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Measured Pipe Stresses on Gas Pipelines in Landslide Areas

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ABSTRACT

Landslides are a risk to buried gas pipeline infrastructure, but these risks are particularly difficult to assess given the complex nature of landslide movements. This paper presents a portion of research conducted at the University of Manitoba where gas pipelines within active landslide areas were monitored over a four-year period. Two locations were examined in Western Manitoba within the Assiniboine river valley where a shallow natural gas pipeline runs parallel to the valley slope. A field investigation and monitoring program was undertaken where surficial ground movements and soil and pipe temperatures and pipe strains through strain gauges were measured.

Monitoring results identified soil near the pipeline does not freeze, and ground movements are <50 mm/year. The monitoring results also showed pipe stresses and behaviour were affected by backfilling, thermal changes, soil-pipe relaxation, and ground movements. An unexpected outcome of the research was the response of the pipeline to slight ground movements was easily captured by the strain gauges and these movements, slow or surges tended to occur at the same time between the two sites suggesting movements occur due to regional environmental effects.

Keyword: Landslides, gas pipelines, strain gauges, soil-pipe interaction

INTRODUCTION

Natural hazards (often referred to as geohazards) are recognized by the pipeline industry as a risk to gas pipeline infrastructure, but these hazards are often underestimated and are not properly incorporated into design and operation of gas pipelines. This lack of consideration is due to the fact that geohazards are not a major contributor to pipeline failures as documented in several studies where only 7 to 9% of pipeline incidents are reported to be attributed to geohazards (European Gas Pipeline Incident Data Group 2020; Allergro Energy Consulting 2005; National Energy Board 2011). In fact, the percentage of pipeline incidents due to geohazards has increased to 15% in some regions, with landslides being the most common cause of incidents (European Gas Pipeline Incident Data Group 2020)(Figure 1). The major causes of pipeline incidents are external interference (40 to 50%), corrosion (15 to 25%) and construction (15 to 20%)(Ferreira 2016). However, the risk posed by natural hazards is proportionally significant, especially in active geological terrain where pipelines cross or run parallel to unstable slopes (landslides), meandering rivers or fault lines. Pipeline failures due to geohazards tend to result in catastrophic failures and complete loss of service (high consequence) while other hazards may result in failures with lower consequences such as slow leaks due to corrosion.

The primary supplier of natural gas in the Province of Manitoba has a pipeline system consisting of over 1,800 km of transmission pipelines and almost 8,100 km of distribution pipelines, almost exclusively comprised of steel pipe. The owner recognizes their pipeline system may be exposed to geotechnical hazards. These

transmission and distribution lines often traverse and run parallel to many rivers, streams and valleys. At these locations, there is a risk of damage to the pipelines due to geotechnical hazards, specifically, the potential for ground movements due to landslides, either transverse or longitudinal to the pipeline since their gas pipelines are typically buried at shallow depths (<1 m). These movements can lead to costly repairs, disruption of service to customers, and dangerous gas leaks. Consequently, there is value in being able to proactively assess the risk of pipeline failure within potential landslide areas, thus providing the ability to defer replacement/repair of a pipeline until it is necessary.

BACKGROUND

Due to the complexity and existing knowledge of soil/pipe interaction, currently there are no generally accepted methods to assess the transmission of stresses and strains onto buried pipelines in landslide areas. This limits the ability of pipeline risk management systems to properly characterize and classify risks associated with pipeline infrastructure.

The first step to determine risk of pipeline failure in landslide areas is to determine the strains induced on buried pipelines within the actively moving landslide. Once the nature of ground movements and magnitudes of movements are understood or have been assumed, determining structural loading due to ground movements is complex. This has lead to considerable uncertainty in available methods (Bruschi et al. 1995; D.G Honegger Consulting et al. 2009). Researchers have studied stresses/strains induced on pipelines due to ground movements predominantly through either

analytical, numerical, or experimental means (either laboratory or field based). Often studied in combination where one approach is used to supplement or verify the outcome of the other approach (Calvetti et al. 2004; Cocchetti et al. 2009a, 2009b; Wijewickreme et al. 2009). Analytical and numerical approaches for predicting stresses/strains induced on pipelines are more common in literature when compared to experimental methods. The analytical and numerical methods available use simplified (e.g. O'Rourke and Nordberg 1992; Triggs and Rizkalla 1994; Rajani et al. 1995) or complex approaches (e.g. Challamel and Buhari 2003; Chan and Wong 2004; Cocchetti et al. 2009a, 2009b) to predicate stresses/strains induced on pipelines due to ground movement. Research focusing on probabilistic approaches to determine limit states failure modes for pipelines subjected to ground movements is even more limited (Zhou 2012).

For analytical and numerical approaches, assumptions, estimates, and idealizations will always be required. These methods approach the problem starting from the soil/ground movement perspective and work towards determining the response of the pipeline as a final outcome.

Research was conducted at the University of Manitoba (Ferreira 2016) to gain a better understanding of stress/strains induced on pipelines due to landslides starting from the pipeline response, working towards linking it to ground movements, and ultimately, determining the risk of pipeline failure. This was achieved by measuring gas pipeline strains in actively moving ground over a four-year period and using

probability theory to determine if reliability based limit states failure criteria was exceeded in actively moving ground.

