Field monitoring and modeling of natural gas pipelines subject to ground movement

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ABSTRACT
The performance of buried pipelines in areas subject to permanent ground displacements is an important engineering consideration to the local gas utility companies, since the failure of such systems poses a huge risk to public and property safety. This paper presents the components of the Natural Hazard and Risk Management program implemented by FortisBC Inc., as the local gas supplier to mitigate the risk of pipe failures triggered from an ongoing slow ground movement in West Quesnel area. Pipe-soil interaction analysis is a key component of this program, as a means of correlating the measured ground movements and its variations over time to the condition of the buried pipe. The challenges in conducting pipe-soil interaction analysis for a large geographical area and complex pipe network are discussed. Also discussed are the recent developments in estimating the pipe strain in small-diameter gas distribution pipe networks and limitations of these methods.

RÉSUMÉ
La performance des canalisations enterrées dans les zones soumises à des déplacements terrestres permanentes est une considération importante de l'ingénierie pour les entreprises de distribution de gaz locales, depuis l'échec de ces systèmes pose un risque énorme pour la sécurité publique et des propriétés. Cet article présente les composantes du programme de catastrophes naturelles et de gestion des risques mis en place par FortisBC Inc., en tant que fournisseur de gaz local pour atténuer le risque de bris des conduites déclenché à partir d'un mouvement de masse lente en cours dans la région de l'Ouest Quesnel. L'analyse de l'interaction conduite-sol est un élément clé de ce programme, comme un moyen de corréler les mouvements du sol mesurées et ses variations dans le temps avec l'état de la canalisation enterrée. Les défis en matière d'analyse de l'interaction conduites-sol pour une vaste zone géographique et réseau de conduites complexes sont discutées. Sont également discuté les développements récents dans l'estimation des déformations de la conduite dans les réseaux de distribution de gaz de petit diamètre et les limites de ces méthodes.

1 INTRODUCTION

Geohazard in the form of landslides is a key consideration to the utility owners due to social, economic and environmental implications that likely to arise from a failure of a pipeline. Understanding the complex landslide movements in natural slopes requires an interpretation of the origin and history of the underlying geological materials. Once the geohazard is identified and quantified, one of the key challenges has been to perform pipeline integrity assessment to quantify the risk of pipeline failure. This paper presents the details of a pipeline integrity management program initiated by FortisBC Inc. to mitigate the risk of the pipeline failure triggered from a slow-moving landslide identified in West Quesnel, British Columbia, Canada (Figure 1). This deep-seated ground movement occurring at a rate of 2 to 7 cm per year has affected about 940 parcels of land, 750 homes, one elementary school and several businesses.

West Quesnel is important to the economic and social viability of the City of Quesnel and is home to almost 25% of the City's population. The area of West Quesnel impacted by the ground movement includes an attractive, established residential community. The degree of impact from the landslide on buildings and infrastructure vary within this area. Some properties have not been impacted as the slip surface is very deep and the ground moves uniformly with minimal differential movement. Contrary, the buildings and buried utilities located in areas undergoing large differential movement have sustained significant damage, which includes structural cracks, broken pipes and damage to roadways.

Figure 1. Impacted area and direction of slide movement

West Quesnel has been the subject of a number of engineering investigations since 1973. The initial investigations were performed by the Ministry of Transportation and Highways, but these studies neither specifically addressed the area nor identified the ground movement as a concern. Subsequent studies in the 1990s were inconclusive, mainly due to the slow rate of the movement which made it difficult to discover. Ground movement in West Quesnel was first conclusively identified in an investigation commissioned by the City in 2000-2002. Between 2003 and 2011, the City commissioned additional geotechnical and hydrogeology work to outline the boundaries of the affected area and to provide guidance on remediation strategies. Recently a remedial program to reduce the slide movement was initiated based on the results of detailed geotechnical and hydrogeological investigations.

1.1 Role of FortisBC

While the City of Quesnel is responsible for managing the deep-seated landslide and its overall impact to the residents, their buildings and its utility infrastructures, FortisBC efforts are limited to effectively managing the integrity of the gas pipelines. FortisBC is working closely with the City in implementing landslide monitoring program, sharing the data and analysis results.

