additionally, three 0.20 m long sections of 60.3 mm pipe, each with two strain gauges attached diametrically opposite to one another have been installed at the site to provide baseline strain gauge readings for the duration of the project. These three pipe sections were buried adjacent to the pipes at their respective burial depths at three different locations across the site.

3.1 Strain Gauge Instrumentation

As described above, one of the main objectives of this research work is to obtain a reliable data set of ground movement and associated pipe strain data. As such, a considerable amount of effort was put in to installing strain gauges along the lengths of each pipe alignment in order to measure strain within the pipe specimens. The previous experimental pipe research (Weerasekara 2011; Groves 2014) proved successful with installing strain gauges onto MDPE pipes using specialized procedures developed at UBC. Based on the previous success, these installation procedures were adopted for the current research and additionally, a waterproof coating procedure was developed to protect the gauges in the field for the duration of the research, which is expected to be several years.

In total, 227 strain gauges were installed along the lengths of the five alignments. A detailed strain gauge labeling procedure was adopted for the program in order to associate the strain gauge readings from the lead wires at the ground surface to the strain gauges attached to the buried alignment. Each of the strain gauge lead wires exiting at the ground surface is labeled with its respective gauge identification.

3.2 Data Collection at Research Site

As part of the ongoing project, the test data that is regularly monitored and collected includes: strain gauge measurements, ground surface movements, pipe displacements, ground temperatures at the pipe burial depth, air temperatures and the precipitation levels.

Further information pertaining to the field test installation details can be obtained from Groves (2014).

4 CONSIDERATIONS FOR USING FIELD DATA FOR PREDICTING AXIAL PIPE STRAIN USING UBC ANALYTICAL MODEL

The following section presents the anticipated approach for using the data from this study in the new analytical model developed at UBC to calculate the pipeline axial strains for the buried pipes. At the time of preparation of this paper (i.e., early stages after installation of the instrumented piping system), the ground movements and pipe strains that have occurred at the site are too small to be accurately identified by survey methods. In consideration of this, a hypothetical scenario of landslide-induced movement has been assumed to conceptually illustrate the anticipated future validation or analysis of the analytical framework. Outcomes from the analytical approaches can be more effectively compared with the field experimental data set as more data becomes available from the field system with passage of time.

4.1 Overview of the UBC Analytical Model

Generally speaking, the overall buried pipe response depends on the pipe properties (e.g. pipe cross-sectional area, stress-strain behaviour of pipe material) and the soil characteristics (e.g. pipe burial depth, soil density, internal friction angle of the soil, interface friction angle between pipe and soil, stiffness of the soil, coefficient of lateral earth pressure). The analytical framework derived by Weerasekara (2011) incorporates all of these aspects into the model.

The new analytical model is a closed-form solution that incorporates a new interface frictional model to idealize more realistically the effect of the soil loads developed from relative axial soil movement. The model was mainly developed to overcome the shortcomings of the soil-pipe bilinear frictional models that are commonly adopted in pipeline guidelines. Additionally, the nonlinear viscoelastic properties of the polyethylene pipes are accounted in the formulation as opposed to the typical linear-elastic or bilinear stress-strain response adopted in practice. The analytical solution was derived to determine the pipe response arising from axial soil loading by combining the new interface friction model and the nonlinear stress-strain behaviour of the pipe material. Further details pertaining to the derivation of the new analytical model can be obtained from Weerasekara (2011) and Wijewickreme & Weerasekara (2014).

The validity of the closed-form solution was previously assessed by comparing the calculated response of 60-mm and 114-mm diameter pipes in axial pullout with experimental results from pullout tests performed on the same diameter pipes using the soil chamber at UBC (Weerasekara 2011) The predictions were made using parameters determined from element testing of pipe and soil combined with experience-based judgment from axial tests conducted on steel pipes.

The experimental pullout resistance and strain characteristics were obtained from load cell and strain gauge readings directly from the axial pullout tests performed on the pipes. A close match between the predicted and experimental results for the tests validated the parameter selection for the formulation of the closed-form solution (Wijewickreme & Weerasekara 2014). Very good agreement between the measured and the predicted values were observed, confirming the ability of the closed-form solution to represent the mobilization of friction along the pipe length at low to moderate strains in general.

4.2 Summary of Field Data for Model Input Parameters

The following sections provide a summary of the field data required for the model as input parameters to calculate the pipeline axial strain for the current field study. It also presents ways to conceptualize the landslide geometry at the subject site, selection of input parameters, and underlying assumptions to enable predictions using the model.

4.3 Identifying Slide Geometry at the Site

In order to apply a soil-pipe interaction model to a real-life scenario, identifying the geometry of the sliding soil mass is of significant importance. The sets of equations in the model have been developed for a slide geometry in which the ground moves as a block in the vicinity of the pipe as opposed to flowing around the pipe.

Generally, under a landslide, tensile stresses can develop in the pipe section at the ground separation zone when the sliding block is separated from the stable ground. For experimental studies on pipeline components, a block-displacement type ground deformation is a reasonable simplification for reproducing the soil displacement conditions occurring around a relatively localized section of pipeline (Anderson 2004).