This paper presents the field investigation, instrumentation installations, and monitoring results. Interpretation of the monitoring data along with general observations are also presented.

Contributors to Strains/Stresses on Pipe

Possible sources of load that may be inducing strains/stresses on the pipe needed to be determined in order to determine the strains/stresses induced on a pipe solely due to landslide movements. Four primary sources (loading conditions) may potentially be imposing strains/stresses on pipelines (stress-state) in landslide areas. Other sources were reviewed, but were deemed inconsequential in comparison to the four primary load conditions identified. These four sources may occur individually or in combination and may change seasonally. The four primary sources are:

- Landslides movements
- Soil volume changes due to freezing/thawing of the soil around the pipe or water content changes in expansive soils (*e.g.* fine-grained cohesive soils)
- Soil Creep
- Elongation/Compression of the pipe due to temperature change (thermal effects)

Three of the four stresses are due to soil displacement around the pipe either due to ground movements or related to volume change associated with water. Stress change in the pipe related to temperature and soil volume changes is variable and transient, while the change in stress due to ground movements are expected to be cumulative, unless the axial displacement of the pipe exceeds the soil-pipe adhesion allowing the pipe to slip through the soil or the pipe permanently deforms (plastic behaviour).

Soil volume changes due to water content changes are difficult to measure or estimate, especially within the vadose zone where the pipeline in this research project is situated (± 1 m burial). Soil water content within the vadose zone is transient during non-winter months, however soil water content within the vadose zone would trend towards a natural water content if measured over a large enough period of time in an established environment. This would result in a relatively constant volume where notable changes in volume would only occur due to extreme events (drought, unseasonably wet year). The magnitude of applied stresses due to water content changes was therefore assumed to be minor most of the time when compared to the other sources of load identified and consequently, stresses induced on the pipe due to water content related soil volume changes were not examined.

SELECTION OF RESEARCH SITES AND FIELD PROGRAM DETAIL

Two gas pipeline sites referred to as Harrowby and St. Lazare sites were selected due to the risk of landslides affecting gas services and the complex geological features at the sites. The sites represent conditions where a gas pipeline transverses a potential

landslide area (unstable slope) or a slope undergoing creep movements on a larger scale since the pipelines run parallel to and across a deep river valley. The potential for ground movements at the sites were deemed to be either translational (assumed to be relatively shallow) or rotational associated with deep seated movements or combination thereof.

Both sites are located near the Saskatchewan/Manitoba border (Figure 2). The St. Lazare valley site is located about 1.3 km southwest of the town of St. Lazare (Figure 3) while the Harrowby valley site is located adjacent to the community with the same name which is about 12 km west of Russell, Manitoba (Figure 4). The sites are about 37 km apart, roughly north-south of each other.

Field Program Details

The field program was developed in a manner to measure, directly or indirectly, the possible sources of stresses on the pipes and to determine soil-pipe adhesion characteristics. The field program included:

- **Drilling of test holes** to gather sub-surface soil and groundwater information to aid in analysis (slope stability, freeze/thaw potential, soil-pipe adhesion).
- **Installation of slope inclinometers and vibrating piezometers** to determine if ground movements are occurring and to assess if movements are translational or rotational.

- **Installation of strain gauges** directly on the active gas pipelines to measure pipe strains to determine axial, bending, and torsional shear stresses over time.
- **Installation of temperature** gauges on the pipe and within the ground in the vicinity of the pipe to calculate structural stresses resulting from temperature changes and to assess freezing/thawing conditions.
- **Conducting ground surveys** to gather topographic information, capture instrumentation and test hole locations, and measure surficial ground movements over time.
- **Conduct field pipe push tests** on an abandoned gas pipeline at St. Lazare to provide direct measurements of soil-pipe adhesion characteristics under field conditions.

Five of the six slope inclinometers (SIs) became inoperable due to ground movements early on (within months) following baseline readings at depths ranging between 4 to 19 m below ground (Figure 5 and Figure 6). It was decided to abandon monitoring the remaining SI and switch to a survey-based method to monitor ground movements by surveying monitoring pins (rebar) installed at ground surface using RTK GPS equipment. This new approach is an appropriate alternative to SIs to measure ground movements given the magnitude of movement inferred by the failed SI installations would be measurable with enough duration based on a horizontal accuracy of <10 mm for RTK GPS equipment.

The short duration in which the SI's sheared indicates valley movements are on-going and ground movements are not limited to creep movements. This outcome was

unexpected as landslide movements at the sites were thought to be ancestral and not particularly active. Several of the VW piezometers (4 of 8) also become inoperable during the four years of monitoring, also suspected to be due to active landslide movements. In this regard, understanding the level of stability of the slope ($FS \approx$ unity) in actively moving ground was not critical and therefore was not examined. Thus, detailed information related to SIs and VWs have are not presented herein.

To accurately predict pipeline stresses due to landslides, an understanding of the maximum soil-pipe adhesion force is critical as pipe slippage through the soil may not allow for load accumulation on the pipe due to on-going ground movements. Pipe push tests were therefore conducted on a recently abandoned pipeline segment at St. Lazare to measure soil-pipe adhesion, in particular, the maximum soil-pipe adhesion force. Details related to the pipe push tests are included and discussed in Ferreira (2016).