In 2001, FortisBC (then BC Gas) replaced its entire steel gas distribution piping system with a flexible medium density polyethylene (MDPE) piping system at a cost of $2 million. Despite the better performance history in accommodating large differential ground movements, the MDPE pipes have been straining from the ongoing slow ground movement since its initial replacement. The key challenge has been to relate the measured ground displacement to the strain in the pipe, such that FortisBC can undertake the necessary remedial measures.

1.2 Challenges

FortisBC is faced with several unique challenges while implementing a pipeline integrity management system to the pipe network at West Quesnel. First, there are challenges in conducting pipe-integrity assessments for a complex pipe network that spans over a large geographical area. For example, the gas distribution network consists of over 17 km of buried pipes spanning over an area of about 2 km^2. This is different to a typical an assessment conducted for a transmission pipe, where the impacted pipe length from the geohazard is typically limited to a relatively smaller length such that it can be modeled relatively easily using a numerical or analytical tool (e.g., pipe crossing a river or an active fault).

Secondly, the existing analytical techniques have been developed for large-diameter steel transmission pipelines, and there is considerable uncertainty when attempting to extend these methods to analyse plastic pipes that exhibit smaller deformation stiffness, highly nonlinear stress-strain response and complex loading from surrounding soil. In addition, the analysis becomes complex due to presence of frequent pipe connections in distribution pipe networks. At West Quesnel, gas distribution system forms a complex pipe network that comprises pipe diameter ranging from 42 mm to 114 mm, except for the 25 mm diameter tubes that connects the service tees to residences.

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2 GEOHAZARD MANAGEMENT PROGRAM

With this background, FortisBC has implemented a specific program on Geohazards Management program known as Natural Hazard and Risk Management (NHRM) Program for identification, assessment, monitoring and, where necessary, undertaking remediation of seismic, hydrotechnical, and geotechnical hazards. The NHRM program dictates continued inspection and monitoring of the identified hazards at a frequency proportionate to the risk to pipeline. In addition, the program is used to maintain an audit of each hazard site, track changes in the risk, and document actions/mitigation tasks performed to those sites across the FortisBC gas supply pipeline system.

The program requires all probable geohazards identified in the detailed baseline surveys to be entered into the database. The database contains specific details of each hazard site, an assessment of risk of pipeline exposure, recommendations for future inspection or mitigation and priority actions depending on the risk of pipeline failure. The results of the NHRM program are managed and reported through a Geohazards Dashboard` and the performance indicators are evaluated in quarterly-basis.

Under the NHRM program, the following has been implemented since 2002 for the West Quesnel area:

1. Ground movement monitoring using over 60 survey hubs (jointly performed by the City and FortisBC)
2. Soil–pipe interaction analysis using numerical and analytical models
3. Dig-program to validate the results from pipe-soil interaction analysis
4. Research partnerships with academic institutions and private consultants to address the limitations in current understanding of pipe-soil interaction analysis
5. Geotechnical drilling, groundwater and slope inclinometer measurements (by the City)
6. Leak detection program

The subsequent discussions in this paper are predominantly focused on the pipe-soil interaction analysis conducted on small-diameter MDPE pipes. The challenges in conducting pipe-soil interaction analysis for small-diameter flexible pipelines and limitations in the approaches are also discussed.

3 PIPE-SOIL INTERACTION ANALYSIS

Despite being able to measure the ground movements and its variation with time with reasonable accuracy, correlating these movements to the condition of pipe (i.e., strain in pipe) is a difficult undertaking. As a result, pipe-soil interaction analysis is an essential component of the pipeline integrity management program in order to quantify the pipe strain based on the measured ground displacement. The steps involved in this process are described in the following sections.

