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DEVELOPMENT OF A PIPELINE SURFACE LOADING SCREENING PROCESS

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ABSTRACT

Pipeline Operators receive numerous requests annually to cross their pipelines. In many of these cases detailed analysis using a number of different methods are performed since no simplified approach is available. The Canadian Energy Pipeline Association (CEPA) with Kiefner and Associates, Inc. undertook the development of a screening methodology for vehicle loading. The hope is a standard approach to these analyses might be established to assist pipeline operating companies.

This paper describes an approach detailing the development and implementation of a simplified screening process to assess the effects of surface loads on buried pipelines. A design basis was established based on a literature review to identify theoretical models, standards, codes, and recommended practices that are currently used to assess the surface loading effects on buried pipelines. This design basis was incorporated into a methodology utilized to develop a screening tool which provides a simple "pass/no pass" determination and is based on attributes which are generally easy to obtain (e.g., wheel or axle load, ground surface loading pressure, depth of cover, maximum allowable operating pressure and design factor). Situations which pass the initial screening would require no additional analysis while situations that do not pass the initial screening may need to be evaluated on a more detailed basis. Simplified graphs have been developed to assist in additional screening prior to performing a more detailed evaluation.

INTRODUCTION

Pipeline Operators receive numerous requests annually to cross their pipelines with various types of vehicles. In many of these cases detailed analysis using a number of different methods are performed however no simplified or standardized approach is available or mandated. Recognizing there was an opportunity to develop an alternative approach the Canadian Energy Pipeline Association (CEPA) with Kiefner and Associates, Inc. undertook the development of a screening methodology for vehicle loading. The hope is a standard approach to these analyses might be established to assist pipeline operating companies simplify the processing of crossing applications.

Despite all of the information required to make an assessment of a buried pipe subject to fill and surface loads, it is feasible to develop a relatively simple buried pipe screening procedure based on parametric analyses of various combinations of the input information. The idea is to perform the necessary calculations required to develop a series of appropriate charts for evaluation of a range of practical buried pipe and loading configurations on a simple "pass/no pass" basis. Situations which pass this initial screening would require no additional analysis while situations that do not pass the initial screening may need to be evaluated on a more detailed basis. The development of this screening procedure will obviously have to rely on calculations using the existing methods for evaluating vertical load effects on buried pipe. Ideally, the calculations will be conservative but not overly so.

LITERATURE SEARCH

The pipeline industry has a long-standing interest in the problem of evaluating the effects of fill and surface loads on buried pipelines. A limited literature survey was performed to identify theoretical models, standards, codes, and recommended practices that are currently used to assess the surface loading effects on buried pipelines.

The review of codes and standards revealed no particular analysis method is mandated. Further there is a diversity of approaches used concerning what constitutes acceptable levels of hoop, combined circumferential and total effective stresses. The results of these reviews have been used to determine the basis for the design loading criteria included for the reader in Appendix A.

The results of the literature review were used to develop Table 1, as a starting point for selecting the appropriate calculation method for the screening process. The table provides a comparative assessment of the main existing methods, identifying their strengths and limitations. In-addition method 4 has been included showing the modified approach developed later in this paper.

Table 1

Method	Strength	Limitation	Comments
1) Spangler Stress Formula	• Easy to program • Includes pressure stiffening • Applies for full range of bedding angles	• Neglects soil restraint	• Requires coefficients from Boussinesq theory to estimate load at top of pipe • Considered to be conservative
2) Iowa Formula	• Easy to program • Includes lateral soil restraint	• Computes deflection, not stress • Neglects pressure stiffening • Need to select soil parameter E' • Need to select lag factor • Hardwired to 30 degree bedding angle	• Requires coefficients from Boussinesq theory to estimate load at top of pipe
3) API RP 1102, 1993	• Provides detailed flow chart • Computes multiple stress components • Performs stress demand-capacity checks • Includes check for fatigue	• Based on auger bore construction • Limited to cover depths ≥ 3 feet • Hardwired to AASHTO H20 truck loads with tire pressures typically in-excess of 550 kPa (80 psig).	• Difficult to manually perform calculations • Requires PC-PISCES
4) Modified Spangler Stress Equation with Soil Restraint	• Easy to program • Includes pressure stiffening • Includes lateral soil restraint	• Need to select soil parameter E' • Need to select lag factor	• Requires coefficients from Boussinesq theory to estimate load at top of pipe. • Inclusion of soil restraint term removes some conservatism

Virtually all of the pipeline industry research on this topic refers back to the collective works of M. G. Spangler (and his graduate students) at Iowa State University during the 1940's through 1960's time frame. The main developments from Spangler's work include the so-called "Spangler stress formula" (used to compute stresses in buried pressurized pipe) and the "Iowa formula" (used to compute ovality in buried culverts). A brief overview of these formulas is provided in the following sections.

FORMULAE

The Spangler Stress Formula

The Spangler stress formula computes an estimate of the additive circumferential bending stress (σ) at the bottom of the pipe cross section due to vertical load as follows:

$$\sigma = \frac{6 \cdot K_b \cdot W_{vertical} \cdot E \cdot t \cdot r}{E \cdot t^3 + 24 \cdot K_z \cdot P \cdot r^3} \text{ psi} \quad (1)$$

The terms K_b and K_z (Note: a glossary of variables is provided at the end of the paper) are bending moment and deflection parameters, respectively. They are based on theory of elasticity solutions for elastic ring bending) which depend on the bedding angle. A tabulation of typical values can be found in Appendix B.

Note that the denominator of this expression includes a pipe stiffness term ($E \cdot t^3$) and a pressure term ($24 \cdot K_z \cdot P \cdot r^3$) which is sometimes referred to as a "pressure stiffening" term since the pipe internal pressure will provide resistance ovalling. Bedding angles of 0, 30 and 90 degrees are taken as corresponding to consolidated rock, open trench and bored trench conditions, respectively. Numerous references in the literature are "hardwired" based on a bedding angle of 30^o (i.e., K_b=0.235 and K_z=0.108). The Spangler stress equation is used to compute circumferential stresses due to vertical loads in several pipeline industry guideline documents[2,6,8].

According to Spangler, 1964 "… *this expression* (the Spangler stress equation) *is limited to pipes laid in open ditches that are backfilled without any particular effort to compact the soil at the sides and to bored in place pipe at an early stage before soil has moved into effective contact with the sides of the pipe. This expression probably gives stresses that are too high in installations where the soil at the sides of the pipe is well compacted in tight contact with the pipe...*". This limitation statement clearly implies that stresses predicted using Spangler stress formula are conservative for buried pipe that is in intimate contact with the soil at the side walls.

The Iowa Formula

The Iowa Formula computes an estimate of the pipe ovality due to vertical load as follows:

$$\Delta X = \frac{K_z \cdot [D_L \cdot W_{vertical}] \cdot r^3}{E \cdot I + 0.061 \cdot E' \cdot r^3} \text{ inches} \quad (2)$$

Note that the denominator of this expression includes a pipe stiffness term ($E \cdot I$) and a soil resistance term ($0.061 \cdot E' \cdot r^3$) but does not include a pressure stiffening term since it was developed for un-pressurized, flexible casing pipes. The deflection parameter (K_z) is normally "hardwired" based on a bedding angle of 30^o (i.e., K_z=0.108).

