Field Trial of Resource Road Pipeline Crossings

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Report for the Canadian Forest Service, Natural Resources Canada.

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1. INTRODUCTION

Resource extraction companies in western Canada share the same road networks and, as such, frequently must construct road crossings of buried pipelines. Regulations require that construction within the pipeline right-of-way be approved and supervised by the pipeline owner, and be positively located prior to construction. The form of crossing, however, is not well defined and requirements vary between pipeline companies and, even, between construction supervisors working for the same pipeline company. Delays in receiving crossing permits, scheduling difficulties with arranging for pipeline locating and for pipeline representatives to be on site for the construction, and varying and ill-defined construction requirements are challenges for both forestry and oil and gas companies that must cross buried pipelines.

At the request of its Alberta member companies, FPInnovations conducted a survey to define the most common resource road pipeline crossings, and to propose some generally acceptable crossing arrangements based on the state-of-practice. In 2013, FPInnovations undertook an integrity test of four buried pipe segments at Access Pipeline's Surgeon Terminal to evaluate the magnitude of stresses in pipelines buried to different depths, with compacted and uncompacted backfill, and for various traffic loadings. In October 2015, FPInnovations and Midwest Pipeline undertook a project to evaluate pipeline responses to trafficking with various sizes and types of pipeline construction equipment, and with two different resource road-pipeline crossing structures. Testing was conducted in a vacant agricultural field adjacent to Midwest Pipeline's equipment yard in Spruce Grove, AB.

The objective of this project was to provide recommendations for resource road-pipeline crossing design, and to support the development of a generally accepted set of construction arrangements that protect pipeline integrity. This objective was achieved by evaluating pipe responses under a variety of operating conditions (e.g., various sizes of both tracked and wheeled equipment, large and small diameter pipe, two burial depths, two crossing arrangements each with 50% and 100% of the conventional amount of fill thickness). Additional modeling was conducted to estimate pipeline integrity for soil types not evaluated in the two field tests, for trafficking by log hauling trucks loaded to maximum on-highway and off-highway levels, and for in-block pipelines subjected to crossing by forest harvesting equipment.

2. METHODOLOGY

Pipe properties

Pipeline integrity was of paramount concern in this work. Excessive levels of strain and stress in pipelines can cause permanent deformation (ovaling), which may lead to ruptures and product spills. Peak strains due to trafficking of a buried stiff-walled pipe occur on the outer and inner surfaces of the top and bottom of the pipe. Pipelines are constructed with high strength steel that is very stiff and has limited ductility. Stiff-walled pipe resists permanent deformation. Small strains (deformation) in a pipeline may occur with heavy traffic or construction equipment loading but, if the pipe stresses do not exceed the elastic limit of the pipe steel, the steel elastically springs back to its original shape after the loading is removed. Further, as long as the pipeline steel operates within its elastic range of stresses, it is not subject to fatigue.

Three pipe segments were used for trafficking in the Midwest Pipeline field trial. One of these was collector line-size pipe (pipe A) and two were transmission line-size pipes (pipes B and C)[1]. All three pipes were X80 high-strength streel, with yield strength (stress at which a predetermined amount of permanent deformation occurs) of approximately 550 MPa and an ultimate strength of 620 MPa (stress that can cause failure).[2] The yield strength of typical steel (e.g., structural steel ASTM A36) is much less than that of the X80 steel and may be as low as 250 MPa. Another notable difference between these steels is that high strength X80 steel is brittle and has very little ductility (gap between the yield and the ultimate strength) (Figure 1).

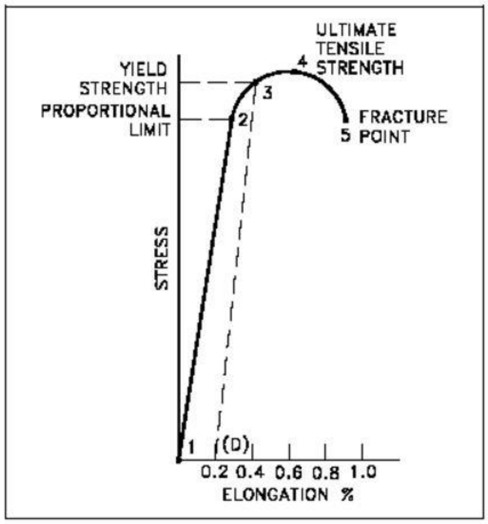

Figure 1. Typical stress-strain curve for brittle materials like high strength X80 steel (Engineers Edge)3.

Erreur ! Référence non valide pour un signet. summarises the physical properties of the segments of pipeline that were tested. All pipes were tested unpressurized, per typical construction conditions. Testing under unpressurized conditions was expected to produce larger pipe responses to more clearly illustrate the relative differences due to equipment size and road structure.

[1] 'National size pipes' refers to large diameter pipes commonly used to transfer oil & gas products in inter-provincial or international pipelines; 'provincial size pipes' refers to smaller diameter pipes commonly used for shipping raw or unfinished oil & gas products between production facilities within a province.
[2] From http://www.europipe.com/files/ep_tp_47_02en.pdf
[3] From http://www.engineersedge.com/material_science/yield_strength.htm

Table 1. Properties of pipe segments

	pipe A	pipe B	pipe C
Pipe inside diameter (m)	0.406 (16”)	0.91 (36”)	0.91 (36”)
Pipe wall thickness (mm)	6.4	11.8	11.8
Pipe yield strength (MPa)	550	550	550
Ultimate strength (MPa)	620	620	620
Minimum pipe toughness (MPa)	483	483	483
Typical operating pressure (kPa)	14 500	11 900	11 900
Approximate mass of pipe segment (kg)	1225	4600	5005
Length of pipe segment (m)	13.7	17.0	18.5
Outside treatment	Uncoated	coated	coated

Strain gauging

Rectangular strain gauge rosettes were used for strain data collection, each consisting of three strain gauges: 0º, 45º, and 90º to the pipe centreline. Three rosettes were installed on each pipe at 0.30 m apart in order to capture maximum strains regardless of travel path wander. The central rosette on each pipe measured strain in all three directions, while the two outer rosettes measured circumferential and longitudinal strain. The rosettes were installed at the top of each pipe (12 o’clock position): on the inside of the two 0.91 m-diameter pipes and on the outside surface of the 0.41 m-diameter pipe (shown in Figure 2 below). This position captures some of the highest strains and stresses present in the pipe because of how the stiff-walled pipe flexes when loaded from above. Slightly higher tensile strains and stresses are anticipated on the bottom outside surface of the pipe (6 o’clock). Two strain gauges were damaged after backfilling the pipes. Due to limitations of the data acquisition unit only the 45° gauges on the central rosette assemblies could be activated for the testing. A more detailed overview and schematic of strain gauge locations can be found in Appendix A.

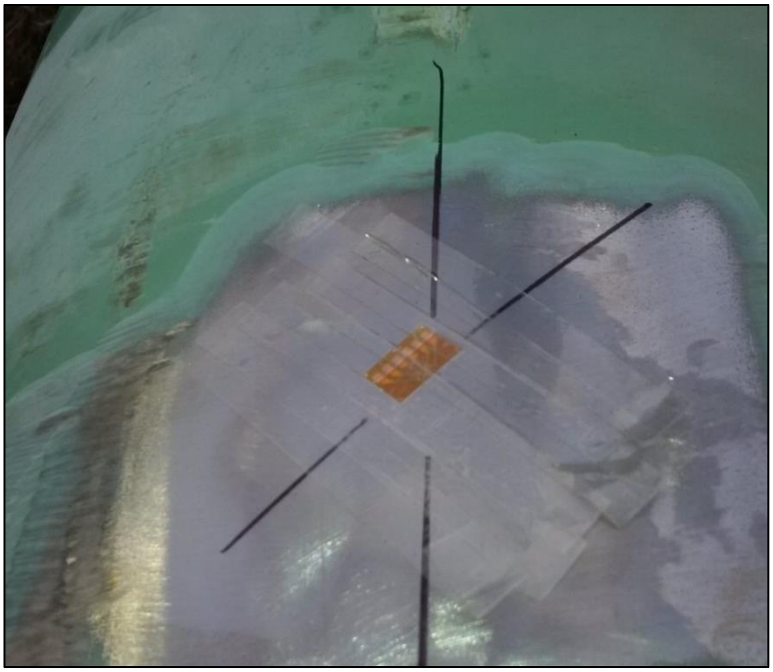

Figure 2. A rectangular strain gauge rosette being glued to a pipe surface. Its three strain gauges were oriented with the pipe axis, pipe circumference, and at 45° to these two directions.

Pipe placement and trench backfilling

Pipe placement

Three trenches were excavated to a depth that would produce 1.2 m of cover over the installed pipe segment (1.7 m for the 0.41 m-diameter pipe in trench A and 2.2 m for the 0.91 m-diameter pipes in trenches B and C). The three pipes were arranged so that the central strain gauge rosette on each pipe lay on a straight line. GPS was used to exactly align the strain gauges, survey the trenches, and mark the location of the strain gauges on the surface after backfilling (Figure 4). An orange paint line was marked on the soil surface between the strain gauge locations to act as a guide for equipment trafficking. Pipes A and B were oriented at 90º to the travel path and pipe C was oriented at 45º to the travel path. Because pipes B and C were the same type and installed with the same cover depth, this allowed for comparison of the effects of pipe orientation on stresses in the pipe. See Figure 3 for an overview of the arrangement of the test site.

Trench backfilling

The trenches were backfilled to the level of the surrounding field from the end closest to the data acquisition station to just before the opposite end of the pipe; the end of each pipe was left exposed for access, if needed. As much pipe as possible was covered in order that the exposed end would not influence strain measurements. To emulate construction practices that would generate the highest strains and stresses in the pipes, the backfill was originally compacted only by tracking back and forth with the D7 bulldozer. On the day before the test, the backfill was compacted further with multiple passes by all of the test vehicles.

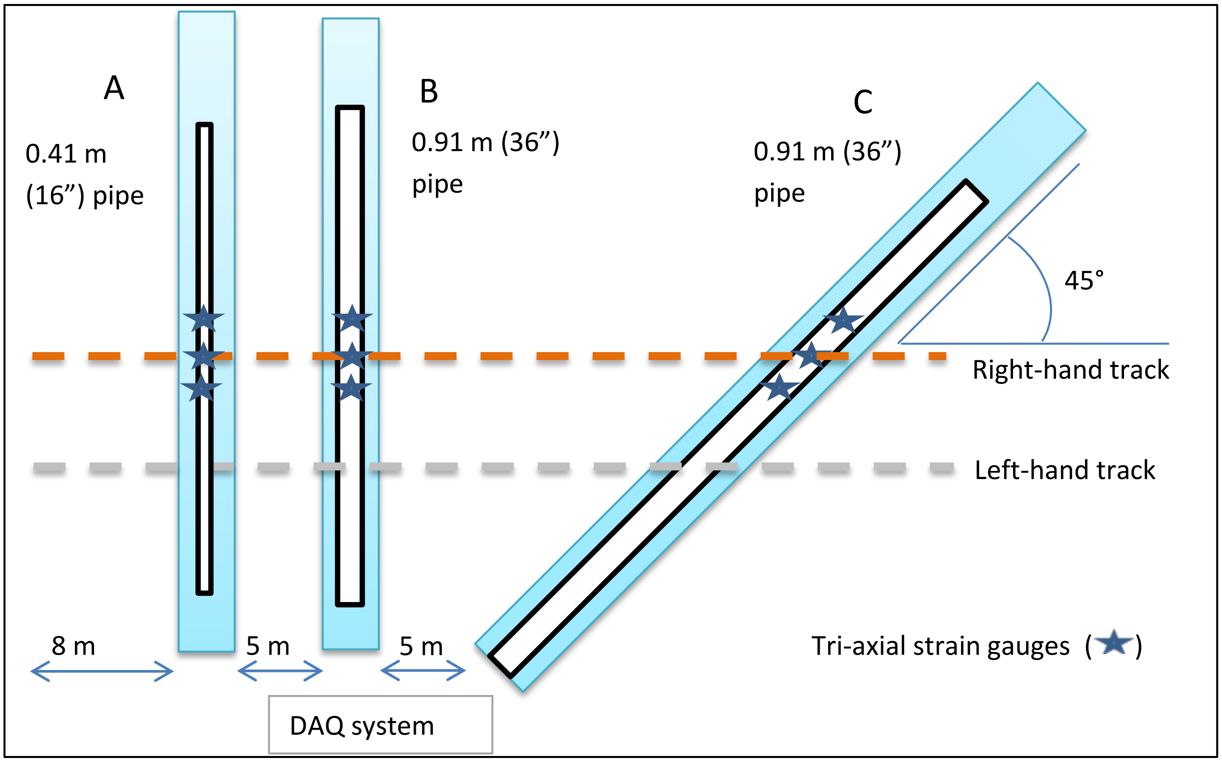

Figure 3. General arrangement of pipe segments in their trenches.