GEOLOGY

The Assiniboine valley in the vicinity of the sites is prone to landslides along the valley walls. The valley walls are visually scarred from historical landslide movements, while active landslides still occur within the valley. The walls are mainly cut into shale and the shale at the two sites represent the Millwood geological member within the Riding Mountain Formation from the Upper Cretaceous period and consists of greenish grey bentonitic clay shale (Klassen 1966:Map). The surficial geology along

the valley walls consists of undifferentiated deposits of glacial drift, colluvium and alluvium (Klassen 1979:Map).

Steeper sections of the valley walls where bentonitic shales (Millwood member) are present along or near the valley wall are particularly susceptible to landslides, especially following significant rainfall events (Blatz et al. 2004). The bentonitic shales are well-known to be problematic and have been attributed to many landslides within the Assiniboine River Valley in the vicinity of the sites (Klassen 1979; Baldwin 2007; Blatz et al. 2004). The landslides tend to be retrogressive and can have shallower slides within larger/deeper slump block type movements.

SITE DESCRIPTION

The valley wall at St. Lazare is approximately 55 m high and is sloped at approximately 5.5H:1V (Figure 5) while at Harrowby, the valley is approximately 84 m high and is sloped at approximately 6H:1V (Figure 6).

At both research sites, there are several indicators that the valley walls have undergone previous slope movements (landslides) and may still be active. Terraces are present along the valley slopes which are indicative of large slump block movements (Figure 5 and 6) and tension cracks were identified outside of the owners right-of-way in the vicinity of the lower slump blocks at the sites.

Three test holes were drilled per site along the valley wall; one near the top of the valley, one near the middle of the valley, and one near the bottom at the locations

indicated on Figure 5 and 6. The test holes were located in the terraces (top of the slump blocks) as this area is best suited for ground and pipe instrumentation to capture pipe strains due to ground movements.

The soil stratigraphy is similar at the two sites and generally consists of a thin veneer of topsoil (<0.3 m thick) overlying 6 m to as much as 10 m thick silty clay layer (till or colluvium). Clay shale is present below the silty clay to the maximum depth drilled (28 m) in the test holes. The soil stratigraphy for the sites are shown on Figure 5 and 6. Table 1 presents the soil properties of the major soil units based on laboratory testing. The silty clay contains trace amounts of sand and gravel, and is of high plasticity. The clay shale for the most part is non-cemented ("soil-like"), but two thin layers of cemented shale ("rock-like") were encountered at St. Lazare.

Pipeline Information and Instrumentation Installation

The structural properties of the pipeline at each site are included in Table 2. The steel pipelines have been operational for 30+ years at Harrowby, and 50+ years at St-Lazare. The grade (yield strength) varies between 290 MPa for the oldest pipe at Harrowby to 345 MPa for the newest pipe at St. Lazare. The operating pressure varies depending on the service demand, with more demand over the winter months.

The pipelines were installed using an open cut method where the pipe was installed at a shallow depth (± 1 m in general) and backfilled with excavated material (silty clay). The pipeline profile for the sites are plotted on Figures 5 and 6.

FIELD INSTRUMENTATION AND SET-UP

A total of 6 temperature gauges and 18 strain gauges were installed predominantly along the terraces. Figures 7 illustrate the test hole and instrumentation schematic layout installed at the sites.

Two types of strain foil gauges were used, a uniaxial foil gauge, and a two-element torque rosetta. The soil temperature gauges used a soil/water temperature gauge with a range of -50°C to 70°C.

The strain gauges and temperature gauges were installed on the active pipelines in the fall of 2011. Ground monitoring pins (rebar) were first installed in May 2011 with addition pins installed later the same year. The strain and temperature gauges were connected to a data acquisition (DA) system which recorded readings hourly. The ground monitoring pins were surveyed three to four times a year.

Strain Gauge and Temperature Gauge Set-up

Strain gauges were installed to capture axial compression, axial tension, upward and downward bending along one plane, and pipe torsion. It was assumed that ground movements occurred downslope, parallel to the pipeline and bending would only occur along this plane as shown in Figure 8 and the gauges were oriented accordingly based on this assumption. A schematic of the strain gauge layout is illustrated in Figure 9. Two uniaxial strain gauges and one torsion strain gauge (two element 45° rosette) were installed as a set per location per site; three locations at each of the sites referred to as the Top, Middle, Bottom set-ups.

Temperature gauges were either attached to the outside of the pipe or inserted into the nearby soil. The temperature changes measured on the pipeline was used to apply a temperature correction to strain gauge measurements as well as allow for calculations of strains/stresses induced on the pipe due to thermal expansion/contraction (one of the four sources of stresses outlined). The temperature gauge in the soil is intended to determine if the soil mass within the vicinity of the pipeline freezes, possibly applying stresses to the pipeline (one of the four sources of stresses outlined).

Foil type strain gauges were physically attached to the pipeline using epoxy glue following preparation of the pipeline surface and protected using a single layered system of Teflon tape, butyl rubber, neoprene rubber covered with aluminium tape. A temperature gauge was then installed near the strain gauges. The pipe and instrumentation (strain gauges and temperature gauge) were then wrapped using a shrink sleeve overlapping the protective corrosion coating (yellow jacket) and heated to create a water-tight seal. The temperature gauge in the nearby soil was installed at the same elevation as the pipeline, within an offset of about 1.2 m to 1.5 m from the pipeline depending on the location of the set-up

Monitoring Pin Installation

The monitoring pins comprised of 12.5 mm diameter, 0.6 m long steel rebar installed at ground surface. A set of eight pins were installed at each site in May 2011 with an additional 7 pins and 14 pins installed at St.Lazare and Harrowby in September 2011 and November 2011, respectively. Monitoring pins were concentrated within the

vicinity of the terraces where the pipeline instrumentation was located and where ground movements are most likely to occur.