Spangler recognized that the soil consolidation at the sides of the pipe under fill loads continued with time after installation of the pipe and he accounted for this using the "deflection lag factor" term D_L. His experience had shown that ovalling deflections could increase by as much as 30% over 40 years. For this reason, he recommended the use of a deflection lag factor of 1.5 as a conservative design procedure for fill loads. Other references (e.g., AWWA Manual M11) refer to D_L values in the range from 1.0 to 1.5. We believe that it would be reasonable and appropriate to use the deflection lag factor for fill loads which act on the pipe for long time periods and not for occasional vehicle loads which act on the pipe for short periods of time (i.e., during the vehicle passage).

The modulus of soil reaction, E' which defines the soil's resistance to ovalling is an extremely important parameter in the Iowa formula. Table 2 (after Hartley and Duncan, 1987) provides a range of values of E' for a range of soil types, compaction levels, and cover depths. Hartley and Duncan, 1987 also provide very clear guidance on the selection of E'. This paper indicates that E' can be taken as equal to the constrained modulus of the soil, M_s which can be established based on relatively simple laboratory tests.

Table 2 – Design Values of E' (psi)

Type of Soil	Depth of Cover (ft)	Standard AASHTO* Relative Compaction			
		85 %	90 %	95 %	100 %
Fine-grained soils with less than 25% sand content	0-5 5-10 10-15	500 600 700	700 1,000 1,200	1,000 1,400 1,600	1,500 2,000 2,300
Coarse-grained soils with fines	0-5 5-10 10-15	600 900 1,000	1,000 1,400 1,500	1,200 1,800 2,100	1,900 2,700 3,200
Coarse-grained soils with little or no fines	0-5 5-10 10-15	700 1,000 1,050	1,000 1,500 1,600	1,600 2,200 2,400	2,500 3,300 3,600

*Note: AASHTO is the American Association of State Highway Transportation Officials.

The reader is directed to references 9, 12, and 13 for additional useful background, discussion on the selection of *E'* and tabulated values.

Discussion of Load Terms in Spangler Stress Formula and Iowa Formula

As described above, the Spangler stress formula and the Iowa Formula both operate on a load per unit length of pipe, $W_{vertical}$ resulting from either fill or/or surface loads. Hence, a key aspect of these formulas is the estimation of the effective fill and surface loads at the top of the pipe. These loads are discussed in this section.

Pipe Load Due to Fill

Spangler computed the pressure transmitted to the pipe due to earth (fill) load based on Marston's load theory (Marston, 1913) as follows:

$$W_{fill} = C_d \cdot \gamma \cdot B_d^2 \tag{3}$$

Values of the fill coefficient C_d for different soils are tabulated as a function of the trench geometry and soil type in several references [8,17].

Pipe Load Due to Surface Wheel Load

Spangler computed the load transmitted to the pipe due to surface wheel load using Boussinesq theory for a surface point load based on numerical integration performed by Hall (see Spangler and Hennessy, 1946 [17]) as follows:

$$W_{wheel} = 4 \cdot C_t \cdot \frac{W}{L} \tag{4}$$

Values of the wheel load coefficient C_t are tabulated for different trench geometries in several references [17, 18].

Pipe Load Due to Surface Rectangular Footprint Load

Spangler computed the load transmitted to the pipe due to surface load with a rectangular footprint using Boussinesq theory based on numerical integration performed by Newmark[14] as follows:

$$W_{rectangular} = 4 \cdot C_r \cdot \frac{W_r \cdot D}{A} \tag{5}$$

Values of the rectangular load coefficient C_r are tabulated for different trench geometries and rectangular footprints in several references (e.g., AWWA M11[4], Spangler 1964[19], etc.).

Given the computed loading on the buried pipe from either fill or traffic (i.e., point load or rectangular footprint) loads (i.e., W_{fill}, W_{wheel}, or $W_{rectangular}$ or as a more general vertical load term $W_{vertical}$), the Spangler stress and Iowa formulas can be used directly.

A Proposed Modification to the Spangler Stress Equation

Based on our experience with the available methods to evaluate fill and surface loading effects on buried pipelines, we favor the use of industry accepted Boussinesq-type expressions that relate the fraction of surface load transferred to the pipe at the depth of soil cover combined with "Spangler type" calculations to compute pipe stresses due to fill and/or surface loads over the step-by-step evaluation procedure provided in the 1993 version of API RP 1102, especially for the purposes of initial screening evaluations.

The Spangler stress formula can be extended to include the beneficial effects of lateral soil restraint based on Watkins work[21]. This first-principles approach can be applied to a variety of equipment loads and are not limited to particular ranges of physical variables. It also provides a means of removing some of the conservatism inherent in the original Spangler stress equation by including lateral soil restraint. In order to modify the Spangler circumferential stress formula to include a soil resistance term that is consistent with the one used in the Iowa Formula, it is necessary to manipulate the stress and ovality Equations (1) and (2). This is accomplished using a relationship between ovality and circumferential stress. Based on information provided in Spangler, 1964, it can be shown that the maximum through-wall circumferential bending stress due to ovality ΔX is:

$$\sigma = \frac{K_b}{2 \cdot K_z} \cdot \frac{\Delta X \cdot E \cdot t}{r^2} \tag{6}$$

where all of the variables are as previously defined. Solving Equation (6) for ΔX and substituting the circumferential stress σ from Equation (1) leads to the following expression of the Spangler stress formula in terms of ovality:

$$\Delta X = \frac{12 \cdot K_z \cdot W_{vertical} \cdot r^3}{E \cdot t^3 + 24 \cdot K_z \cdot P \cdot r^3} \tag{7}$$

Recall that the 0.108 (K_z) coefficient in the Iowa formula corresponds to a 30° bedding angle. Setting K_z=0.108 in Equation (7), then aligning the resulting expression next to the Iowa formula yields the following:

Spangler Stress Expression and Iowa Formulae

$$\Delta X = \frac{1.296 \cdot W_{vertical} \cdot r^3}{E \cdot t^3 + 2.592 \cdot P \cdot r^3} \qquad \text{(Spangler – 8a)}$$

$$\Delta X = \frac{0.108 \cdot W^*_{vertical} \cdot r^3}{E \cdot I + 0.061 \cdot E' \cdot r^3} \qquad \text{(Iowa – 8b)}$$

Recognizing that $E \cdot t^3$ is equal to $12 \cdot E \cdot I$, the numerator and denominator of the Spangler stress expression for ΔX (in the above) can be multiplied by 1/12 in order to cast the denominator of both expressions in terms of the pipe wall bending stiffness (E·I):

$$\Delta X = \frac{0.108 \cdot W_{vertical} \cdot r^3}{E \cdot I + 0.216 \cdot P \cdot r^3} \qquad \text{(9a)}$$

$$\Delta X = \frac{0.108 \cdot W^*_{vertical} \cdot r^3}{E \cdot I + 0.061 \cdot E' \cdot r^3} \qquad \text{(9b)}$$

Note that the only difference between the numerators of these two expressions is that the one based on the Iowa formula (9b) includes a load term $W^*_{vertical}$ which is equal to $W_{vertical}$ multiplied by the deflection lag factor. By scaling the deflection lag factor as a ratio of the two denominators (discussed later), the soil term from the Iowa formula can be added directly to the denominator of the Spangler stress expression for ovality to obtain a combined ovality expression (dropping the * on the vertical load term):

$$\Delta X = \frac{0.108 \cdot W_{vertical} \cdot r^3}{E \cdot I + 0.216 \cdot P \cdot r^3 + 0.061 \cdot E' \cdot r^3} \quad (9c)$$

It is worth noting here that Rodabaugh suggested a very similar expression to qualitatively combine pressure stiffening and soil restraint effects[15].