Figure 4. GPS was used to align the middle strain gauge assembly of each pipe in a straight line. During trafficking, the right-hand track or wheels passed directly over this line.

Soil characterization

Samples gathered from material excavated from the trenches for identification. Testing of this uniformly fine grained soil was confined to Atterberg Limits tests and hydrometer gradation testing; and, the tests were done on two soil samples to confirm the accuracy and variability of results. Table 2 summarises the lab test results; the soil was classified, according to the Universal Soil Classification System (USCS), as clay of low plasticity.

Table 2. Atterberg Limits, grain size, and USCS classification of the site soil

Physical Properties	
Liquid limit	40
Plastic limit	23
Plasticity index	17
% sand (% by weight)	18
% silt (% by weight)	53
% clay (% by weight)	30
USCS classification	CL

Decagon GS-1 moisture sensors were used to quantify moisture content of the undisturbed soil at the bottom of trench B, as well as of the backfill at 1.2 m and 0.6 m from the surface in trench C. The moisture sensors were calibrated using backfill; this process is claimed by Decagon to achieve an accuracy of ±1% in soil moisture measurements. There was no measureable precipitation during the test period, and the soil moisture contents are summarized in Table 3. Soil moisture content was 30% in the undisturbed soil at 2.2 m down from the surface. Excavated and backfilled soil displayed slightly drier moisture contents – likely because of air in the un-compacted backfill and exposure to wind and sun. Given the cool and dry temperatures during testing, level site conditions, and apparent uniformity of the excavated soils, it is believed that both the soil type and moisture variation with depth was representative of conditions throughout the trench area.

Table 3. Moisture content of test site soils

Measurement location	**Average moisture content (% by dry weight)**
0.6 m below surface of backfill	27% (variation = ±0.1%)
1.2 m below surface of backfill	22% (variation = ±0.2%)
2.2 m below surface of backfill (undisturbed trench bottom)	30% (variation = ±0.04%)
Number of measurements	120

Trafficking equipment

Trafficking of the pipeline crossing road structures was by light, medium, and heavy bulldozers and by a 3-axle water truck loaded to allowable highway axle weights. These vehicles have all been used by Midwest Pipeline in its pipeline construction operations, and they represented a typical range of masses for tracked and wheeled construction equipment. Equipment weights were provided by Midwest Pipeline, and were based upon historical weights measured at Alberta Transportation highway weight scale facilities. Table 4 provides basic specifications of the test equipment.

Table 4. Trafficking equipment specifications

	Make	Model	Operating mass
Light bulldozer	CAT	D6 LGP	26 050 kg
Medium bulldozer	CAT	D7E	28 504 kg
Heavy bulldozer	CAT	D8T	43 500 kg
Medium excavator	CAT	329E	31 040 kg
Water truck (16000 L capacity)	Kenworth	T-800	22 980 kg

Travel Speed

Travel speeds were maintained at a constant velocity of 2 to 4 km/h (0.6 - 1.0 m/s).

Calibration: Influence of trafficking on soil strength

Soil compaction due to trafficking was identified as a possible variable that might skew results. If it was shown that the soil compaction levels varied significantly over the course of the testing process, a factor would need to be applied to account for these effects. Two approaches were used to test this hypothesis: a comparison of the strain responses to the D7E bulldozer runs at the start and the end of testing, and a comparison of soil shear strength measurements before, during, and after the test passes.

D7E strain comparison

To identify changes in strain results, the D7E bulldozer (which was also used in other calibration testing) was trafficked over the three pipes before and after the rest of the vehicles. The resulting comparison is found below in Table 5, which shows the difference between before and after circumferential strain results for each gauge. Apart from gauge A-3, which showed a 13.6% increase, the change in maximum circumferential strain response in the other 6 gauges was no more than 4%, leading to the conclusion that the change in pipe strain responses due to soil compaction throughout the testing was negligible.

Table 5. Before- and after-trafficking strain comparison with D7E bulldozer

Gauge	Before trafficking	After trafficking	Change
	microstrain	Microstrain	% of before-trafficking strain
B-1	57.2	59.3	3.7%
C-1	56.9	56.6	-0.5%
A-2	-43.7	-43.7	0.0%
B-2	54.5	56.4	3.5%
C-2	48.9	44.8	-8.4%
A-3	-66.4	-75.4	13.6%
B-3	45.8	47.6	3.9%

Estimating and comparing soil strength

A dynamic cone penetrometer (DCP) was used to measure the strength of the pipeline trench backfill soil during the test to quantify changes in soil bearing capacity due to compaction by the vehicles. DCP measurements were gathered in the top 0.6 m of soil in trenches A, B and C. Results in trench B at various stages of the testing can be seen in Figure 5. As expected, the backfill near the surface was more compacted by the original tracking than was the soil deeper down. The values of bearing strength (correlated to and expressed as California Bearing Capacity or CBR) at 0.6 m depth were found to be approximately 50% of those at the surface. The bearing capacity of the backfill increased by no more than 3 CBR in the trenches with changes at 0.6 m depth being no more than 2 CBR. As with the D7E strain comparison method, the differences in soil compaction throughout the trafficking process were found to be negligible.

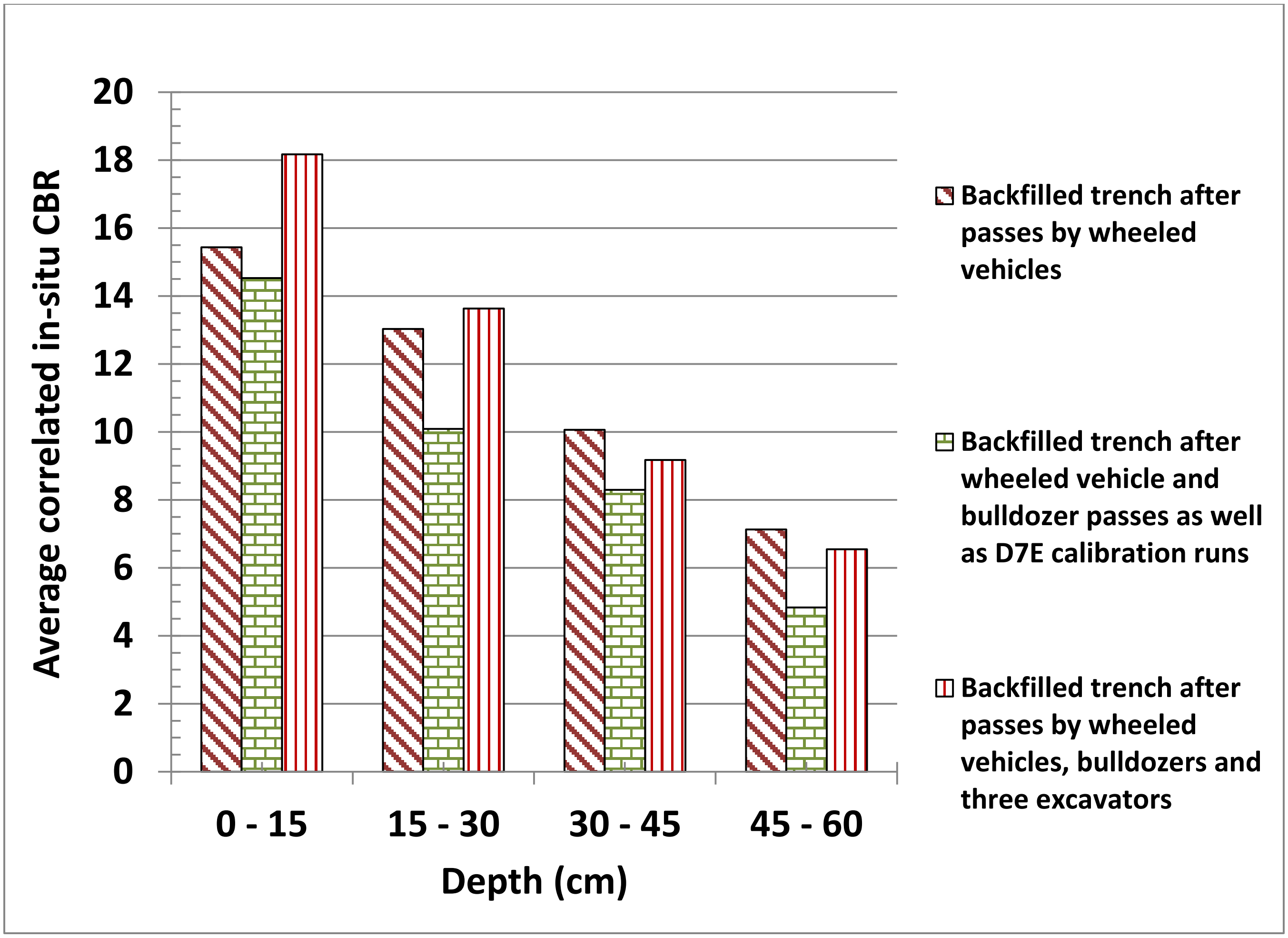

Figure 5. Bearing capacity at trench B before and after trafficking.

Calibration: Accounting for travel path wander

Trafficking over each strain gauge assembly at 90° allowed FPInnovations to develop relations between measured strains and offset between travel path and the strain gauge location. For each pass, the offset distance between the central strain gauges line (normal travel path) and the centreline of the equipment's right-hand-side tire/ dual tire assembly/ track was recorded when the equipment was directly over each pipe (Figure 6). This value then was used, with the calculated % strain vs. distance equations for each pipe, to factor the strain readings and account for the offset. Due to the straight-line tracking capabilities of the tracked machines, the wheeled vehicles had the majority of the non-zero recorded offsets and were affected the most by the factoring.

Interestingly, a trend emerged in pipes B and C where the maximum stresses occurred when the offset was not zero. That is, both pipes had higher strain responses when the right-hand-side track or wheel(s) was offset to the right of the central strain gauge rosette. In the charts of Figure 7, offsets to the right are portrayed as negative offset values. This trend is believed to have occurred because at minor offsets the middle strain gauge array started to experience loading from the left-hand-side track or wheel(s) while still feeling the full loading of the right track or wheel(s).

Figure 6. Monitoring travel path offset from orange line connecting middle strain gauges on pipes.

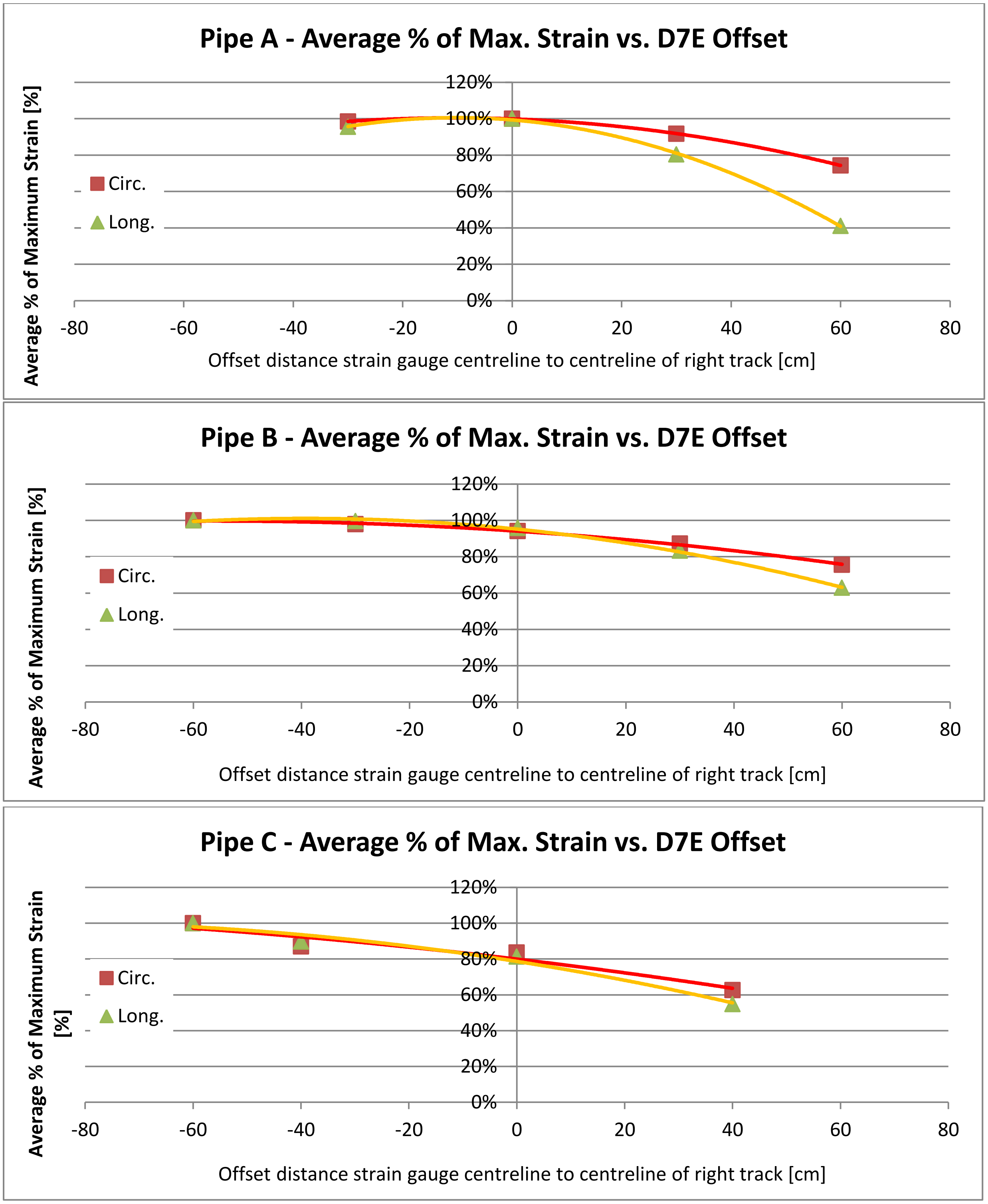

Figure 7. Calibration curves for pipes, average % of maximum circumferential and longitudinal strains vs. right-hand track offset distance from middle strain gauge (negative offset is in the direction away from centreline of vehicle).

