Pipeline response to cover depth and soil compaction: Results from a field trial

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By:

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ACKNOWLEDGEMENTS

The authors gratefully acknowledge the many in-kind contributions provided by Access Pipeline Inc. and, especially, the project management and technical expertise of Samim Aminzadah, Evert Smith, and Rianto Baskoro. Thanks also to Doug Kulba (Alberta Energy and Sustainable Resource Development) and Randy Galbreath of Stratus Pipelines Ltd. for their contributions to this work.

This project was financially supported by Natural Resources Canada under the NRCan/ FPInnovations CFS contribution agreement.

FRONT COVER

Compacting fill beside pipeline segment no. 2 with prototype, excavator-mounted, dual wheel compactor. Strain gauge wires are bundled on top of pipe 2 and at the surface at the stakes above the end of buried pipe 1.

CONTACT

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1. INTRODUCTION AND PROJECT RATIONAL

FPInnovations, with funding from the Canadian Forest Service, is currently investigating the feasibility and form of standardized road - pipeline crossings. FPInnovations and Access Pipeline Inc. jointly conducted a field trial to evaluate the structural responses from heavy vehicle traffic to large (National) pipeline segments buried within a native earth road. This field trial was intended to contribute to the general knowledge of the industry, and more specifically to document the structural performance of large diameter, stiff-walled (pipeline) pipe buried under roads that are crossed by heavy equipment.

The field trial was designed to measure the strains and stresses acting on unpressurized pipeline segments installed with two cover depths using two backfill compaction methods; a total of four different combinations of cover depth and compaction method were evaluated. There was no additional protection over the pipe other than the earth fill. Access Pipeline introduced a novel compaction method for this research initiative which helps to reduce the volume of spoil left after the installation of pipeline. The method utilizes a prototype, excavator-mounted, dual-wheel compactor that compacts fill on both sides of the pipe simultaneously. Extreme care was taken to protect the integrity of the pipe and its coating during compaction with this prototype compactor.

Please note that the Dual-Wheel Compactor is only being used for research purposes and is not intended, recommended or implied to be used as part of the pipeline construction process.

The strains in the four pipe segments were measured in response to both static and dynamic vehicle loading. The strains provided a direct, relative, comparison of the effectiveness of cover depth and soil compaction to protect the pipeline from high traffic-induced stresses. In the future, the measurements may be used to support modeling of resource road crossings over buried pipelines.

2. METHODOLOGY

Access Pipeline provided four 23 m-long segments of X60 heavy pipe for the field trial. Table 1 summarizes the properties of the field test pipe segments.

Table 1. Properties of field test pipe

Pipe property	
Pipe diameter	1.07 m (42”) (typical of National pipeline)
Pipe wall thickness	13.8 mm (typical summer heavy pipe)
Minimum pipe toughness	448 MPa (X60 grade steel)
Outside treatment	uncoated
Approximate mass of pipe segment	8000 kg (17 500 lbs)
Typical operating pressure	9930 kPa

FPInnovations instrumented each pipe segment with strain gauges on the inner surface at the uppermost or 12 o'clock position. Each pipe had three strain gauges installed approximately 30 cm apart so that the maximum strain would be captured even if the test truck varied its wheel path by up to 30 cm. The central strain gauge was a rosette assembly that provided readings in the circumferential direction and at 45° and -45° to this. Two other gauges were attached 30 cm (1 foot) to either side of the rosette and measured only circumferential strains (Figure 1).

The pipe segments were buried in level 2.01 m-wide trenches that were excavated beside a native earth road accessing the Access Pipeline IPS test site near Fort Saskatchewan, AB. Two segments had a cover depth of 1.2 m (a typical roadway depth) and the other two had only 0.75 m (typical cover for installations in agricultural fields). For one pipe segment at each cover depth, fill beside the pipe was compacted using a prototype, excavator-mounted, twin wheeled compactor (see report cover). For all four pipes, the fill over the pipe was compacted using a 1.07 m-wide, 5 tonne, vibratory, tamping foot, compactor. Table 2 summarizes the treatments used to install each pipe segment. Figure 1 illustrates the arrangement of the pipes in the test road.

Table 2. Compaction and cover treatments for installed pipe segments

	Compaction method	**Cover depth (m)**
Pipe 1	Vibratory tamping foot compactor	1.2
Pipe 2	Both the prototype dual wheel and a vibratory tamping foot compactor	0.75
Pipe 3	Both the prototype dual wheel and a vibratory tamping foot compactor	1.2
Pipe 4	Vibratory tamping foot compactor	0.75

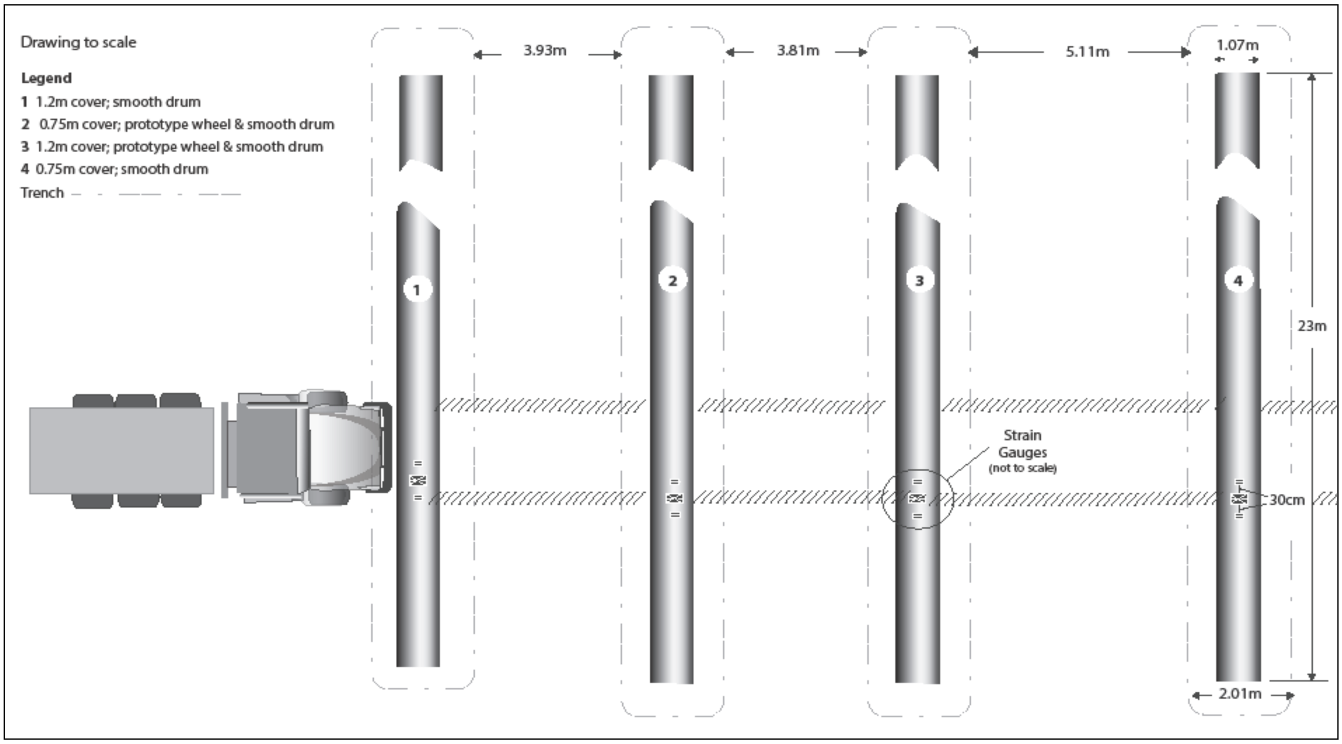

Figure 1. Schematic of the arrangement of four instrumented pipes in the earth road. The test trucks aimed to pass over the central, rosette strain gauge assembly.

Strain responses in the pipes were measured as vehicles slowly drove over the pipes (dynamic loading) and when the vehicles were stopped above the pipes (static loading). Each vehicle passed over the four instrumented pipes in the road a total of four times; twice in the forward direction and twice in reverse; travel speeds ranged from 4 to 7 km/ h. Static loading tests of each pipe were conducted by stopping each truck with its steering axle, then drive axle group, and then trailer axle group over the pipe, and measuring the pipe strains for approximately 20 seconds.