Monitoring Disruptions, Instrumentation Noise, and Equipment Issues

In general, the strain gauges and temperature instrumentation worked well. Some instrumentation issues were anticipated due to the complexity of the field program, DA system set-up, and the delicate nature of strain gauges. In this regard, the quantity and layout of the instrumentation was developed to provide some redundancy in case of instrumentation malfunctions or failure. The issues that occurred included false readings due to a poor connectivity or faulty instrumentation, unrealistic readings due to noise in data, and disruptions in the monitoring due to animal sabotage. The false readings (predominately the torsion gauges) were removed from the data and the noise in the data was filtered by truncating extremes in the data followed by the application of a digital filter to cleanse noisy data sets. A butterworth digital filter was used for the post processing of the noisy data sets using the method outlined in Winter (2009) and Yu et al. (1999)

MONITORING RESULTS

Ground Movement

The ground monitoring pins were monitored over a four year period and Figure 10 plots pin ground movements parallel and perpendicular to the pipeline. The figure does not include Pins 1, 4, 9 and 11 for St-Lazare and Pin 20 from Harrowby as the monitoring results were deemed erroneous for these pins.

In general, measured ground movements are downslope, oriented perpendicular or slightly perpendicular to the slope as expected. One of the survey monitoring events (St. Lazare Oct 2013) showed movements were trending upslope with similar magnitudes (~ 30 mm) for all the pins, but this is likely due to a survey error. Although movements are not entirely downslope, the assumption that the ground movements are perpendicular to the valley slopes is considered appropriate. Thus, the strain gauges are orientated correctly to predominantly capture pipe strains along one plane based on the direction of observed ground movements.

Ground monitoring Pins 1 to 8 for both valley sites were monitored for a longer duration (over four years) and therefore the cumulative displacements are larger than those measured from the remaining monitoring pins, which were monitored for about two years. The average rate of downslope movement is 25 mm/year and 40 mm/year at Harrowby and St-Lazare, respectively. The monitoring pins decreased in elevation an average of about 12 mm/year to 14 mm/year for the Harrowby and St-Lazare sites, respectively as expected due to downslope movement.

Ground and Pipe Temperature

Measured ground temperatures ranged between lows of about -1°C to 2°C to highs of 12°C to 15°C depending on the research site (Figure 11). Measured temperatures below 0°C occurred on four occasions over the four winters, one in 2012 and three occasions in 2014. The freezing temperatures measured were only slightly below 0°C with a minimum temperature of about -1°C for a short period of time, likely not sufficient in magnitude and duration to freeze the ground in the vicinity of the pipe.

Therefore, the ground in vicinity of the buried pipe did not freeze at the research sites and stresses induced on the pipe due to freezing were not considered in the research.

Pipe temperatures (outside of the pipe) mimicked ground temperatures usually within $\pm 1^\circ\text{C}$. Freezing temperatures on a pipe were recorded once for about two and half months at the Harrowby Top of Valley set-up with a recorded minimum temperature of -0.4°C during that time (Figure 11).

Pipe Stresses

A temperature correction was applied to the raw strain gauge measurements to determine the actual strain induced on the pipe. The corrected strain values were then converted into stress using the Young's modulus of the steel pipe. The theoretical Young's modulus of steel pipe is well established, but the actual Young's modulus of manufactured steel may vary depending on the manufacturer, especially for older pipe. Two field specimens from a pipe repair near the Harrowby research site were tested in the lab to confirm the Young's modulus of the steel pipe. The field specimens were taken from a pipeline which was originally installed in the 1960s, predating the pipeline at the Harrowby site. The test results suggested the theoretical Young's modulus can be considered an average and therefore was deemed appropriate to be used in determining stresses from measured strain values. The Young's modulus was assumed to be constant (linear elastic) when calculating pipe stresses from measured strains since specific stress-strain relationship information was not available for the pipelines at the sites. This assumption is valid since measured strains were for the most part was not large enough to yield the pipe. Linear elasticity is also considered

to be conservative as pipe stresses would be over predicted at larger strains, in particular close to or beyond pipe yield. The following equations were used to determine stresses in the pipe:

Stress Calculations from Strain:

$$\sigma = E(\epsilon) \quad \text{eq. 1}$$

Where:

σ = stress, MPa

E = Young's modulus of steel, 207 GPa

ϵ = temperature corrected strain from the uniaxial gauges

Shear Stress Calculations:

$$\tau = \frac{\epsilon(E)}{1 + \nu} \quad \text{eq. 2}$$

Where:

τ = torque shear stress, MPa

ϵ = measured strain from the two element 45° rosette

E = Young's modulus of steel, 207 MPa

ν = poisson's ratio of steel, 0.3

Calculated pipe stresses from measured strains are referred to as monitored or observed stresses as they were not directly measured. The strain gauge data has been reduced to produce plots of axial, bending and shear stress with time and change in seasons (Figures 12 and 13). Calculating stresses from strain gauge data is well established with the equations being readily available through many sources and is therefore not presented.