Pipeline crossing road structures

The pipes were buried in trenches with a cover depth of 1.2 m of lightly compacted backfill used to fill the trench to grade level. After the trenches were backfilled and the strain gauge calibration process was complete, a resource road crossing structure was constructed over pipes A and B, consisting of a 0.6 m-thick lift of un-compacted earth placed on grade and its surface tracked down to make it trafficable. A second lift of earth, 0.6 m thick, was added and the new surface tracked down to make it trafficable. Earthen crossing structures featuring a 1.0 – 1.5 m-thick lift of soil are a very common arrangement used where resource roads cross pipelines in Alberta (Gillies 2015).

Strain measurements in response to trafficking by the D6, D7E, and D8T bulldozers and by the water truck were gathered in the pipes at grade level before adding any lift (a baseline - no crossing case), when lift thickness was 0.6 m, and when the full 1.2 m of lift was in place. Figure 8 illustrates the 1.2 m-thick lift pipeline crossing road structure. Figure 9 illustrates the D8T trafficking pipeline B while it negotiates the 1.2 m-thick lift structure.

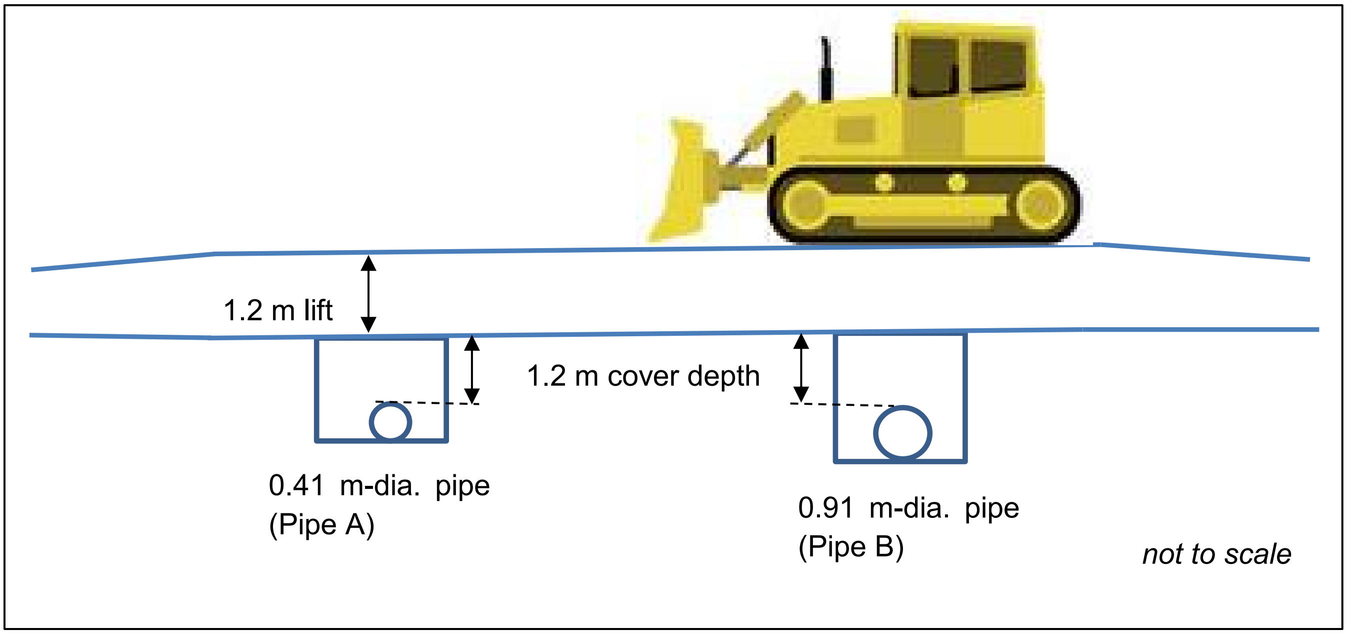

Figure 8. 1.2 m-thick lift pipeline crossing road structure.

Figure 9. D8T bulldozer trafficking over the 1.2 m-thick lift pipeline crossing road structure constructed over a 0.91-m-diameter pipeline (pipe B).

Subsequently, the lift of soil was removed and a layer of logs (referred to as corduroy) was placed butt-to-top on grade and perpendicular to the travel path. Smaller diameter logs were placed 1½ deep while larger diameter logs were placed one deep such that the general depth of the layer was consistently between 0.45 and 0.5 m. The logs were pulp quality black cottonwood and trembling aspen. Log butt diameter was 31 cm, on average, with a range of 21 to 49 cm-diameter; the logs were bucked to 6.0 m (20') lengths.

A 0.5 m-thick lift of un-compacted soil was placed on top of the corduroy and track packed before testing. After testing, another 0.5 m of soil was added to the crossing structure to create a 1.0 m-thick lift of earth on top of the corduroy. Testing was repeated on this second, thicker, earth and corduroy crossing structure. Earth and corduroy crossing structure featuring 1-1.5 log-deep corduroy overlain by 1.0 m of soil also is a very common arrangement used where resource roads cross Alberta pipelines (Gillies 2015).

Strain measurements in response to trafficking by the D7E bulldozer and the water truck were gathered in the pipes before the corduroy was placed, when the lift depth over the corduroy was 0.5 m, and when the full 1 m of lift had been added. Figure 10**Erreur ! Source du renvoi introuvable.** illustrates the lift-over-corduroy pipeline crossing road structure.

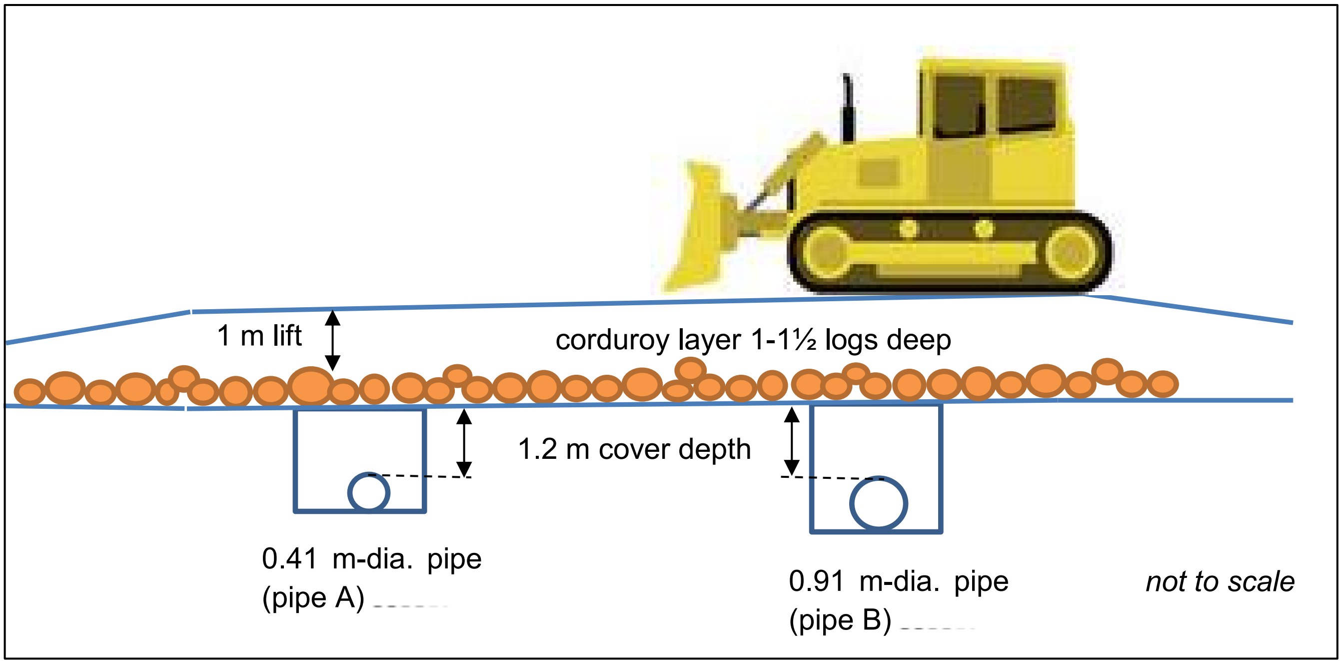

Figure 10. 1 m-lift-over-corduroy pipeline crossing road structure.

Data collection and post-processing

Sampling and filtering

The strain gauge data was collected at a frequency of 200 Hz, resulting in a sample every 5 thousandths of a second, and giving more than enough data at the low travel speeds of the study. A rectangular smoothing window was used to filter out noise in the data. The data was normalized to make the strains in the unloaded, buried pipes equal to zero. All trafficking tests were repeated until 4 sets of noise-free and comparable strain traces were obtained.

Stress and average maximums

The maximum circumferential and longitudinal strain values for each pipe in each test run were calculated as the average of the corresponding maximum strains in each of the 4 runs. Strains were converted to stress using the following relations:

$$\sigma_c = \frac{E}{1-v^2}(\epsilon_c + v\,\epsilon_l), \qquad \sigma_l = \frac{E}{1-v^2}(\epsilon_l + v\,\epsilon_c)$$

Where $E = 200\ GPa,\ \ v = 0.285$

These values are very representative of X80 steel. (According to the API 5L Standard, X80 *steel*’s elastic modulus is 207 GPa (30,000,000,000 psi).)

Stress directionality

The tensile circumferential stresses in the larger pipes were seen as the most likely to cause failure, by cracking or otherwise and, therefore, have been used as the main metric of comparing pipe responses. As can be seen in the following charts, trends in magnitude of stress for the circumferential direction are similar to the trends for the longitudinal direction. Two important and recurring trends regarding the direction of the data were:

- In pipe A, stresses in both the circumferential and longitudinal direction were negative, indicating compression. This 0.41-m-diameter pipe had the strain gauges mounted on the outside top of the pipe.

- Both pipes B and C experienced tensile stresses in the circumferential direction and compressive stresses in the longitudinal direction. These 0.91-m-diameter pipes had the strain gauges mounted on the inside top of the pipe.

3. RESULTS AND DISCUSSION

Nominal ground contact pressures

Nominal ground contact pressures were calculated as the operating mass divided by the measured contact area of each vehicle. Contact areas for tracked equipment were estimated using track dimensions; gross contact areas for wheeled vehicles were estimated using a paper imprint method.

The purpose of this metric was to find a suitable way of identifying the vehicles that generate the highest stresses on the pipe. Simply put, is stress in the pipe affected more by vehicle mass, contact shape (track or wheel), or contact pressure? The answer will identify whether or not tracked vehicles (having much lower contact pressures due to their large track area) compare to wheeled vehicles in terms of stresses they generate in the buried pipelines. Table 6 summarizes the contact pressures of the equipment used for trafficking the pipeline crossing structures.

Table 6. Test equipment mass, track contact area, and nominal ground contact pressure

	Operating mass	**Track contact area**	**Nominal contact pressure**	
	(kg)	(m^2)	(kPa)	(psi)
CAT D6 LGP bulldozer	26 050	5.563	46	7
CAT D7E bulldozer	28 504	4.028	69	10
CAT D8T bulldozer	43 500	4.565	93	14
Water truck steering axle	5 920	0.061	473	69
Water truck tandem drive	17 060	0.045	463	68

It is evident from Table 6 that *__the equipment with the greatest mass do not necessarily generate the highest ground contact pressure__*. The water truck generates significantly higher contact pressure than any of the tracked equipment despite it being lighter than either.