The vehicles used for the field trial ranged from heavy off-highway loadings that might travel over a pipeline along a resource road to typical vehicles such as a 5 tonne service truck. The mass of the axle groups of each test vehicle were measured on site with portable pad scales and are shown in Table 3. The vehicles that traversed the test section were a 7-axle lowbed transporting a 50-t excavator (Figure 2); the same 7-axle lowbed unloaded; a filled water truck; and a 5-tonne service truck. To achieve off-highway axle loadings, a very heavy excavator (CAT 345C L) was provided by Stratus Pipeline, the lowbed dropped its tandem axle jeep, and the water truck overfilled its water tank.

Figure 2. 7-axle tri-drive/ tridem lowbed loaded with a 50 tonne excavator.

Table 3. Test vehicle loadings

Test vehicle	Steering axle (kg)	Drive axle group (kg)	Trailer axle group (kg)
Tri-drive/ tridem lowbed semi-trailer (unloaded)	8400	12 930	8230
Tri-drive/ tridem lowbed semi-trailer (loaded)	9080	31 410	30 760
Tandem drive water truck (loaded)	7790	17 810	n/a
Single drive service truck	2120	2570	n/a

The test vehicles were equipped with a variety of tire sizes as appropriate to application and load range. Tire contact area was measured on site when tire loads were gathered. Steering axle tires were the largest tires and these developed large contact areas (footprints); the service truck was equipped with the smallest sized tires and these developed relatively small contact footprints. Table 4 summarizes the tire sizes, configurations and average footprint areas of the test vehicles.

Table 4. Tire size and contact area

Test vehicle	Tire size			Tire contact area (cm^2)		
	Steer	Drive	Trailer	Steer	Drive	Trailer
Tri-drive/ tridem lowbed semi-trailer (loaded)	425/65R22.5	11R24.5 dual tires	275/70R22.5 dual tires	1082	730	615
Tri-drive/ tridem lowbed semi-trailer (unloaded)	425/65R22.5	11R24.5 dual tires	275/70R22.5 dual tires	1008	433	296
Tandem drive water truck (loaded)	385/65R22.5	11R24.5 dual tires		1038	674	
Single drive service truck	LT225/75R17	LT225/75R17 single		357	454	

3. RESULTS AND DISCUSSION

Pipe responses to trafficking were discrete and allowed the identification of structural responses as each axle passed directly over the pipe. Figure 3 shows a typical stress response pattern recorded for the 7-axle loaded lowbed. It can be seen that the top of the pipe goes into compression (-ve stress) as the wheel approaches, into tension (+ve stress) when the wheel is directly above, and then briefly into compression as the wheel moves away. Compressive stresses in the top of the pipe indicate that the pipe is being squished from the sides as the wheel approaches or recedes; tensile stresses in the top of the pipe indicate that the pipe is being squished downwards by the wheel being directly over top. Responses from all three strain gauges are plotted; L1 and L2 are the single strain gauges and R2 is the strain response from the 3-gauge rosette. Typically the rosette recorded the largest strains (green lines), however, sometimes L1 or L2 were greater because of vehicle wander.

Another observation of note is the relatively higher stresses induced by the drive axles compared to the trailer axles for similar loads. This is partly due to the influence of the steer tire load being relatively close to the drive group, whereas the trailer group is located a greater distance from other axles and not influenced by other axle loads.

The measured strains at the top of the pipe were converted to stresses using equation 1:

$$\sigma \text{ (MPa)} = \xi \,.\, E \text{ (MPa)} \tag{1}$$

Where σ is the pipe stress, ξ is the pipe strain and E is the steel pipe's elastic modulus (typically equal to 200,000 MPa).

The elastic limit of steel stress (σ) can range from 200 to 1000 MPa depending on the ductile properties of the steel. The steel in the X60 pipe segments used for the field trial had an elastic limit of 448 MPa.

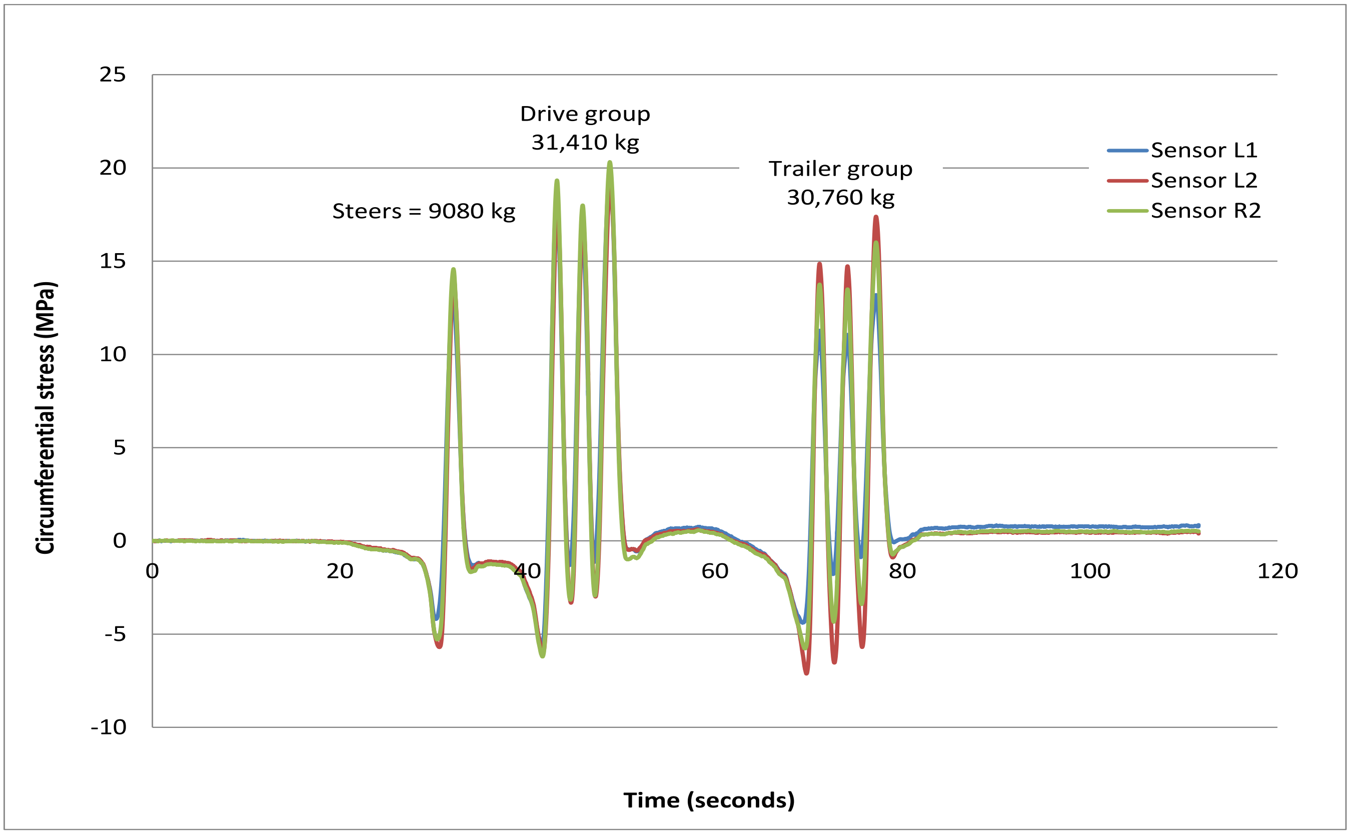

Figure 3. Pipe segment 2 response to trafficking by the loaded lowbed truck.

In order to avoid the pipe being permanently deformed from round (called "ovaling"), the stress responses from the traffic loading must not exceed the elastic limit of 448 MPa. The loaded lowbed carried the highest axle group loadings in the field test but generated a maximum pipe stress of less than 21 MPa. None of the circumferential stresses measured during the field test approached the 448 MPa elastic limit of the pipe steel. Therefore, it is concluded that the pipe segments were never at risk of ovaling.

The field test was conducted with unpressurised pipe segments. Had the pipe been pressurized to 9930 kPa, as is typical for in-service operating conditions, the strains and stresses experienced at the top of the pipe would have been even less. The earth road structure in the field test was minimal and built to a lower standard than a resource road. Had the road structure been constructed like a typical resource road the measured strains and stresses are also expected to have been much less. What, then, was the reason for measuring strains in unpressurized pipe installed in a substandard roadway? The purpose of the testing was to compare the structural impacts of compaction and cover depth on pipeline pipe under low risk testing conditions. The data collected provides an opportunity to evaluate correlations of the external factors acting on the pipe, and may ultimately support the development of standardized crossing designs.