Understanding axial and bending strains (and ultimately the calculated stresses) acting on the pipe based on two uniaxial strain gauge measurements requires interpretation of the results to ultimately determine the longitudinal stresses (combination of axial and bending) acting on the pipe. The axial strains are calculated by taking the summation of the two uniaxial strain gauges and dividing it by two since each uniaxial gauge measurement includes a component of axial (doubling of measurements). Bending is calculated as the difference in strain between the top and bottom gauges divided by two

The stress plots are absolute stresses measured in the pipe. The sign convention adopted for pipe stresses is positive bending is for downward deflection of the pipe, and tension acting on the pipe is positive while positive shear stress relates to torsion in the clockwise direction from the perspective of looking upslope.

The calculated axial stresses at the sites include a component of stress due to thermal expansion and contraction of the pipeline. These stresses have been removed from the axial stress data in Figures 12 and 13 to allow for interpretation axial stresses that may be attributed to landslide related ground movements.

von Mises Combined Equivalent Stress

The von Mises stress theory was used to determine if the minimum yielding strength of the pipe was exceeded based on observed stresses using the following formula:

$$\sigma_{ef} \leq F_y \quad \text{eq. 3}$$

Where:

F_y = effective specified minimum yield strength, MPa

σ_{ef} = combined equivalent stress (von Mises), MPa

The combined equivalent stress for a thin walled cylinder is calculated using the following equation:

$$\sigma_{ef} = \sqrt{\sigma_h^2 + \sigma_L^2 - \sigma_h\sigma_L + 3\tau^2} \quad \text{eq. 4}$$

Where:

σ_{ef} = combined equivalent stress, MPa

σ_h = hoop stress, MPa

τ = tangential shear stress, MPa

σ_L = longitudinal stress (axial and bending), MPa where

$$\sigma_L = \frac{M}{S} + \frac{P_A}{A} \quad \text{eq. 5}$$

Where:

σ_L = longitudinal stress, MPa

M = bending moment, MN per m

S = section modulus, m³

P_A = axial force, MN

A = cross-sectional radius, m²

Figure 14 plots the calculated combined equivalent stress against the von-Mises yield loci.

INTERPRETATION OF MONITORING DATA AND OBSERVATIONS

Ground Movements

The measured downslope movement is suspected to be due to either shallow translational or deeper rotational landslide activity, or a combination thereof. This is supported by the Assiniboine valley being historically prone to landslides, the ground pin monitoring results (shallower movements), the failure depths of the SI's (deeper movements), and presence of ancestral large slump blocks at the sites.

Based on the measured ground movement, the sites are considered to be a very slowing moving landslide (16 mm/year to 1.6 m/year) using the classification system develop by Cruden and Varnes (1996). Although considered to be very slow moving, the potential degree of damage to infrastructure is expected to be moderate based on work completed by Mansour et al. (2011) as shown in Figure 15.

Pipe Stresses

The stress plots (Figures 12 and 13) allows for interpretation of trends related to pipeline behaviour and changes in stresses that may be attributed to ground movements.

Backfilling

An unexpected outcome of the research is the magnitude of longitudinal pipe stresses (axial and bending) induced on the pipelines due to backfilling of excavations required to install the instrumentation. The excavations were sufficient in size and depth below the pipe to safely install the pipe instrumentation. Material excavated was used as backfill and the backfilling method consisted of placing material carefully around and beneath the pipe with an excavator. The material was compacted with the back of the excavator bucket and care was taken to compact the material beneath the pipe as much as practically possible without risking damage to the pipe. The backfill above the pipe was not compacted until sufficient cover was placed (about 1 m) before the backfill was lightly compacted.

Backfilling operations induced strains (bending, axial, torsion) on the pipe with bending being the larger of the strains measured. Torsion due to backfilling tended to be negligible or small when compared to longitudinal strains (bending, axial). These stresses either maintained initial levels, somewhat decreased, or released completely over the four years of monitoring.

The largest backfill stresses were measured at the middle of the valley at Harrowby and it appears these stresses have “locked-in” with calculated bending, axial, and shear stresses of 170 MPa, 60 MPa, and 100 MPa, respectively. The combined equivalent stress induced on pipe due to backfilling likely yielded the pipe at this location based the von Mises yield criteria (Figure 14).

Temperature

The thermal effects on the pipe have resulted in a cyclic measured axial stress profile for all the sites with axial stress increasing in the fall/winter and decreasing in the spring/summer as shown in Figure 12 and 13. Without the thermal stress, axial stresses reduce by as much as 40 MPa resulting in many of the monitored locations showing axial stresses close to zero suggesting little to no axial load is applied to the pipelines that maybe attributed to landslide movements. The axial stresses without thermal effects plotted does include the axial component of hoop stress ($v\sigma_h$) since the pipelines are pressurized with gas, ranging between 3.45 and 7.23 MPa. However, the axial component of hoop stress is low (less than a maximum of 1.5 MPa) and therefore, the axial stresses profile without thermal effects is essentially unchanged when removing the axial component of hoop stress.

Pipe Stresses due to Landslide Movements

The axial and bending stress profiles with time exhibit similar magnitudes and trends between the three set-up locations within each site and also show similarities between the two valley sites.