Pipeline response to pipeline crossing road structure

Influence of lift thickness

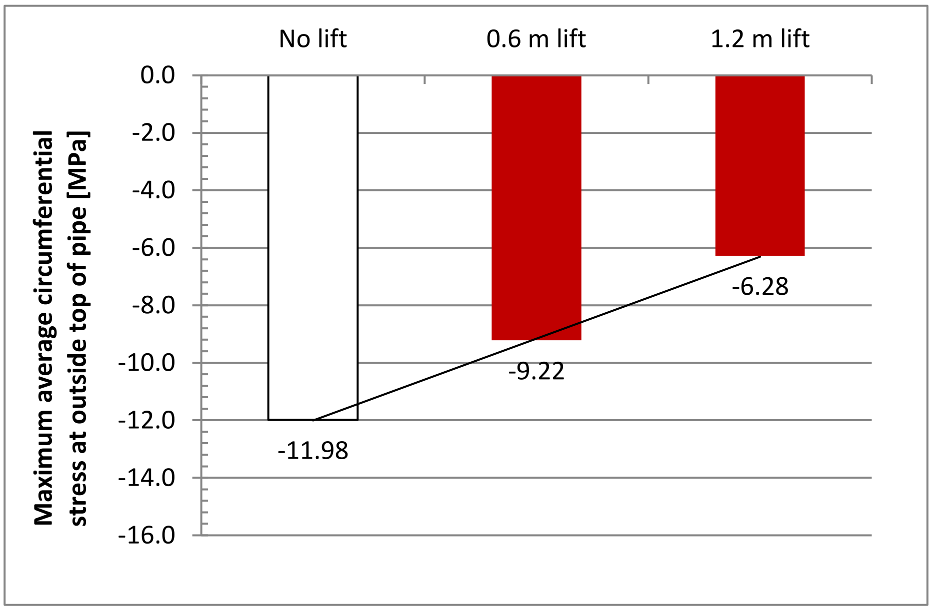

Figure 11. Comparison of maximum pipe stress with two different depths of earth lift versus without any crossing structure (0.41 m-diameter pipeline, D7E bulldozer).

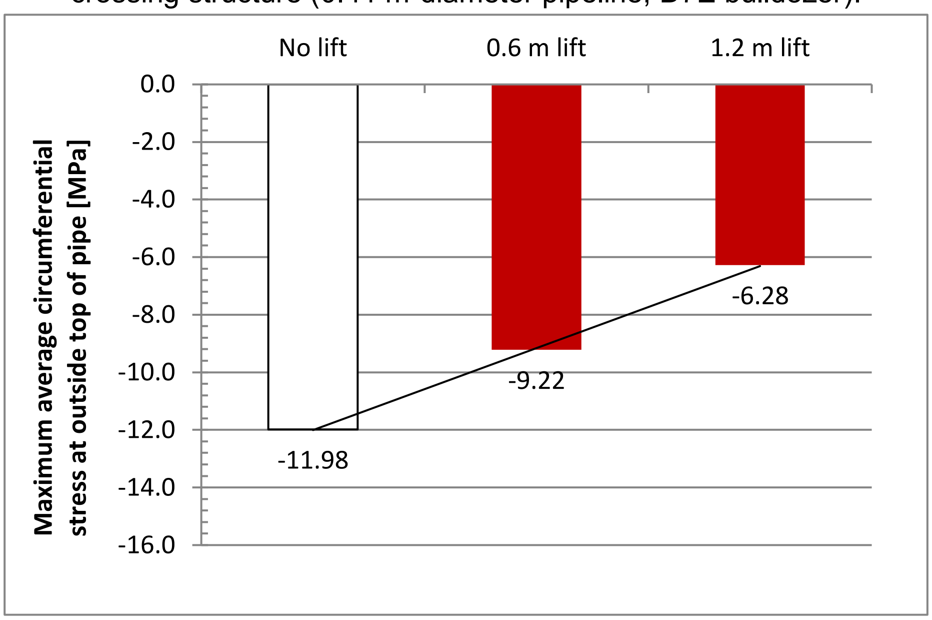

Figure 11, Figure 12, Figure 13, and Figure 14 illustrate the differences in collector line and transmission line-sized maximum pipeline stress levels due to trafficking of 2 crossing structures with different lift thicknesses; trafficking was by three common bulldozers and a 3-axle water tanker truck. Stresses were derived from strains measured in unpressurized pipe sections (top outside location on the 0.41 m-diameter pipe and top inside location on the 0.91 m-diameter pipe). Positive values of maximum stress in the following charts are tensile stresses in the circumferential direction while negative values indicate compressive stresses in the circumferential direction.

Figure 10, Figure 11, Figure 12, and Figure 13 illustrate that there is a roughly linear trend between lift thickness and the maximum circumferential stress felt by the pipeline. That is, doubling the lift thickness resulted in approximately half the circumferential stress at the top of the pipe.

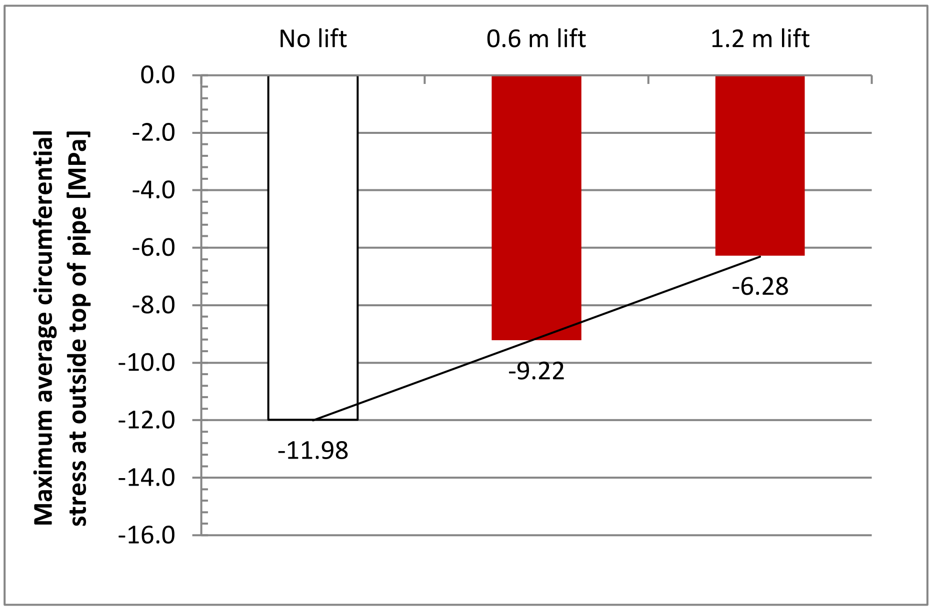

Figure 11. Comparison of maximum pipe stress with two different depths of earth lift versus without any crossing structure (0.41 m-diameter pipeline, D7E bulldozer).

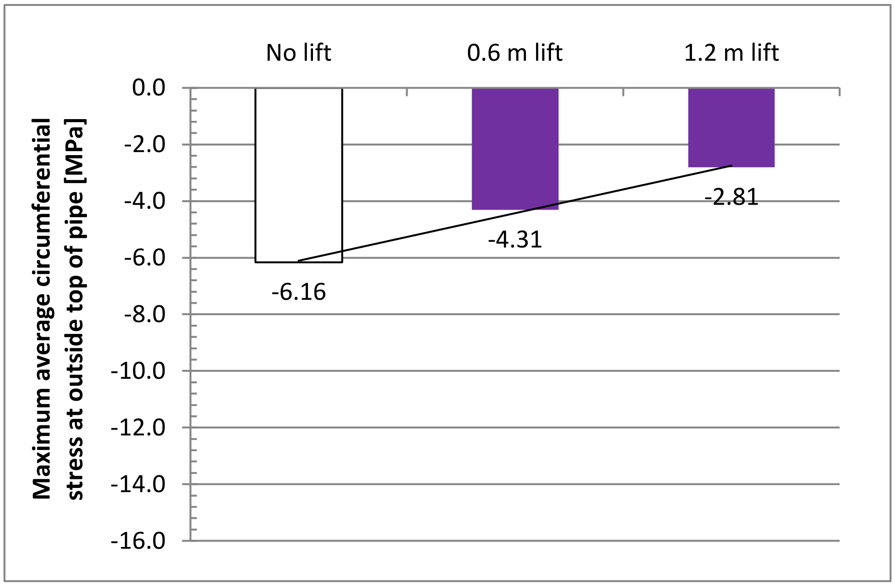

Figure 12. Comparison of maximum pipe stress with two different depths of earth lift versus without any crossing structure (0.41 m-diameter pipeline, water truck).

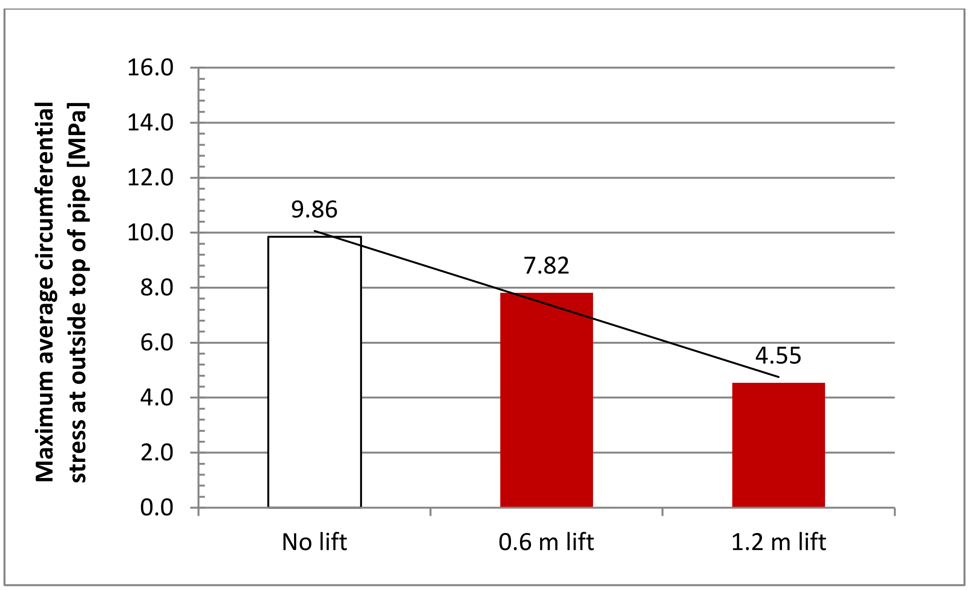

Figure 13. Comparison of maximum pipe stress with two different depths of earth lift versus without any crossing structure (0.91 m-diameter pipeline, D7E bulldozer).

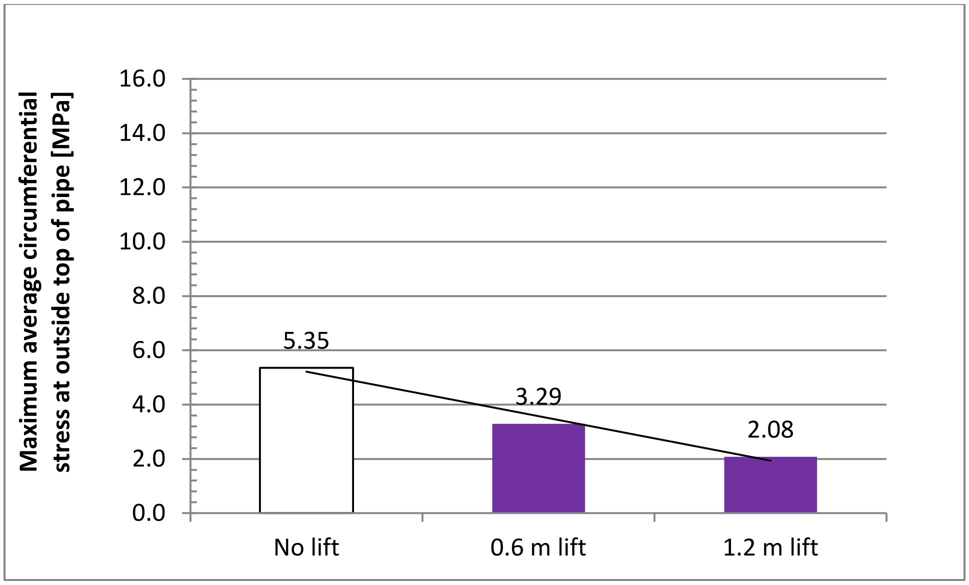

Figure 14. Comparison of maximum pipe stress with two different depths of earth lift versus without any crossing structure (0.91 m-diameter pipeline, water truck).