Multiplying both the numerator and denominator of the combined ovality expression (9c) by 12 gives:

$$\Delta X = \frac{1.296 \cdot W_{vertical} \cdot r^3}{E \cdot t^3 + 2.592 \cdot P \cdot r^3 + 0.732 \cdot E' \cdot r^3} \quad (9d)$$

Then converting back to stress using Equation (6) results in the following combined expression for circumferential pipe stress:

$$\sigma = \frac{1.41 \cdot W_{vertical} \cdot E \cdot t \cdot r}{E \cdot t^3 + 2.592 \cdot P \cdot r^3 + 0.732 \cdot E' \cdot r^3} \quad (10)$$

Note: The above equation has both (K_z & K_b) "hardwired" based on a bedding angle of 30^o (i.e., K_z=0.108, K_b=0.235) which is considered conservative. The equation in its full form is as follows:

$$\sigma = \frac{6 \cdot K_b \cdot W_{vertical} \cdot E \cdot t \cdot r}{E \cdot t^3 + 24 \cdot K_z \cdot P \cdot r^3 + 0.732 \cdot E' \cdot r^3} \quad (11)$$

Notice that if the term *E'* in the denominator is set equal to zero, Equation (10) reduces to the original Spangler stress formula and if the *P* term in the denominator is set equal to zero, this expression reduces to a stress that is consistent with the Iowa formula (when the load term $W_{vertical}$ includes the deflection lag factor).

As previously noted, we believe that it would be reasonable and appropriate to consider the use of a different deflection lag factor for fill loads which act on the pipe for long time periods than for traffic loads which act on the pipe for short periods of time (i.e., during the vehicle passage). Recall that the lag factor is used to account for Spangler's observations that ovality due to earth fill can increase by up to 30% over long time periods. Spangler recommended a value of 1.5 as a conservative design procedure. Moser, 1990[13] and AWWA M11, 1999[4] refer to a range from 1.0 to 1.5 and Rodabaugh[15] suggested a value of 1.25. If the modified Spangler stress formula is used, we recommend a deflection lag factor for fill loads equal to the lesser of 1.30 or the ratio of the denominator in the modified Spangler stress formula to the denominator in the original Spangler stress formula. Since surface traffic loads act on the pipe for short time periods (i.e., during the vehicle passage) a deflection lag factor of 1.0 is recommended for short term vehicle loading.

PIPELINE SURFACE LOADING ACCEPTABILITY

The pipe to be subjected to surface loading should be checked for various pipe stress demand-capacity measures including the total circumferential stress due to internal pressure, fill and surface loads, and biaxial stress combinations for circumferential plus longitudinal stress (due to temperature differential, Poisson's effect and bending) in order to guard against yielding as well as cyclic stress range demand-capacity checks to guard against fatigue damage. The following process flow diagram entitled "Pipeline Surface Loading Acceptability" (Figure 1) has been developed indicating the recommended process to be followed in determining the acceptability of surface loading. Figure 1 incorporates the design loading criteria as defined in Appendix A and is the basis on which the screening process has been developed.

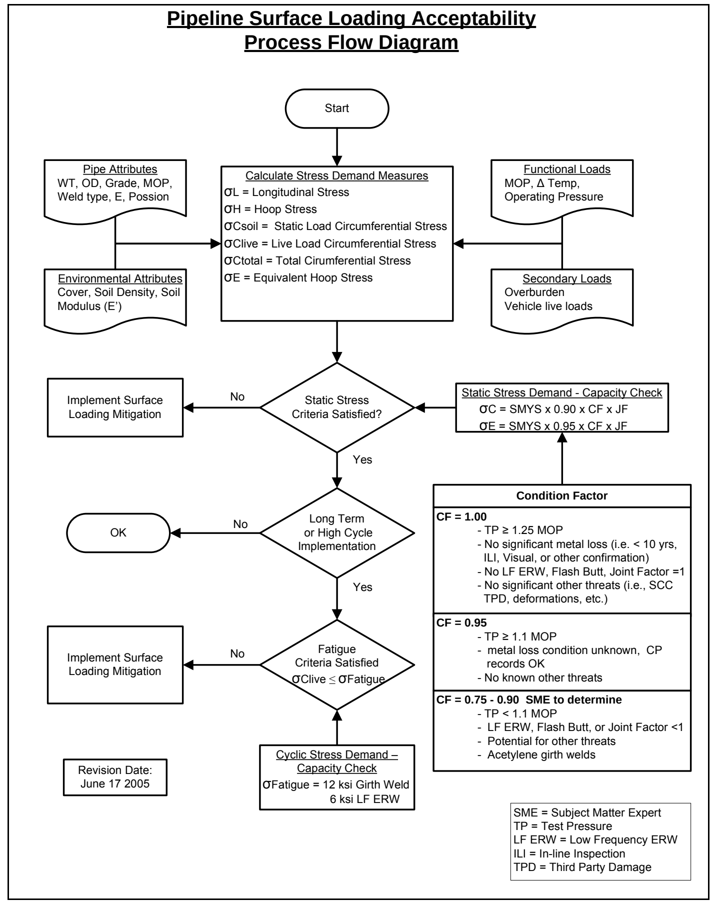


Figure 1 – Process flow diagram

DEVELOPMENT OF A SCREENING PROCESS

In the previous section, a modified version of the Spangler stress formula was developed (Equation 11). To assist in minimizing the number of variables the equation has been adjusted into the non-dimensional form D/t as follows. The right hand side of Equation (11) has been manipulated into the following form by dividing both the numerator and the denominator by $E \cdot t^3$ and substituting D/2 for r.

$$\sigma = \frac{3 \cdot K_b \cdot \frac{W_{vertical}}{D} \cdot \left(\frac{D}{t}\right)^2}{1 + 3 \cdot K_z \cdot \frac{P}{E} \cdot \left(\frac{D}{t}\right)^3 + 0.0915 \cdot \frac{E'}{E} \cdot \left(\frac{D}{t}\right)^3} \quad (12)$$

The stress formula in Equation (12) described above requires a load per unit diameter of pipe, $W_{vertical}$ resulting from either fill and/or surface loads.

The load transmitted to the pipe due to earth (fill) load can be computed based on Marston's load theory (previously discussed, Equation 3).

Note that in Equation (12), the pipe diameter to the extent possible has been rearranged into the non-dimensional form D/t. Therefore, the only place that the pipe diameter appears in Equation (12) is as a normalizing factor for the load term $W_{vertical}$ (i.e., $W_{vertical}/D$). Hence, other than in the $W_{vertical}/D$ term, Equation (12) is independent of the pipe diameter.

The fill loads from Equation (3) have been plotted in Figure 2 as W_{fill}/D for selected parameter values as a function of diameter such that a representative value of W_{fill}/D can be selected that will represent a full range of diameters such that Equation (12) becomes fully independent of pipe diameter. A B_d value of D + 10 cm (4 inches) has been selected to represent the long term consolidation of soil around the pipe. The dashed lines represent the value selected for use in the screening tool which will be constant for all pipe diameters. This value is representative and/or conservative for diameters ranging from 273 (10”) through 1219 mm (48”).