The expected accumulation of stresses due to active ground movements did not occur in contradiction to the measured persistent downslope movements. Some trends in the observed stress data can be attributed to landslide movement where stresses started to build (typically in the spring), but these periods are followed by a release of stresses by some other means.

Changes in longitudinal pipe stresses (axial and bending) can be indicators that landslide induced ground movements are causing pipe stresses, especially if the changes are notable or distinct. Distinct changes in observed stress profiles are those that are larger than generally observed in the monitoring data and occur over a short duration (hours or days) while notable changes in stress are measurements that tend to be less in magnitude and occur over a larger duration (days or weeks). Distinct and notable changes in stress are noted on Figure 12 and 13. At St. Lazare, several distinct changes in bending stresses occurred at the middle of the valley set-up during the last year of monitoring. But these observed changes in stress may be due to construction activities which occurred close to the middle of the valley set-up during that time and may not be a result of ground movements. In addition, one of the uniaxial strain gauges at this set-up contained noise for approximately six months within the last year, and the filtered axial and bending stress profiles may not accurately capture distinct stress changes as the filtering process attenuates both noisy and real data.

The pipe monitoring results showed that there are roughly three general combinations of distinct or notable changes in longitudinal pipe stresses:

Combination 1 - increased downward bending stresses and axial tension either increased or was relatively unchanged,

Combination 2 - decreased downward bending and increased axial tension, and

Combination 3 - decreased downward bending and axial tension either decreased or was relatively unchanged.

Table 3 provides a summary of the combination of load conditions and the frequency of which they occurred.

For the first combination, distinct increases in longitudinal pipe stresses (downward bending and axial tension) in the data strongly suggest the pipe is responding to sudden landslide movements (surges). Slower landslide movements are likely the cause of slower increases in axial tension and downward bending. Rotational landslide movements cause surficial ground movements that typically result in mostly downward soil displacements, δ_d , with a smaller component of downslope displacements, δ_a (Figure 16, a). The pipeline response to rotational movements is an increase in downward bending and possibly, an increase in axial tension (combination 1) depending on the point along the pipeline being examined in relation to the extent of the rotation landslide area. Vertical ground movements are more prevalent at the extents of a rotational landslide than downslope movements, while a more balanced proportion of downward movements to downslope movements

would be expected near the center of a rotational landslide. Therefore, axial tension stresses may or may not increase depending on the location along the pipeline profile within a rotational slide. The pipeline monitoring locations were placed within the top, relatively flat portion of the large ancestral slump blocks. This location would likely coincide with the extent of where the ancestral rotational landslide likely occurred and observed changes to longitudinal stresses (combination 1) would be expected.

Mechanisms causing the other two combinations (2 and 3) are not as clear. Some of the observed decreases in longitudinal stresses could be attributed to ground movements (Combination 2) or could be due to a form of relaxation based on the interaction between the soil and pipe (Combination 3).

The observed release (decrease) of longitudinal stresses (Combination 2 or 3) are not due to plastic deformation of the pipeline as the observed pipe stresses at the sites (excluding the middle of valley set-up at Harrowby) are within the elastic range of the structural member. Also, analysis and interpretation of the pipe push tests suggest at the St. Lazare Site the maximum allowable soil-pipe adhesion was not exceeded due to the observed ground movement and associated measured axial strains, therefore did not “slip” through the soil mass releasing axial stresses. While pipe slippage may or may not have occurred at the Harrowby Site.

The ground pin monitoring results suggest continuous shallow movements are occurring and could be attributed to translational landslide. A transitional landslide would result in downslope soil displacements as shown in Figure 16, b. The pipeline

is not perfectly straight and translational ground movements cause a pull on the pipe in the longitudinal direction due to soil-pipe adhesion. The decrease in downward bending stresses measured at the sites may be a result of the pipe straightening out due to translational movements. The deflected shape of the pipe would have to straighten out only very slightly to reduce bending stresses. This explanation is strengthened when increased axial tension stresses are measured on the pipe as downward bending stresses decrease. In this regard, the combination of decreased downward bending and increased axial tension (combination 2) has been assumed to be due to landslide movements.

Soil-Pipe Relaxation Mechanisms

Landslide movements cannot easily explain the monitoring results where downward bending stresses decreased and axial tensions either decreased or were maintained (combination 3) and are speculated to be due to some form of soil-pipe relaxation.

Several researchers have noted or indirectly commented on the possible existence of a soil-pipe relaxation mechanism not attributed to plastic deformation of a pipe member. Cavanagh and Rizkalla (1992) while evaluating the results of a 16-year monitoring program for a pipeline in a landslide area where ground displacements were measured, commented on *"there were large, unresolved discrepancies between the ground movement trends observed in the slope indicators and the pipeline displacements as derived from the precise survey monitoring"*. Bruschi et al. (1995) remarked on the discrepancy between field (pipe strain and soil movement)

monitoring results and the lack of pipeline rupture in the following statement “*the field experience shows that soil movements are not unequivocally linked to a potential for pipe rupture*”. The strongest supporting evidence of the existence of a soil-pipe relaxation mechanism in landslide areas comes from research conducted by Scarpelli et al. (1995) where four case studies of pipelines in landslide areas were examined that included pipe strain gauges and ground movement monitoring. In one of the case studies, the pipeline did not respond with expected large pipe strains as a result of significant ground movements and Scarpelli et al. (1995) commented as follows: “*It is not clear yet how this observed behaviour, i.e. a small strain accumulation in spite of large and continuous soils displacements, can be explained*”.