Compaction method and cover depth

Soil identification and density testing were performed on samples gathered from various depths in the backfilled trenches. The in-situ soil was a fine grained mix of silt, sand and clay and was classified as

CI (USCS method). The soil had a maximum dry density of 1834 kg/ m^3 at an optimum moisture content of 14.0%. Density testing of the soil compacted by the prototype compactor found that it increased soil density by 6% to 11% over shading (placing un-compacted fill beside and over the pipes). The increased soil density may promote some soil arching which would reduce the forces felt by the pipeline. The soil testing results provided by Shelby Engineering Ltd. is included in Appendix 4.

Compaction method and cover depth were key factors influencing the degree to which traffic loading was felt by the pipeline segments. In order to quantify the effect of depth and compaction on pipe performance, pipe responses from trafficking with different axle group loads, axle group configurations, and vehicle types were compared. Figure 4 illustrates the peak circumferential stress measured in the four pipe segments in response to dynamic loading by the drive axle group of each of the three test vehicles. The drive axles were the most heavily loaded axle group on each of the test vehicles and were, therefore, used for illustrative purposes. The trends illustrated in Figure 4, however, were also observed in response to the steer axles and trailer groups for all the tested vehicles (Appendix 1).

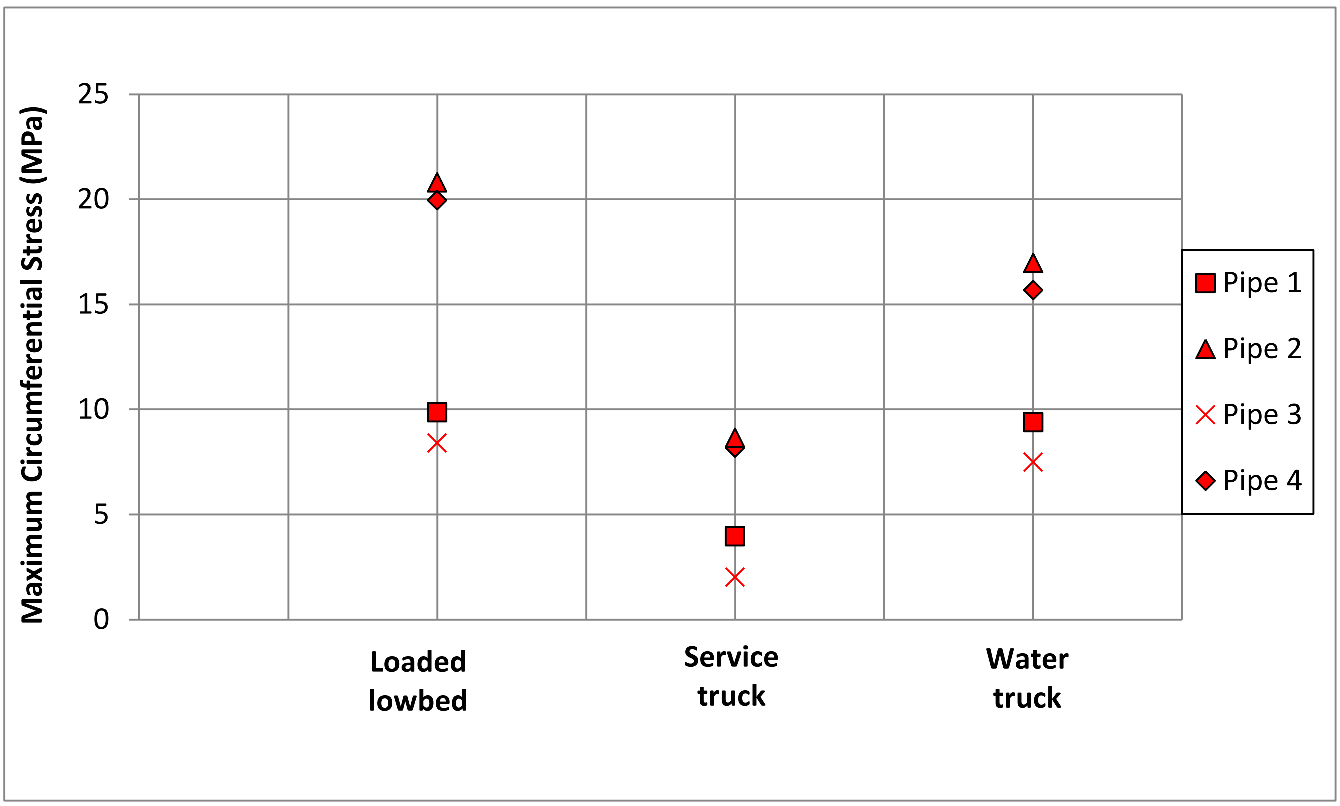

Figure 4. Example of the effect of compaction method and cover depth on pipe response for drive axle dynamic loading.

The highest stresses were measured in pipe 2 (0.75m cover depth and compacted with both the prototype wheel and the vibratory tamping foot compactor). The lowest stresses were measured in pipe 3 (1.2m cover depth compacted with only the vibratory tamping foot compactor). Pipes 2 and 4 had very comparable stress levels indicating that cover depth strongly influenced structural response but compaction had only a minor effect.

Two trends are discussed below:

- **Effect of cover depth:** As expected, the cover depth had a strong influence on the pipe response. Figure 4 illustrates that 1.5 to 2 higher stresses occurred at a cover depth of 0.75m than at a cover depth of 1.2m. That is, a 60% increase in cover depth reduced stresses by, on average, 54%. The reduction in traffic-induced pipe stress with depth of cover is believed to be due to the diminishing of the vertical soil stresses with increasing depth (i.e., spreading out of the soil pressure bulb with depth).
- **Effect of compaction method:** The effect of the compaction method on pipe response was minor and more obvious at the deeper cover depth. At 1.2m cover depth, the 6-11% higher compaction achieved with the prototype compactor in the soil beside the pipe consistently reduced pipe stresses by 1 to 2 MPa (pipe 3 < pipe 1). At 0.75m cover depth, the 6-11% higher compaction achieved with the prototype compactor in the soil beside the pipe consistently increased pipe stresses by 0.2 to 1 MPa (pipe 2 > pipe 4). While a reduction in circumferential pipe stresses with compaction can be explained by soil arching around the pipe, the reason for an increase in stresses felt with greater soil compaction and at a shallower cover depth is less intuitive. This may be the result of high water content in the pipe 2 trench weakening the soils.

Effect of wheel load and configuration on pipe response

As expected, stress responses in the buried pipeline segments were strongly influenced by the magnitude of axle loading. Higher axle loads resulted in higher pipe stresses. Axle group loads of 1 to 2.2 t generated pipe stresses in the order of 2 to 8 MPa whereas loads of 4 to 5.2 t generated pipe stresses in the order of 5 to 20 MPa. The range of stress values was due to pipes having different cover depths (and to a minor amount compaction level) as well as the loads being applied by different wheel configurations.

Figure 5 presents pipe stress responses as function of wheel configuration, wheel load, and cover depth. The loads vs stress response linear relations showed strong correlations and had correlation coefficients (R^2) ranging from 0.6 to 0.95. On the strength of the high correlation coefficients, especially at 0.75m cover depth (R^2 of 0.85 and 0.95), the following observations were made:

- The impacts of the wheel configuration (single versus dual) determined that for each cover depth there was a unique cross over where the impact to the pipe was greater depending on the weight of the load. A single wheel had a greater impact at lower loads. At 0.75m cover depth, pipe response was greater for single tires carrying under 4500 kg. This accounts for all typical steering axle loading. We believe that this is because the dual tires apply the wheel load to a greater footprint area and this reduces the vertical pressure reaching the pipe. At a 1.2m cover depth, the pipe response was greater for single tires carrying under 3000 kg.
- At both cover depths, when tire load was less than 1143 kg, the pipe response was greater for single (steering) tires than for dual tires. This trend reversed for tire loads exceeding 1143 kg. That is, stresses were greater for dual tire assemblies carrying 2285 kg than single tires carrying 1143 kg. This suggests that the steering tire concentrates load more than dual tire assemblies but at a total weight of 2285 kg or greater the concentrating effect becomes less important than total load.