The peak stresses on the top outside surface of the 0.41 m-diameter pipe (collector line pipe) were compressive, and were slightly greater in magnitude than the peak tensile stresses occurring on the top inside surface of the 0.91 m-diameter pipe (transmission line pipe). Pipelines can fail due to high external stresses (e.g., from traffic loading) causing permanent deformation (ovaling). To keep the measured responses in perspective, the maximum tensile stress measured in either pipe under an earthen lift road structure was 10.38 MPa and this is **less than 1.9% of the (550 MPa) yield strength** of the X80 pipe steel. The average maximum compressive stress measured in either pipe under an earthen lift road structure was 12.39 MPa and this is **only 2.25% of the yield strength (550 MPa)** of the pipe steel. Yield strength can be defined as that stress at which the pipe steel would first start to yield (i.e., permanently or plastically deform) – stresses less than this could cause temporary, elastic, deformation in the pipe that springs back when the vehicle has crossed over the pipe and the stress is relieved. It should be further noted that testing was with unpressurized pipe segments and, under actual service conditions, pipelines are often pressurized which reinforces the pipe wall and helps to resist deformation.

Table 7 summarises the maximum circumferential stresses measured under the pipeline crossing earth road structures. Table 9 summarizes the same stresses but as percentages of the X80 steel's yield strength.

Table 7. Summary of maximum pipeline stresses measured for pipeline crossing earth road structures

		Maximum circumferential stress in 0.41 m pipe [MPa] (-ve sign denotes compression)			Maximum circumferential stress in 0.91 m pipe [MPa] (tension)		
Vehicle	**Mass [kg]**	No crossing structure	0.6 m lift	1.2 m lift	No crossing structure	0.6 m lift	1.2 m lift
CAT D6	26 050	- 9.62	- 6.95	- 4.95	6.97	5.56	3.53
CAT D7E	28 504	- 11.98	- 9.22	- 6.28	9.86	7.82	4.55
CAT D8T	43 500	- 16.30	- 12.39	- 8.92	12.04	10.38	6.52
Water truck	22 980	- 6.16	- 4.31	- 2.81	5.35	3.29	2.08

Table 8. Summary of maximum pipeline stresses measured for pipeline crossing earth road structures relative to the X80 pipe steel's 550 MPa yield strength

		Maximum circumferential stress in 0.41 m pipe relative to X80 yield strength (compressive stresses)			Maximum circumferential stress in 0.91 m pipe relative to X80 yield strength (tensile stresses)		
Vehicle	**Mass [kg]**	No crossing structure	0.6 m lift	1.2 m lift	No crossing structure	0.6 m lift	1.2 m lift
CAT D6	26 050	1.75%	1.26%	0.90%	1.27%	1.01%	0.64%
CAT D7E	28 504	2.18%	1.68%	1.14%	1.79%	1.42%	0.83%
CAT D8T	43 500	2.96%	2.25%	1.62%	2.19%	1.89%	1.19%
Water truck	22 980	1.12%	0.78%	0.51%	0.97%	0.60%	0.38%

Influence of lift thickness on top of corduroy

Erreur ! Source du renvoi introuvable., **Erreur ! Source du renvoi introuvable.**, **Erreur ! Source renvoi introuvable.**, and **Erreur ! Source du renvoi introuvable.** illustrate the differences in maximum stress levels between collector line and transmission line-sized pipeline due to trafficking of crossing structures with different earthen lift thicknesses, and with or without a layer of corduroy placed underneath the earth lift. As can be seen, adding corduroy logs to the road structure was more effective at dissipating the forces acting on the pipeline than was the earth lift alone. For example, adding a 1.0 m lift of earth on corduroy crossing structure to the grade above the 0.41 m pipe reduced maximum pipe stresses from 11.98 MPa to 4.28 MPa (a 64% reduction), whereas adding the 1.2 m earth lift alone reduced maximum stresses to 6.28 MPa (a 48% reduction). Similarly, adding the 0.5 m of lift on corduroy crossing structure reduced maximum pipe stresses from 11.98 MPa to 8.24 MPa (a 31% reduction), as compared to a 23% reduction with the 0.6 m earth lift alone.

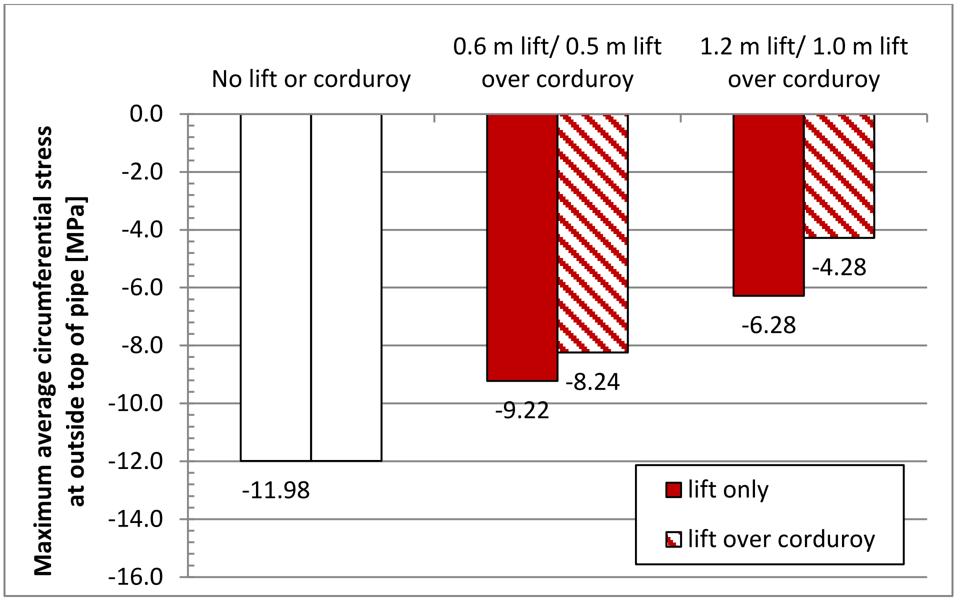

Figure 15. Comparison of impact on pipe stress of lift and lift-over-corduroy crossing structures (0.41 m-diameter pipeline, D7E bulldozer).

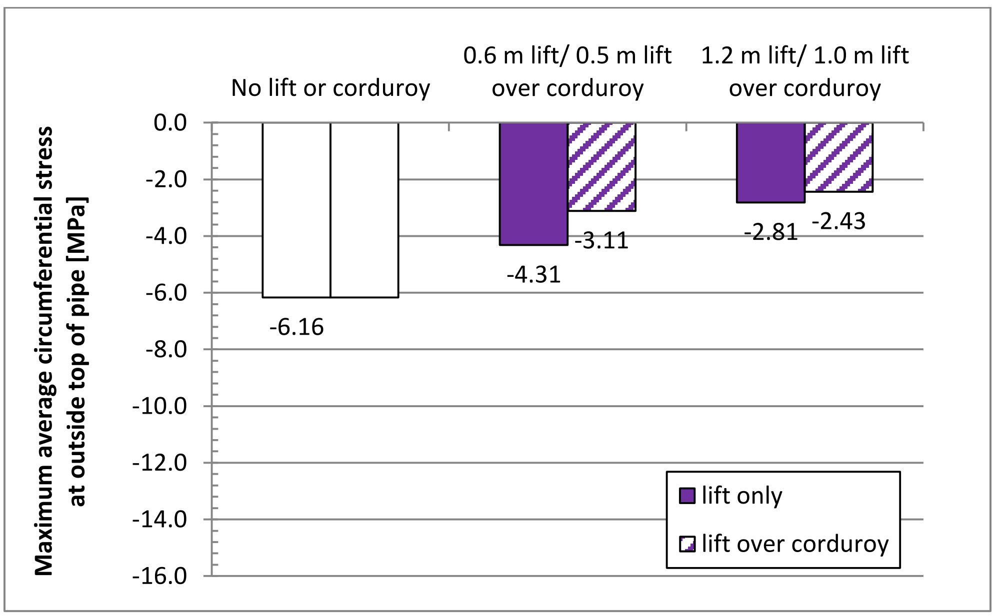

Figure 16. Comparison of impact on pipe stress of lift and lift-over-corduroy crossing structures (0.41 m-diameter pipeline, water truck).

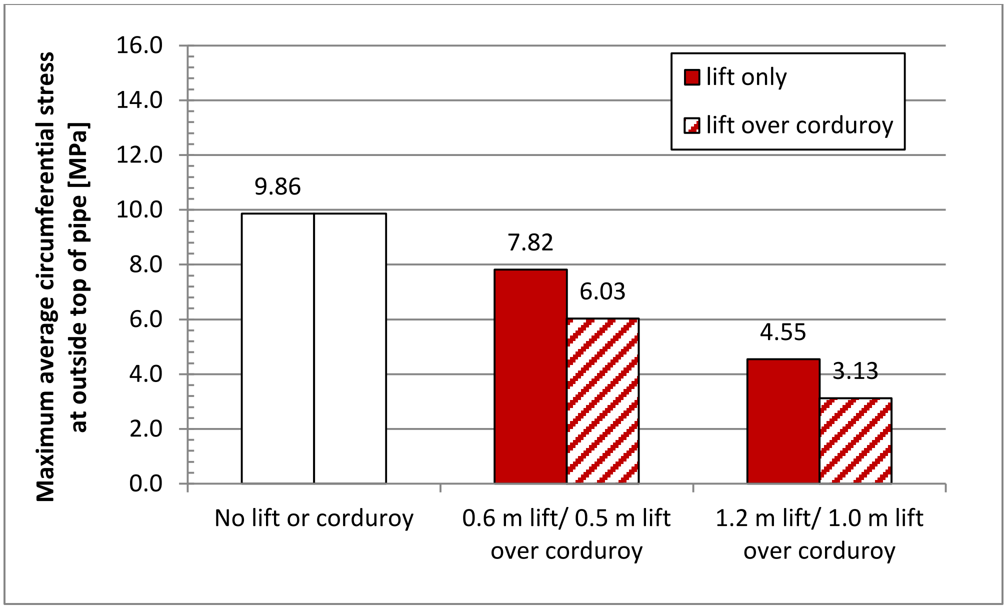

Figure 17. Comparison of impact on pipe stress of lift and lift-over-corduroy crossing structures (0.91 m-diameter pipeline, D7E bulldozer).

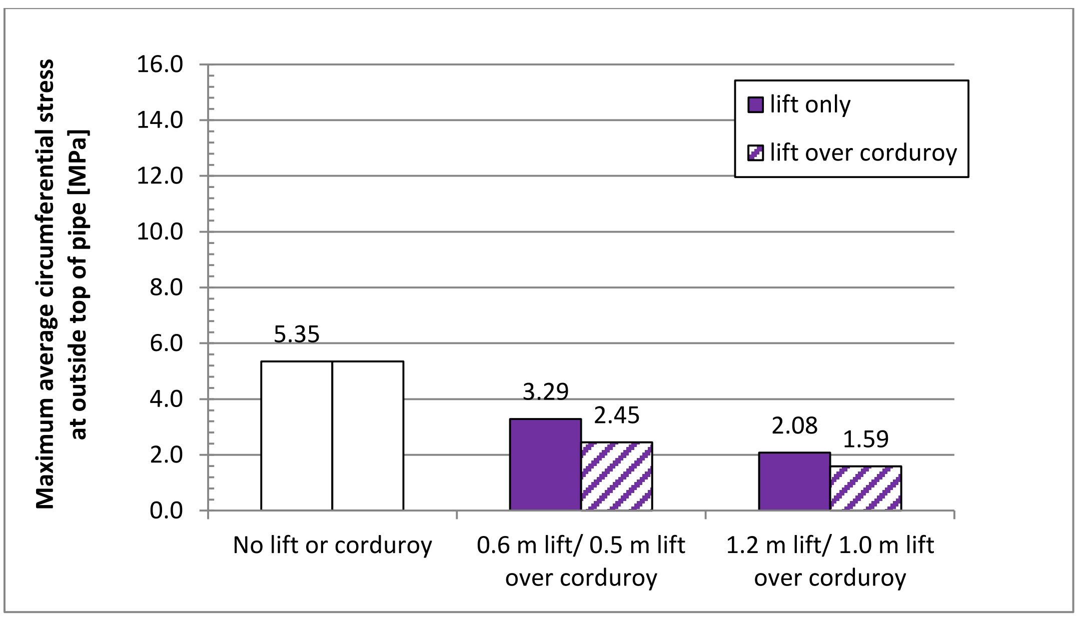

Figure 18. Comparison of impact on pipe stress of lift and lift-over-corduroy crossing structures (0.91 m-diameter pipeline, water truck).