3.1 Initial Screening and Determination of Ground Deformation Pattern

Due to the larger scale of the geohazard, an initial screening was required prior to discretizing the pipe network into smaller sections for undertaking detailed pipe-soil interaction analysis. For this screening, preliminary estimation for pipe strain was made using the analytical tools discussed in Section 3.2. Although, these analytical tools require several input parameters, for the screening, only three key input parameters were considered: (i) pipe diameter, (ii) pipe orientation with respect to ground movement and (iii) relative ground movement. Typical values were assumed for the remaining parameters. For pipes subject to soil loading along their axes, Figure 2 shows the variation of pipe strain with ground movement for three different pipe diameters commonly employed in gas distribution industry. Based on the strain estimated using these plots, the pipe sections were ranked as high, medium and low-risk. FortisBC currently employs 8% as the maximum allowable strain for MDPE pipes and any pipe section experiencing greater than 6% axial strain (high-risk) was selected for the detailed analysis described in Section 3.2. The ground monitoring program has identified the approximate boundaries of the toe and head scarp of the slide mass, and the largest distress in pipe are generally expected at these boundaries.

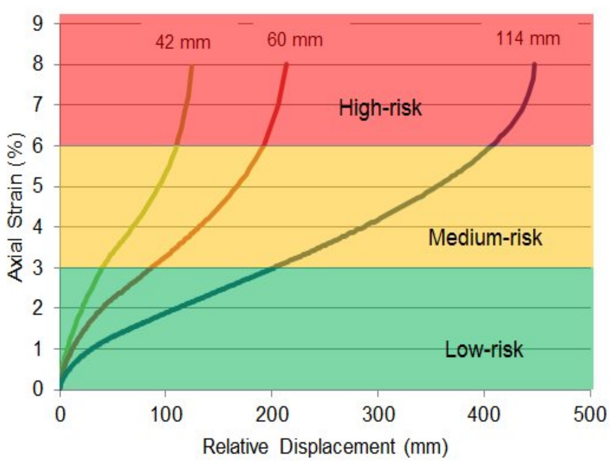

Figure 2. Variation for of axial strain with relative ground displacement occurring along the pipe axis (for screening purpose only).

Despite over 60 survey hub installed in the area, on average, the distance between survey hubs is about 150 m. For a small-diameter, highly flexible pipe, the impacted length from abrupt ground movement could be as small as 10 m even when the strain exceeds the allowable strain limit. As a result, additional survey hubs have been placed at these critical locations for accurately estimating the ground deformation pattern. Note that the accurate modeling of the ground displacement pattern is an important consideration as discussed later in this paper. Figure 3 shows such critical pipe section between along Abbott Drive, near the toe of the slope, where 9 additional survey hubs were installed in 2011.

Figure 3. Additional survey hub installed along Abbott Drive

3.2 Pipe-Soil Interaction Modelling of Plastic Pipes

FortisBC's research collaboration with the University of British Columbia (UBC) has led to the development of improved analytical model to estimate the pipe strains. Arising from this research undertaking, Weerasekara (2011) proposed two analytical models for estimating the pipe strain arising from soil loading along the pipe axis (i.e., axial model) and perpendicular to the pipe axis (i.e., lateral model).

In the "axial model", the non-linear viscoelastic stress-strain behavior (i.e., strain-rate dependant) of plastic pipe was considered. In addition, an improved interface friction model was developed to account for the increased friction due to constrained dilation of the soil, which has a significant impact on small diameter pipes. This interface friction model was combined with the nonlinear pipe stress–strain model to derive an analytical solution based on the element-level equilibrium of pipe. Using this model, axial force, strain and mobilized length along the pipe can be determined for a measured ground displacement. Large-scale field pipe pullout tests were performed to verify the results obtained from the analytical model, in which good agreements were observed for tests conducted at different soil/burial conditions, displacement rates and pipe properties.

The model developed for lateral loading directly account for the axial tensile force development due to elongation of the pipe. This has led to more realistic pipe behavior estimations by overcoming some of the limitations in the mathematical models used in certain commercial programs. However, the model for lateral loading has not been validated using large-scale tests due to logistical constrains in performing such tests. For brevity, details of these analytical models are not discussed in this paper.

In addition to the analytical modeling, certain pipe segments were selected for Finite Element (FE) modeling to model more complex loading conditions and pipe configurations, however details are not discussed herein.

4 RESULTS AND DISCUSSION

The purpose of this paper is to illustrate the general approach and limitations in the current methods, therefore, the model or input parameters are not discussed in detail. The results of the pipe-soil interaction analysis and the uncertainties in the estimated strains from this approach are listed below. For discussion purposes, 42 mm diameter pipe section between Allison and Avery Avenues was selected.