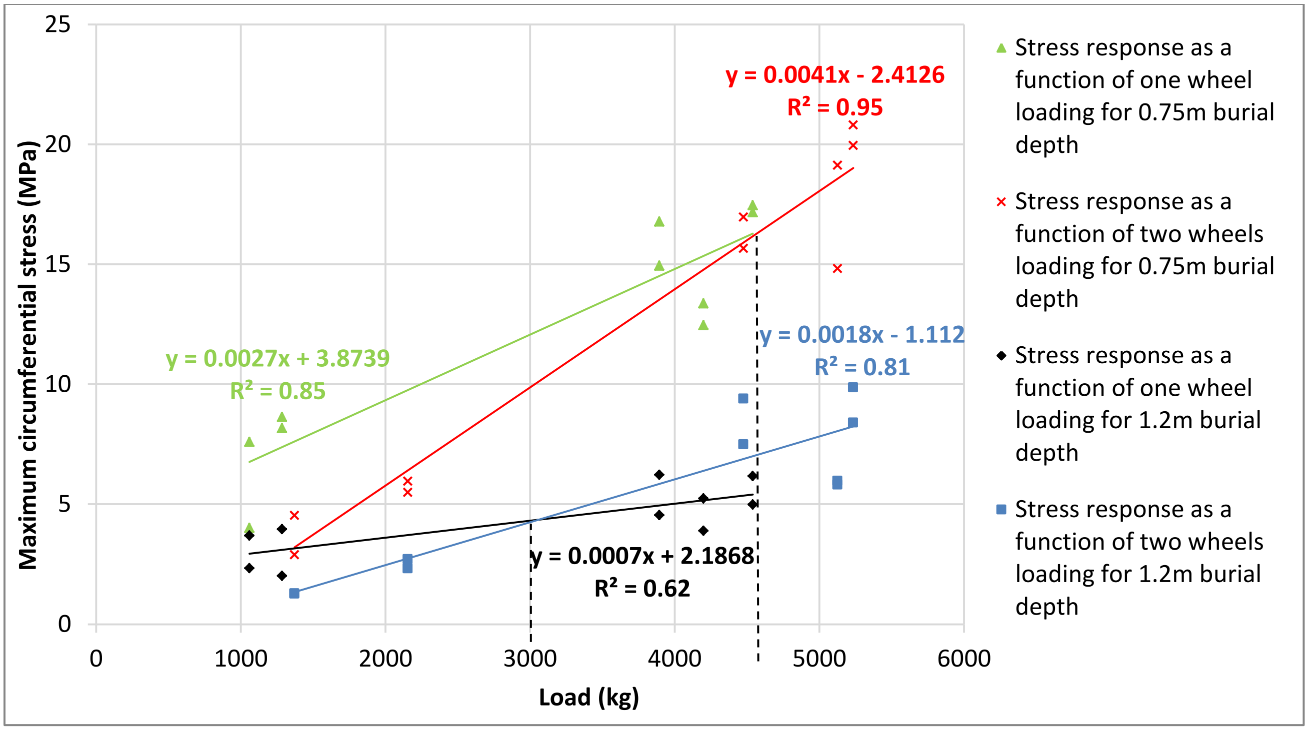

Figure 5. Effect of the wheel load, wheel configuration (single vs dual) and cover depth on pipe stress.

As seen in the Table 4, tire sizes and tire configurations, relate to the contact area in which the load is applied, and has an impact on the pipe response. Table 4 also shows that the steering sizes are bigger and therefore create a bigger footprint, as a comparison to a drive or trailer axle. That explains why, for the same loading, the contact stresses are smaller for a bigger tire size.

4. CONCLUSIONS

FPInnovations and Access Pipeline Inc. jointly conducted a field trial to evaluate the structural responses from heavy vehicle traffic to large pipeline segments buried within an earth road. This trial was intended to contribute to the general knowledge of the industry, and more specifically to document the structural performance of large diameter, stiff-walled (pipeline) pipe buried under roads that are crossed by heavy equipment.

The field trial was designed to measure the strains and stresses acting on unpressurized pipeline segments installed with two cover depths using two backfill compaction methods. Strain responses in the pipes were measured as vehicles slowly drove over the pipes (dynamic loading) and when the vehicles were stopped above the pipes (static loading). The vehicles used for the field trial ranged from heavy off-highway loadings that might travel over a pipeline along a resource road to typical vehicles such as a 5 tonne service truck.

The bullets below describe three results from the trial.

- Despite the high axle loads and minimal road structure, the measured stress levels in the test pipes never exceeded 5% of the elastic limit of the pipeline steel and would never have caused permanent deformation of the pipes.
- The effect on pipe response of trafficking pipes with two cover depths produced a clear and obvious pattern showing that deeper pipes (1.2 m cover) experienced, on average, 54% less stress than pipes with shallower cover (0.75 m).
- The effect of compaction method on pipe response did not produce a clear and obvious trend. The measured pipe stresses produced opposite trends depending on the pipe cover depth.

APPENDIX 1: PIPELINE RESPONSES TO DYNAMIC AND STATIC LOADING- STEERING AND TRAILER AXLES

The graphs shown in Figure 6 and Figure 7 represent the pipes responses from the dynamic loading by the different steering axles and trailers groups. These graphs complement the graph shown in Figure 4 and show the same overall trends. Figure 8 and Figure 9 present the static loading.

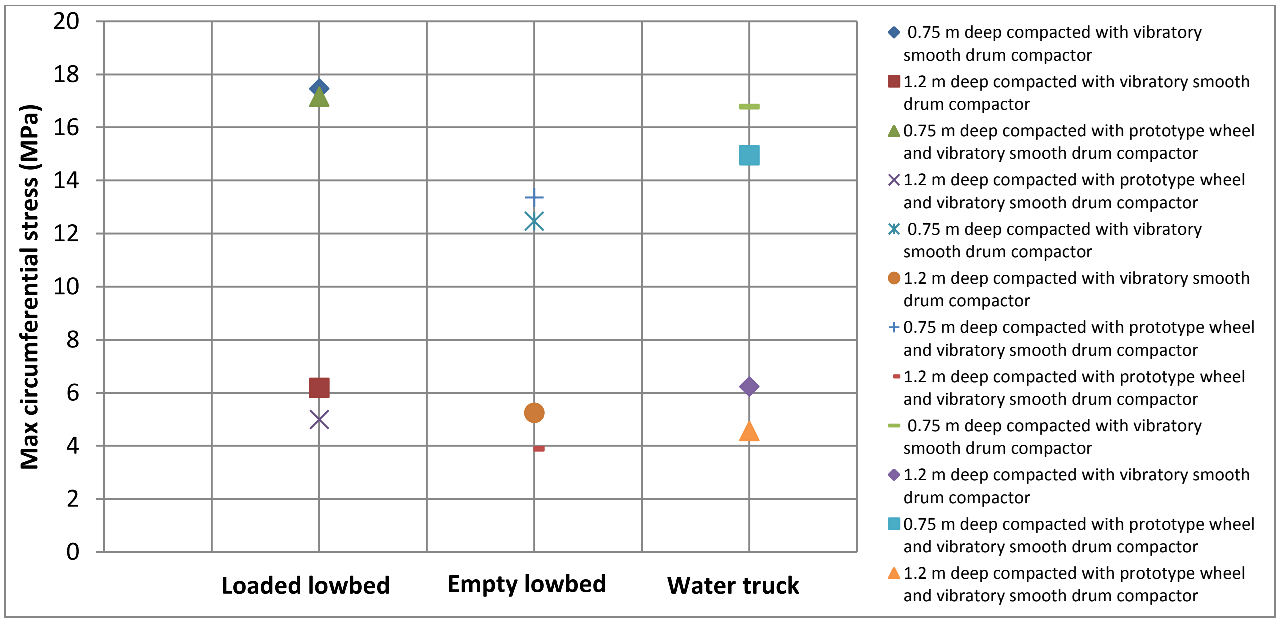

Figure 6. Pipeline response to axle load and installation method; dynamic loading by steering axle.