The addition of logs to create lift-over-corduroy road structures effectively reduced pipe stresses in both pipes. Table 9 summarises the average maximum circumferential stresses measured under the lift-over-corduroy crossing structures. Table 11 summarises the same maximum pipe stresses as percentages of the X80 pipe steel's yield strength. As with the lift road structures, the maximum stresses measured in the 0.41 m-diameter pipe were noticeably greater in magnitude than in the 0.91 m-diameter pipe for the lift-over-corduroy road structures. Also, the larger pipe experienced higher tensile stresses than the smaller pipe. The average maximum tensile stress measured in either pipe under a lift-over-corduroy road structure was 7.76 MPa and this is **only 1.41% of the yield strength (550 MPa)** of the pipe steel. The average maximum compressive stress measured in either pipe under a lift-over-corduroy road structure was 11.42 MPa and this is **only 2.08% of the yield strength (550 MPa)** of the pipe steel.

Table 9. Summary of average maximum pipeline stresses measured for lift-over-corduroy road structures

		Average maximum circumferential stress in 0.41 m pipe [MPa] (compression)			**Average maximum circumferential stress in 0.91 m pipe [MPa] (tension)**		
Vehicle	**Mass [kg]**	No crossing structure	0.5 m lift-over - corduroy	1.0 m lift-over - corduroy	No crossing structure	0.5 m lift-over - corduroy	1.0 m lift-over - corduroy
CAT D6	26 050	- 9.62	- 6.14	- 3.42	6.97	4.67	2.71
CAT D7E	28 504	- 11.98	- 8.24	- 4.28	9.86	6.03	3.13
CAT D8T	43 500	- 16.30	- 11.42	- 6.39	12.04	7.76	5.05
Water truck	22 980	- 6.16	- 3.11	- 2.43	5.35	2.45	1.59

Table 10. Summary of maximum pipeline stresses measured for earth road crossing structures relative to the X80 pipe steel's 550 MPa yield strength

		Average maximum circumferential stress in 0.41 m pipe [MPa] (compressive stresses)			**Average maximum circumferential stress in 0.91 m pipe [MPa] (tensile stresses)**		
Vehicle	**Mass [kg]**	No crossing structure	0.5 m lift-over - corduroy	1.0 m lift-over - corduroy	No crossing structure	0.5 m lift-over - corduroy	1.0 m lift-over - corduroy
CAT D6	26 050	1.75%	1.12%	0.62%	1.27%	0.85%	0.49%
CAT D7E	28 504	2.18%	1.50%	0.78%	1.79%	1.10%	0.57%
CAT D8T	43 500	2.96%	**2.08%**	1.16%	2.19%	**1.41%**	0.92%
Water truck	22 980	1.12%	0.57%	0.44%	0.97%	0.45%	0.29%

Table 11 summarizes the reduction in maximum stress in the collector line-sized pipeline due to different road structures and for each of the test equipment. The average stress reduction for the tracked equipment, from adding a 0.5-m lift of backfill onto grade, was 25%. The stress reduction was greater with lighter equipment (i.e., for the water truck and the D6 bulldozer). Increasing the lift thickness to 1.2 m increased the average stress reduction to 47%. Combining corduroy with a 0.5-m lift road structure reduced the average stress to 32%, again with the largest reductions occurring with lighter equipment. Combining corduroy with a 1.0-m lift road structure further reduced the average stress to 63%; however, now the stress reductions were comparable for all sizes of equipment. The thicker road structures were more effective at spreading live load (via soil arching) and resulted in the most consistent reductions in pipeline stress regardless of equipment size or the form of load transfer (wheel or track).

Table 11. Effectiveness of road pipeline crossing structure type at reducing pipeline stresses (0.41-m-diameter pipe)

	Reduction in average maximum pipeline circumferential stress due to road structure (as a % of the maximum stress without any crossing road structure)			
	0.6 m lift	0.5 m lift-over-corduroy	1.2 m lift	1.0 m lift-over-corduroy
Water Truck	-30%	-50%	-54%	-61%
D6 bulldozer	-28%	-36%	-49%	-64%
D7E bulldozer	-23%	-31%	-48%	-64%
D8T bulldozer	-24%	-30%	-45%	-61%
Average of all tracked equipment	-25%	-32%	-47%	-63%

Table 12 summarizes the reduction in maximum stress in a transmission line-sized pipeline due to different road structures and for all of the test equipment. The average stress reduction for tracked equipment from adding a 0.6-m lift of backfill onto grade was 18%; the stress reduction was much more with the light wheeled vehicle (i.e., the water truck). Unlike the collector line-sized pipe results, the D6 bulldozer had comparable results to the other bulldozers. Increasing the lift thickness to 1.2 m resulted in the average stress reduction for the tracked equipment being 50%. Combining corduroy with a 0.5-m lift road structure resulted in the average tracked equipment stress reduction being 36%. Combining corduroy with a 1.0 m-thick lift road structure resulted in the largest stress reductions. Although more variable than for the collector line-sized pipe the results still indicate that the thicker road structures were quite effective at spreading live load and resulted in the most consistent reductions in pipeline stress regardless of equipment size or the form of equipment contact patch (wheel or track).

Table 12. Effectiveness of road crossing structure at reducing pipeline stresses (0.91-m-diameter pipe)

	Reduction in average maximum pipeline circumferential stress due to road structure (as a % of maximum stress without lift or corduroy)			
	0.6 m lift	0.5 m lift-over-corduroy	1.2 m lift	1.0 m lift-over-corduroy
Water Truck	-39%	-54%	-61%	-70%
D6 bulldozer	-20%	-33%	-49%	-61%
D7E bulldozer	-21%	-39%	-54%	-68%
D8T bulldozer	-14%	-36%	-46%	-58%
Average of all tracked equipment	-18%	-36%	-50%	-62%

Pipeline stress response to tracked vs. wheeled equipment

The tracked construction equipment was heavier than the wheeled water truck but generated lower contact pressures due to the tracks' relatively large contact areas (refer to Table 6). Despite their lower ground contact pressures, the tracked equipment caused higher pipe stresses; and, these were not proportionate to their heavier masses. For example, the D8T bulldozer weighed 189% of the drive axle group of the water truck but caused 300% higher maximum stresses measured in the buried pipe (Table 13). The concentrated loading imparted by the continuous track and the vibrational loading created by the undercarriage drivetrain are believed to be why the tracked equipment generated higher pipeline stresses than would have wheeled vehicles of the same mass. Very similar results were obtained from a comparison of stresses with the 0.91 m-diameter pipe.

Table 13. Stress response of tracked equipment vs. wheeled water truck (0.41-m-diameter pipe)

	Ratio of maximum circumferential stresses		
Road structure	D6/ water truck	D7E/ water truck	D8T/ water truck
No crossing structure	1.56	1.94	2.64
0.6 m lift	1.61	2.14	2.87
0.5 m lift-over-corduroy	1.76	2.23	3.17
1.2 m lift	1.97	2.65	3.67
1.0 m lift-over-corduroy	1.41	1.76	2.63
Average ratio	1.66	2.15	3.00
Ratio of water truck's drive axle mass to bulldozer mass	1.53	1.67	2.55

Pipeline response to on- and off-highway truck loads

How well do road-pipeline crossing structures dissipate the forces created by heavy forestry trucks (e.g., log hauling trucks carrying Alberta on- or off-highway sized loads)? Although loaded log hauling trucks were not evaluated in this field trial, they can be estimated by considering the pipeline responses to wheel passages from this and a previous field trial. The following describes the analysis procedure and results.

The linear relation found between axle loads and the peak stresses felt by the buried pipe agrees well with results from a previous integrity trial with Access Pipeline (Thiam et al. 2014). In this trial, a linear relation was found when trucks with on- and off-highway sized axle loads passed over four, buried, 1.07 m-diameter pipes. Two of the pipes were buried to a 1.2 m cover depth with lightly compacted, wet, lean clay; trafficking was at grade without any crossing structure. The stress responses in buried pipes, for soil lift crossing structures trafficked by heavy trucks (e.g., log trucks), was modelled using results from both trials, combined with layered elastic analyses of the trench soils with and without a soil lift crossing structure.

It was observed in both field trials that stress measured in buried pipes occurs as discrete responses to individual axle loads crossing above. To predict how well road-pipeline structures dissipate the forces created by heavy trucks, therefore, it is appropriate to consider individual axles groups rather than the entire truck at once. During the Midwest Pipeline field trial, trafficking was conducted with a 3-axle water truck loaded to Alberta legal axle loadings. When crossing at grade, the truck's tandem axle group generated tensile stresses of up to 5.35 MPa in the 0.91 m-diameter pipe, and compressive stresses of up to 6.16 MPa in the 0.41 m-diameter pipe. Pipe stresses were greatly reduced with the addition of 0.6 m and 1.2 m-deep lift structures. As expected, an analysis of the vertical soil stresses adjacent to the tops of the pipes found a strong relation between soil stress and pipe stress. WinJULEA, a layered elastic model, was utilized to model the trench soil stresses; input resilient moduli for the lean clay soil were approximated using the DCP data collected during the test. Modeled soil stresses at the top of the pipe and peak stress measured in the top of the pipe were correlated for the tandem axle group. This linear correlation equation, with modeled soil stresses as inputs, was then used to predict peak pipe stresses in response to a tridem axle group at full legal loading. Figure 18 and Table 15 summarise the analysis for the 0.91 m-diameter pipe.

This analysis revealed that the tandem and tridem axle groups created almost identical stress responses in the 0.91 m pipe. Very similar results were obtained for the 0.41 m pipe. The peak stress in either pipe under a lifted road crossing structure was 4.31 MPa and this is less than 0.8% of the yield strength (550 MPa) of the pipe steel. This low level of stress in the pipe is far less than the point at which permanent deformation (e.g., ovaling) occurs and could be even less under actual service conditions when internal pipe pressures stiffen the pipe wall and help resist deformation.

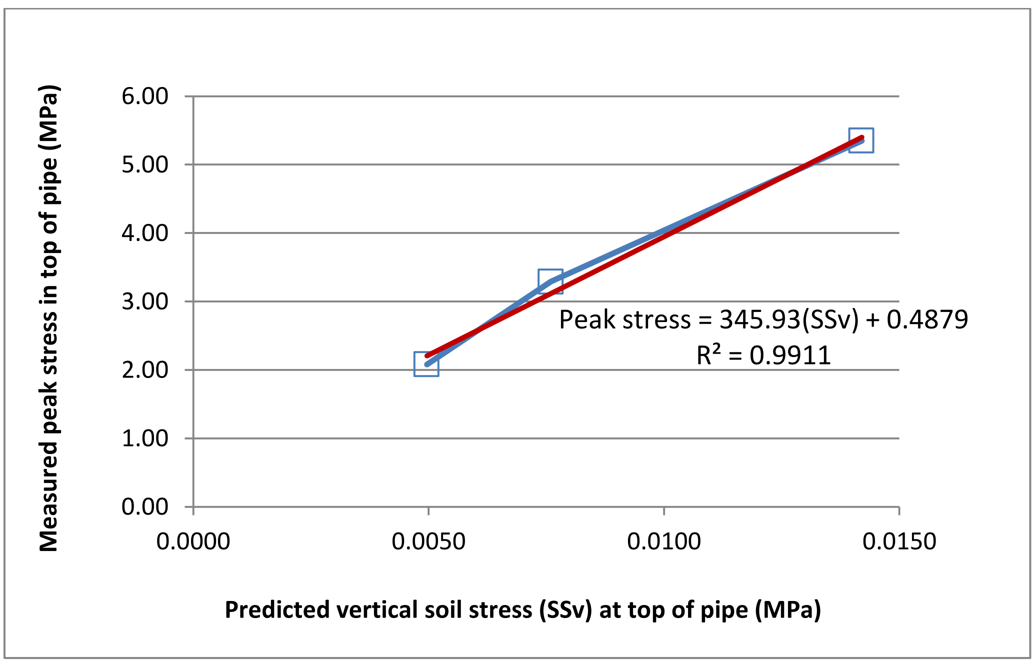

Figure 19. Correlation of peak pipe stress to predicted soil stress at top of pipe (0.91 m pipe, 17 t tandem axle group).

Table 14. Peak pipe stresses under soil crossing structures in response to AB legal truck axle loadings

	0.91 m-diameter unpressurized pipe, 1.2 m cover depth		
Loading	**Crossing structure lift thickness (m)**	**Vertical soil stress level with top of pipe (MPa)**	**Peak stress in top of pipe (MPa)**
17 t tandem axle drive group	0 (no lift)	0.0142	5.35 (measured)
17 t tandem axle drive group	0.6	0.0076	3.29 (measured)
17 t tandem axle drive group	1.2	0.0050	2.08 (measured)
24 t tridem axle drive group	0 (no lift)	0.0135	5.00 (predicted)
24 t tridem axle drive group	0.6	0.0075	3.00 (predicted)
24 t tridem axle drive group	1.2	0.0048	2.11 (predicted)

The results of this analysis were extrapolated to include off-highway-sized axle loads. Relations of peak stress to axle load, for steering, tandem drive, and tridem drive axle groups crossing at grade were reported in (Thiam et al. 2014). These relations allowed the extrapolation of peak pipe stresses in response to very heavy single, tandem, and tridem axle loads crossing at grade. Finally, using the same procedure as followed for the legally loaded tandem and tridem axle groups, pipe responses were predicted for the very heavy off-highway axle loads and two soil lift crossing structures. Table 16 summarises the results.