(i) Uncertainties in Soil Parameters & Burial Conditions: Although all soil input parameters (e.g., shear modulus, interface friction angle, lateral earth pressure coefficient, density, etc.) and burial condition (e.g., burial depth) can be determined through field measurements or by laboratory testing, for this analysis these parameters were estimated based on limited field visits. As a result, sensitivity analysis was conducted establish the best-estimate, lower-bound and upper-bound estimates for pipe strain. Figure 4 shows the maximum strain and corresponding mobilized lengths estimated based on the survey conducted in August 2013. As illustrated in Figure 5, a pipe with an increased interface friction would require a shorter mobilized pipe length to reach the same level of strain. As discussed later in this paper, this aspect is an important consideration in deciding whether the anchoring resistance of a pipe connection has been mobilized.

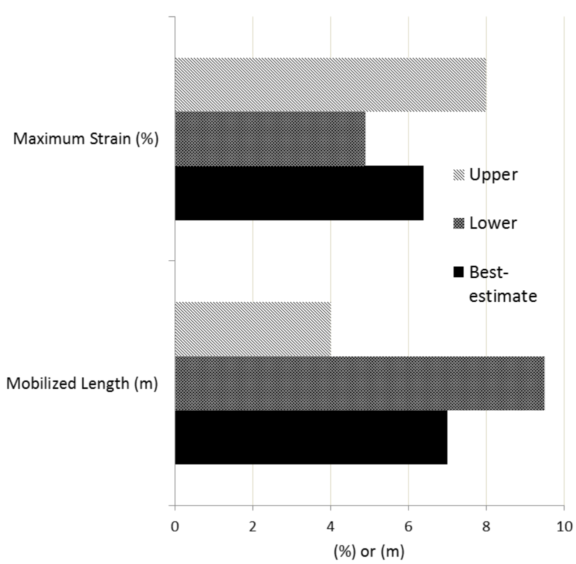

Figure 4. The best-estimate, upper and lower bound estimates for pipe strain and mobilized length as of Aug 2013.

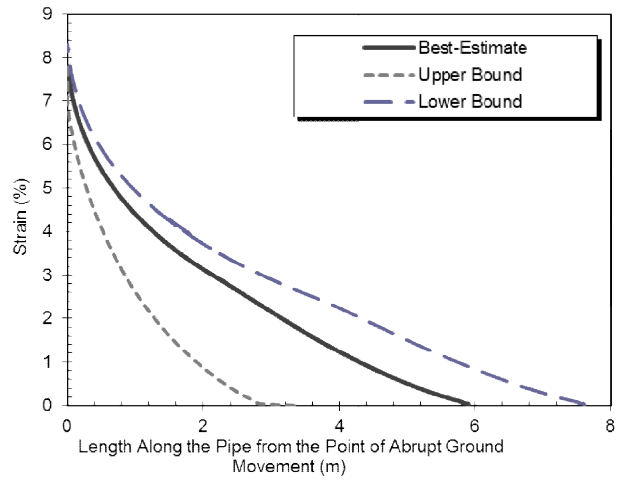

Figure 5. The distribution of strain along the pipe for best-estimate, upper and lower bound estimates.

(ii) Uncertainties in Ground Displacement Rate and Pipe Material Behavior: Since MDPE pipes are viscoelastic and the stress-strain response is strain-rate dependant, the estimated pipe strain and stress depend on the selected ground displacement rate. The ground displacements are surveyed quarterly basis; however, the actual ground movement could occur at a much faster rate, generally during the period with high precipitation. As per Figure 6, larger strains and smaller stresses are expected for a slower ground displacement rate.

Most commercial programs do not have built-in models to simulate the actual strain-rate dependant viscoelastic behaviours. For the FE modelling conducted for this study, the non-linear stress-strain behaviour of the pipe material was modelled using a hyperbolic stress-strain model that corresponds to a constant strain rate of loading. However, it is important to note that pipe strain rate will vary, even if the rate of soil block movement remains constant.