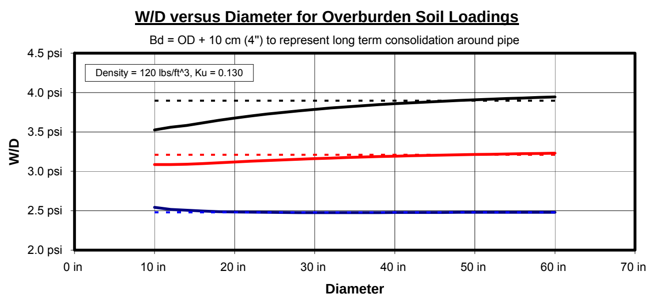


Figure 2

As previously discussed, the load transmitted to the pipe due to surface load with a rectangular footprint is developed using Boussinesq theory based on numerical integration resulting in Equation (5). Values of the rectangular load coefficient C_r are computed using a regression formula to compute the coefficient C_r as a function of the rectangular surface footprint of dimensions (X,Y) over a depth of cover H as follows: (13)

$$C_r = 0.25 - \frac{1}{2\pi}\left[\left(\sin^{-1} H\sqrt{\frac{\left(\frac{X}{2}\right)^2+\left(\frac{Y}{2}\right)^2+H^2}{\left(\left(\frac{X}{2}\right)^2+H^2\right)\left(\left(\frac{Y}{2}\right)^2+H^2\right)}}\right) - \frac{\left(\frac{X}{2}\right)\left(\frac{Y}{2}\right)H}{\sqrt{\left(\frac{X}{2}\right)^2+\left(\frac{Y}{2}\right)^2+H^2}}\left(\frac{1}{\left(\frac{X}{2}\right)^2+H^2}+\frac{1}{\left(\frac{Y}{2}\right)^2+H^2}\right)\right]$$

Note that because the Equation (5) for $W_{rectangular}$ has a pipe diameter D term in the numerator, normalizing by D directly removes the diameter dependence in the normalized load expression.

$$\frac{W_{rectangular}}{D} = 4 \cdot C_t \cdot \frac{W}{A} \qquad (14)$$

The computed normalized loading on the buried pipe from either fill or traffic loads (i.e., W_{fill}/D, $W_{rectangular}/D$) can be expressed as a more general vertical load term $W_{vertical}/D$ for use in Equation (12).

> Note: The equation 4 point load can be conservatively estimated by utilizing a rectangular footprint with a surface contact pressure of 550 kPa (80 psi) and therefore does not need to be utilized in the screening process.

Sensitivity of Surface Contact Pressure

Fixed loads spread over larger rectangular areas i.e.; track load (35 kpa or 5 psi) versus truck tire (550 kpa or 80 psi) generally have significantly less impact on a buried pipeline. Figure 3 shows the effect of allowable loads on a pipeline based on low ground pressure equipment (such as track vehicles) versus that of point loads (such as truck tires).

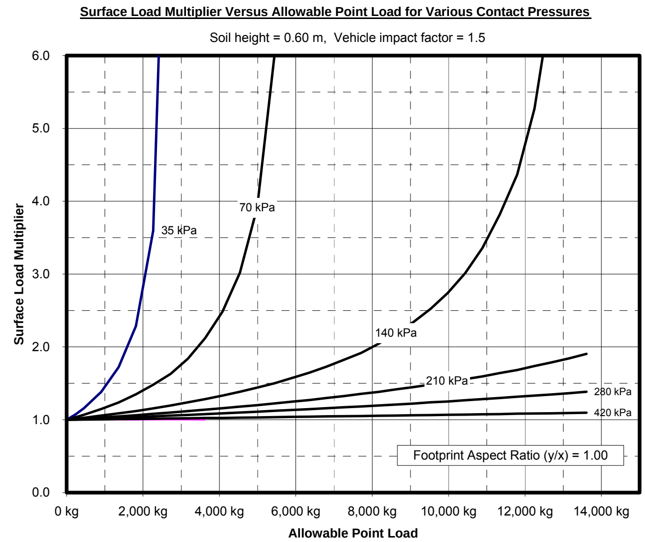


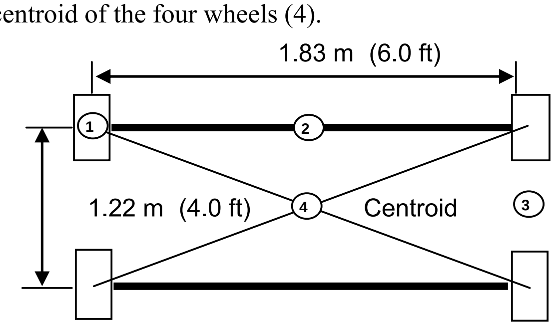
Figure 3

Multiple Wheel Factor

A key consideration in determining live load pressure on the pipe is the location of vehicle wheels relative to the pipe. A higher pressure may occur below a point between the axles or between two adjacent axles than directly under a single vehicle wheel. This depends on the depth of cover and the spacing of the wheels.

When depths are not greater than one meter (3 feet), a single wheel directly over the pipe generally produces the largest load. At depths greater than one meter the maximum load may shift.

The multiple wheel factor is utilized in the screening tool to account for this and varies with depth using the worst case scenario for load applied by two axles of 1.83m (6-ft) width and a 1.22m (4-ft) space between the axles. The projected area of the wheel load at pipeline depth is calculated using Boussinesq's equation to determine the stress applied at pipeline depth by one or more of the load points in this configuration. Figure 4 illustrates the points of analysis. The calculation considers the load at pipe level from these axles at the point directly under each wheel (1), at the center of the axle (2), between the front and rear wheels (3) and at the centroid of the four wheels (4).



Four Points Analyzed to Determine Worst-Case Loading for Various Depths

Note: This configuration is conservative in cases where the actual axle length is greater and the axle spacing is longer.

Figure 4

APPLICATION OF THE PROPOSED APPROACH

The stress calculation approach described above is described in the following steps:

1. Determine the pipe steel grade, the design factor (0.72, 0.80), the maximum allowable circumferential stress (see Appendix A "Design Loading Criteria"), D/t $\leq$ 125 (majority of pipelines will be less than this value) and the other pertinent analysis parameters (E', cover depth, etc.).
2. For a selected internal pressure, compute the D/t ratio corresponding D/t = $2 \cdot \sigma_y \cdot DF/P$, then compute the circumferential stress due to combined internal pressure (using Barlow's formula) and fill loads using Equation (12) with $W_{vertical}$ set equal to W_{fill} computed using Equation (3).
3. Compute the difference between the circumferential stress due to combined internal pressure and fill loads and the allowable circumferential stress. This is the "available circumferential stress capacity" for surface load.
4. Check to see if the available circumferential stress capacity is greater than the established fatigue limits. If so, determine if the loads are frequent and adjust appropriately.
5. Set the right hand side (the stress) of Equation (12) equal to the "available circumferential stress capacity" for surface load computed in Step 3 above and solve for the corresponding $W_{vertical}$.
6. Set $W_{rectangular}$ equal to $W_{vertical}$ and use Equation (14) to solve for the allowable load on the rectangular footprint *W*.
7. Repeat steps 2 through 6 for a range of pressures.

Application of this approach for a wheel loading example was used to develop the plot shown in Figure 5 showing allowable wheel load vs. internal pressure for a cover of 0.9 meters (3 ft), for Grades of pipe ranging from 207 MPa to 483 MPa (X30 to X70).