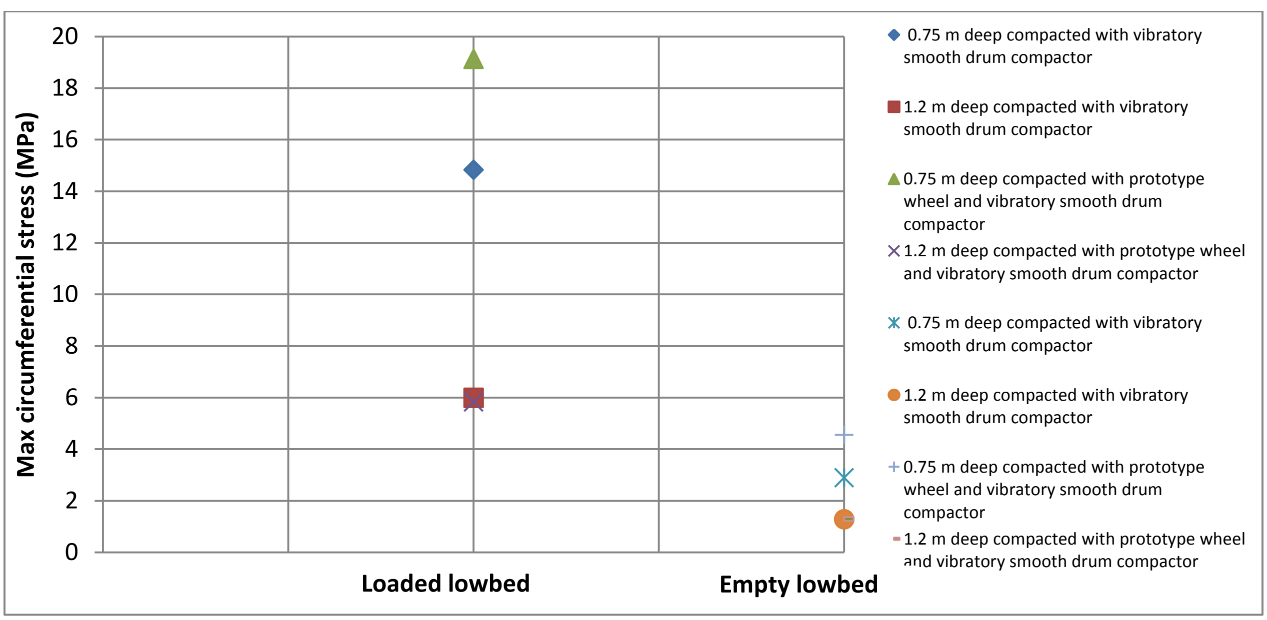

Figure 7. Pipeline response to axle load and installation method; dynamic loading by trailer axle group.

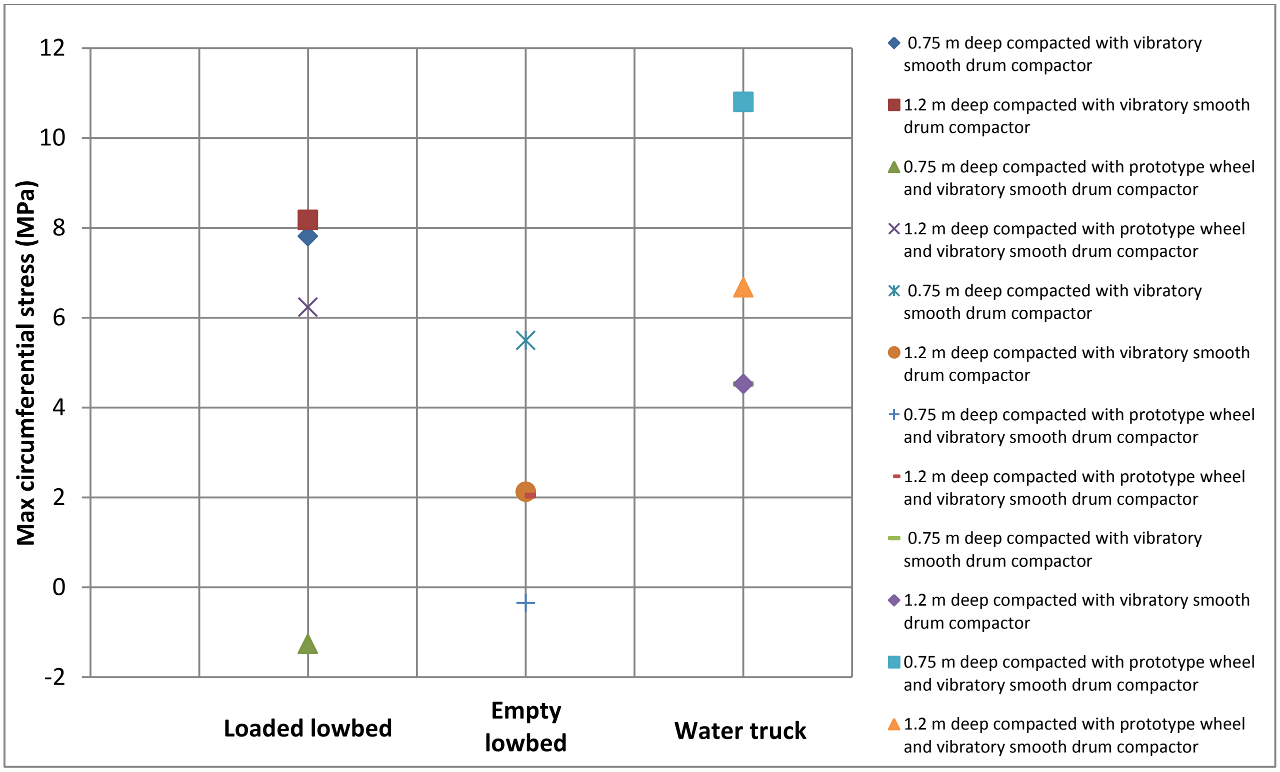

Figure 8. Pipeline response to axle load and installation method; static loading by steering axle

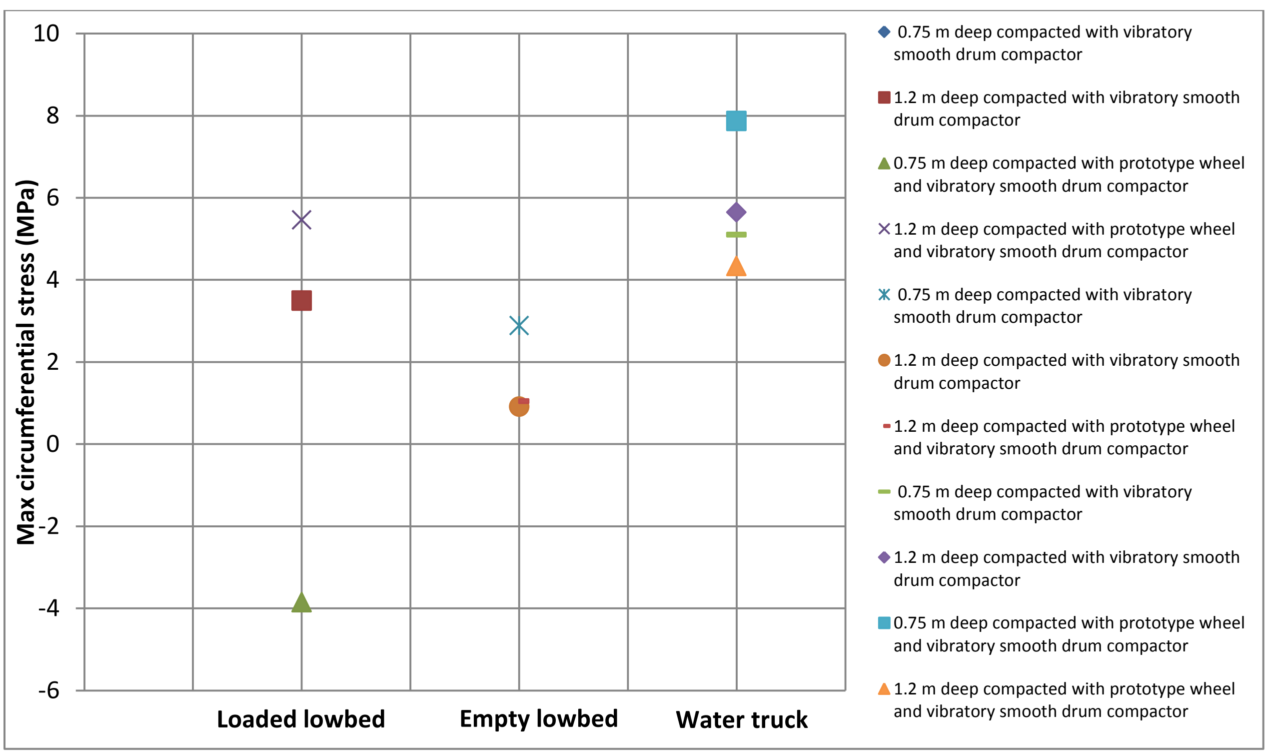

Figure 9. Pipeline response to axle load and installation method; static loading by trailer axle group.