Several hypothetical mechanisms causing soil-pipe relaxation are presented in Ferreira (2016) where it is proposed three soil-pipe relaxation mechanisms as possible explanations of the pipe behaviour observed. The three mechanisms focus on soil-pipe interactions that could result in decreases in downward bending (and sometimes axial) stresses and the mechanisms are as follows:

- Upward block movement
- Soil displaces around the pipeline
- Loss of soil-pipe contact due to soil volume change

The first two mechanisms are related to soil displacements around (e.g. flow) the pipeline in the downward direction which could explain the reduction of downward bending. The last mechanism is independent of soil displacement or ground movements and may account for the reduction in both downward bending stresses

and axial tension observed at the research sites. The hypothetical mechanisms are discussed in detail in Ferreira (2016).

REGIONAL AFFECTS

The observed stress profiles exhibited a tendency for distinct and notable changes of stresses, in particularly bending stress, to commonly occur (typically in the spring) at roughly the same time at both sites, year over year. The consistency in these events occurring suggests a connection with changes in pipe stress at the sites at a regional scale, likely due to ground movements related to simultaneous movements of the valley walls, even kilometers apart.

Table 4 summarizes the dates where distinct changes in bending stress occurred between the sites for the various set-up locations. It appears that distinct changes in bending stress occur every spring at roughly the same time between the sites. Figure 17 plots the bending stress profile with time and seasons and notes when distinct changes in stress occur at both sites, typically each spring. Other notable changes in bending stress, but not necessarily distinct, which occur between the sites are also noted on Figure 17.

The closeness in time between changes in bending stress between the sites occurs in multiple independent years strongly suggest ground movements can occur on a regional scale and typically occurred during a change of season (Winter to Spring). But also are not limited to site specific conditions (e.g. slopes, soil strength) or changes in local conditions to trigger movements (e.g. rainfall, groundwater). The

sites are far enough apart (37 kilometers), even though they are within the same geological formation with similar site conditions, you would not expect such a strong tendency for ground movements to occur at roughly the same time. These occurrences cannot be directly connected to weather which tends to strongly influence landslide movements at a regional scale. Weather data from the closest station (about 60 km away from both sites) was reviewed for the particular days these events occurred and no noteworthy changes or trends in weather such as unseasonable warm days in the spring causing rapid thaw or consistently following significant regional rainfall events. The distinct changes in the spring can be generally attributed to spring thaw, but occurred either at the start, middle or end of a spring warming trend at different 7-day average (moving) daily temperatures ranging between -14.1 to 9.8°C. Some of the events in the summer and fall could be linked to precipitation events greater than 50 mm occurring over a few days or weeks (a wet period). But there were as many or more wet periods that did not result in distinct changes in bending stress. The lack of temperature data and especially rainfall data closer to the sites makes these correlations somewhat questionable and thus, these observations require further research.

Summary and Conclusions

A comprehensive field and monitoring program was undertaken to identify and quantify possible sources of load that may be inducing strains/stresses on pipelines and the sources examined include landslide ground movements, soil volume change

due to freeze-thaw, and elongation/compression of the pipe due to temperature change. Instrumentation on the pipeline and within the nearby soil were installed at six locations between two sites along the Assiniboine River Valley in Western Manitoba. The instrumentation monitored temperature changes (soil and pipe), and longitudinal (axial and bending) and torsional pipe strains. Ground movements were monitored by surveying surficial pins installed along the valley slopes. The sites were monitored over a four period with some issues, in particular noise and unrealistic measurements in the strain gage data. However, the strain gauges did provide useful data, but their reliability can be problematic.

Axial, bending and torsional stresses were calculated for each monitoring location and showed that backfilling, thermal effects, a soil-pipe relaxation mechanism (speculated), and ground movements all affected pipe stresses and behaviour. Large backfill stresses enough to yield the pipe were induced on the pipe and these stresses (predominantly bending) were “locked-in”, or dissipated partially or fully over time. The soil in the vicinity of the buried gas pipelines did not freeze and therefore freeze/thaw induced pipe stresses did not occur. Pipe thermal effects dominated the measured axial stress, with little to no axial stresses measured without thermal effects.

The monitored pipeline indirectly acted like a ground monitoring instrument that can identify subtle changes in applied strains because of the sensitive nature of strain gauges. Changes in pipe strains and thus calculated stresses are a result of the pipeline deforming in response to soil displacements surrounding the pipe (predominantly

within the elastic range of the pipe). These soil displacements around the pipeline can be attributed to either landslide related ground movements or other soil-pipe interactions (soil-pipe relaxation). Decreasing or full release of axial tension stresses cannot be directly attributed to exceeding the soil-pipe adhesion resulting in pipe slippage. Distinct changes in longitudinal pipe stress identified in the stress profiles assumes sudden ground movements, while notable changes in longitudinal pipe stresses assume slower rates of ground movements are occurring. Some of these changes, in particular distinct changes in bending pipe stresses, occur at roughly the same time (spring) between the sites and may attributed to the influence of regional affects.