Table 15. Peak pipe stresses under soil crossing structures in response to heavy off-highway truck axle loadings

	1.07 m-diameter unpressurized pipe, 1.2 m burial depth		
Loading	**Crossing structure**	**Vertical soil stress beside top of pipe (MPa)**	**Peak stress in top of pipe (MPa)**
9 t steering axle	No lift (at grade)	0.0130	5.40
9 t steering axle	0.6 m lift	0.0054	2.34
9 t steering axle	1.2 m lift	0.0029	1.50
23 t tandem axle group	No lift (at grade)	0.0185	**8.80**
23 t tandem axle group	0.6 m lift	0.0096	3.81
23 t tandem axle group	1.2 m lift	0.0059	2.52
35 t tridem axle group	No lift (at grade)	0.0190	8.30
35 t tridem axle group	0.6 m lift	0.0104	4.08
35 t tridem axle group	1.2 m lift	0.0068	2.82

As can be seen, peak pipe stresses of no more than 8.8 MPa are predicted for trucks with very heavy axle loads trafficking earthen lift crossing structures. Comparable levels of stress would be expected in 0.91 m-diameter and 0.41 m-diameter pipes. The peak pipe stress under a 0.6 m-thick soil lift crossing structure was predicted to be 4.08 MPa, and this equals only 0.74% of the yield strength (550 MPa) of the pipe steel. This low level of stress and strain in the pipe is far below the point of yielding (i.e., permanent deformation and ovaling) and would be even less if the pipeline were pressurized. Even lower levels of stress and strain are anticipated for crossings comprised of corduroy overtopped with a lift of soil.

Considering the measured integrity results in the Midwest and Access Pipeline field tests, and the results of this analysis, it is apparent that pipeline integrity will be assured using any of the four evaluated road crossing structures. That is, the stresses and strains that occur in response to trafficking by heavy trucks or tracked construction equipment will be minimal – provided that the pipes are buried to 1.2 m depth in the trench, and overtopped with any of the four evaluated road crossing structures.

Pipeline response under extremely weak soil conditions

In order to evaluate the sensitivity of the field trial results to different operating conditions, a sensitivity analysis was conducted with the layered elastic model of the buried pipes that was utilized to evaluate on- and off-highway truck loadings. Although the soils evaluated in FPInnovations' two field trials were relatively weak, minimum soil strength values (i.e., 30 MPa) were input to predict pipe responses to trafficking when the trench was backfilled with extremely weak and wet soils. The sensitivity analysis was performed using the layered elastic modeling software WinJULEA. Also, properties of the modeled test materials were estimated from published sources. The following table summarizes the modelling inputs and results.

Table 16. Soil sensitivity modeling inputs and results

Soil resilient modulus	30 MPa
Soil Poisson's ratio	0.45
Pipe diameter	0.91 m
Pipe burial depth	1.2 m
Wheel group loading	tandem axle group @ 25 tonnes
Maximum tensile pipe stress	26 MPa
Pipe yield strength	550 MPa
Maximum tensile pipe stress relative to pipe steel's 550 MPa yield strength	4.7%

The sensitivity analysis of extremely weak soil conditions indicates that burial depth is more important to protecting pipeline integrity than the crossing road structure or the trench backfill soil bearing strength. The results also suggest that the findings from the field testing do apply to very wet and weak soils because the stress generated represents only 4.7% of the pipe yield strength (elastic limit).

Requirements for harvesting equipment crossing buried in-block pipelines

Forest harvesting operations also must cross buried pipelines when these pipelines are constructed within the working forest. Like resource road crossings, requirements for harvesting equipment to cross in-block pipelines vary considerably. Although harvesting equipment were not specifically evaluated during the field trials, the range of tracked and wheeled equipment tested in the field trials does allow the inference of results applicable to these types of crossings.

The heaviest forestry equipment used by the Alberta forest industry are feller bunchers and harvesters. These machines, mounted on tracked undercarriages, can weigh up to 37 tonnes but more commonly weigh less than 30 tonnes. As such, they would generate smaller responses in buried pipelines than the 43.5-tonne D8 bulldozer that was tested. The peak responses for the D8 bulldozer passing over buried pipe occurred at field level (with no road crossing structure) and these were approximately 2% - 3% of the pipe steel's yield strength (Table 7). Based on these findings, there appears to be minimal risk associated with the passage of forestry equipment over buried pipelines within the harvest block.

It may be prudent, however, to guard against rutting of the trench backfill if the harvest block area is wet or ruts begin forming at the trench location. A common way to protect harvest block soils against rutting is to operate equipment on top of a brush mat. Numerous studies have documented the effectiveness of brush mats at protecting forest soils from compaction and rutting (Han et al 2006). Studies in New Brunswick (Labelle and Jaeger 2012) have quantified the reduction in soil pressures due to harvesting machine traffic with the use of brush mats, and concluded that soil penetration and soil densification from harvesting machines can be largely mitigated with brushmats of over 20 kg/ m^2 (which corresponds to a mat thickness of 30 – 45 cm thick before trafficking). The authors note that mat effectiveness reduces with trafficking and may need to be replenished for larger amounts of equipment traffic.

4. CONCLUSIONS

Recently, FPInnovations conducted a survey of forestry and energy sector companies to learn about the form of resource road-pipeline crossing structures used in Alberta. The study found that summertime and permanent crossings were frequently crossed using a lift of local soil or a lift-over-corduroy arrangement. In order to provide recommendations towards a standardized set of road-pipeline crossing arrangements that are both safe and economical, a field trial with instrumented and unpressurized pipe sections was conducted in a vacant field adjacent to Midwest Pipeline's equipment yard in Spruce Grove, AB in October 2015. This report describes the methodology of the testing, and compares the relative pipeline responses under earthen lift and lift-over-corduroy crossing structures.

Soil lift crossing structures. Crossing structures comprised of soil lifts are an effective way to reduce stresses in pipelines. The maximum stress levels in buried collector line-sized (0.41 m-diameter) pipeline due to bulldozers passing over were reduced by 25%, on average, with a 0.6 m lift and by 47%, on average, with a 1.2 m lift. The same earthen crossing structures reduced stress levels in buried transmission line-sized (0.91 m-diameter) pipeline by 18%, on average, for the 0.6 m lift and by 50%, on average, for the 1.2 m lift. The average maximum tensile stress measured in either size pipe under an earth crossing structure was 10.38 MPa and this is **less than 1.9% of the yield strength (550 MPa)** of the pipe steel. The average maximum compressive stress measured in either pipe under an earthen lift road structure was 12.39 MPa and this is **only 2.25% of the yield strength (550 MPa)** of the pipe steel. These low levels of stress in the pipes is far below the point at which permanent deformation starts and could be even less under actual service conditions when internal pipe pressures stiffen the pipe wall and help resist deformation.

Lift-on-corduroy crossing structures. Crossings comprised of soil lifts on top of corduroy reduced stress levels in buried collector line-sized pipeline by 32%, on average, if the lift was 0.5 m thick and by 63%, on average, if the lift was 1.0 m thick. Crossings comprised of soil lifts on corduroy reduced stress levels in buried transmission line-sized pipeline by 36%, on average, in 0.5 m lifts and by 62%, on average, in 1.0 m-thick lifts. The average maximum tensile stress measured in either pipe under a lift-over-corduroy road structure was 7.76 MPa and this is **only 1.4% of the yield strength (550 MPa)** of the pipe steel. The average maximum compressive stress measured in either pipe under a lift-over-corduroy road structure was 11.42 MPa and this is **only 2.08% of the yield strength (550 MPa)** of the pipe steel. These low levels of stress in the pipes is far below the point at which permanent deformation starts and could be even less under actual service conditions when internal pipe pressures stiffen the pipe wall and help resist deformation.

Tracks vs. wheels. The tracked construction equipment developed lower ground contact pressures than did the wheeled vehicle; however, the tracked equipment generated significantly higher stresses in proportion to its mass than did the wheeled vehicle. This is believed to be due to the concentrated loading imparted by the continuous track and the vibrational loading created by the undercarriage drivetrain. In the field trials described, burial of pipeline to 1.2 m depth in a trench effectively protected the integrity of the pipe by keeping strains and stresses to low levels. All of the soil lift and lift-over-corduroy crossings structures evaluated in this trial further reduced traffic stresses and strains to very low levels.

On- and off-highway truck loadings. On-highway and off-highway log hauling truck trafficking pipelines at road crossings is an important consideration for the design of crossing structures. The stress responses in buried pipes, for soil lift crossing structures trafficked by heavy trucks (e.g., log hauling trucks), was modelled using results from this and an earlier integrity test, combined with layered elastic analyses of the trench soils with and without a soil lift crossing structure. The results of this analysis predicted that stress and strain levels in the pipeline will be kept to minimal levels, regardless of wheel loading, if the pipeline is buried to a 1.2 m depth in the trench and any of the evaluated crossing structures are used.

General comments about the test results. The site conditions for this test were representative of dry, upland sites. Relatively small pipeline stresses were measured both with and without a crossing structure. The stresses reported in this testing were never more than 16.30 MPa or 2.96% of the steel's yield strength. Similar results were found in a previous field trial conducted on saturated, fine grained soils near Fort Saskatchewan, Alberta. Based on these findings it can be theorized that pipe stresses are kept to very low levels by having sufficient trench burial depths to generate soil arching within the trench. Higher pipe stresses than measured in these field trials would be expected to occur in the case of shallower pipe burial depths or thinner walled pipes.

5. RECOMMENDATIONS

The results of this and a previous integrity testing indicated that pipeline strains and stresses due to equipment and heavy vehicle passes were kept to a minimum by burying the pipe to a sufficient depth in the trench; additional reductions in pipe strains and stresses resulted with the use of earthen lift or earth-on-log crossing structures.

It is recommended that, for the purpose of economy and ease of construction that Albertan resource extraction industries reduce the thickness of resource road-pipeline crossing structures from current levels to some minimal structure that protects the trench backfill from rutting (e.g., 0.5 m lift-over-corduroy or 0.6 m-thick earthen lift). The resultant increases in pipeline stresses and strains with this change are anticipated to be minimal while the benefits will be considerable. In the case of harvesting block crossings that are used only by harvesting equipment, it is recommended that a brush mat 30 cm thick (before trafficking) be installed to protect against rutting of trench soils.

It is recommended that Alberta resource extraction industries adopt a general set of construction arrangements to detail common resource road-pipeline crossing structures. This set of arrangements should include construction arrangements for all season, winter-only, and wetland crossing structures, as well as for in-block crossings.

It is recommended to extend the results from this trial to wet area conditions. This could be done by conducting an integrity test with common wetland crossing structures, such as access (swamp) mats and earthen lift structures (to permit comparisons with results from these trials).