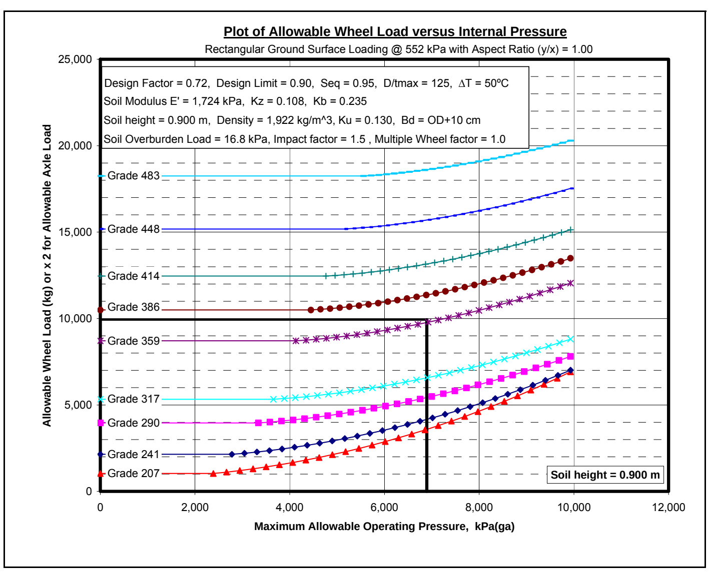


Figure 5

This same approach has been utilized for 1.2 meters (4 ft) of cover as shown in Figure 6

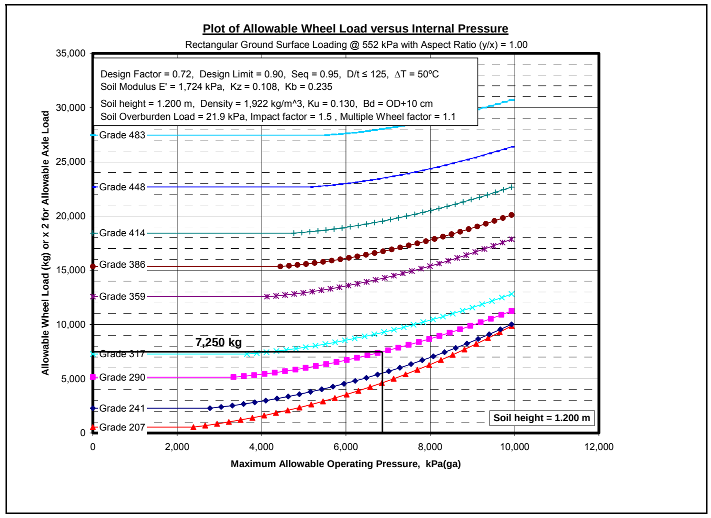


Figure 6

The graphs shown in Figures 5 and 6 represent an initial screening tool that can be utilized by a pipeline operator to determine whether or not a given crossing application requires added protection, or whether a more detailed calculation is appropriate. Appendix C details the proposed screening process.

Sample Calculation

The following is a sample of how the screen tool can be utilized.

A gravel haul contractor has requested a temporary road crossing over the pipeline to transport bank run gravel over the pipeline. They report that the truck will have an effective wheel load of 7,250 kg (16,000 lbs).

Pipe Attributes:

- OD = 610 mm (24-inch)
- WT = 8.14 mm (0.321-inch)
- Grade = 359 MPa, (X-52)
- DF = 0.72
- MOP = 6,895 kPa (ga) (1,000 psig)
- Depth of cover 0.9 meters (2.95 ft)

To perform the initial screening requires the following minimum information.

Grade, MOP, DF $\leq$ 0.72, depth of cover, competent soil (i.e., non-saturated clay), knowledge of pipeline condition (i.e., should not utilize screen tool for pipelines with other known threats such as may be associated with LF ERW or poor corrosion condition, etc.)

Note: The pipeline OD and WT are not required.

From Figure 5 it has been determined that the stress imposed on the pipeline as a result of this wheel loading is acceptable for grades equal to or greater than 359 MPa (X52) *{allowable $W_{L(X52)}$ = 10,000 kg > actual W_L of 7,250 kg}*. For grades below 359 MPa (X52), the initial screening tool has identified that this loading condition has the potential to exceed the allowable limits. As a result the following options are available:

- Perform a more detailed calculation;
- Find a location with additional cover and/or place additional cover over the pipeline, Figure 6 indicates that

1.2 m (4 ft) of cover will be adequate for pipeline grades equal to or greater then 290 MPa (X42);

- Provide supplemental protection (concrete slab, etc.)

ASSESSMENT OF MITIGATION OPTIONS FOR BURIED PIPELINES SUBJECTED TO SURFACE TRAFFIC

Overview of Mitigation Measures

Pipeline engineers have a number of options available to reduce the stresses on buried pipelines subjected to fill and surface traffic loading. Table 3 provides a listing of several different mitigation measures that we have seen utilized along with their relative advantages and disadvantages.

Table 3 - Surface Loading Mitigation Measures

Method	Advantages	Disadvantages
Reduce the operating pressure of the pipeline	Provides a direct reduction of the hoop stress due to internal pressure. This reduction allows for additional circumferential stress due to equipment loads	Could reduce the overall capacity of the pipeline and therefore should not be considered as a long term fix.
Limit surface pressures under vehicles (e.g., using floatation tires or caterpillar tracks)	Spreads the surface load over a larger area and reduces the overall load to the pipe.	Depends on equipment. May not be possible or too costly to implement
Provide additional soil fill over the pipeline in the vicinity of the crossing	Reduces circumferential stresses due to traffic loads.	Increases circumferential stresses due to fill loads.
Deploy steel plates over the crossing	Easy to install.	Flexibility of steel plates can result in bending of the plate with a corresponding reduction in loaded footprint. Need to consider required thickness.
Deploy timber mats over the crossing area	Provides large loading footprint. Relatively easy to deploy.	Flexibility of timber mats can result in bending of the mats with a corresponding reduction in loaded footprint.
Construct a concrete slab with steel reinforcement over the crossing area	Provides large loading footprint. Slab can provide high bending stiffness	Relatively expensive. Usually reserved for permanent crossings. Slab limits access to pipeline for inspections and repairs.
Construct a short bridge crossing over the pipeline	Completely uncouples the traffic loading from the buried pipeline.	Requires construction of foundation structures. Expensive to construct. Usually reserved for permanent crossings.
Relocate the pipeline	Removes pipeline from loaded area.	Expensive to construct. Usually considered only as a last resort.
Lower pipeline	Reduces circumferential stresses due to traffic loads.	Expensive to perform. Usually considered only as a last resort.

Provide Additional Fill Over Pipeline at Crossing

A relatively popular procedure that we have seen utilized for mitigating pipe stresses due to surface vehicle loading is to provide additional soil fill over the pipeline in the vicinity of the crossing. This mitigation method increases the total depth of cover to be used in the pipe stress calculations for fill and traffic loads. This has a direct positive effect of reducing the circumferential stresses due to vehicle loads. It also has a direct negative effect of increasing the circumferential stresses due to fill loads. For many applications (e.g., situations with high impact factors and/or high traffic stress but with relative low stresses due to fill), the beneficial effect of the reduction in traffic stress can far exceed the negative effect of increased fill stress. This tradeoff can easily be investigated by performing pipe stress calculations for a range of cover depths and comparing the total circumferential stress due to fill and traffic load plus hoop stress due to pressure against appropriate total stress limits and by comparing the traffic stress range against appropriate fatigue stress limits.

NOMENCLATURE

A	the area of the rectangular footprint
B_d	the effective trench width
C_d	a fill coefficient
C_r	a rectangular load coefficient
C_t	a wheel load coefficient
D	the pipe outside diameter (in)
D_L	the deflection lag factor
E	the pipe modulus of elasticity (psi)
E'	the modulus of soil reaction (psi)
H	the depth of cover (ft)
I	the moment of inertia of the cross section of the pipe wall per unit length ($I=t^3/12$, in^3)
L	the effective length of pipe (ft)
M_s	constrained modulus of the soil (psi)
r	the mean pipe radius (inches)
P	the internal pressure (psi)
t	the pipe wall thickness (inches)
W	wheel load (including impact factor) (lb)
W_r	the total load on a rectangular footprint (lb)
$W_{vertical}$	the vertical load due to fill and surface loads including an impact factor (lb/in),
ΔX	the maximum deflection of the pipe (inches)
σ_b	circumferential bending stress (psi)

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The full report on this subject Entitled "Development of a Pipeline Surface Loading Screening Process & Assessment of Surface Load Dispersion Methods can be downloaded from the Kiefner & Associates, Inc website; www.kiefner.com.