Slow moving landslides warrant further attention because of the potential for pipeline damage due to cumulative ground displacements over time. At the sites, annual displacements between 25 mm to 40 mm did not result in high pipe stresses and therefore, structural failure of the pipeline even though the potential degree of damage to infrastructure is expected to be moderate based on work completed by Mansour (2009).

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Figures

Fig. 1. Distribution of Pipeline Incidents 2010 to 2019 (modified from European Gas Pipeline Incident Data Group, 2020)

Fig. 2. Location of Research Sites.

Fig. 3. St-Lazare Research Site.

Fig. 4. Harrowby Research Site.

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Fig. 5. St-Lazare Site Plan and Cross-Section

Fig. 6. Harrowby Site Plan and Cross-Section

Fig. 7. Valley Sites Test Hole and Instrumentation Layout Schematic

Fig. 8. Assumed Direction of Ground Movement at Research Sites

Fig. 9. Strain Gauge Configuration

Fig. 10. Monitoring Pin Movement Parallel and Perpendicular to Pipe Alignment: (a) St. Lazare Parallel; (b) St. Lazare Perpendicular; (c) Harrowby Parallel (d) Harrowby Perpendicular

Fig. 11. Pipe and Ground Temperatures

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Fig. 12. St-Lazare Axial, Bending and Shear Stress (torsion) with Time and Seasons

Fig. 13. Harrowby Axial, Bending and Shear Stress (torsion) with Time and Seasons

Fig. 14. Measured Combined Load *versus* von Mises Yield Loci

Fig. 15. Schematic Representation of Expected Extent of Damage versus Movement Rate (adapted from Mansour et al., 2009).

Fig. 16. Landslide Related Ground Movements at the Research Sites (Ferreira 2016)

- a) Ground movements resulting in increased downward bending and increased axial tension, δ_d = downward displacement causing pipe bending stresses, δ_a = downslope displacement causing pipe axial tension stresses, δ_r = resultant displacement.

- b) Ground movements resulting in decrease downward bending and increased axial tension, δ_a = downslope displacement causing axial tension stresses in the pipeline.

Fig. 17. Bending Stress with Time and Season for the Valley Sites

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Tables

Table 1. Soil Properties

Soil Property	Depth Range ^a	Unit Weight	Liquid Limit	Plastic Limit	Plasticity Index	Clay	Silt	Sand	Undrained Shear Strength ^b
St-Lazare									
Silty Clay	0-7m	-	52-81/73	22-32/26-2	25-55/34	45-68/59	31-39/35	0-22/6	-
Clay Shale	7 ->27.4m	-	69-140/99	20-23/22	56-118/82	51-73/66	27-42/7	0-7/1	-
Harrowby									
Silty Clay	0-8.7m	17.3-18.2/17.9	50-70/65	18-20/19	32-51/46	38-56/48	30-50/40	7-15/13	62.7
Clay Shale	8.7->30.2	-	48-70/60	14-22/18	34-51/42	41-52/47	26-38/33	11-33/20	-

Notes: ##-##/# denotes range/average measurements.
- limited high quality samples were retrieved for unit weight measurements and undrained shear strength testing
^aAverage Depth
^bBased on unconfined compression tests

Table 2. Information at the Research Sites (based on original specifications).

Site	Date Installed	Diameter	Wall Thickness	Grade (Yield Strength)	Max. Operating Pressure
St-Lazare	October 5, 1965	168.3 mm	4.78 mm	345 MPa	7230 kPa
Harrowby	August 21, 1982	88.9 mm	3.18 mm	290 MPa	3450 kPa

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Table 3. Summary of Distinct and Notable Changes in Longitudinal Stresses

Type of Stress Change	St-Lazare			Harrowby		
	Top	Middle	Bottom	Top	Middle	Bottom
<i>Combination 1</i> - Increase in Downward Bending with Axial Tension increasing or remaining ~Constant	6	5	2	5	3	3
<i>Combination 2</i> - Decrease in Downward Bending with Axial Tension increasing	6	2	1	2	4	2
<i>Combination 3</i> – Decrease in Downward Bending with Axial Tension decreasing or remaining ~Constant	3	4	1	4	2	1

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Table 4. Distinct Changes in Bending Stress over Relatively Short Durations.

Dates	St-Lazare			Harrowby		
	Top	Middle	Bottom	Top	Middle	Bottom
March 13 th to 17 th , 2012*	Mar 17 th	Mar 15 th	-	Mar 13 th	Mar 16 th	n/a
April 23 rd to May 1 st , 2013*	Apr 26 th	Apr 23 th	Apr 1 st	Apr 24 th	Apr 26 th	n/a
June 23 to 25 th , 2013	Jun 25 th	Jun 23 th	Jun 23 th	-	-	-
September 25 th to October 11 th , 2013	-	Sept 25 th & Oct 11 th	-	Oct 11 th	-	-
April 8 th to 30 th , 2014	Apr 16 th	Apr 9 th	Apr 8 to 30 th	Apr 8 th	-	Apr 25 th
March 5 th to April 16 th , 2015	Mar 5 th to 13 th	Mar 30 th to Apr 16 th	noise	Apr 13 th	Mar 9 th to 24 th	-

- No distinct or sudden changes in bending stress occurred close to the dates noted

* Distinct changes in bending stress occurred days apart at both valley sites