APPENDIX 2: PIPELINE RESPONSES TO AXLE LOAD AND INSTALLATION METHOD

Figure 10, Figure 11 and Figure 12 shown in this appendix represent the pipeline responses per axle load (Max. circumferential pipe stress per ton of axle load) for the different tested vehicles. It is important to note that the pipe response is expressed per half axle. The concept of half axle relates to the applied weight from half of the overall wheels of an axle. As an example, for a single axle steer with 2 wheels, the half axle load is the load applied to one wheel. The stress is then dependent on the configuration as well as the tire footprint.

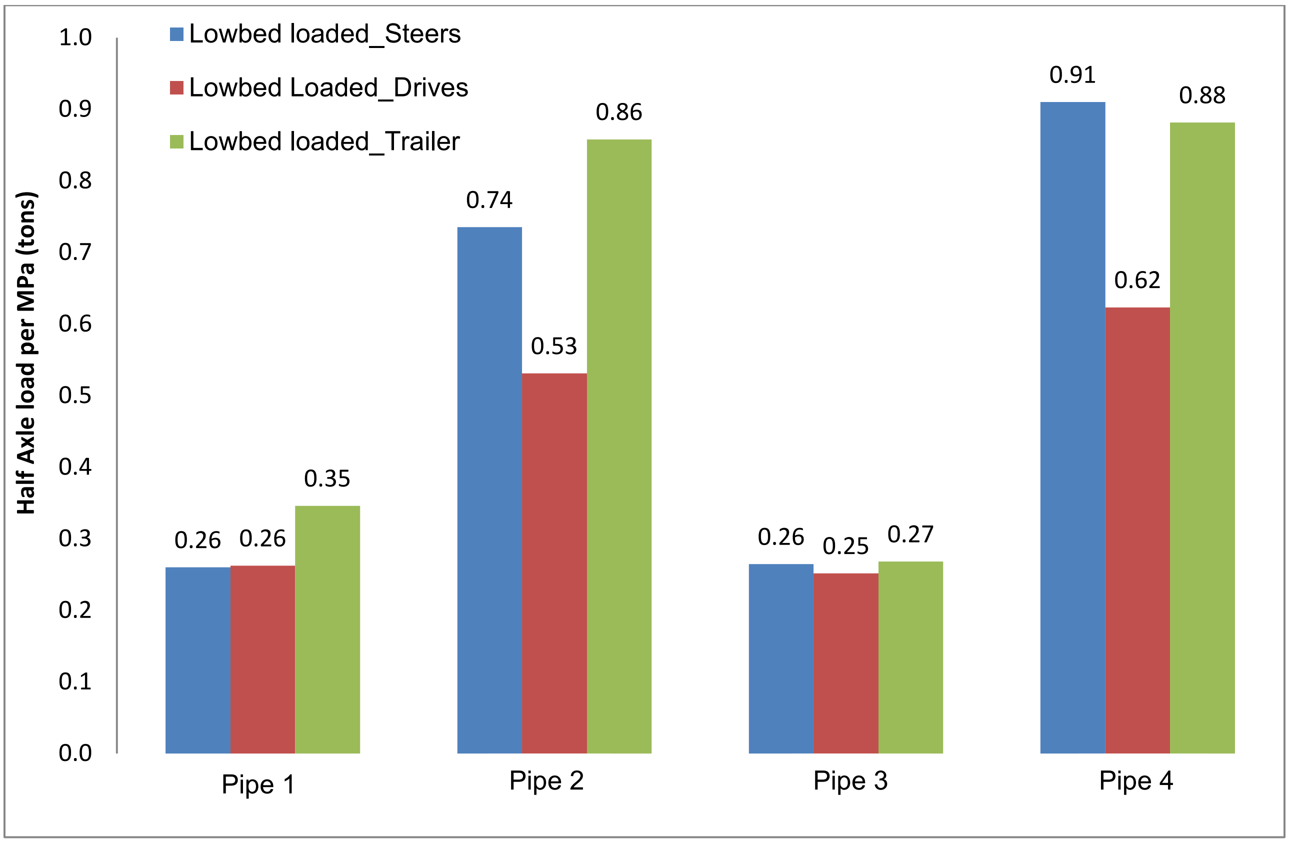

Figure 10. Pipeline response per axle load (max. circumferential pipe stress per tonne of axle load) by installation method; dynamic loading by loaded lowbed.

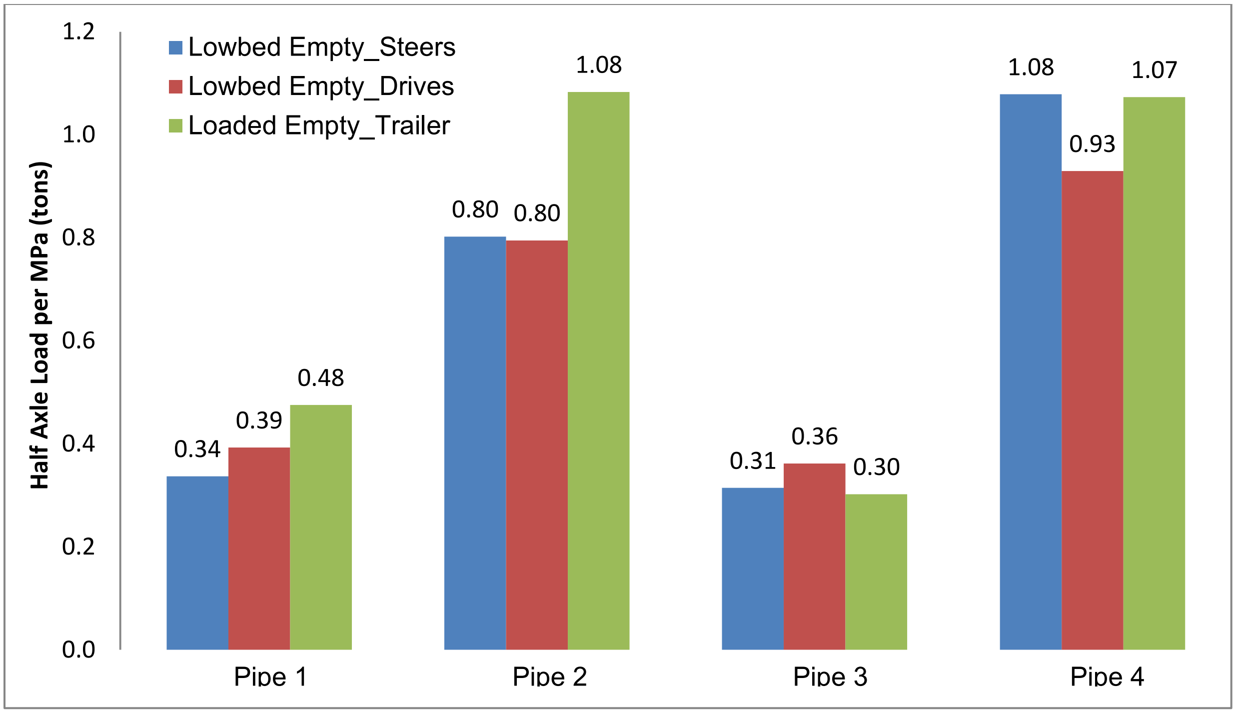

Figure 11. Pipeline response per axle load (max. circumferential pipe stress per tonne of axle load) by installation method; dynamic loading by empty lowbed.