For the present study, ground surface survey hubs that were installed at the research site following the pipeline installations are used to monitor the relative ground displacements. As indicated earlier, it is only early stages after installation of the instrumented piping system; as such, the ground movements that have occurred at the site are too small to be accurately identified by survey methods.

A block type slide movement with the weak soil layer situated below the pipe burial depth is considered to constitute the mobilized field ground movement. Furthermore, it is assumed that the relative ground movements at the site are acting parallel to the axial lengths of Alignments 1, 2, 3 and 4 depicted in Figure 6 and that the ground separation point is located at the axial midpoint of each of the alignments - i.e., at the 12 m point from the uphill ends of the alignments.

As the ground continues to move at the site and more ground surface survey data is collected, further refinements of the slide geometry and relative ground movements can be made allowing for more detailed analysis of the buried alignments.

4.4 Input Parameters of the Analytical Model

Clearly, it is important to have a set of representative input parameters for use in validating the new analytical frameworks. When using the derived equations from the closed-form solution, the geometric parameters of pipe burial depth to springline (H), outside pipe diameter (D), pipe cross-sectional area (A_p) and average soil density (γ) are constants that are measured directly and were accounted for relative easily prior to and during the pipeline installations. Determining appropriate input

parameters for the remainder of the closed-form solution, however, is not straightforward. For the current study, the selection of these parameters generally follows those from the analysis conducted by Weerasekara (2011); therefore, only limited discussion on these are included herein.
Adopting model parameters from previous analysis is considered reasonable for the purpose herein which is to illustrate a framework for strain calculations of the axially loaded pipelines. In accord with this thinking, Table 1 at the end of this paper provides a summary of input parameters for the study to be used for modeling the pipeline performance. In Table 1, ground-movement rates have not been identified at this point in time. However, the model user can choose a ground displacement rate of approximately 5 mm/month for the time being until appreciable ground surface movements have been observed in the field.

5 CONCLUSIONS

A research program was initiated at UBC in collaboration with FortisBC Energy Inc. in British Columbia to investigate the performance of buried MDPE pipelines subjected to ground movements. During the earlier stages of this research, a full-scale pipe-soil testing facility was developed and several full-scale pipe pullout tests on selected sizes and configurations of MDPE pipes were performed. During more recent stages of this research, a field testing program was conducted using axial pipe pullout tests with different burial depths, pullout rates and loading regimes. The laboratory and field pullout tests led to the development of a new analytical model to determine the response of pipes subjected to axial and lateral soil loading. The model was derived using an interface frictional model to account more realistically for the soil dilation and interface friction behaviour, in combination with the MDPE pipe nonlinear pullout stiffness and resistance, displacement as well as mobilized frictional lengths obtained from the experimental data.

In order to extend the applicability and validity of this analytical model to buried pipeline systems in the field, a research program was undertaken involving the installation of buried MDPE pipe alignments in a slow-moving landslide located in Chilliwack, BC. The installed pipes are instrumented with strain gauges for measurement of pipe strains during ground displacements, along with monitoring of the system for overall pipe and land movements.

As a result of the slow rate of the ground movements at the research location and the early stages of this research program, the field results have not yet developed into a significant data set. It is the authors' intention to follow up with future publications to present the field test results and the associated analytical work.

The ultimate goal of this research is to help develop guidelines and criteria to determine the amount of ground displacement associated with the safe operational strain limits of buried natural gas distribution pipelines.

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UBC Model Input Parameter[1]	Align. No. 1	Align. No. 2	Align. No. 3	Align. No. 4	Align. No. 5
Interface friction on MDPE pipe					
Thickness of the soil shear zone outside of the buried pipe diameter (mm)	3	3	3	3	3
Shear modulus of soil at shear stain of γ, $G_{(\gamma=2.5\%)}$(kN/m^2)	600	600	600	600	600
Effective soil unit weight (kN/m^3)	18.1	18.1	18.0	18.4	18.9
Depth to burial to pipe springline (m)	0.75	0.90	0.65	0.75	0.90
Coefficient of lateral earth pressure, K_0	0.5	0.5	0.5	0.5	0.5
Interface friction angle between soil and pipe, δ (degrees)	16	16	16	16	16
Displacement at zero dilation (mm)	50	50	50	50	50
Pipe Properties					
Pipe outside diameter (mm)	60.3	114.3	60.3	60.3	114.3
Pipe wall thickness (mm)	5.48	10.32	5.48	5.48	10.32
Rate dependant hyperbolic constants					
a	2020	2020	2020	2020	2020
b	0.109	0.109	0.109	0.109	0.109
c	43.35	43.35	43.35	43.35	43.35
d	1.37	1.37	1.37	1.37	1.37
Ground movement conditions					
Ground movement rate (mm/mo.)	-	-	-	-	-
Parameters that are not part of the analytical solution					
Alignment Burial length (m)	24.23	24.59	24.17	24.15	23.87

[1]Further details pertaining to the selection of input parameters listed in Table 1 for the UBC model are available from Weerasekara (2011)

Table 1 Summary of input parameters for UBC model