Appendix A: Design Loading Criteria

Design Loading Criteria

The governing code for Canadian pipelines is CSA Z662-03.

Design Pressure to be Calculated using:

CSA Z662-03 Section 4.3.3.1 specifies:

P = (2(SMYS)t/D) x F x J x L x T

Where:

- F = Design Factor
- J = Joint Factor
- L = Location Factor
- T = Temperature Factor
- t = pipe wall thickness
- D = Pipe diameter
- P = Pressure

The design factor is specified as 0.8

The joint factor is 1.0 unless continuous welded pipe is used

The location factor is 1.0 for class 1 locations for both non-sour gas and HVP and LVP. The temperature factor is 1.0 unless design temperature exceeds 120 deg. C.

Combined Hoop and Longitudinal Stress

CSA Z662-03 Section 4.6.2.1

Unless special design measures are implemented to ensure the stability of the pipeline, the hoop stress due to design pressure combined with the net longitudinal stress due to the combined effects of pipe temperature changes and internal fluid pressure shall be limited in accordance with the following formula.

$S_h - S_L \leq 0.90\ S \times T$

Note: This formula does not apply if S_L is positive (i.e., tension)

where

S_h = hoop stress due to design pressure,

S_L = longitudinal compression stress, MPa, as determine using the following formula:

$S_L = \nu\ S_h - E_c\ \alpha(T_2 - T_1)$

where

ν = Poisson's ratio

E_c = modulus of elasticity of steel, MPa

α = linear coefficient of thermal expansion

T_2 = maximum operating temperature, ºC

T_1 = ambient temperature at time of restraint, ºC

Allowable $T_2 - T_1$

Grade		Allowable T_2-T_1 σ_h = 0.80 SMYS		Allowable T_2-T_1 σ_h = 0.72 SMYS	
X-207	X-30	28.3 C	51.0 F	33.0 C	59.4 F
X-241	X-35	33.1 C	59.5 F	38.5 C	69.3 F
X-290	X-42	39.7 C	71.4 F	46.2 C	83.2 F
X-317	X-46	43.4 C	78.2 F	50.6 C	91.1 F
X-359	X-52	49.1 C	88.4 F	57.2 C	103.0 F
X-386	X-56	52.9 C	95.2 F	61.6 C	110.9 F
X-414	X-60	56.7 C	102.0 F	66.0 C	118.8 F
X-448	X-65	61.4 C	110.5 F	71.5 C	128.7 F
X-483	X-70	66.1 C	119.0 F	77.0 C	138.6 F

Pipe Attributes:

Youngs Modulus (E) =	206.8 Gpa	30,000 ksi
Thermal expansion coef (α) =	12.0 x 10^{-6} m/m/ºC	6.67 x 10^{-6} in/in/ºF
Poisson ratio (ν) =	0.3	

Other Loadings and Dynamic Effects

CSA Z662-03 Section 4.2.4.1 states:

The stress design requirements in this Standard are specifically limited to design conditions for operating pressure, thermal expansion ranges, temperature differential, and sustained force and wind loadings. Additional loadings other than the specified operating loads are not specifically addressed in this Standard;

however, the designer shall determine whether supplemental design criteria are necessary for such loadings and whether additional strength or protection against damage modes, or both, should be provided. Examples of such loadings include:…

h) excessive overburden loads and cyclical traffic loads.

Circumferential stresses as a result of traffic loads are considered additional loads in CSA and therefore the designer shall determine whether additional design criteria are necessary. The following sections address the additional design criteria.

Maximum Allowable Sum of Circumferential Stress

CSA Z662-03 does not specifically have a clause that places a limit on maximum allowable sum of circumferential stresses. ASME B31.8-2003 Section 833.9 (b) specifies the following:

The maximum allowable sum of circumferential stress due to internal pressure and circumferential through-wall bending stress caused by surface vehicle loads or other local loads is 0.9 S T, where S is the specified minimum yield strength, and T is the temperature derating factor.

ASME B31.4 § 451.9 (a) specifies the following:

When an existing pipeline is to be crossed by a new road or railroad, the operating company shall analyze the pipeline in the area to be crossed in terms of the new anticipated external loads. If the sum of the circumferential stresses caused by internal pressure and newly imposed external loads (including both live and dead loads) exceeds 0.90 SMYS, the company shall install mechanical reinforcement, structural protection, or suitable pipe to reduce the stress to 0.90 SMYS or less.

Based on the above the screening tool has adopted the following:

$$S_h + S_{cb} \leq 0.90 \text{ S x T}$$

where

S_h = hoop stress due to design pressure,

S_{cb} = circumferential through-wall bending stress caused by surface vehicle loads or other local loads.

Maximum Combined Effective Stress

CSA Z662-03 Section 4.2.4.1 specifies that all relevant loads need to be assessed using good engineering practices. CSA does not directly provide a limit to the maximum combined effective stress allowed for onshore pipelines however Section 11.2.4.2.2.5 allows for a combined effective stress of up to the SMYS for offshore pipelines.

ASME B31.8-2003 Section 833.4 allows for loads of long duration up to 0.9 x SMYS and for occasional non-periodic loads of short durations up to SMYS.

> Note: In-general, a maximum combined effective stress of up to the SMYS is acceptable for onshore pipelines when all relevant loads have been assessed. In-addition, limit state design analysis will allow for values beyond SMYS for displacement-controlled events (settlement, landslides, etc.). A value equal to 95% SMYS has been considered in the initial screening process. This value takes into account a temperature differential of ΔT = 50º C or the maximum temperature limitation as per CSA Clause 4.6.2.1 (section 2 above) whichever is the lower.

Fatigue Strength of Line Pipe

The fatigue strength of line pipe depends on whether the pipe is seamless, has an electric-resistance weld (ERW) seam, or has a double submerged arc weld (DSAW) seam, in either the longitudinal or spiral direction. Data on line pipe from the German Standard DIN 2413 showed that the limiting variable stress was about 138 MPa (20 ksi) for ERW or seamless line pipe, and 83 MPa (12 ksi) for DSAW line pipe. This compares favorably with information from the International Institute of Welding, the American Institute of Steel Construction, and the AREA Manual for Railway Engineering. The version of CSA 662-2003 Section 4.8.3.2 Uncased Railway Crossings has established a fluctuating stress limitation of 69 MPa (10 ksi) based on 2 million cycles. This value is conservative as it applies to new facilities, however may be more appropriate with regards to older facilities. Certain pipe seam types such as LF ERW and EFW may be subject to seam susceptibility. The operator should consider these factors if heavy equipment cross the pipeline at high frequencies.

Appendix B:

Sensitivity Analysis of Factors Utilized in Screening Model with Regards to Equipment with Low Surface Contact Pressures

This section provides for a sensitivity analysis of factors utilized in the Screening Model which when applied to equipment with low surface contact pressures have the potential to provide for additional conservatism.

Impact Factor

An impact factor of 1.5 has been utilized in the model to address the dynamic nature of traffic loads on flexible surfaces. This value is based on a recommendation by the ASME committee on Pipeline Crossings of Railways and Highway. The specification called for an impact factor of 1.5 to be applied to traffic live loads for roads with flexible pavements. No impact factor is required for roads with rigid pavements.