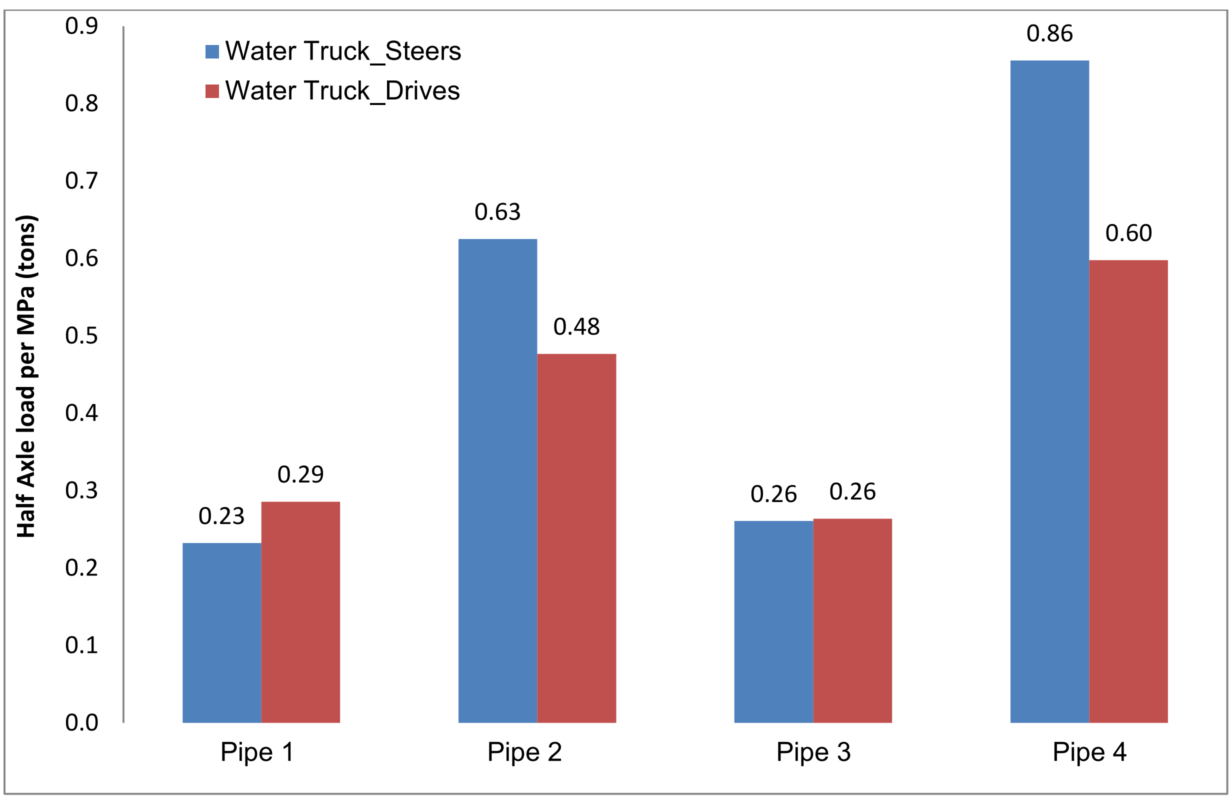

Figure 12. Pipeline response per axle load (max. circumferential pipe stress per tonne of axle load) by installation method; dynamic loading by loaded water truck.

APPENDIX 3: MAXIMUM CIRCUMFERENTIAL STRESSES FROM DYNAMIC LOADINGS

Figure 13, Figure 14 and Figure 15 shown in this appendix represent the maximum circumferential stresses from dynamic loading for the different tested vehicles. The pipe response is expressed in half axle. The maximum stress is referred to as the highest pipe response from the dynamic loading. Figure 12 shows that the drive axle has created the highest stresses for the loaded lowbed whereas Figure 13 shows that the steering axle has created the highest stresses for the empty lowbed.

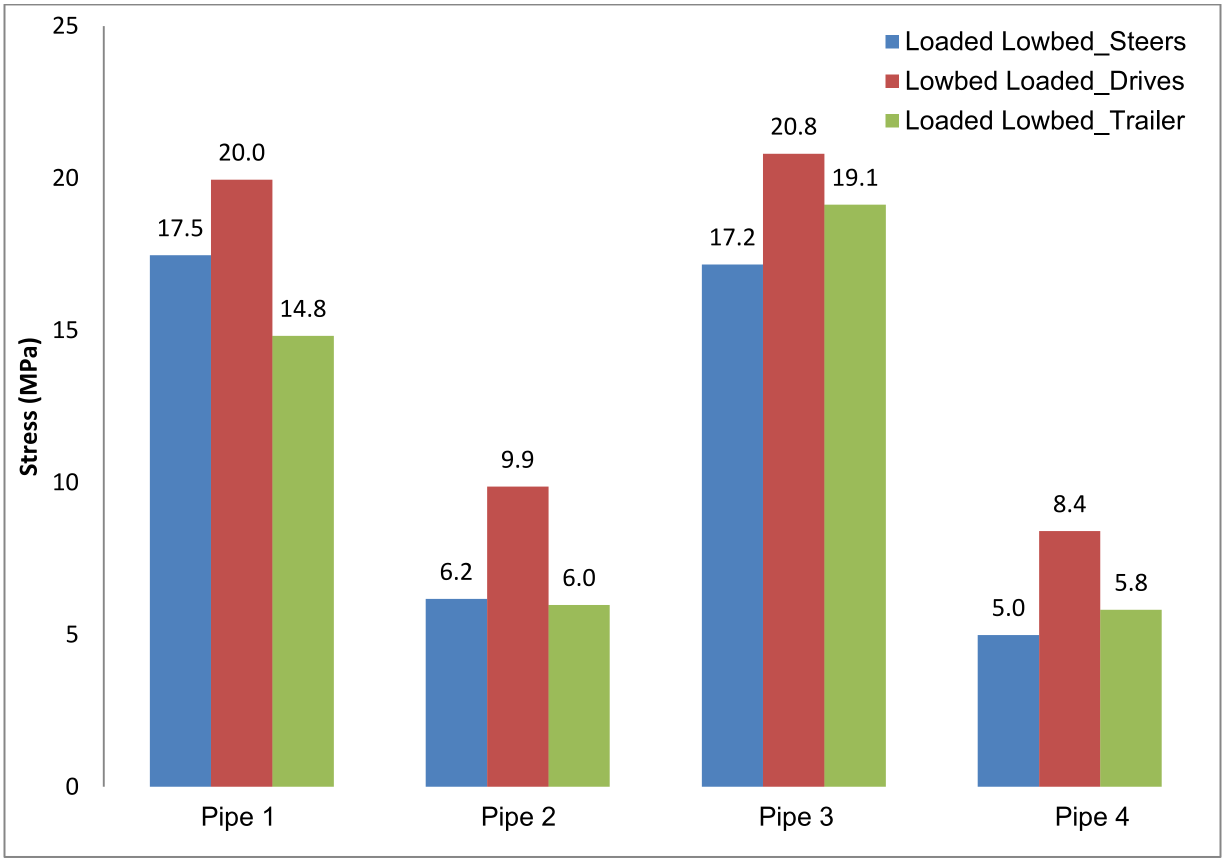

Figure 13. Pipeline response by installation method; dynamic loading by loaded lowbed.

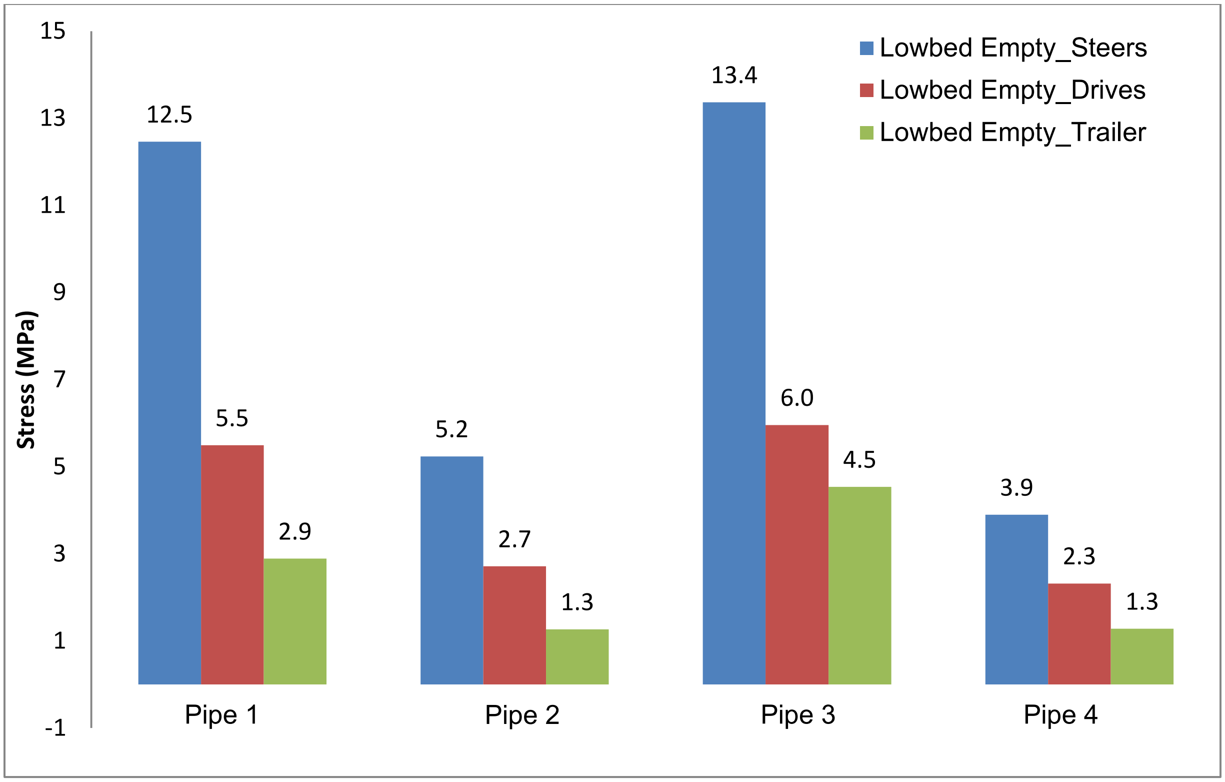

Figure 14. Dynamic loading maximum stresses for the empty lowbed.