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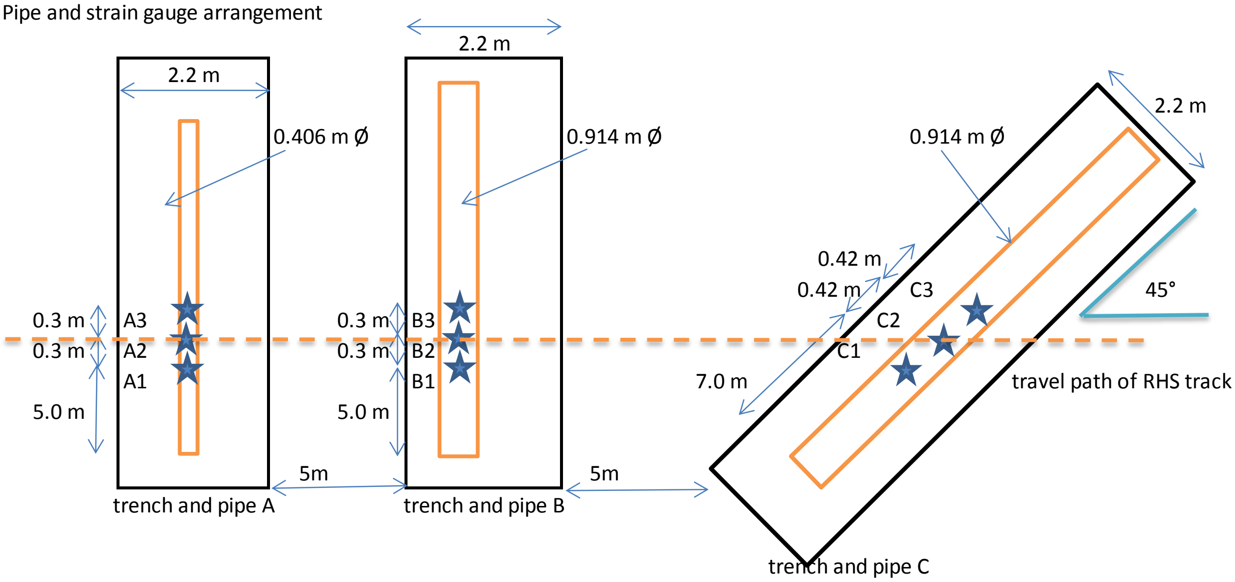
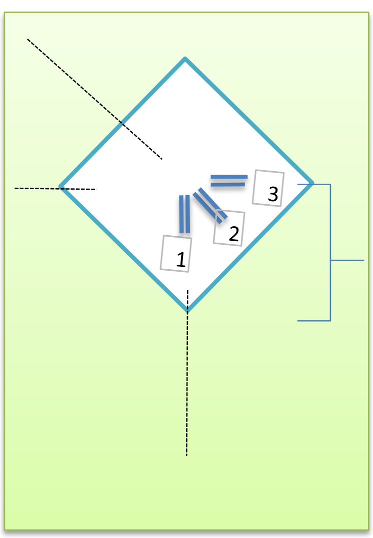
APPENDIX A. STRAIN GAUGE INFORMATION

Pipe and strain gauge arrangement



Strain Gauge Map: 21 datalogger channels					
Pipe A's gauges on outside of pipe barrel. Pipes B and C gauges installed inside barrel					
A3.1	longitudinal	B3.1	longitudinal	C3.1	longitudinal
A3.2	*not connected*	B3.2	*not connected*	C3.2	*not connected*
A3.3	radial	B3.3	radial	C3.3	***damaged - no signal***
A2.1	longitudinal	B2.1	longitudinal	C2.1	longitudinal
A2.2	45°	B2.2	45°	C2.2	45°
A2.3	radial	B2.3	radial	C2.3	radial
A1.1	longitudinal	B1.1	longitudinal	C1.1	longitudinal
A1.2	*not connected*	B1.2	*not connected*	C1.2	*not connected*
A1.3	***damaged - no signal***	B1.3	radial	C1.3	radial

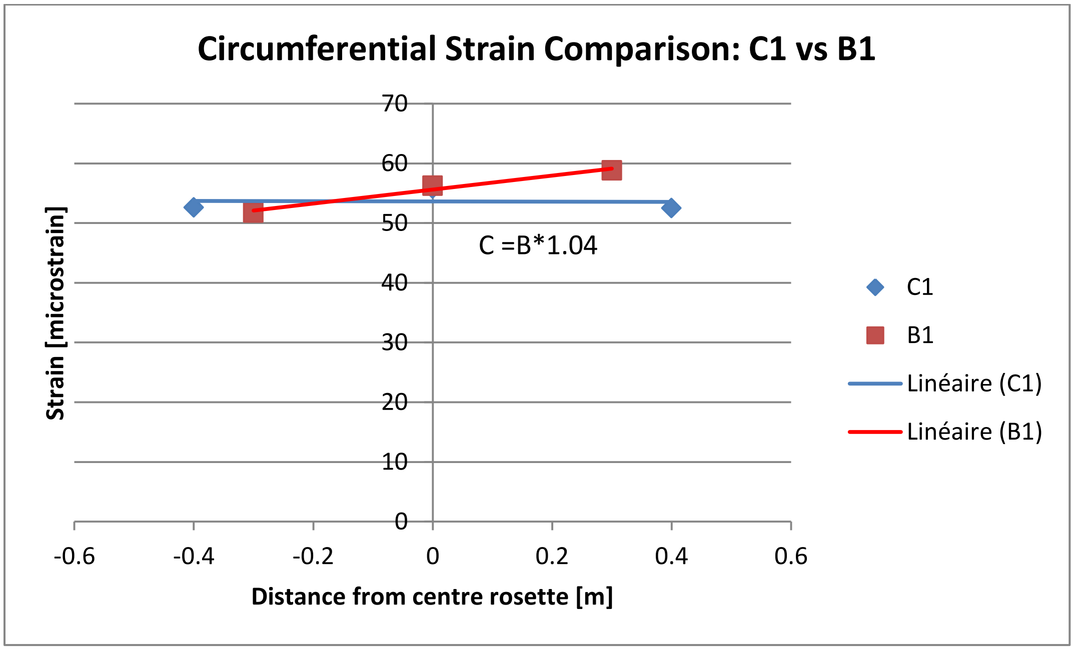


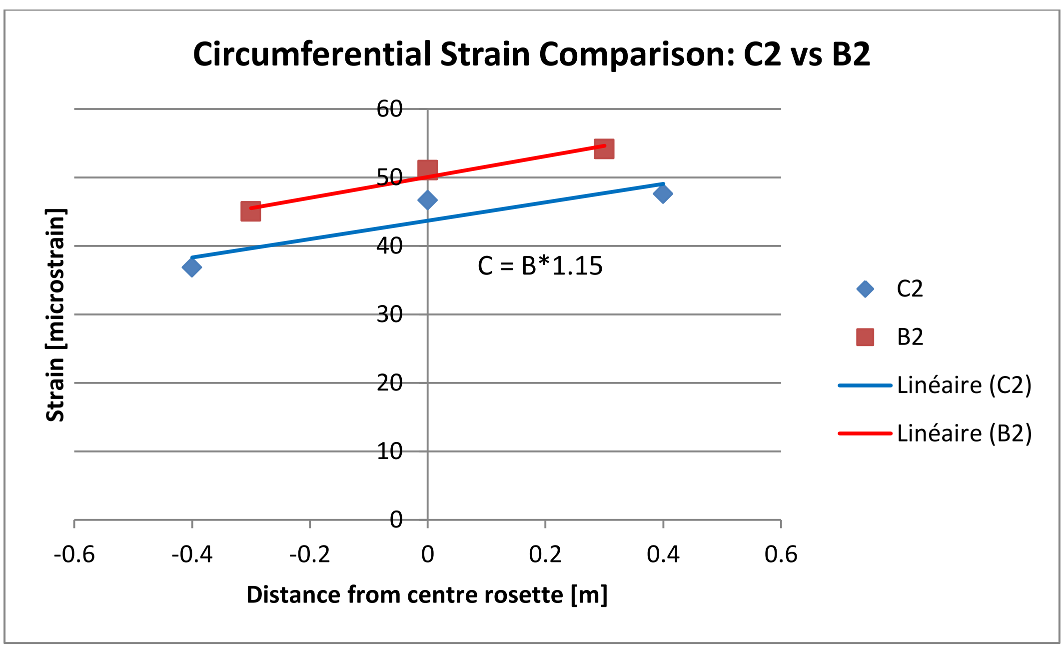
general arrangement of a tri-axial strain gauge on the pipeline barrel
gauge 1 aligned with longitudinal axis of barrel
gauge 2 aligned at 45° from longitudinal and radial directions
gauge 3 aligned with radial axis of barrel

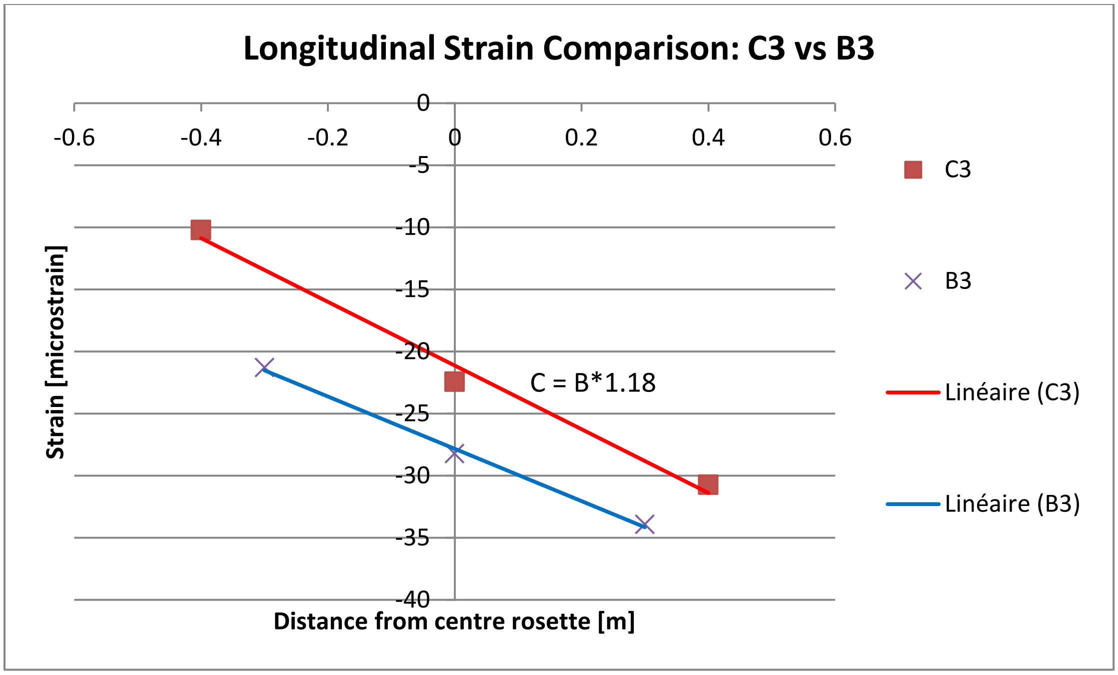
strain gauge numbering pattern

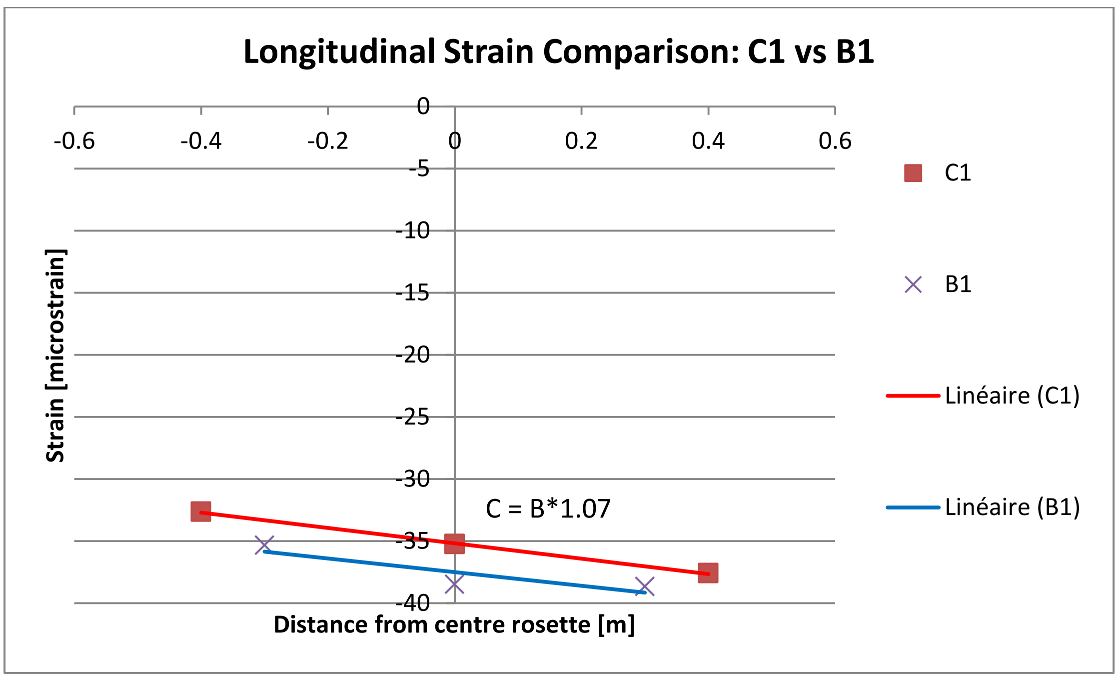
APPENDIX B. SOIL COMPACTION CALIBRATION

Strain responses were compared between the 0.915 m (36”) diameter pipes buried in trenches B and C to quantify and account for differences in the density of the backfill. In the following charts, the relation is listed that compares strains in pipe C to those strains in pipe B. The differences were relatively minor and indicated that the soil densities were similar. These relations were used to adjust strain values in pipe C relative to pipe B.






Longitudinal Strain Comparison: C3 vs B3
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0
-5
-10
-15
-20
-25
-30
-35
-40
Strain [microstrain]
Distance from centre rosette [m]
C = B*1.18
C3
B3
Linéaire (C3)
Linéaire (B3)


Longitudinal Strain Comparison: C1 vs B1
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0
-5
-10
-15
-20
-25
-30
-35
-40
Strain [microstrain]
Distance from centre rosette [m]
C = B*1.07
C1
B1
Linéaire (C1)
Linéaire (B1)

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