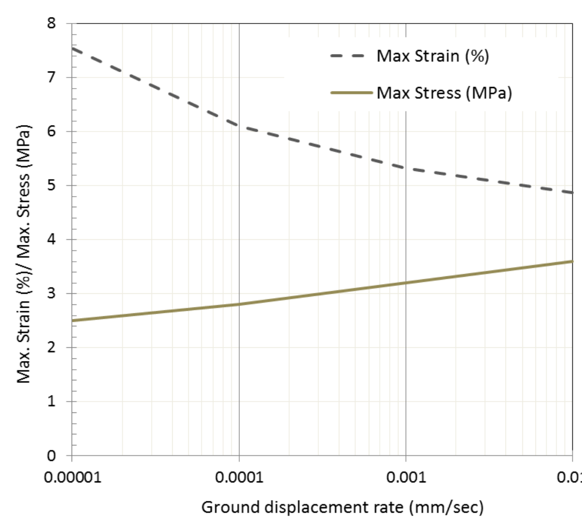

Figure 6. Impact of ground displacement rate on the measured stress and strain in pipe

(iii) Anchoring resistance from pipe joints: As discussed by Weerasekara (2007), the anchoring resistance generated from the “tapping-tee” connection has a significant impact on the performance of smaller diameter pipes, especially, if the MDPE pipe is less than 114 mm in diameter. When this resistance is mobilized, a very large increase in localized strains near the tapping tee has been observed. The strain distribution along the pipe before and after mobilizing the anchoring resistance of tee connection is shown in Figure 7.

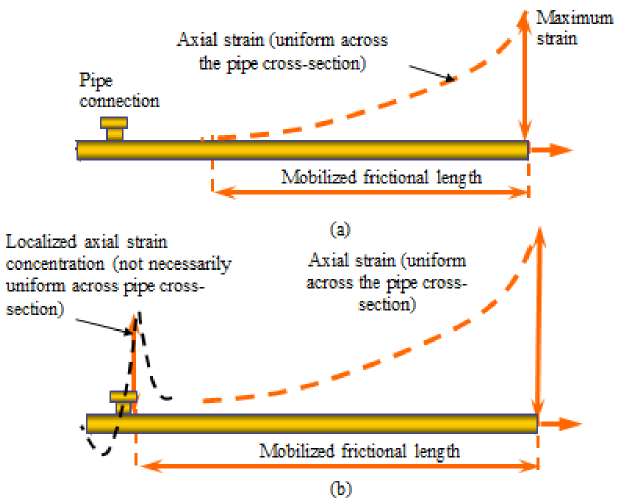

Figure 7: Schematic illustration of the axial strain distribution along a pipe (a) before and (b) after mobilizing the anchoring resistance of the tee connection.

Once mobilized, the maximum soil resistance from the tee connection (F_T) can be determined using the following equation (Weerasekara 2007):

$$F_T = (N_q \gamma H) A_t \qquad [1]$$

Where *H* is burial depth, γ is soil unit weight, A_t is the projected area of the tee in a plane perpendicular to the direction of the movement, horizontal bearing capacity factor (N_q) is obtained from ASCE (1984) guidelines for vertical anchor plates/pipes, which depends on the H/D ratio and peak friction angle (D is the pipe diameter). If a bilinear soil-spring model is considered, the displacement required to mobilize the maximum anchoring resistance of the tapping tee (y_h) is estimated to be about $y_h/H = 0.02$ which is in accord with the experimental observations reported for pipes and vertical anchor plates buried in dense sand (ASCE 1984). Using this approach, F_T of a typical tapping tee is expected to be about 2.0 kN, which is significant compared to the frictional forces developed in pipes with diameters 60 mm and smaller.

(iv) Uncertainties in slide geometry: The strains developed in buried pipes as a result of the differential displacements occurring in adjacent soil blocks. In particular, near the toe of the slide, it is difficult to distinguish the stationary and moving soil blocks due to complex translational and rotational block movements occurring within the transition zones. As a result, the relative displacement between the pipe and ground is expected to change gradually compared to an abrupt change in displacement. The abrupt soil block movements will lead to larger strain concentrations compared to a slide geometry consist of gradual change in displacement. To illustrate this aspect, for the pipe section between Allison and Avery Avenues, a maximum strain of 6.5% was estimated assuming an abrupt block type movement; whereas the maximum strain is expected to be about 3.5% if the ground displacement is gradually changing over the pipe length.