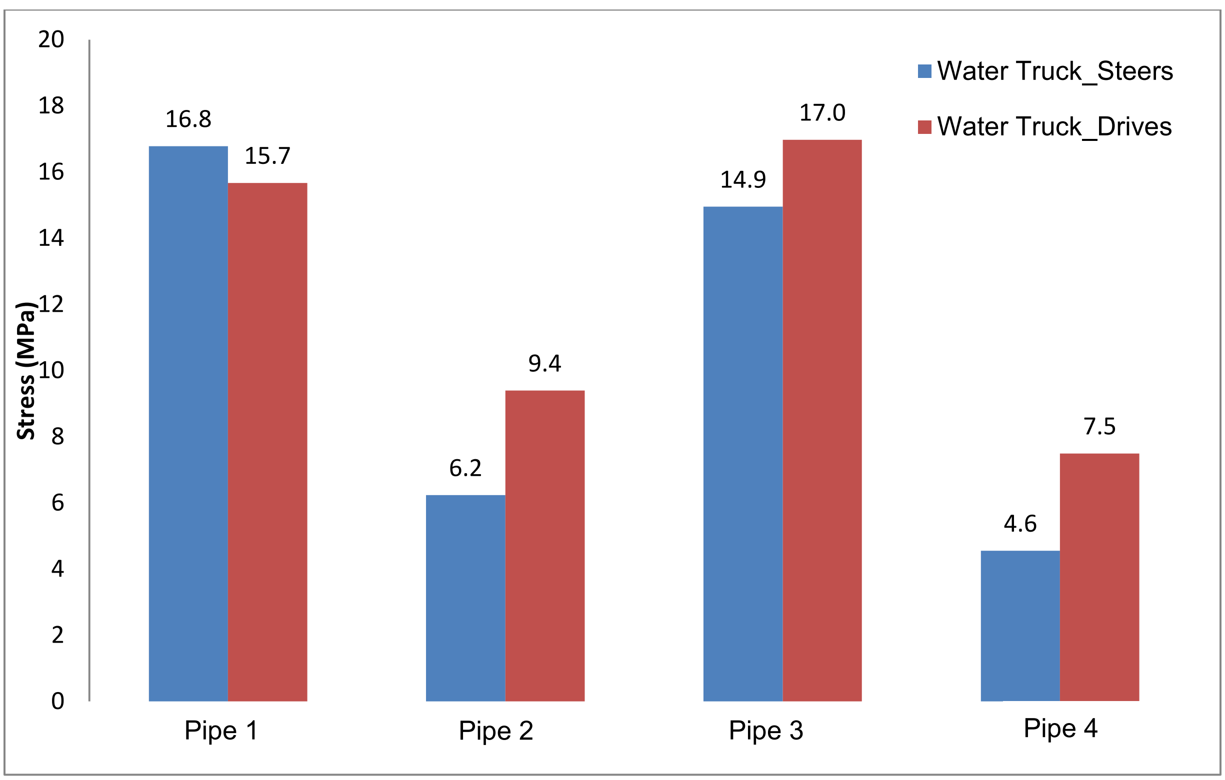

Figure 15. Dynamic loading maximum stresses for the water truck.

APPENDIX 4. SOIL TESTING RESULTS

SHELBY ENGINEERING LTD

Geotechnical and Material Consultants
9632-54 Avenue, Edmonton, Alberta T6E 5V1
Phone: (780) 438-2540 Fax: (780) 434-3089

August 20, 2013
File No. 2-16,999

Access Pipeline Inc.
Suite 1510, 540 – 5th Avenue SW
Calgary, AB T2P 0M2

Attention: Samin Aminzadah

RE: MATERIAL TESTING
STURGEON TERMINAL
13km EAST OF GIBBONS ON HWY 643

Dear Sir:

The following moisture-density relationship has been determined for materials encountered at this site.

Proctor No.	Material	Standard Proctor Max. Dry Density kg/m^3	Optimum Moisture Content %
10	Silt & Sand, little clay light brown (A862) Description of soil is CI Moisture Content 10.4%	1834	14.0

Yours truly,

SHELBY ENGINEERING LTD.

FOR David K. McNicoll, P.Eng.

DKM/epl/email

SHELBY ENGINEERING LTD

9632 - 54 AVENUE
EDMONTON, AB
T6E 5V1
PHONE: (780) 438-2540
FAX: (780) 434-3089

FIELD DENSITY REPORT

Client:	Access Pipeline Inc.
Attn:	Samin Aminzadah
Report Distribution	email Client: Saminazdah@accesspipeline.com
File No:	2-16,999
Project:	Sturgeon Terminal, 13km E of Gibbons on Hwy 643

Test No.	Date Tested	Area/Structure Tested	Location	Soil Type	Test Depth (m)	Field: Dry Density (kg/m³)	Field: Moisture Content (%)	Laboratory: Proctor Density (kg/m³)	Laboratory: Opt. Moisture (%)	Compaction: In Place (%)	Compaction: Spec. (%)	Comments
54	08/23/13	Pipe #1 not compacted	Centre of pipe	Silt & Sand	1' below ground	1771	12.6	1834	14.0	96.6	-	
55	"	"	"	"	2' below ground	1747	13.7	1834	14.0	95.3	-	
56	"	"	"	"	3' below ground	1757	10.6	1834	14.0	95.8	-	
57	"	"	"	"	4' below ground	1520	21.1	1834	14.0	82.9	-	
58	"	"	Just South of Pipe	"	5' below ground	1605	16.4	1834	14.0	87.5	-	
59	"	"	"	"	6' below ground	1537	19.6	1834	14.0	83.8	-	
60	"	"	"	"	7' below ground	-	-	-	-	-	-	Soil was too wet at 7'
60	"	Pipe #3 compacted	Centre of pipe	"	1' below ground	1716	18.1	1834	14.0	93.6	-	
62	"	"	"	"	2' below ground	1739	14.1	1834	14.0	94.8	-	
63	"	"	"	"	3' below ground	1508	25.2	1834	14.0	82.2	-	
64	"		Just North of Pipe	"	4' below ground	1699	16.4	1834	14.0	92.6	-	
65	"	"	Just South of Pipe	"	5' below ground	1672	13.6	1834	14.0	91.2	-	

Remarks:

Reviewed By:

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Test data reported as above had been preformed by a Shelby Engineering Ltd. technician to recognized industry standards, unless otherwise stipulated. No other warranty is made. Density test data does not include or represent any interpretation or opinion of specification compliance or material suitability. Shelby Engineering Ltd. can provide this service on request.

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FIELD DENSITY REPORT

Client:	Access Pipeline Inc.
Attn:	Samin Aminzadah
Report Distribution	email Client: Saminazdah@accesspipeline.com
File No:	2-16,999
Project:	Sturgeon Terminal, 13km E of Gibbons on Hwy 643

Test No.	Date Tested	Area/Structure Tested	Location	Soil Type	Test Depth (m)	Field: Dry Density (kg/m^3)	Field: Moisture Content (%)	Laboratory: Proctor Density (kg/m^3)	Laboratory: Opt. Moisture (%)	Compaction: In Place (%)	Compaction: Spec. (%)	Comments
66	08/23/13	Pipe #3 compacted	1m S of test 54 & 55	Sand & Silt	5' below ground	1735	16.9	1834	14.0	94.6	-	
67	"	"	Just South of Pipe	"	6' below ground	1621	21.1	1834	14.0	88.4	-	
68	"	"	1m S of test 67	"	6' below ground	1796	16.2	1834	14.0	97.9	-	

Remarks: ______________________________

Reviewed By: ______________

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