It is important to note that AASHTO specifies impact factors in its specifications. Impact factors of 1.3, 1.2, 1.1, and 1.0 are applied at depths of 0, 0.1 to 1 ft, 1.1 to 2.0 ft and 2.1 to 3.0 ft, respectively. It is noted that the concrete design manual utilized by many in the industry also utilizes the same factors.

The factors that govern the magnitude of impact factor are as follows:

- Impact factors increase with increasing vehicle speed,
- Impact factors increase with increased tire pressure
- Impact factors increase with increased roughness of the ground.

With respect to the above factors, equipment with low surface contact pressures will produce less of an impact than that of a truck for the following reasons.

1) the equipment is specifically design to have low ground surface pressure as not to compact the soil strata.
2) equipment of this design normally utilize low pressure pneumatic tires with contact pressure << 200 kPa(ga) (30 psig).
3) this type of equipment typically operate at lower velocities < 15 kph (10 mph)

The effects of reducing the impact factor from 1.5 to 1.25 for equipment with low surface contact pressures is equal to the ratio of 1.5/1.25 or 1.2.

Bedding Angle of Support

The terms K_b and K_z are bending moment and deflection parameters, respectively (based on theory of elasticity solutions for elastic ring bending) which depend on the bedding angle as shown in Table B-1.

Table B-1 Spangler Stress Formula Parameters K_b and K_z

Bedding Angle (deg)	Moment Parameter K_b	Deflection Parameter K_z
0	0.294	0.110
30	0.235	0.108
60	0.189	0.103
90	0.157	0.096
120	0.138	0.089
150	0.128	0.085
180	0.125	0.083

Bedding angles of 0, 30 and 90 degrees are taken as corresponding to consolidated rock, open trench and bored trench conditions, respectively. A 30 degree angle is typically utilized and is representative of open trench construction with relatively unconsolidated backfill such that fully bearing support of the pipe is not achieved. While this is an acceptable and generally conservative value to utilize for a newly constructed pipeline, one could argue that as the soil re-consolidates around the pipeline over time the actual bearing support will be much greater.

The effects of changing the bedding support angle are significant and range from 1.28 to 1.75 for a change from 30 to 60 degrees and from 1.47 to 2.37 for a change from 30 to 90 degrees.

Modulus of Soil Reaction E' (or Z)

The modulus of soil reaction, *E'* (or Z) defines the soil's resistance to pipeline ovalling as a result of dead and live loads acting on the pipeline. A value of 250 psi has been utilized as a conservative number and represents fine grained soils of medium compaction. Values in the range of 1,000 psi are not uncommon. A value of 500 psi would be acceptable in soil conditions where additional soil consolidation around the pipe has occurred.

A stress multiplier of approximately 0.9 was observed as a result of doubling the modulus of soil reaction from 250 to 500 psi.

Appendix C:

Proposed Screening Process – Infrequent Crossings of Existing Pipelines at Non-Road Locations

Where practical, crossings of pipelines shall occur at designated locations along the right-of-way preferably at purpose-built locations such as roads designed for such use.

In-situations, where existing pipelines are to be crossed at locations not specifically designed as a crossing location, it shall be permissible to cross the pipeline by equipment imposing surface loads, provided that the following requirements are met:

(a) the crossing of the pipeline is infrequent and /or temporary and is not anticipated to cause a major disturbance to the surface of the ROW.

(b) The pipeline is suitable for continued service at the established operating pressure. The pipeline operator shall consider service history and anticipated service conditions in this evaluation.

(c) The piping is not subjected to significant secondary stresses, other than those directly imposed by the crossing of the pipeline.

(d) The anticipated surface loading is below that provided in Figure C-1(a) and C-1(b) or as modified by Figures C-2.

As an alternative to Clauses a thru d, an engineering assessment of site-specific conditions is acceptable. This detailed engineering analysis shall consider the resulting combined stresses on the pipeline as a results of all loads expected to be imposed during its usage as a crossing location.

Figure C-1(a) and C-1(b) present the maximum live surface "point" load in kilograms for a cover depth of 90 cm (2.95 ft), and design operating pressures of 72% SMYS and 80% SMYS. The following notes apply to these figures:

(1) For intermediate operating pressure or grades, it shall be permissible to determine the surface load by interpolation.

(2) Design conditions used to develop the table are as follows:

  (a) Depth of cover, as indicated

  (b) Maximum hoop stress of 72% or 80% percent SMYS, as indicated

  (c) Maximum combined circumferential stress of 90 percent SMYS

  (d) Surface loading based on a contact pressure of 550 kPa (80 psi) applied over a rectangular area with aspect ratio (y/x) = 1. This contact pressure is designated as the "point" load case.

  (e) Fluctuating stress limitation of 82.7 MPa (12 ksi) based upon 2,000,000 cycles

  (f) Maximum D/t ratio of 125.

  (g) Soil Modulus E' = 1,724 kPa (250 psi) at pipe.

  (h) Soil Density = 1,922 kg/m^3 (120 lbs/ft^3)

  (i) Loading criteria includes an impact factor of 1.5.

  (j) Maximum combined effective stress of up to 95 percent SMYS. This value takes into account a temperature differential of ΔT = 50º C or the maximum temperature limitation as per CSA Clause 4.6.2.1 whichever is the lower.

  (k) Multiple wheel influence factor (if applicable)

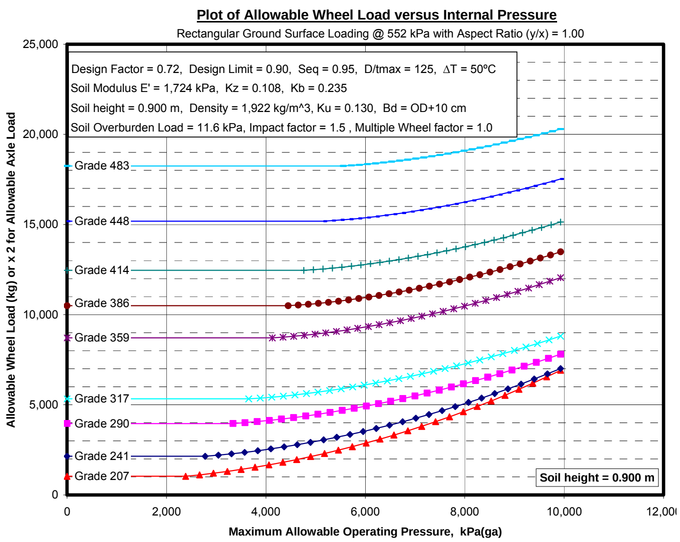

Figure C-1(a) – Soil Height = 0.90 meters, DF = 0.72

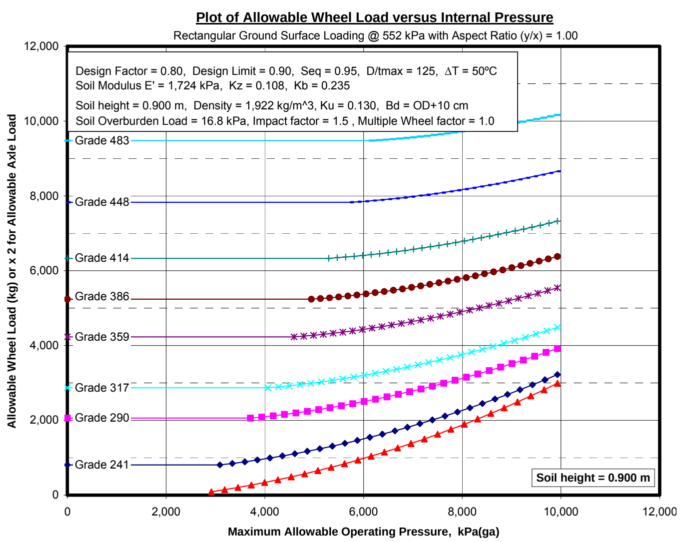

Figure C-1(b) – Soil Height = 0.90 meters, DF = 0.80

Figure C-2 present the Load Multiplier that can be applied to the previous determined allowable live surface "point" load for surface loads applied over a square footprint with contact pressures ranging from 35 kPa through 420 kPa (5 psi through 60 psi).

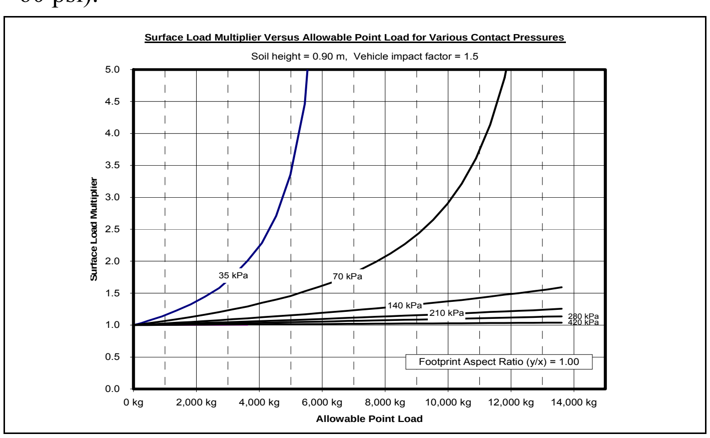

Figure C-2 – Soil Height = 0.9 meters

Appendix D:

Proposed Screening Process – Equipment with Low Surface Contact Pressure Crossing of Existing Pipelines

Where practical, crossings of pipelines shall occur at designated locations along the right-of-way preferably at purpose-built locations such as roads designed for such use. In-situations, where existing pipelines are to be crossed at locations not specifically designed as a crossing location, it shall be permissible to cross the pipeline by equipment imposing low surface contact loads, provided that the following requirements are met:

(a) the crossing of the pipeline is infrequent.

(b) The pipeline is suitable for continued service at the established operating pressure. The pipeline operator shall consider service history and anticipated service conditions in this evaluation.

(c) The piping is not subjected to significant secondary stresses, other than those directly imposed by the crossing of the pipeline.

(d) The anticipated surface loading is below that provided in Figure D-1(a) and D-1(b).

(e) As an alternative to Clauses a thru d, an engineering assessment of site specific conditions is acceptable. This detailed engineering analysis shall consider the resulting combined stresses on the pipeline as a results of all loads expected to be imposed during its usage as a crossing location.

Note: Figures D-1(a) & D-1(b) utilize a 60 degree bedding angle. A 30 degree angle is typically utilized and is representative of open trench construction with relatively unconsolidated backfill such that the full bearing support of the pipe is not achieved. While this is an acceptable and generally conservative value to utilize for a newly constructed pipeline, a 60 degree bedding angle has been utilized to reflect a mature pipeline where soil has re-consolidated around the pipeline providing additional support.

Note: Figures D-1(a) & D-1(b) utilize an Impact Factor of 1.25 versus 1.50 to take into account that equipment with low surface contact pressures are:

Typically designed not to compact the soil strata.

Designed to utilize low pressure pneumatic tires with contact pressure < 200 kPa(ga) (30 psig)

Designed to operate at lower velocities < 15 kph. (10 mph)

Figure D-1(a) and D-1(b) present the maximum wheel load in kilograms for a cover depth of 90 cm (2.95 ft), and design operating pressures of 72% SMYS and 80% SMYS.

Notes applicable to Figures D-1(a) & (b):

1) For intermediate operating pressure or grades, it shall be permissible to determine the surface load by interpolation.

2) Design conditions used to develop the table are as follows:

(a) Depth of cover as indicated

(b) Maximum hoop stress of 72% or 80% percent SMYS as indicated

(c) Maximum combined circumferential stress of 90 percent SMYS

(d) Surface wheel loading based on a contact pressure of 207 kPa (30 psi) applied over a rectangular area with aspect ratio (y/x) = 1

(e) Fluctuating stress limitation of 82.7 MPa (12 ksi) based upon 2,000,000 cycles

(f) Maximum D/t ratio of 125.

(g) Soil Modulus E' = 1,724 kPa at pipe.

(h) Soil Density = 1,922 kg/m^3

(i) Loading criteria includes an impact factor of 1.25.

(j) Maximum combined effective stress of up to 95 percent SMYS. This value takes into account a temperature differential of ΔT = 50º C or the maximum temperature limitation as per CSA Clause 4.6.2.1 (Appendix A) whichever is the lower.

(k) A 60 degree bedding angle has been utilized reflecting a mature pipeline where the soil has re-consolidated around the pipeline providing additional support.

(l) Multiple wheel influence factor (if applicable)

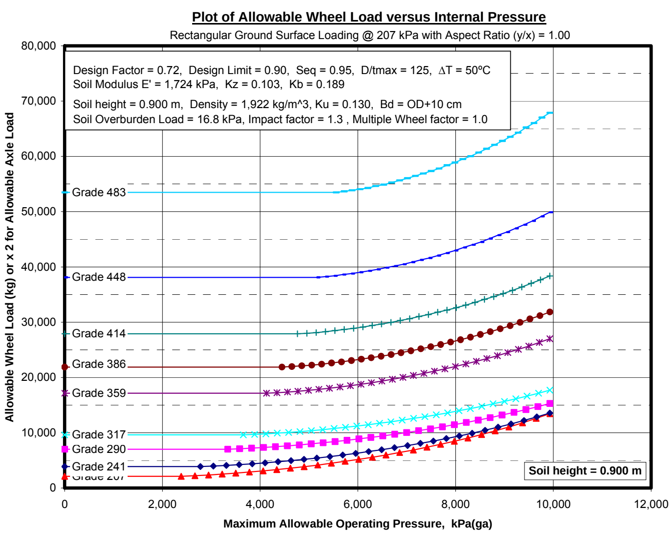

Figure D-1(a) – Soil Height = 0.90 meters, DF = 0.72

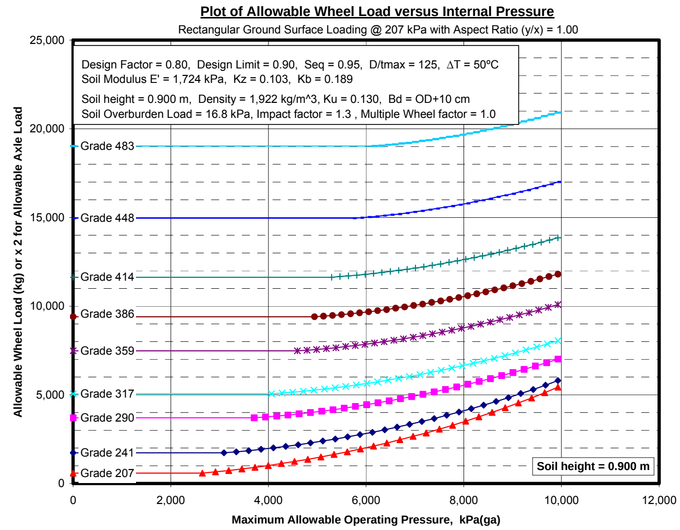

Figure D-1(b) – Soil Height = 0.9 meters, DF = 0.8