(v) Uncertainties resulting from temperature effects: Although the temperature effects are not explicitly accounted in these analyses, the same analytical framework can be used to account for the temperature dependency. As noted by Stewart et al (1999), the modulus change of about 15% is expected when temperature changes from 18 to 23C. Further research is required to quantify the temperature dependant stress-strain behavior.

(vi) Strain redistribution in MDPE Pipes: Field pipe pullout tests conducted at UBC has shown evidence of pipe strain redistribution. Under a sustained load, the polymer strands in the pipe will orient themselves in the direction of the external load, relieving some the stresses and mobilizing more pipe length over time. In these tests, about 30% drop in maximum strain was observed within a period of ten days. At the same time, the mobilized frictional length was increased by about 2 m. The material models used in FE analyses or in UBC analytical model are not capable of capturing such complex behaviour.

Considering the inherent uncertainties and limitations in pipe-soil interaction analysis, FortisBC has implemented a ‘dig program’ in conjunction with the ongoing analytical studies. Several critical pipe sections identified from the pipe-soil interaction analysis were selected for the dig program. However, several limitations in dig program prevent it from using as a method for validating the pipe-soil interaction models. For example, when a pipe section is exposed, the locked-in stresses in pipe are relived; hence it is not possible to detect the actual distress that pipe has undergone in its original burial condition. In addition, as the impacted pipe length is small in flexible small diameter pipes, detecting the most critical zone during a dig program is challenging due to difficulties in establishing the boundaries of the moving and non-moving soil blocks. Due to these limitations, the results from the dig program have been used only for qualitative assessments of the pipe condition.

Besides the limitations in pipe-soil interaction modeling, the estimated maximum pipe strain is expected to be less than 8% in the gas distribution system at West Quesnel. Note that FortisBC is currently adopting an allowable strain limit of 8%, and this value is likely to be revised based on the ongoing pipe material testing. The observations from the dig program also confirmed that certain pipe sections are distressed, although it was not able to quantify the strain. There is a possibility that some pipes to experience significant localized strains which are not being captured by the survey hubs. This possibility cannot be completely eliminated, but a larger number of survey points could reasonably improve the estimation of pipeline strain.

5 FUTURE RESEARCH REQUIREMENTS

The following research requirements have been identified to reduce the uncertainties discussed in the previous section.

(i) Field pipe strain monitoring program has been implemented with the aim of validating the analytical model in the existing field conditions. Depending on the outcome, the model will be calibrated and/or further refinement will be undertaken.

(ii) Regular monitoring of the landslides with a much larger number of survey points attached directly to the pipes at each slide location could improve our understating of the pipe performance. Additional ground surveys in selected survey points (located in critical areas) will be undertaken during the seasons with high precipitations to track the actual rate of ground movement.

(iii) Additional testing on branch pipe configurations will be undertaken to quantify the anchoring resistance of the tapping tees and its impact on the trunk and branch pipes.

(iv) A research program is planned to better characterize material stress-strain behavior with respect to temperature changes, material anisotropy (compression versus tension) and strain rate dependency.

6 CONCLUSIONS

This paper discusses the importance of using appropriate parameters and models for soil-pipe interaction analysis for estimating the strain/deformations of gas distribution pipe networks. In this regard, UBC analytical model provides the framework to relate the measured ground displacement to pipe strain, force (or stress) and affected length of the pipe. This model overcomes the deficiencies in current models in addressing in pipe-soil interaction aspects in flexible small diameter pipes. Nevertheless conducting sensitivity analysis to establish a likely range of strains is an important consideration due to the limitations in the model and uncertainties in estimating the input parameters. Further study on this subject should be undertaken to address the issues pointed out in this paper, which should make this model available and applicable for general users.

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REFERENCES

ASCE 1984. Guidelines for the seismic design of oil and gas pipeline systems, Committee on Gas and Liquid Fuel Lifelines, Technical Council on Lifeline Earthquake Engineering, ASCE, New York

Weerasekara, L. 2007. Response of buried natural gas pipelines subjected to ground movements, M.A.Sc thesis, Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada, 243 p.

Weerasekara, L. 2011. Pipe-soil interaction aspects in buried extensible pipes, Ph.D thesis, Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada.