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Final Report

Development of a Pipeline Surface Loading Screening Process & Assessment of Surface Load Dispersing Methods

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1.0 INTRODUCTION

The Canadian Energy Pipeline Association (CEPA) represents Canada's oil and gas transmission pipeline operators who are world leaders in providing safe, reliable long-distance energy transportation. CEPA member companies receive numerous requests annually from all over Canada to cross their pipelines. In some cases, these crossing applications are for the establishment of permanent roads over the existing pipelines but in many others they are for temporary crossing by vehicles and equipment in locations without established roads. Regulations compel member companies to determine the potential loading effects of the crossing application and where determined to be excessive, take mitigative measures to reduce the applied stresses to acceptable levels.

A survey by CEPA of member companies indicates that they employ a variety of techniques to evaluate and mitigate surface loading effects on their buried pipelines. One widely used practice, embodied in API 1102 (1993, reaffirmed 2002), is limited to cover depths greater than or equal to 3 feet and has been specifically developed based on AASHTO H20 truck loads with small footprints associated with tire pressures typically in-excess of 550 kPa (80 psig). Several important limitations are inherent to this method. The method cannot be effectively extrapolated to shallow cover situations. It also may not scale correctly to different types of equipment that ride on floatation tires or caterpillar tracks where ground surface pressures are less than 350 kPa (50 psig). Further, it determines pipeline stresses in a non-traditional manner. These conditions create a barrier to uniform adoption of the method.

The National Energy Board (NEB) has requested that CEPA study the issues and determine the feasibility of a standard approach. CEPA wants to examine the above stated limitations as well as to determine the feasibility of a phased approach to crossing assessments that would eliminate the need to perform detailed calculations in most, if not all, cases. At the same time CEPA has identified the need to examine the various temporary load-spreading measures or other mitigation techniques to identify which are the most effective. Kiefner and Associates, Inc. (KAI) jointly with SSD, Inc. conducted this work for CEPA. The following report represents the results of this study.

1.1 Summary

Presented herein is a report detailing the development and implementation of a simplified screening process to assess the effects of surface loads on buried pipelines. The first section provides an overview of the results of a literature survey to identify theoretical models, standards, codes, and recommended practices that are currently used to assess the surface loading effects on buried pipelines.

The second section provides the methodology utilized to develop the 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 contact area and/or surface loading pressure, depth of cover, maximum allowable operating pressure and design factor). Situations that 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. Additional simplified graphs have been included to assist in additional screening prior to performing a more detailed evaluation.

The third section identifies various temporary or permanent surface load-dispersal techniques and other mitigation approaches that are often used as a means to lessen the effects of surface loading. The effectiveness of various methods is also discussed.

In the Appendices are general guidelines and charts that can be adopted by pipeline operators to address infrequent crossings of existing pipelines.

2.0 LITERATURE SEARCH SUMMARY

2.1 Introduction

A limited literature survey has been performed to identify theoretical models, standards, codes, and recommended practices that are currently used to assess the surface loading effects on buried pipelines. Included in this review is the position paper put out by the Canadian Standards Association (CSA) task force at railway crossings on this topic. The goal of this review is to highlight the following items:

- When the techniques were developed and by whom;
- Where they are used;
- The technical nature of the calculations performed;
- A comparative assessment of each method, identifying their strengths and limitations;
- Recommendations as to which method(s) may be suitable for adoption as standard practice;

- Knowledge gaps and areas that might require further study;
- Description of significant pipeline incidents caused by surface vehicle loadings.

2.2 Description of Significant Pipeline Incidents Caused by Surface Vehicle Loadings

Reference GRI-88/0287 provides a section that reviews the performance record of buried pipe crossings based on National Transportation Safety Board (NTSB) pipeline accident reports. At the time of this report publication, a total of four pipeline failures at railway or highway crossings were reported. All of these failures involved cased carrier pipes. The first failure occurred at a substandard girth weld located within the casing that experienced flexure due to soil movements beneath the carrier pipe outside of the casing. The second failure involved a pressure surge which caused failure of a carrier pipe inside of a casing at an area thinned by corrosion. The third failure involved tensile failure due to thermal contraction in a plastic carrier pipe at a coupling located outside the limits of the casing. The fourth failure occurred in a carrier pipe inside of a casing at a location where the wall thickness was reduced to 35% of its initial value due to corrosion. Cased pipeline crossings account for about 20% (a disproportionately high fraction) of corrosion-related reportable incidents, because it is difficult to protect the pipe from corrosion inside the casing and also difficult to monitor corrosion activity therein.

It is our observation and experience that the vast majority of pipeline crossing scenarios require little in the way of special measures to protect the pipeline provided the pipeline is in sound condition and has sufficient amounts of competent soil protection. Exceptions exist such as where muskeg soils or exceptionally heavy equipment or very shallow cover might be involved. We are aware of only one pipeline incident associated with a ground surface vehicle. The line was either a cast iron or old steel gas main with very shallow one-foot cover that ruptured under a cement mixer on a car/boat dealer's parking lot. The resulting fire burned up the truck and the dealer's inventory. We are not aware if it was ever established whether the main collapsed under the vehicle load or merely failed due to corrosion coincidentally when a vehicle was parked there. Overall, our familiarity with causes of pipeline failures informs us that the effects of surface vehicle loadings, even in fairly exceptional circumstances, has not historically been implicated as an important or frequent cause of pipeline incidents. This understanding suggests that the practice of carrying out elaborate analyses for every routine situation may be unwarranted. However, we fully recognize the regulatory, social, and business need to assess, and where necessary, mitigate threats.

2.3 Methods Used to Assess Fill and Surface Loading Effects on Buried Pipelines

2.3.1 Review of Spangler's Work

The pipeline industry has a longstanding interest in the problem of evaluating the effects of fill and surface loads on buried pipelines. 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 1940s through 1960s time frame, and no review on this subject would be complete without a discussion of Spangler's work. Spangler's most important publications include the following:

- Spangler, 1941. Spangler, M. G., "*The Structural Design of Flexible Pipe Culverts*", Bulletin 153, Iowa Engineering Experiment Station, Ames, Iowa, 1941.
- Spangler, 1946. Spangler, M.G. and Hennessy, R.L., "*A Method of Computing Live Loads Transmitted to Underground Conduits*", Proceedings Highway Research Board, 26:179, 1946.
- Spangler, 1954. Spangler, M.G., "*Secondary Stresses in Buried High Pressure Pipe Lines*", The Petroleum Engineer, November, 1954.
- Spangler, 1964. Spangler, M.G., "*Pipeline Crossings Under Railroads and Highways*", Journal of the AWWA, August, 1964.
- Watkins and Spangler, 1968. Watkins, R.K., and Spangler, M.G., "*Some Characteristics of the Modulus of Passive Resistance of Soil – A Study in Similitude*", Highway Research Board Proceedings, Vol. 37, 1968 pp. 567-583.

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.

2.3.1.1 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 (in psi) due to vertical load as follows:

$$\sigma = \frac{6 \cdot K_b \cdot W_{vertical} \cdot E \cdot t \cdot r}{E \cdot t^3 + 24 \cdot K_z \cdot P \cdot r^3} \qquad (2.1)$$

where $W_{vertical}$ is the vertical load due to fill and surface loads including an impact factor (lb/in), E is the pipe modulus of elasticity (psi), t is the pipe wall thickness (inches), r is the mean pipe radius (inches) and P is the internal pressure (psi). 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 2-1.

Table 2-1. 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

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 to 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° (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 including:

API RP 1102. American Petroleum Institute, "*Steel Pipelines Crossing Railroads and Highways*", API Recommended Practice 1102, Sixth Edition, April 1993 (reaffirmed July 2002).

GPTC, 1998/2000. GPTC Guide for Gas Transmission and Distribution Systems - 1995-1998 and 1998-2000, Guide Material Appendix G-192-15, "*Design of Uncased Pipeline Crossings of Highways and Railroads*", American Gas Associations, Arlington, VA.

CSA Z662, While not specifically referenced in CSA Z662 the equation was utilized in the development of the section on uncased railway crossings.

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.

2.3.1.2 The Iowa Formula

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

$$\Delta X = \frac{K_z \cdot [D_L \cdot W_{vertical}] \cdot r^3}{E \cdot I + 0.061 \cdot E' \cdot r^3} \quad (2.2)$$

where the terms that have not been previously defined in Section 2.3.1.1 are; ΔX the maximum deflection of the pipe (inches), D_L is the "deflection lag factor", I is the moment of inertia of the cross section of the pipe wall per unit length ($I=t^3/12$, in^3) and E' is the modulus of soil reaction (psi). 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° (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 condition 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 consider the use of a different deflection lag factor for fill loads which act on the pipe for long time periods rather than for traffic 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. Useful background and discussion on the selection of E' values are presented in the following references:

Moser, 1990. Moser, A.P., "*Buried Pipe Design*", McGraw Hill, 1990.
Hartley and Duncan, 1987. Hartley, J.D. and Duncan, J.M., "*E' and its Variation with Depth*", ASCE Journal of Transportation Engineering, Vol. 113, No. 5, September, 1987.
Masada, 2000. Masada, T., "*Modified Iowa Formula for Vertical Deflection of Buried Flexible Pipe*", ASCE Journal of Transportation Engineering, September/October, 2000.

Table 2-2 (after Moser, 1990) provides published average values of the modulus of soil reaction E' for a range of soil types under different levels of bedding compaction.

Table 2.3 (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.

The Iowa formula is used as a basis for estimating ovalling deflections due to vertical loads in several pipeline industry guideline documents including:

- AWWA M11, 1999. American Water Works Association, "*Steel Pipe – A Guide for Design and Installation*", AWWA Manual M11, 3rd Edition, 1999.
- ALA, 2001. American Lifelines Alliance, "*Guidelines for the Design of Buried Steel Pipe*", Published by the ASCE American Lifelines Alliance, www.americanlifelinesalliance.org, July 2001.

Table 2-2. Design Values of E', psi (From Moser, 1990)

TABLE 3.4 Average Values of Modulus of Soil Reaction, E' (For Initial Flexible Pipe Deflection)

Soil type-pipe bedding material (Unified Classification System*)	E' for degree of compaction of bedding, lb/in^2: Dumped	Slight, < 85% proctor, < 40% relative density	Moderate, 85%–95% proctor, 40%–70% relative density	High, >95% proctor, > 70% relative density
Fine-grained soils (LL > 50)† Soils with medium to high plasticity CH, MH, CH-MH	No data available; consult a competent soils engineer; Otherwise use $E' = 0$			
Fine-grained soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with less than 25% coarse-grained particles	50	200	400	1000
Fine-grained soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25% coarse-grained particles Coarse-grained soils with fines GM, GC, SM, SC contains more than 12% fines	100	400	1000	2000
Coarse-grained soils with little or no fines GW, GP, SW, SP‡ contains less than 12% fines	200	1000	2000	3000
Crushed rock	1000	3000	3000	3000
Accuracy in terms of percentage deflection§	± 2	± 2	± 1	± 0.5

*ASTM Designation D2487, USBR Designation E-3
†LL = liquid Limit
‡Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC)
§For ± 1% accuracy and predicted deflection of 3%, actual deflection would be between 2% and 4%.

NOTE: Values applicable only for fills less than 50 ft (15 m). Table does not include any safety factor. For use in predicting initial deflections only, appropriate deflection lag factor must be applied for long-term deflections. If bedding falls on the borderline between two compaction categories, select lower E' value or average the two values. Percentage proctor based on laboratory maximum dry density from test standards using about 12,500 ft-lb/ft^3 (598,000 J/m^3) (ASTM D698, AASHO T-99, USBR Designation E-11). 1 lb/in^2 = 6.9 kN/m^2.

SOURCE: Amster K. Howard, "Soil Reaction for Buried Flexible Pipe," U.S. Bureau of Reclamation, Denver, Colo. Reprinted with Permission from American Society of Civil Engineers *J. Geotech. Eng. Div.*, January 1977, pp. 33–43.

Table 2-3. Design Values of E', psi (from Hartley and Duncan, 1987)

Type of Soil	Depth of Cover (ft)	Standard AASHTO* Relative Compaction			
		85 %	90 %	95 %	100 %
Fine-grained soils with less than 25 percent sand content (CL, ML, CL-ML)	0-5	500	700	1,000	1,500
	5-10	600	1,000	1,400	2,000
	10-15	700	1,200	1,600	2,300
	15-20	800	1,300	1,800	2,600
Coarse-grained soils with fines (SM, SC)	0-5	600	1,000	1,200	1,900
	5-10	900	1,400	1,800	2,700
	10-15	1,000	1,500	2,100	3,200
	15-20	1,100	1,600	2,400	3,700
Coarse-grained soils with little or no fines (SP, SW, GP, GW)	0-5	700	1,000	1,600	2,500
	5-10	1,000	1,500	2,200	3,300
	10-15	1,050	1,600	2,400	3,600
	15-20	1,100	1,700	2,500	3,800

*Note: AASHTO is the American Association of State Highway Transportation Officials.
Table reproduced from Hartley and Duncan, 1987

2.3.1.3 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 and/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:

$$W_{fill} = C_d \cdot \gamma \cdot B_d^2 \qquad (2.3)$$

where C_d is a fill coefficient, γ is the soil density and B_d is the effective trench width. Values of the fill coefficient C_d for different soils are tabulated as a function of the trench geometry (defined based on the ratio of the depth of soil cover H to the effective trench width B_d) and soil type in several references (e.g., the GPTC Guide, Spangler and Hennessy, 1946, etc.).

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) as follows:

$$W_{wheel} = 4 \cdot C_t \cdot \frac{W}{L} \tag{2.4}$$

where C_t is a wheel load coefficient, W is the wheel load (including an impact factor) and L is the effective length of pipe (most references to this equation use an effective length L=3 feet). Values of the wheel load coefficient C_t are tabulated for different trench geometries (i.e., based on the ratios of $D/2H$ and $L/2H$) in several references (e.g., Spangler and Hennessy, 1946, Spangler, 1954, etc.).

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 (see Newmark, 1935) as follows:

$$W_{rectangular} = 4 \cdot C_t \cdot \frac{W \cdot D}{A} \tag{2.5}$$

where C_t is a rectangular load coefficient, W the total load on a rectangular footprint (including an impact factor), D is the pipe diameter, and A is the area of the rectangular footprint. Values of the rectangular load coefficient C_t are tabulated for different trench geometries and rectangular footprints in several references (e.g., AWWA M11, Spangler 1964, etc.).

Given the computed loading on the buried pipe from either fill or traffic 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.

2.3.2 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 (as discussed in Sections 2.3.1 and 2.3.2) 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 (see Watkins and Spangler, 1968). 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 even if only for the purpose of performing "what if" analyses. 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 (2.1) and (2.2). 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:

$$\sigma = \frac{K_b}{2 \cdot K_z} \cdot \frac{\Delta X \cdot E \cdot t}{r^2} \qquad (2.6)$$

where all of the variables are as previously defined. Solving Equation (2.6) for ΔX and substituting the circumferential stress σ from Equation (2.1) leads to the following expression of the Spangler stress formula in terms of ovality:

$$\Delta X = \frac{12 \cdot K_z \cdot W_{vertical} \cdot r^3}{E \cdot t^3 + 24 \cdot K_z \cdot P \cdot r^3} \qquad (2.7)$$

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 (2.7), then aligning the resulting expression next to the Iowa formula yields the following:

Spangler Stress Expression	Iowa Formula	
$\Delta X = \frac{1.296 \cdot W_{vertical} \cdot r^3}{E \cdot t^3 + 2.592 \cdot P \cdot r^3}$	$\Delta X = \frac{0.108 \cdot W^*_{vertical} \cdot r^3}{E \cdot I + 0.061 \cdot E' \cdot r^3}$	(2.8)

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 (on the left) 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):

$$\Delta X = \frac{0.108 \cdot W_{vertical} \cdot r^3}{E \cdot I + 0.216 \cdot P \cdot r^3} \qquad \Delta X = \frac{0.108 \cdot W^*_{vertical} \cdot r^3}{E \cdot I + 0.061 \cdot E' \cdot r^3} \qquad (2.9)$$

Note that the only difference between the numerators of these two expressions is that the one based on the Iowa formula (on the right) 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):

$$\Delta X = \frac{0.108 \cdot W_{vertical} \cdot r^3}{E \cdot I + 0.216 \cdot P \cdot r^3 + 0.061 \cdot E' \cdot r^3} \qquad (2.10)$$

It is worth noting here that Rodabaugh (Rodabaugh, 1968) suggested a very similar expression to qualitatively combine pressure stiffening and soil restraint effects:

$$\Delta X = \frac{0.135 \cdot W_{vertical} \cdot r^3}{E \cdot I + 0.216 \cdot P \cdot r^3 + 0.061 \cdot E' \cdot r^3} \qquad (2.11)$$

where the coefficient of 0.135 in the numerator corresponds to a bedding angle of 30° with an effective deflection lag factor of 1.25 (i.e., 0.135=0.108·1.25).

Multiplying both the numerator and denominator of the combined ovality expression (2.10) by 12 gives:

$$\Delta X = \frac{1.296 \cdot W_{vertical} \cdot r^3}{E \cdot t^3 + 2.592 \cdot P \cdot r^3 + 0.732 \cdot E' \cdot r^3} \qquad (2.13)$$

Then converting back to stress using Equation (2.6) results in the following combined expression for circumferential pipe stress:

$$\sigma = \frac{1.41 \cdot W_{vertical} \cdot E \cdot t \cdot r}{E \cdot t^3 + 2.592 \cdot P \cdot r^3 + 0.732 \cdot E' \cdot r^3} \qquad (2.14)$$

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

$$\sigma = \frac{6 \cdot K_b \cdot W_{vertical} \cdot E \cdot t \cdot r}{E \cdot t^3 + 24 \cdot K_z \cdot P \cdot r^3 + 0.732 \cdot E' \cdot r^3} \qquad (2.15)$$

Notice that if the term *E'* in the denominator is set equal to zero, Equation (2.14) reduces to the original Spangler stress formula. 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 instead of 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 and AWWA M11, 1999 refer to a range from 1.0 to 1.5, and Rodabaugh (Rodabaugh, 1968) 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.

2.3.3 Review of Recent Pipeline Industry Research

Pipeline industry research on the subject of loads on buried pipes has continued from the Spangler era to the present day. Without undertaking a totally comprehensive review of this work, we have elected to highlight some of the more important modern references on this subject, some of which contain their own literature reviews.

In a multi-year project sponsored by the Gas Research Institute, researchers at Cornell University:

- performed a review of current practices for pipeline crossings at highways and railways,
- reviewed existing analytical models to estimate buried pipe stresses,
- undertook detailed finite element analysis (FEA) of buried pipe configurations subject to fill and surface loads, and
- performed experimental evaluations of augerbored pipelines at rail road crossings.

The primary reports from this research are:

- GRI, 1987. Gas Research Institute, "*Analytical Study of Stresses in Transmission and Distribution Pipelines Beneath Railroads*", Topical Report of Task 2, June 1985-February 1987, Department of Structural Engineering, Cornell University, September 15, 1987.

- GRI, 1988. Gas Research Institute, "*State-of-the-Art Review: Practices for Pipelines Crossings at Highways*", Topical Report, June 1987-June 1988, School of Civil and Environmental Engineering, Cornell University, September, 1988.

- GRI, 1991. Ingraffea, A. R., O'Rourke, T. D., and Stewart, H. E., "*Technical Summary and Database for Guidelines for Pipelines Crossing Railroads and Highways*", Cornell University School of Civil and Environmental Engineering Final Report to Gas Research Institute, GRI-91/0285, Dec. 1991.

Each of these references is focused on pipes installed via bored-in-place construction which is common for highway and railway crossings. This research provides a very useful summary of the important factors affecting buried pipe response to fill and surface loads as well as a review of the existing analysis methods (i.e., the Spangler stress formula and the Iowa formula) for evaluating the pipe response to fill and surface loads. The main findings from the review of the existing methods were:

- The Boussinesq theory used to estimate the surface load experienced by the pipe assumes that the loaded soil mass is homogeneous and neglects the presence of the pipe within the soil.
- The Spangler stress formula and the Iowa formulas have an inconsistent treatment for pressure stiffening and soil resistance effects.

Reference (GRI, 1987) provides modified expressions for the loads due to fill (analogous to Equation 2.3) and the loads due to surface loads (analogous to Equations 2.4 and 2.5) for pipe installed via bored-in-place construction. This reference also proposes a modified version of the Spangler stress formula (analogous to Equation 2.14) for pipe installed via bored-in-place construction with three resistance terms in the denominator (one for pipe stiffness, one for pressure stiffening, and one for soil resistance). A significant contribution of the Cornell/GRI research is that in addition to providing equations to compute pipe circumferential stresses on buried pipes due to fill and surface loads, it also highlights:

- the possible development of longitudinal stresses due to bending of the pipe under surface loads,
- the evaluation of combined or bi-axial (e.g., von Mises) stress conditions with respect to appropriate stress limits, and
- the evaluation of cyclic stresses with respect to a fatigue endurance stress limit.

The Cornell/GRI work led to the development of guidelines for the design and evaluation of uncased pipelines that cross railroads and highways, which have been implemented into a personal computer program called PC-PISCES. The results of the Cornell/GRI work are also embodied in the following pipeline industry recommended practice document:

- API RP 1102, 1993. American Petroleum Institute, "*Steel Pipelines Crossing Railroads and Highways*", API Recommended Practice 1102, Sixth Edition, April 1993 (reaffirmed 2003).

The Cornell/GRI/API guidelines consist of a set of equations for the circumferential and longitudinal pipe stresses that are created by surface live load, earth dead load, and internal pressure. The equations for the live load stresses are nonlinear, with functions/curves that were fit to the results of a series of FEA simulations. The FEA results were validated through comparisons with experimental data from tests on two full-scale auger bored pipeline crossings.

Various combinations of the computed pipe stresses are checked to guard against fatigue damage of longitudinal and girth welds and to guard against excessive yielding.

While these guidelines were developed from tests and analyses of uncased pipelines that are installed with auger boring beneath railroads and highways, they are often employed by pipeline engineers for the more common case of pipelines installed via trenched construction. The procedure is also restricted to cover depths greater than or equal to 3 feet and has been specifically developed based on AASHTO H20 truck loads with small footprints associated with tire pressures typically in excess of 550 kPa (80 psig). Several important limitations are inherent to these guidelines, namely that the approach cannot be extrapolated to shallow cover situations. It also may not scale correctly to different types of equipment that ride on floatation tires or caterpillar tracks where ground surface pressures are less than 50 psig. Further, it determines pipeline stresses in a non-traditional manner. These issues may create a barrier to uniform adoption by pipeline companies.

Several ongoing research programs have been undertaken by the Pipeline Research Council International, Inc. (PRCI) and SoCalGas with an emphasis on the determination of stresses developed in pipes with shallow cover and subject to extreme loading situations. The first project is Project Number PR-15-9521 (Phase 1) and PRCI-15-9911 (Phase 2): *Effects of Non-Typical Loading Conditions on Buried Pipelines* being performed by Southwest Research Institute (SwRI). This work includes full-scale tests of shallow covered pipes buried in sand and clay with diameters ranging from 16 to 36 inches and subjected to fill, concentrated, and distributed surface loads. A related follow-on project, Project Number GRI-8442: "*Centrifuge and Full-Scale Modeling Comparison for Pipeline Stress Due To Heavy Equipment Encroachment*," is currently being undertaken by C-CORE. This project includes full-scale tests of 16-inch diameter, shallow pipe subject to concentrated surface loads and complementary centrifuge modeling. Results of this study will be used to determine if small-scale testing performed in a centrifuge is a reliable means for expanding the data set developed by SwRI for surface model/guidelines development. Another approach to database development is being studied in a project titled "*Buried Pipelines Subjected to Surcharge Loads: Finite-Element Simulations.*" This study is being undertaken by the University of Texas-Austin, and involves the development and validation of a finite element analysis procedure for simulating shallow covered pipelines subjected to rectangular footprint surface loadings based on the SwRI distributed load tests. The most recent follow-on project, led by C-FER Technologies, is Project Number PR-244-03158: "*Effects of Static and Cyclic Surface Loadings on the Performance of Welds in Pre-1970 Pipelines.*" It is intended to apply the SwRI shallow cover test database and all other related databases in the development of analysis tools with special emphasis on the evaluation of welds in pre-1970's pipelines. Unfortunately, none of these ongoing projects have been completed or documented at the time of this study. We recommend that this work be reviewed as the reports become available.

2.3.4 Review of CSA Standard Z183 Working Group on Crossings Position Paper

The paper CSA Standard Z183 Working Group on Crossings, *"Position Paper on Recommended Technical Specifications for Pipeline Crossings of Railways,"* provides a useful overview of issues surrounding oil and gas pipeline crossings at railroads as well as other crossings in Canada. This document provides a review of applicable standards and regulations in other countries, compiles a list of references that an engineer could use for a site-specific crossing analysis, and develops a summary recommendation for a conservative design for common crossings that could be incorporated into a standard or regulation. It also provides useful commentary and background on the procedures for the analysis of buried pipe loads and stresses, design approaches (including the Spangler stress and Iowa formulas), and the selection of design variables. Several key points from this reference are summarized as follows:

- For computing pipe stresses, the CSA Z183 Working Group advocated the use of both the Spangler stress formula and the Iowa formula to superimpose the results such that the Iowa formula would be used to establish the maximum bending stress of the pipe. The Spangler pressured formula would be utilized if the resultant stress was less than the result of the Iowa formula. Recommended values of various design parameters (e.g., soil density, soil type, impact factor, load coefficient, etc.) are provided.
- The Working Group points out that the computed pipe stress should be compared to allowable pipe stresses, including an appropriate safety factor, and the potential for fatigue damage due to the cyclic loading on the longitudinal or spiral pipe seam should be addressed.
- The Working Group paper also provided discussion on the fatigue capacity of pipes. The fatigue endurance limit ultimately adopted in CSA Z662 was 69 MPa (10 ksi).
- The Working Group provides a recommended limit on the D/t ratio for railroad crossings to a maximum of 85.
- The Working Group recommended the following stress limits with respect to railroad crossings: a maximum hoop stress due to internal pressure of 50% specified minimum yield stress (SMYS), a maximum combined circumferential stress (due to pressure, fill and traffic) of 72% SMYS, and a maximum combined equivalent stress of 90% SMYS.

2.4 Summary of Principle Methods for Evaluating Vertical Loading Effects on Buried Pipelines

Section 2.3 of this report provided a review of what we believe are the principle methods for evaluating the effects of fill and surface loads on buried pipes. Any method for evaluating these loading effects must consider the following:

- The pipe properties including diameter D, wall thickness t, and modulus of elasticity E
- The internal pressure P
- The depth of soil cover H, the effective trench width B_d, and the soil type
- The effective length of the pipe L
- The construction method and the pipe bedding angle
- The modulus of soil resistance E'
- The magnitude of the surface load W
- The footprint of the load (e.g., point load or rectangular load)
- The impact factor corresponding to a given surface load
- The effective number of cycles corresponding to a given surface load

Given these parameters, it is possible to develop estimates of the pipe stresses and ovalling deflections that result from fill and surface loads. With the stress and deflection estimates, the engineer must make decisions regarding the safety of the buried pipe which requires additional information including:

- The specified minimum yield stress (SMYS) of the pipe
- The type of longitudinal weld
- The quality of the girth welds
- The possible presence of corrosion or other anomalies
- Stresses due to other loads including:
    - internal pressure
    - temperature differential
    - longitudinal bending or roping of the pipe

The results of the evaluation should be checked for various pipe stress demand-capacity measures, including the total circumferential stress due to internal pressure, fill and surface loads. The results should also be checked for biaxial stress combinations of the circumferential and the longitudinal stress due to temperature differential and Poisson's effect and bending. There should also be cyclic stress range demand-capacity checks to guard against fatigue damage. The following process flow diagram entitled "Pipeline Surface Loading Acceptability" (Figure 2-1) has been developed to illustrate the recommended process to be followed in determining the acceptability of surface loading. The following sections address the development of a simplified screening process that embodies the process identified in the diagram.

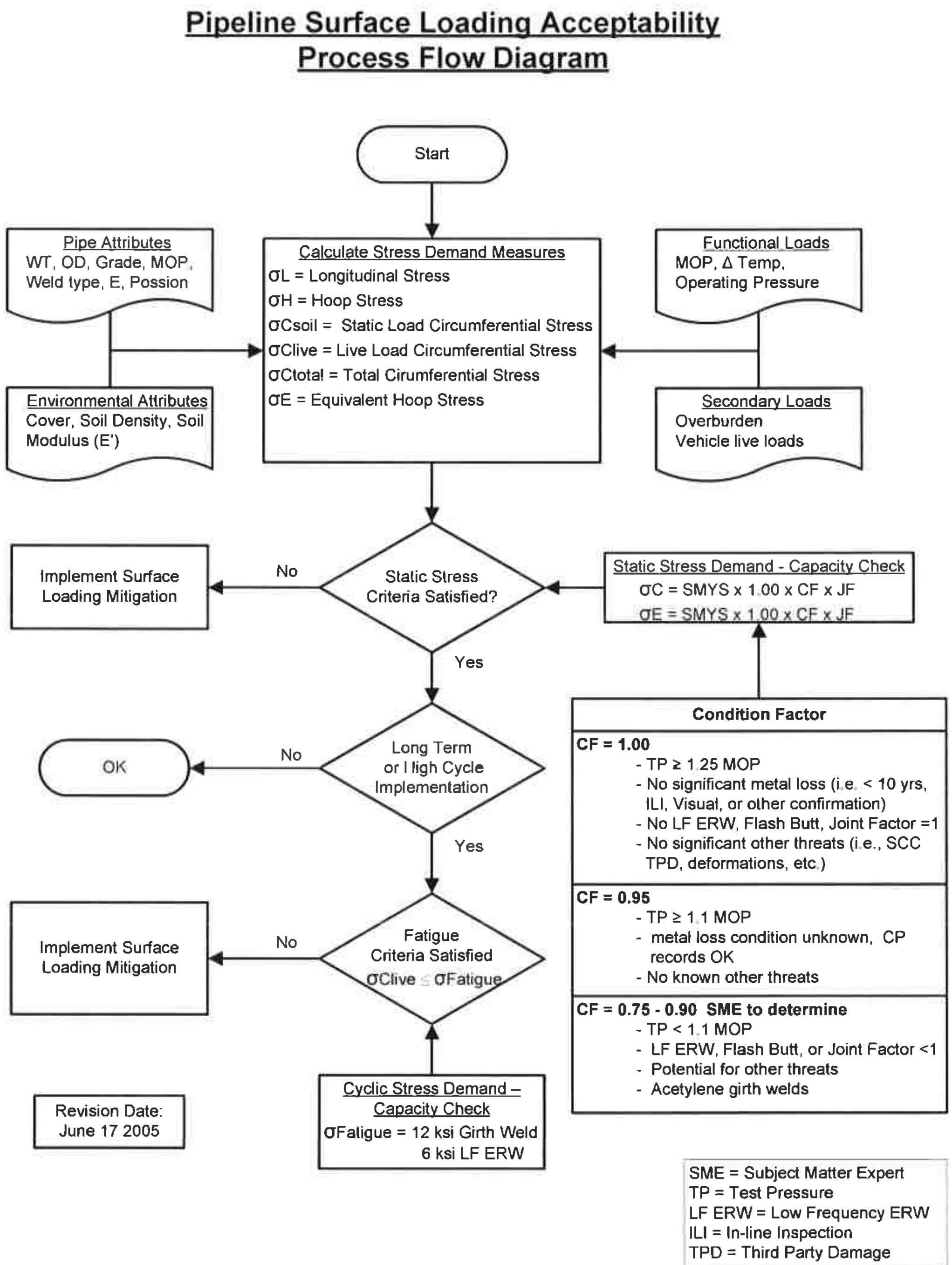

Figure 2-1. Pipeline Surface Loading Acceptability Process Flow Diagram

2.5 Proposed Development of Screening Process

Once all of the information described in this section is gathered, an engineer can perform the necessary calculations required to make an evaluation of the buried pipe situation at hand. In addition, by having an understanding of the theory behind and the limitations of the calculations used to develop the estimated stresses, the engineer must utilize judgment and experience to make decisions regarding the pipeline integrity and safety.

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 use the developed theory to develop a series of charts that can evaluate 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 the existing methods for evaluating vertical load effects on buried pipe. Ideally the calculations will be reasonably conservative. Table 2-4, which was developed as a starting point to selecting the appropriate calculation method, provides a comparative assessment of the principle methods.

The second task of the proposed work for this project (see Section 3) is the development of a simple screening method which will allow a pipeline operator to determine whether or not a given crossing application requires added protection or whether a more detailed calculation is appropriate. The goal of the screening method is to implement a relatively simple procedure based on easily obtainable attributes such as wheel or axle load, ground surface contact area and/or surface loading pressure, depth of cover, maximum allowable operating pressure and design factor.

Table 2-4. Comparison of Principle Methods for Evaluating Vertical Loading Effects on Buried Pipelines

Method	Strength	Limitation	Comments
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
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
API RP 1102, 1993	• Provides detailed flow chart • Computes multiple stress components • Performs stress demand-capacity checks • Includes check for fatigue	• Limited to 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 or technical toolbox
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

2.6 References

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3.0 PROPOSED APPROACH FOR SCREENING BURIED PIPELINES SUBJECTED TO SURFACE TRAFFIC

3.1 Introduction

Section 2 provided a *Literature Search Summary* which documented the available methods for evaluating the effects of fill and surface loads on buried pipelines. Using this information as a starting point, the second work task was to develop a simple screening method. This method will allow a pipeline operator to determine whether or not a given crossing application requires added protection or if a more detailed calculation is appropriate. The goal of the screening method is to use relatively simple and easily obtainable attributes (e.g., wheel or axle load, ground surface contact area and/or surface loading pressure, depth of cover, maximum allowable operating pressure and design factor). The screening calculations are summarized in the next section.

3.2 Overview of Screening Approach

A modified version of the Spangler stress formula was presented in Section 2. The modified formula is:

$$\sigma = \frac{6 \cdot K_b \cdot W_{vertical} \cdot E \cdot t \cdot r}{E \cdot t^3 + 24 \cdot K_z \cdot P \cdot r^3 + 0.732 \cdot E' r^3} \qquad (3.1)$$

where $W_{vertical}$ is the vertical load due to fill and surface loads including an impact factor (lb/in), E is the pipe modulus of elasticity (psi), t is the pipe wall thickness (inches), r is the mean pipe radius (inches), P is the internal pressure (psi), and E' is the modulus of soil reaction (psi). 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. The right hand side of Equation (3.1) 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, where D equals the outside diameter of the pipe.

$$\sigma = \frac{3 \cdot K_b \cdot \frac{W_{vertical}}{D} \cdot \left(\frac{D}{t}\right)^2}{1 + 3 \cdot K_z \cdot \frac{P}{E} \cdot \left(\frac{D}{t}\right)^3 + 0.0915 \cdot \frac{E'}{E} \cdot \left(\frac{D}{t}\right)^3} \qquad (3.2)$$

The stress relationship from Equation (3.2) is plotted at different levels of internal pressure as a function of D/t ratio in Figure 3-1 below. The fixed parameters are shown in the figure box.

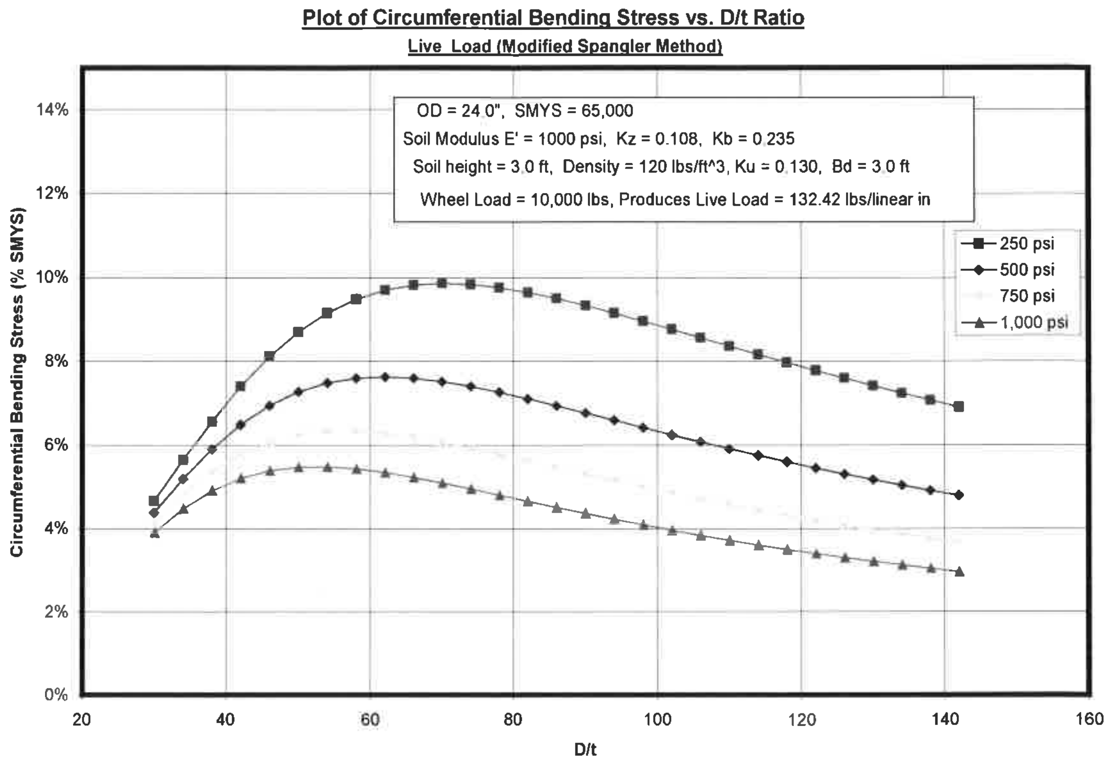

Figure 3-1. Plot of Circumferential Bending Stress vs. D/t Ratio

3.3 Review of Loading Terms

The stress formula described above (Equation 3.2) requires a load per unit length of pipe, $W_{vertical}$ resulting from either fill and/or surface loads. Section 2.3.1.3 provides an overview of how Spangler computed these load terms.

The load transmitted to the pipe in a ditch due to earth (fill) load can be computed based on Marston's load theory as follows:

$$W_{fill} = C_d \cdot \gamma \cdot B_d^2 \qquad (3.3)$$

$$C_d = \frac{1-e^{-2K\mu'\left(\frac{H}{B_d}\right)}}{2K\mu'} \qquad (3.4)$$

where C_d is a fill coefficient, γ is the soil density, B_d is the effective trench width, K is the ratio of active lateral unit pressure to vertical unit pressure, μ' is the coefficient of friction between the fill material and sides of the ditch and H is the height of fill over the pipe. Kμ' can vary between 0.111 and 0.165 depending on the soil conditions. Equation 3.4 is for ditch loading on the pipe. It is recommended that the reader refer to Spangler and Handy's book *Soil Engineering* to ensure that they fully understand how to use Equations 3.3 and 3.4. An alternative method for determining the fill load is to use the prism equation recommended by Moser in *Buried Pipe Design*. The prism formula is:

$$W_{fill} = \gamma \cdot H \cdot D \qquad (3.5)$$

No deflection lag factor is required if the prism formula is used.

Note that in Equation (3.2), the pipe diameter (to the extent possible) has been rearranged into the non-dimensional form D/t. The only place that the pipe diameter appears in Equation (3.2) 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 (3.2) is independent of the pipe diameter.

The fill loads from Equation (3.3) have been plotted in Figure 3-2 for W_{fill}/D as a function of diameter so that a representative value of W_{fill}/D can be selected that is independent of 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 W_{fill}/D selected to be constant for all pipe diameters.

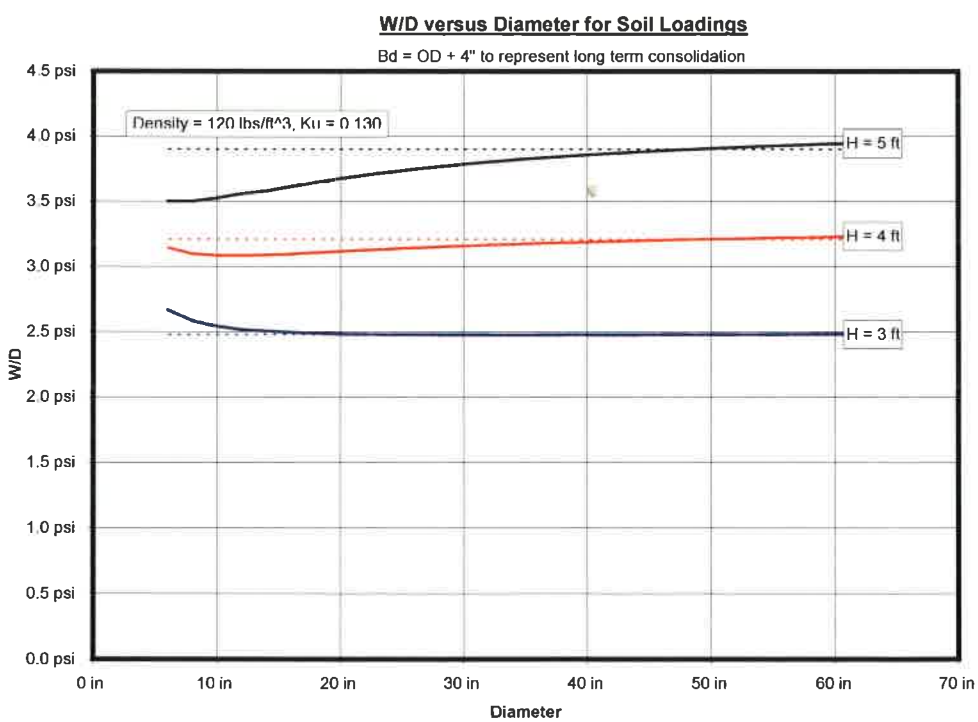

Figure 3-2. W/D versus Diameter for Soil Loadings

The load transmitted to the pipe due to surface wheel load is developed using a numerical integration of the Boussinesq theory for a surface point load:

$$W_{wheel} = 4 \cdot C_l \cdot \frac{W}{L} \tag{3.6}$$

where C_l is a wheel load coefficient, W is the wheel load (including an impact factor) and L is the effective length of pipe (most references to this equation use an effective length L=3 feet). Values of the wheel load coefficient C_l are tabulated for different trench geometries (i.e., based on the ratios of $D/2H$ and $L/2H$) in several references. A formula to compute the coefficient C_l as a function of $D/2H$ and $L/2H$ has been developed as follows:

$$C_l = 0.25 - \frac{1}{2\pi}\left[\left(\sin^{-1} H\sqrt{\frac{\left(\frac{D}{2}\right)^2+\left(\frac{L}{2}\right)^2+H^2}{\left(\left(\frac{D}{2}\right)^2+H^2\right)\left(\left(\frac{L}{2}\right)^2+H^2\right)}}\right) - \frac{\left(\frac{D}{2}\right)\left(\frac{L}{2}\right)H}{\sqrt{\left(\left(\frac{D}{2}\right)^2+\left(\frac{L}{2}\right)^2+H^2\right)}}\left(\frac{1}{\left(\frac{D}{2}\right)^2+H^2}+\frac{1}{\left(\frac{L}{2}\right)^2+H^2}\right)\right] \tag{3.7}$$

As stated previously, the D/t value as defined by Equation (3.2) has been made non-dimensional with respect to pipe diameter. Therefore, if a representative value of the W_{wheel}/D term can be selected to cover a full range of diameters, then Equation (3.2) would be fully independent of the pipe diameter.

The wheel loads from Equation (3.6) have been plotted in Figure 3-3 for W_{wheel}/D as a function of diameter so that a representative value of W_{wheel}/D can be selected that represents a full range of diameters independent of pipe diameter. The dashed lines represent the value W_{wheel}/D selected to be constant for all pipe diameters.

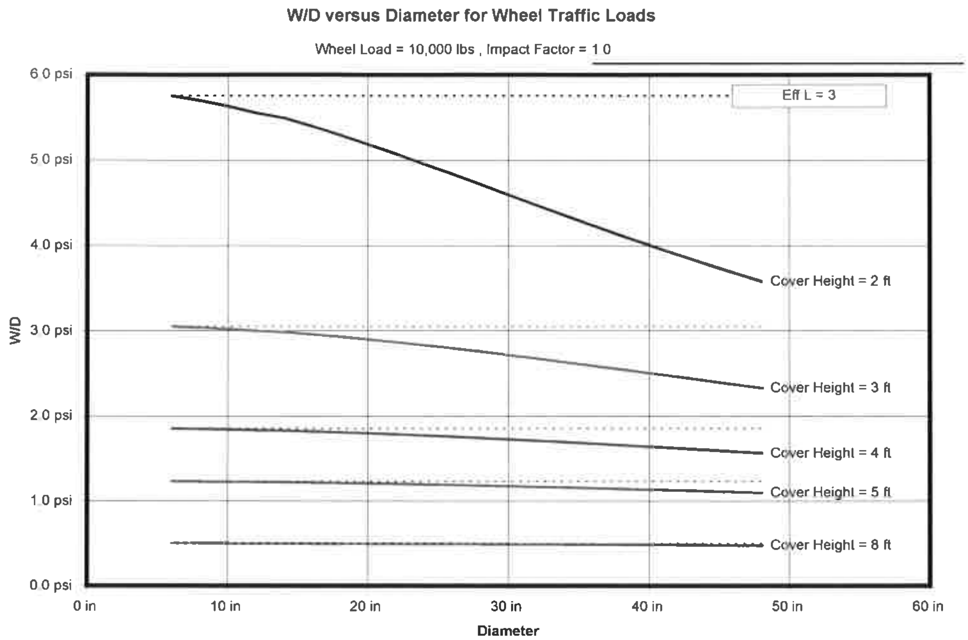

Figure 3-3. W/D versus Diameter for Wheel Traffic Loads

The load transmitted to the pipe due to surface load with a rectangular footprint based on numerical integration of the Boussinesq theory is:

$$W_{rectangular} = 4 \cdot C_{t} \cdot \frac{W \cdot D}{A} \tag{3.8}$$

where C_t is a rectangular load coefficient, W the total load on a rectangular footprint (including an impact factor), D is the pipe diameter and A is the area of the rectangular footprint. C_t is a function of the length and width of the rectangular footprint (L_{rect} and B_{rect}) and the depth of cover H. Although equations 3.8 and 3.6 are the solutions for different loading scenarios, Spangler points out (Spangler and Handy, 1973) that C_t in Equation 3.8 can be determined from Equation 3.7 by replacing L/2 with L_{rect} /2 and D/2 with B_{rect}/2.

Note that because Equation (3.8) 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.

$$\frac{W_{rectangular}}{D} = 4 \cdot C_{t} \cdot \frac{W}{A} \tag{3.9}$$

The computed normalized loading on the buried pipe from either fill or traffic loads (i.e., W_{fill}/D, W_{wheel}/D, or $W_{rectangular}/D$) can be expressed as a more general vertical load term $W_{vertical}/D$ for use in Equation (3.2).

Note: A point load can be conservatively estimated by utilizing a rectangular footprint with a surface contact pressure of 550 kPa (80 psi).

3.4 Sensitivity of Surface Contact Pressure

Fixed loads spread over larger rectangular areas generally have significantly less impact on a buried pipeline. The magnitude of change is related to depth of cover with shallow cover exhibiting the larger effects. Figure 3-4 shows the effects of varying surface contact pressures.

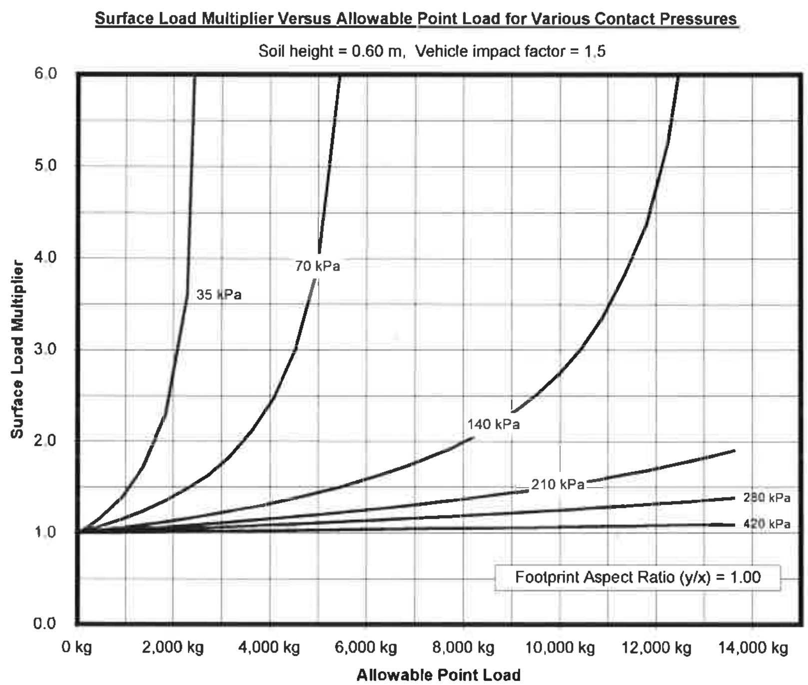

Figure 3-4. Surface Load Multiplier versus Allowable Point Load for Various Contact Pressures

Appendix C contains a full series of plots addressing contact pressures.

3.5 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 rather 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 shift and varies with depth. The wheel factor uses the worst case scenario of a load applied by two axles of 6-foot width and a 4-foot space between the axles. The stress at pipeline depth at different locations is calculated using Boussinesq's equation. Figure 3-5 illustrates the analysis locations. 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).

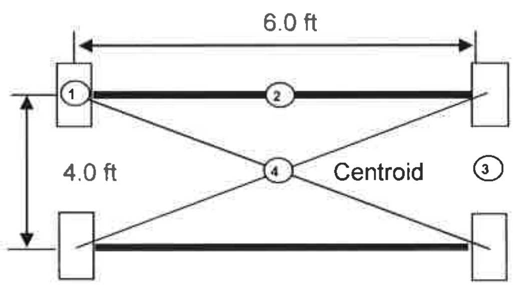

Figure 3-5. Four Locations Analyzed to Determine Worst-Case Loading for Various Depths

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

3.6 Application of the Proposed Approach

The stress calculation approach explained 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 (the authors recommend that a value of 1.00 SMYS is a reasonable maximum combined circumferential stress at pipeline vehicular crossings, see Appendix C "Design Loading Criteria"), D/t_{max}= 125, and the other pertinent analysis parameters (E', cover depth, etc.).
2. For a selected internal pressure, compute the D/t ratio corresponding to $D/t = 2 \cdot \sigma_y \cdot DF/P$. Then compute the circumferential stress due to combined internal pressure using Barlow's formula and fill load. The fill load is calculated from Equation (3.2) with $W_{vertical}$ set equal to W_{fill} in Equation (3.3).
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 (3.2) equal to the "available circumferential stress capacity" for surface load computed in Step 3 above and solve for the corresponding $W_{vertical}$
6. If the surface loading is a point (wheel) load, set W_{wheel} equal to $W_{vertical}$ and use Equation (3.6) to solve for the allowable point load W. If the surface loading is a rectangular footprint load, set $W_{rectangular}$ equal to $W_{vertical}$ and use Equation (3.8) 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 3-6. The figure shows allowable wheel load versus internal pressure for cover of 0.9 meters (3 ft) and for Grades of pipe ranging from 207 MPa to 483 MPa (Grade A to X70).

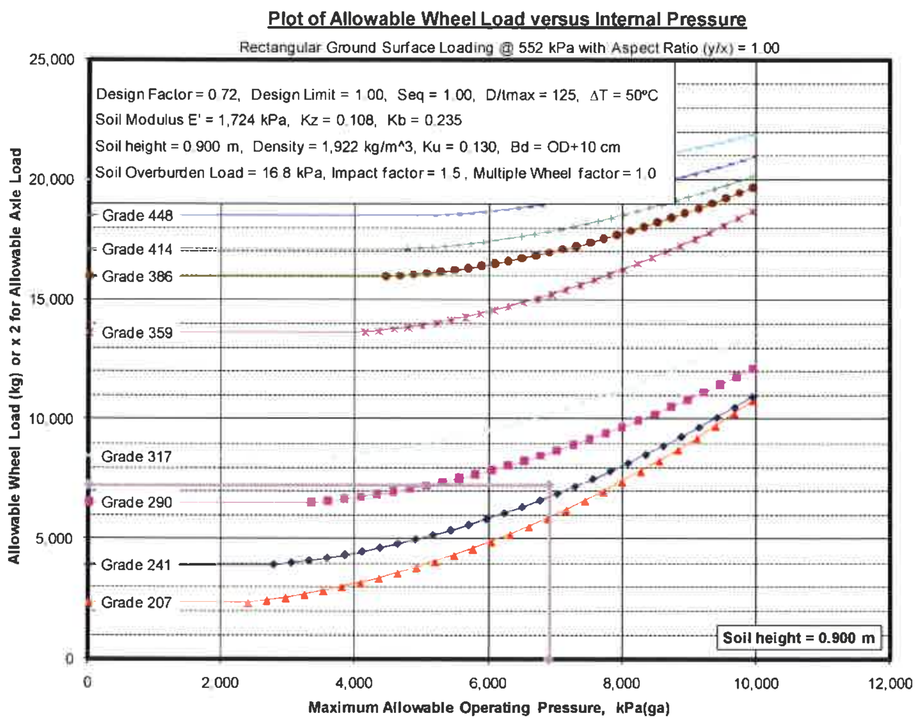

Figure 3-6. Plot of Allowable Wheel Load versus Internal Pressure

This same approach has been utilized for 1.2 meters (4 ft) of cover as shown in Figure 3-7.

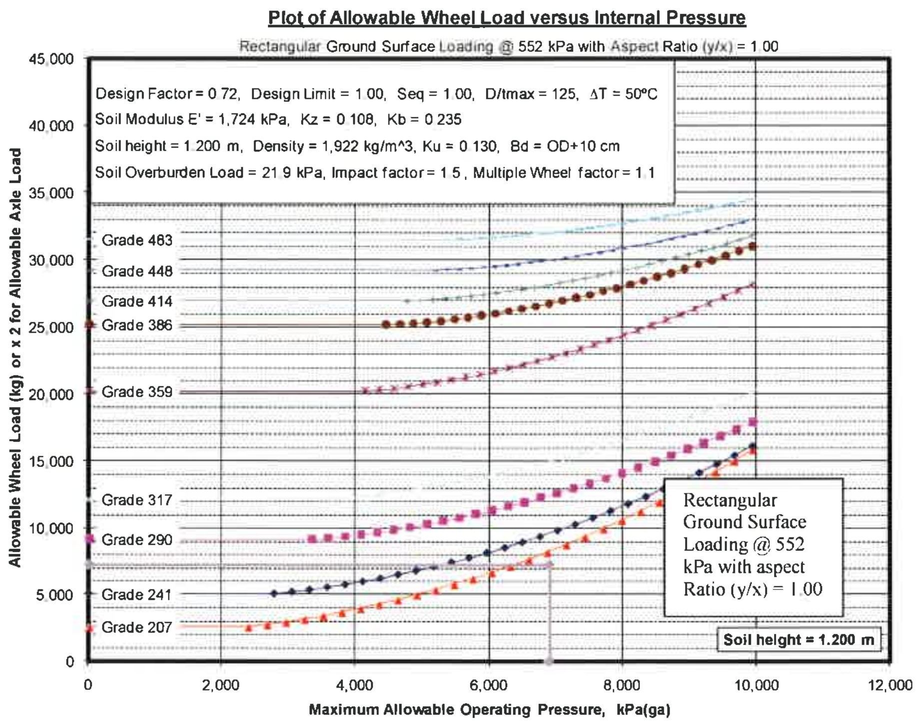

Figure 3-7. Plot of Allowable Wheel Load versus Internal Pressure

The graphs shown in Figures 3-6 and 3-7 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 contains a series of plots addressing a full range of conditions.

3.7 Sample Calculation

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

A Pipeline Company operates a pipeline in northern Canada. 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)

The initial screening requires the following minimum information:

Grade, MOP, DF $\leq$ 0.72, depth of cover, competent soil (i.e., non-saturated clay), and 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. This approach can be used as a quick screening tool for nontechnical persons but it is very conservative. The user should refer to the procedure outlined above to develop a less conservative approach.

From Figure 3-6 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 290 MPa (42,000 psi). Therefore, the crossing is acceptable. For grades below 290 MPa (42,000 psi), the initial screening tool identified that this loading condition has the potential to exceed the allowable limits. If the grade is lower than 290 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 3-7 indicates that 4 feet of cover will be adequate for pipeline grades equal to or greater than 241 MPa (35,000 psi);
- Provide supplemental protection (concrete slab, etc.).

4.0 Assessment of Mitigation Options for Buried Pipelines Subjected to Surface Traffic

4.1 Introduction

The first task of this project for CEPA was a "*Literature Search Summary*" which documented the available methods for evaluating the effects of fill and surface loads on buried pipelines as summarized in Section 2. Using Section 2 as a starting point, the second work task developed a simple screening method which allows a pipeline operator to determine if a given crossing application requires added protection or if a more detailed calculation is appropriate. The goal of the screening method is to use relatively simple and easily obtainable attributes (e.g., wheel or axle load, ground surface contact area and/or surface loading pressure, depth of cover, maximum allowable operating pressure and design factor). The screening calculations are summarized in the Section 3.

Building on these two previous work tasks, the third work task is to evaluate various temporary surface load-dispersal techniques and other mitigation approaches that are often used as a means to lessen the effects of surface loading. The effectiveness of various methods will be investigated with the goal of ranking the methods based on their capabilities for reducing adverse effects on the pipeline and ease of installation. This task will also define minimum requirements such as slab or mat stiffness, thickness, and length necessary in order to provide the desired protection and identify situations where a given technique may be ineffective.

4.2 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 4-1 provides a listing of different mitigation measures that we have seen utilized along with their relative advantages and disadvantages. The following sections provide a more detailed discussion of these mitigation methods.

4.3 Reduction of Pipe Internal Pressure during Vehicle Passage

Mitigation scenarios which reduce the pipe internal pressure to reduce hoop stress due to pressure are worthy of consideration even though reducing the internal pressure tends to increase the circumferential stresses due to fill and traffic loads. Fill and surface traffic stress analyses of the total circumferential stress (i.e., hoop stress plus fill and traffic stress) over a range of pipe internal pressures will show an optimum pressure that results in the minimum total circumferential stress. At the "trough point" of a plot of the total circumferential stress versus internal pressure, the increases in fill and traffic load induced stresses due to reduced internal pressure are offset by the reduction in hoop stress. In addition to the total circumferential stress, this approach should also be evaluated by comparing the traffic component of the circumferential stress to a fatigue endurance limit. Reducing the pipe internal pressure is attractive as a short-term solution (e.g., for mitigating a limited number passages of a crane over a buried line near a construction site). However, because a reduction of line pressure can have a direct impact on pipeline throughput, it is not attractive as a long-term or permanent solution.

4.4 Surface Protection via Limiting Surface Vehicle Footprint Pressure

Several of the mitigation methods listed in Table 4-1 (i.e., steel plates, timber mats, concrete slab) can be classified as "Surface Protection" methods. These methods deploy a flat surface structure (e.g., plate, mat or slab) on the ground surface as a means of dispersing the surface vehicle load over a wider area. The idea behind these methods is that they distribute the surface loads over a larger "footprint" area than that provided by the surface vehicle alone. The effective footprint area of the vehicle load would be distributed uniformly over the entire footprint of the surface structure for a rigid flat surface structure centered under a vehicle load. In cases where the vehicle load is applied eccentrically on the flat surface structure, for very large surface vehicle loads and/or relatively flexible flat surface structures, the actual distribution of pressure on the ground surface may be far from uniform. In fact, portions of the flat surface structure can actually lift off of the ground surface. The behavior of flat surface structure mitigation methods can be investigated using beam on elastic foundation analysis methods. The analysis considers the distribution of the vehicle load on top of the flat surface structure, the bending flexibility of the flat surface structure, and the stiffness of the soil below the flat surface structure. Given this information, it is possible to estimate an effective footprint for the loading situation, which may be significantly less than the full footprint of the pad, mat, or plate.

Under ideal circumstances, a heavy vehicle crossing a buried pipeline would be arranged such that the heavy vehicle's path of travel crosses the pipeline at a 90° angle. For a beam on elastic foundation analysis, the essential structural characteristic of the flat surface structure (i.e., the "beam") are the modulus of elasticity and the moment of inertia (E and I). The moment of inertia is usually based on a unit width of the flat surface structure in the direction perpendicular to the pipeline. The foundation component of the model can be developed based on the soil spring computation procedures used for strip foundation analysis and design. For previous applications, we have modeled the "bearing" spring stiffness values using the procedures described in [ALA]. The required input properties include the soil density, soil friction angle, and soil cohesion. The resulting "spring" properties include the ultimate resistance of the "strip" foundation (in force per unit length, e.g., klf), the "yield" displacement (usually taken as some fraction of the strip foundation width, e.g., inches), and the corresponding elastic stiffness (in force per unit length per unit displacement, e.g., klf per inch). The loading on the model includes a uniform self-weight of the surface structure plus the vehicle load (e.g., a point load or short uniform load) that acts on top of the unit width of the surface structure.

The results of this type of analysis include the deflection profile of the flat surface structure and the distribution of bearing force along the length of the flat surface structure and along the pipeline. In general, the results show a distribution of bearing force and downward deflection of the surface structure that is largest directly under the center of the vehicle load and diminishes with distance away from the center of the vehicle load. Depending on the relative stiffnesses of the flat surface structure and the soil foundation, it is possible for portions (e.g., the ends) of the flat surface structure to deflect upward, creating a gap between the bottom of the flat surface structure and the top of the soil surface which reduces the length that is in contact with the ground surface. Based on this information, the engineer can perform additional surface traffic stress calculations using a range of rectangular load footprint assumptions to approximate the bearing pressure distribution. The bounding assumptions are to apply the entire vehicle load over the portion of the surface structure that remains in contact with the ground surface (e.g., use an effective along-the pipe length) or apply a load that generates an equivalent maximum bearing pressure over a shorter along-the pipe length (e.g., use an effective bearing pressure).

We have adopted the following formula to determine the revised footprint of the dispersed load. This formula is referred to as the radius of stiffness and is commonly utilized to determine the pressure intensity on rigid pavements.

$$L = \sqrt[4]{\frac{E \cdot h^3}{12 \cdot (1 - v^2) \cdot Es'}} \tag{4.1}$$

where:
- L = radius of stiffness of slab/plate
- E = modulus of elasticity of slab/plate
- h = thickness of slab/plate
- v = Poisson's ratio of slab/plate
- E_s' = Elastic modulus of soil in contact with the slab

A review of the formula shows that the thickness of the slab plays the most significant role in spreading the surface load. Figures 4-1 through 4-4 show the effects of placing slabs on the ground surface as a means to spread the surface load over a larger area for steel and concrete slabs. Based on a review of these figures, a 7.6 cm (3-inch) thick steel slab provides the same surface load spread as does a 15.2 cm (6-inch) thick concrete slab. Since steel is significantly more costly to use than concrete this comparison suggests that concrete may be more cost effective to utilize. We have also performed a similar review of timber mats. The results indicate that a 20 cm (8-inch) thick timber mat results in a similar load spread to the 15.2 (6-inch) concrete slab. Based on this information, a timber mat may be more cost effective to use than either steel or concrete. Figures 4.5 and 4.6 show the effects of placing timber mats on the on the ground surface as a means of spreading the surface load over a larger area. It is important to note that the individual timbers within the mat must be tied in a manner that provides for a uniformly transfer of load between timbers making up the mat.

Equation 4.1 can be used to determine the minimum size of the surface protection mat. At a minimum the protection must extend a distance of L/2 beyond the wheel/track in all directions. To ensure the proper load transfer we recommend 1.5 times this value.

Table 4-1. 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	Reduces the beneficial effect of internal pressure on the pipe circumferential bending stresses due to fill and traffic 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
Consider the beneficial effect of lateral soil restraint on circumferential stress	Has effect similar to pressure stiffening	Requires estimates of soil stiffness parameter, E'
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. Bridge structure may limit access to pipeline for inspections and repairs.
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.

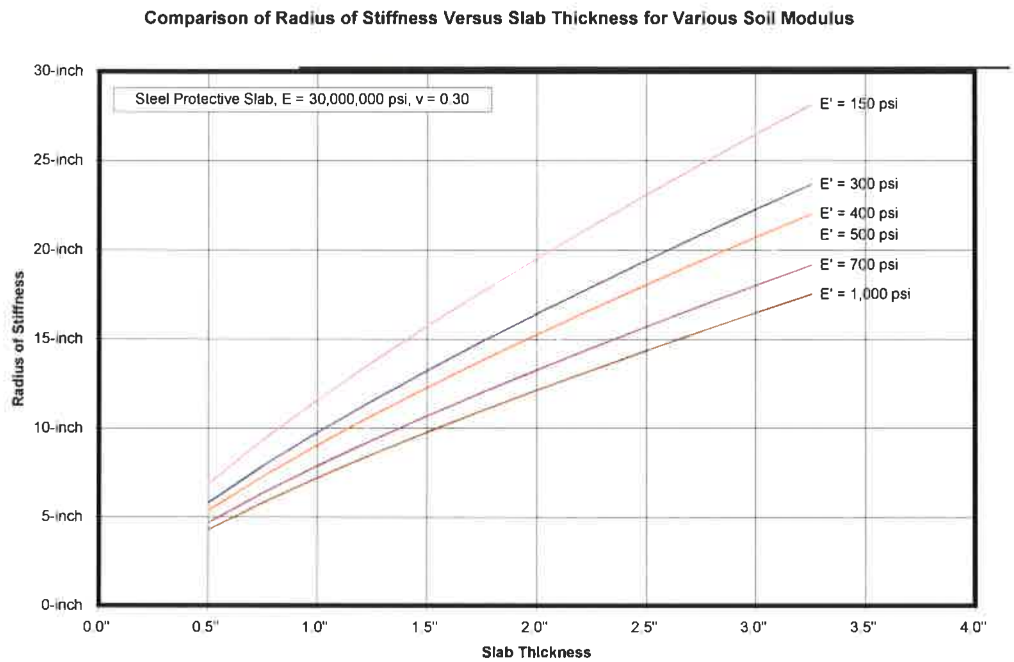

Figure 4-1. Comparison of Radius of Stiffness versus Steel Slab thickness for Various Soil Modulus

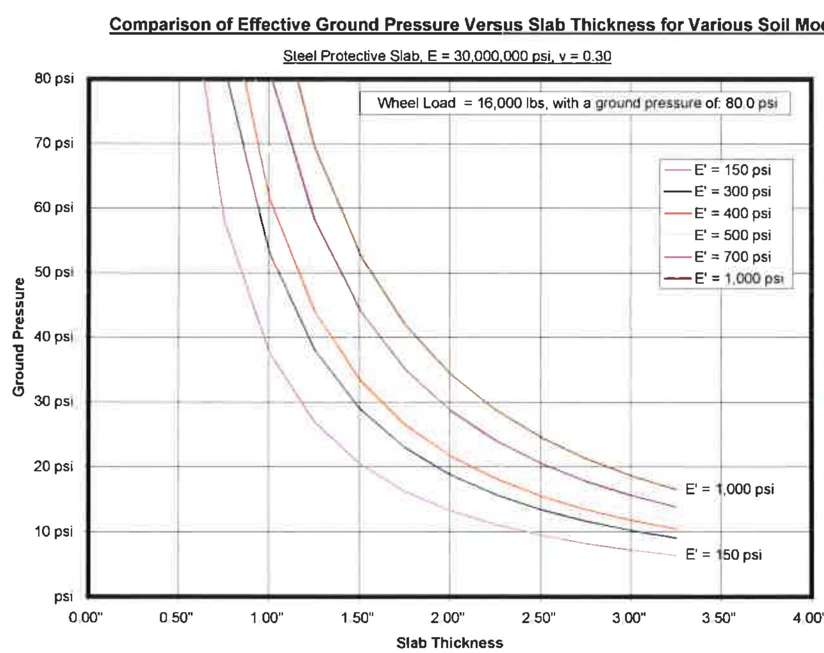

Figure 4-2. Comparison of Effective Ground Pressure versus Steel Slab thickness for Various Soil Modulus

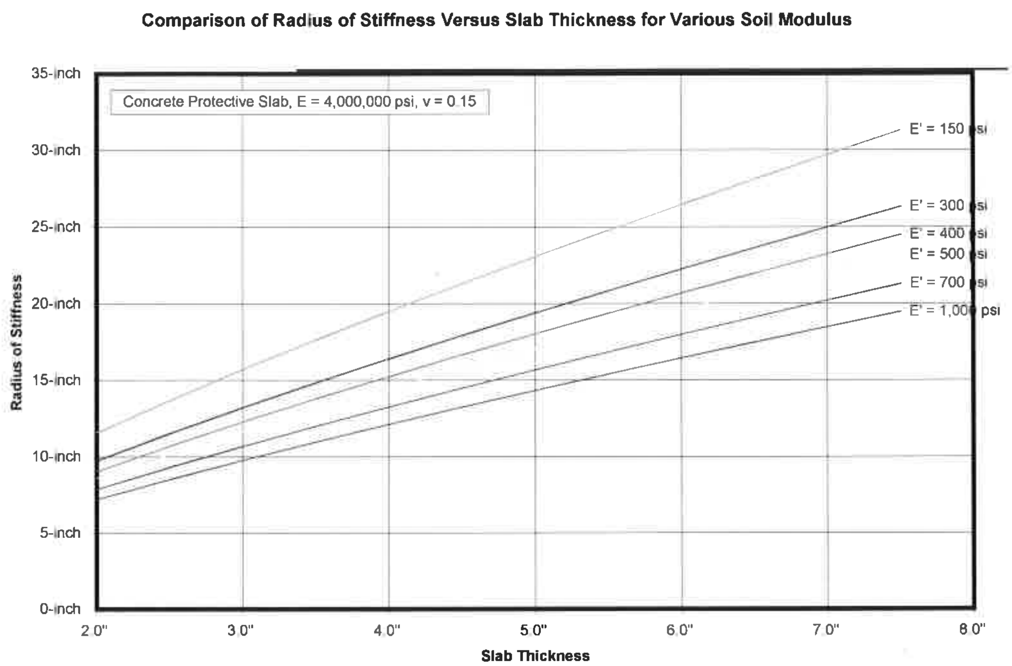

Figure 4-3. Comparison of Radius of Stiffness versus Concrete Slab Thickness for Various Soil Modulus

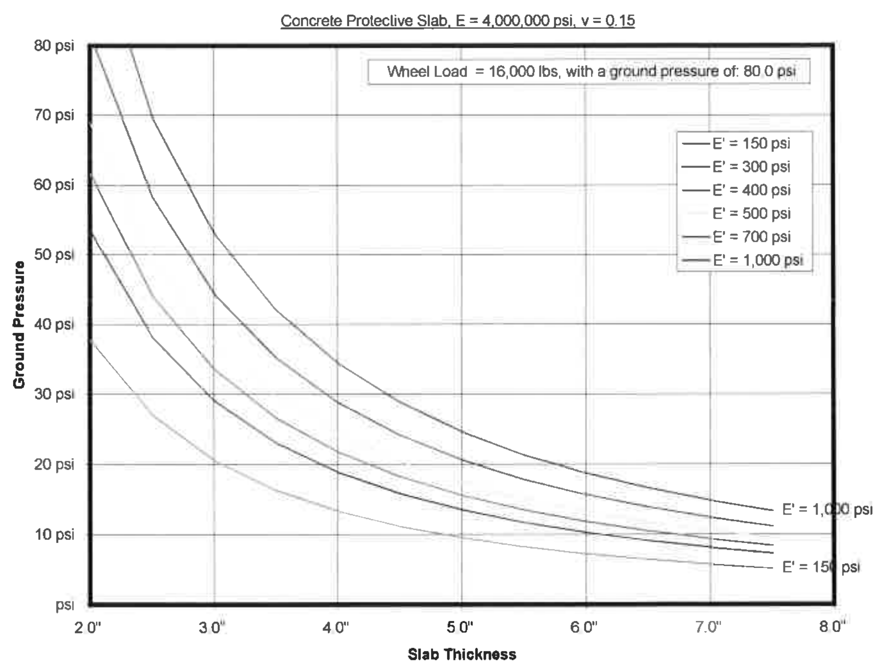

Figure 4-4. Comparison of Effective Ground Pressure versus Concrete Slab thickness for Various Soil Modulus

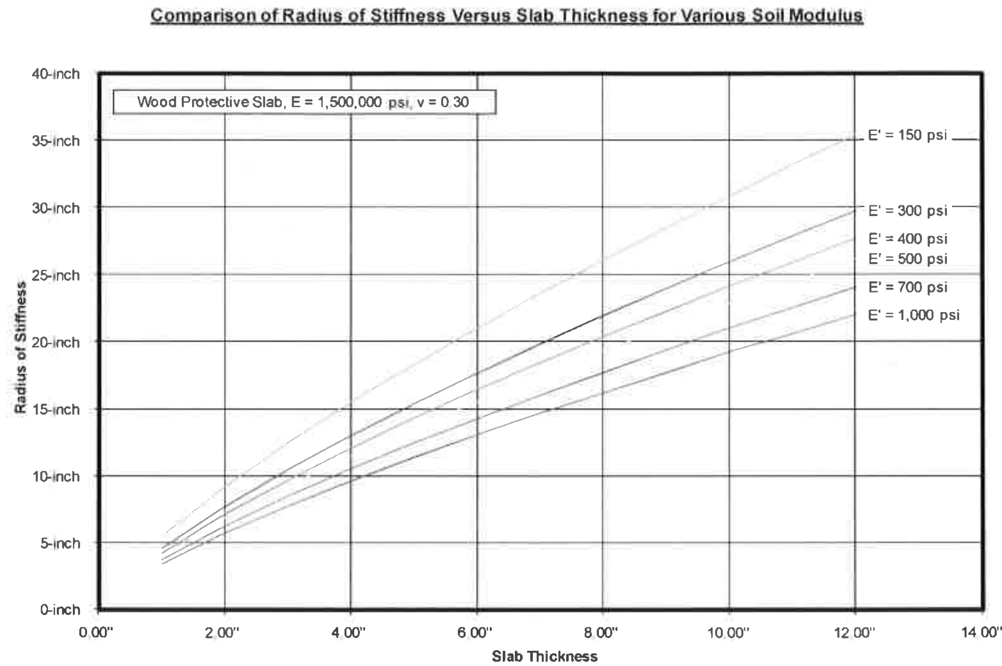

Figure 4-5. Comparison of Radius of Stiffness versus Wood Slab Thickness for Various Soil Modulus

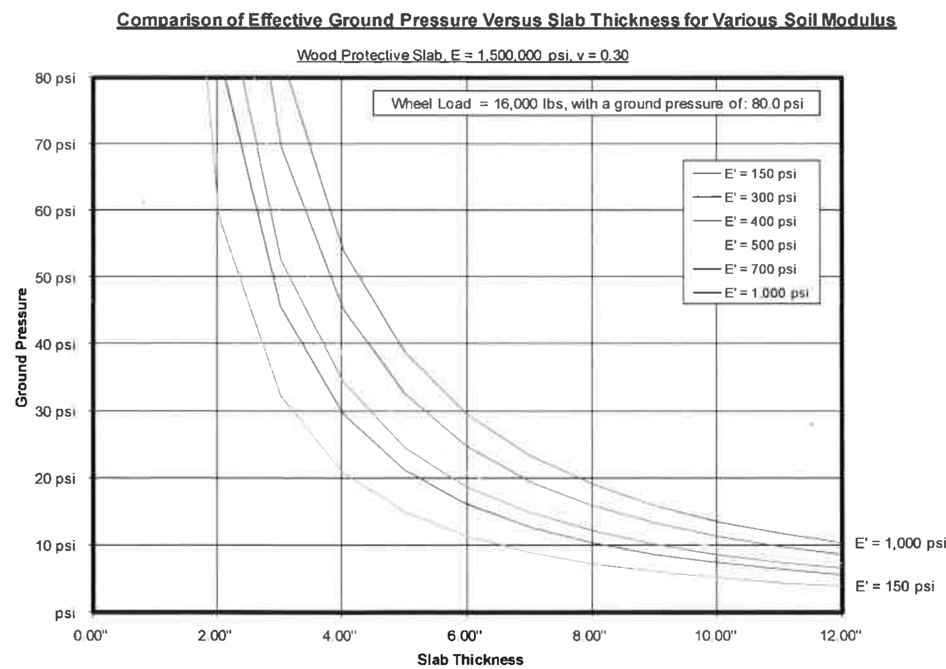

Figure 4-6. Comparison of Effective Ground Pressure versus Wood Slab thickness for Various Soil Modulus

4.5 Consideration of Ovalling Restraint Provided By Soil

Sections 2 and 3 give equations that show the effect of ovalling restraint resulting from the soil around the pipe as a function of the modulus of soil restraint, E'. When E' is set equal to zero, the equations decompose to those which neglect soil restraint while non-zero values of E' allow the beneficial effect of soil restraint to be considered. Cases that barely exceed the allowable stress check(s) when soil restraint is neglected or set as a lower bound may be able to pass the allowable stress check(s) when modest levels of soil stiffness are considered. Therefore, the ability to include or exclude the effects of soil restraint in the screening calculations provides the engineer with the ability to easily perform "what if" analyses of a given configuration as a basis for assessing a given crossing scheme.

4.6 Provide Additional Fill over Pipeline at Crossing

A relatively popular procedure that has been utilized for mitigating pipe stresses due to surface vehicle loading is to provide additional soil fill over the pipeline at the crossing. This mitigation method increases the total depth of cover 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. One can compare the effect of fill and traffic load on the total circumferential stress against appropriate total stress limits and compare the traffic stress range against appropriate fatigue stress limits.

4.7 Combination of Mitigation Methods

Additional mitigation can be provided by using combinations of the various measures described above to reduce the overall stress level on the pipeline.

4.8 References

[ALA] ASCE American Lifelines Alliance *"Guidelines for the Design of Buried Steel Pipe"*, Published by the ASCE American Lifelines Alliance, www.americanlifelinesalliance.org, July 2001.

APPENDIX A:

A-1 Design Loading Criteria

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

1. **Design Pressure to be Calculated using:**

   CSA Z662-03 Section 4.3.3.1 specifies:

   $P = (2(SMYS)t/D) \times F \times J \times L \times T$

   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.

2. **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 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, units

   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, units
   T_2 = maximum operating temperature, °C
   T_1 = ambient temperature at time of restraint, °C
   S = SMYS

T = Temperature Factor

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. F	33. 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. 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. F	66. 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. F	77. C	138.6 F
Pipe Attributes:					
Youngs Modulus (E) =			206.8 GPa	30,000 ksi	
Thermal Expansion Coef. (α) =			12.0×10^6 m/m/C	6.67×10^6 in/in/F	
Poisson's Ratio (υ) =			0.3		

Note: The provisions of Clause 4.6.2.1 places restrictions on the combination of hoop stress based on Barlow's equation and longitudinal stress based on the Poisson effect of Barlow's equation and temperature differential. You will note that additional loads such as external circumferential stresses have not specifically been included in this restriction. As a result, the provisions of Clause 4.6.2.1 are independent of the additional circumferential stresses as a result of overburden loads and traffic loads.

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 follow sections address the additional design criteria.

4. 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. Further guidance for the allowable limit for the combined effective stress can be found in the ASME Boiler and Pressure Vessel Code Sections VIII Division 2 (BPVC). The BPVC differentiates between membrane and bending stresses. In the case of a pipeline, the membrane stress is the stress resulting from the internal pressure in the pipe. This stress is limited in CSA Z662-03 to the design factor of 0.8 SMYS. The additional stress that results from overburden and surface loading are bending stresses. An object can obtain yield at the outer surface in bending and still have a large amount of residual load carrying capacity as a result of the bending stress distribution. For example, the moment on a beam in bending at the outer fiber yield is 2/3 of the collapse moment. There is also additional load carrying capacity resulting from the strain hardening of the steel. For this reason, the BPVC allows the combination of membrane and bending stresses to go as high as the yield strength of the material.

Based on the above argument the screening tool has adopted the following as the limit for the combined effective stress:

$S_{eq} \leq 1.00 \text{ S x T}$

where

Seq = the combined effective stress.

5. 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. If the longitudinal stress is greater than zero the circumferential stress can exceed the yield stress of the material and the combined effective stress still remain below the yield stress of the material. If the longitudinal stress is reduced there could be yielding beyond the surface of the pipe. In order to insure that there is no gross yielding in the pipe wall, the sum of the circumferential stress should also be limited to the SMYS of the pipe.

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

$S_h + S_{cb} \leq 1.00 \text{ S x T}$

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.

6. 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 data 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, it may be more appropriate with regard 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.

B-1 Impact Factor

We recommend using a reduced impact factor of 1.25 for slow moving equipment with low pressure tires. This value meets the AASHTO specification for cover depths greater than 0.3 m. An impact factor of 1.5 has been used 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 recommends 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 uses the same factors.

The variables 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:

- The equipment are specifically design to have low ground surface pressure to reduce compacting of the soil strata;
- Equipment of this design normally utilize low pressure pneumatic tires with contact pressure << 200 kPa(ga) (30 psig);
- This type of equipment typically operates at lower velocities < 15 kph (10 mph).

Figures B-1 through B-6 show the effects of reducing the impact factor from 1.5 to 1.25 for equipment with low surface contact pressures. It is noted that the effects are constant based on the ratio of 1.5/1.25 or 1.2 for the results shown.

B-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.

Figures B-1 through B-6 show the effects of increasing the bedding support angles from 30 to 60 degrees as well as from 30 to 90 degrees. 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.

B-3 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.

Figures B-1 through B-6 shows the effects of increasing the modulus of soil reaction from 250 psi to 500 psi. A multiplier of approximately 1.1 was observed as a result of doubling the modulus of soil reaction from 250 to 500 psi. This multiplier decreases with increased pressure.

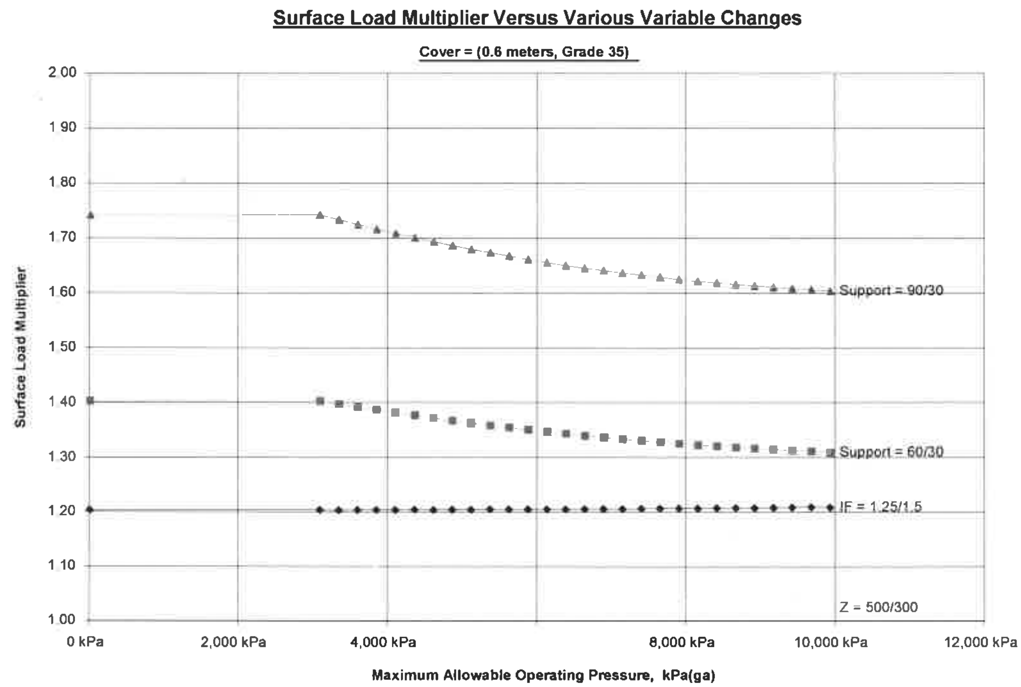

Figure B-1. Surface Load Multiplier versus Various Variable Changes

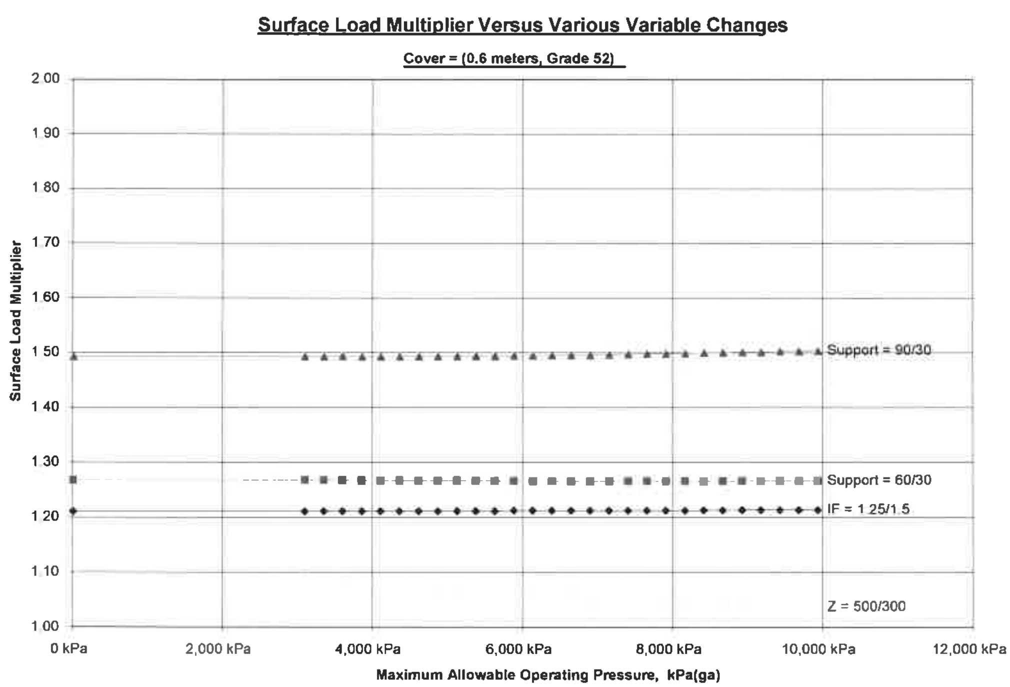

Figure B-2. Surface Load Multiplier versus Various Variable Changes

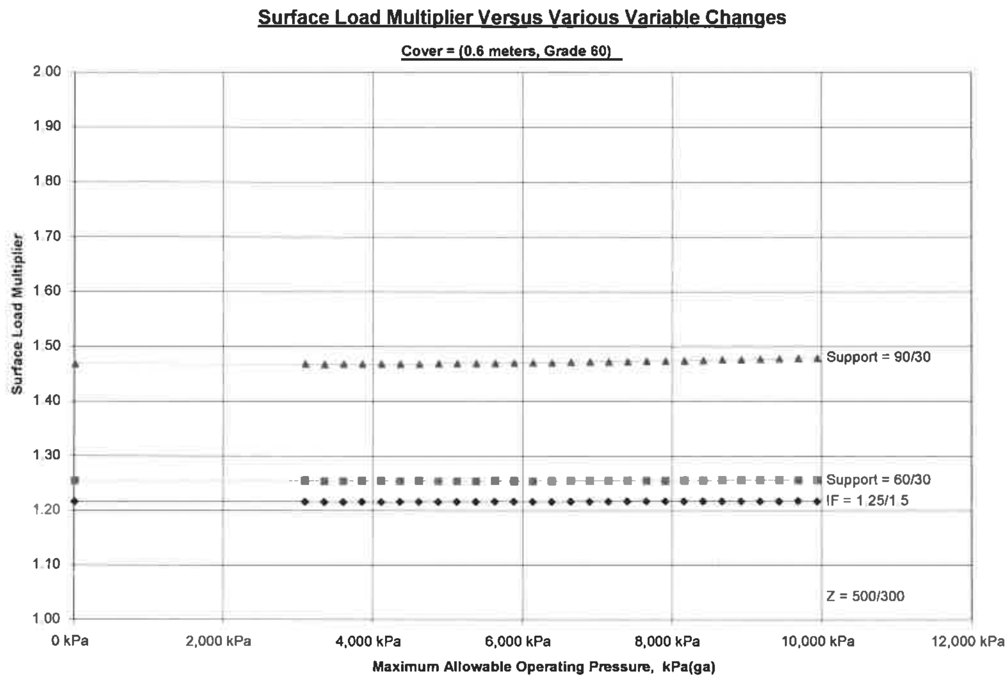

Figure B-3. Surface Load Multiplier versus Various Variable Changes

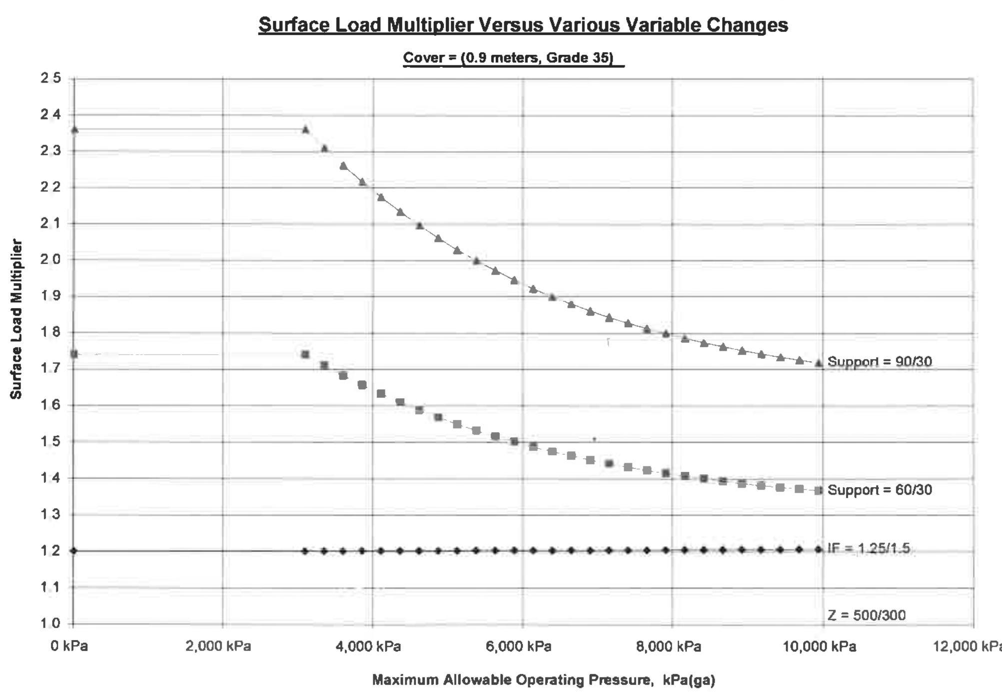

Figure B-4. Surface Load Multiplier versus Various Variable Changes

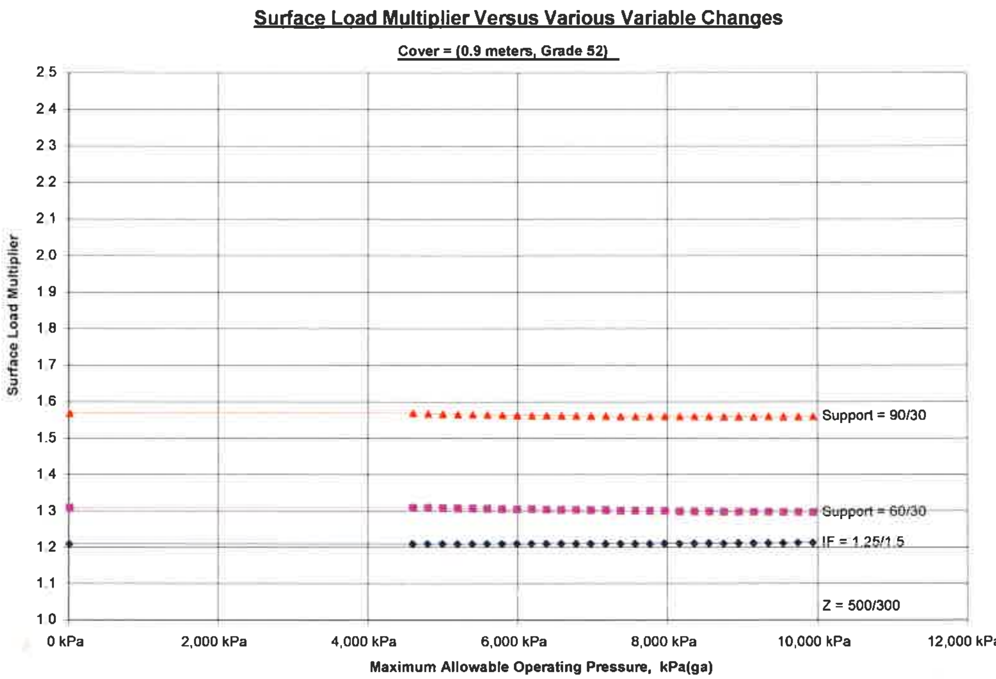

Figure B-5. Surface Load Multiplier versus Various Variable Changes

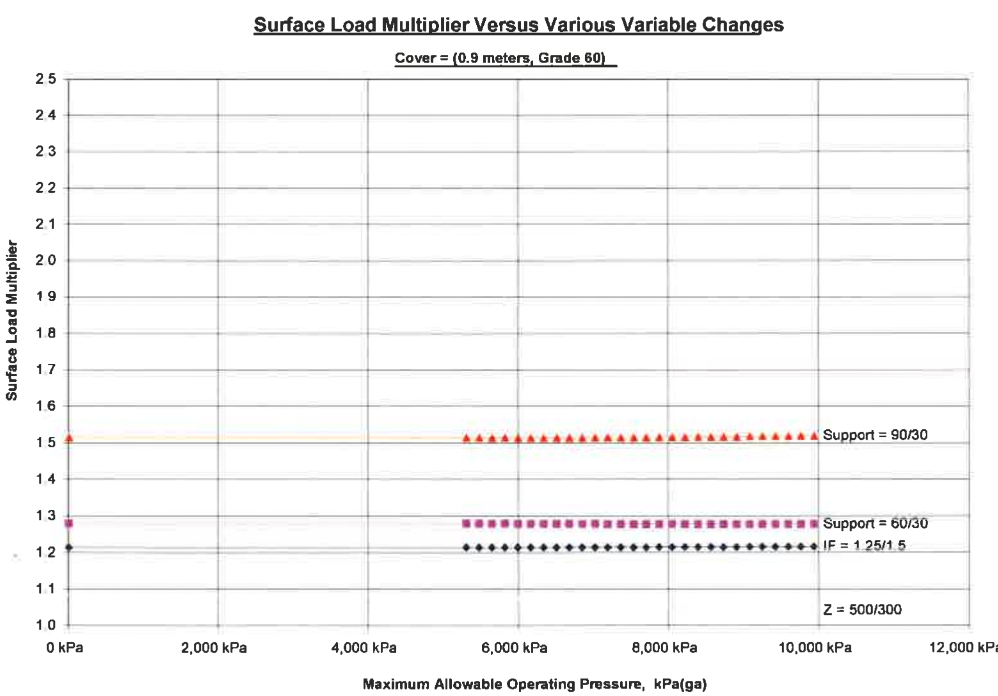

Figure B-6. Surface Load Multiplier versus Various Variable Changes

APPENDIX C:

Proposed Guideline – 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 temporary.
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 given below are used in Figure C-1(a) through C-1(h) and modified by Figures C-2, C-3, or C-4.

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 result of all loads expected to be imposed during its usage as a crossing location.

Figures C-1(a) thru C-1(h)

Figure C-1(a) through C-1(h) present the maximum live surface "point" load in kilograms for cover depths of 60 cm, 90 cm, 120 cm, and 150 cm and design operating pressures of 72% SMYS and 80% SMYS.

Notes applicable to Figures C-1 (a - h):

(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:
- Depth of cover, as indicated.
- Maximum hoop stress of 72% or 80% percent SMYS, as indicated.
- Maximum combined circumferential stress of 100 percent SMYS.
- 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.
- Fluctuating stress limitation of 82.7 MPa (12 ksi) based upon 2,000,000 cycles.

- Maximum D/t ratio of 125.
- Soil Modulus E' = 1,724 kPa (250 psi) at pipe.
- Soil Density = 1,922 kg/m^3 (120 lbs/ft^3).
- Loading criteria includes an impact factor of 1.5.
- Maximum combined effective stress of up to 100 percent SMYS.
- A temperature differential of $\Delta T = 50° C$ or the maximum temperature limitation as per CSA Clause 4.6.2.1 (section 2 above) whichever is the lower is included in the calculated the longitudinal stress.
- Multiple wheel influence factor (if applicable).

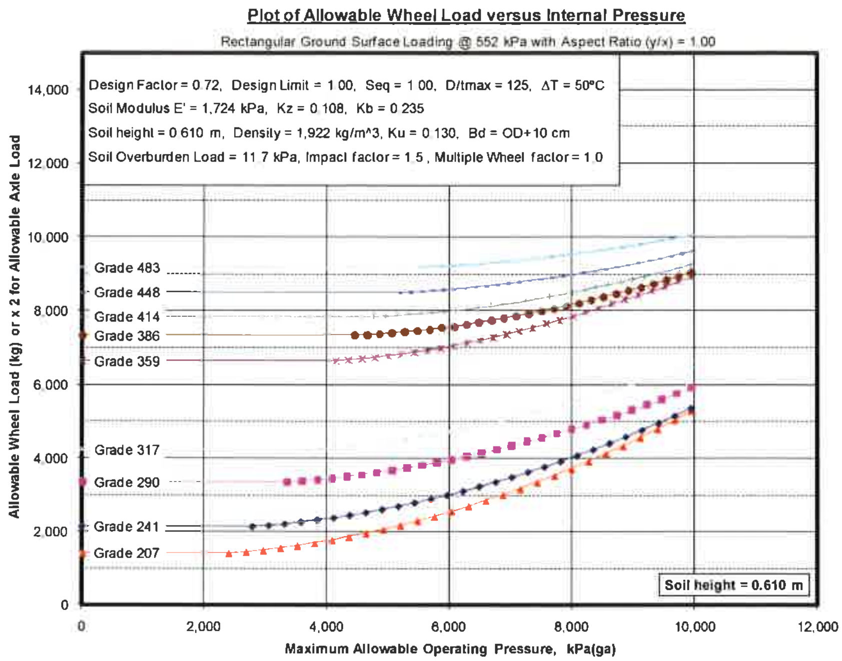

Figure C-1(a) – Soil Height = 0.61 meters, DF = 0.72

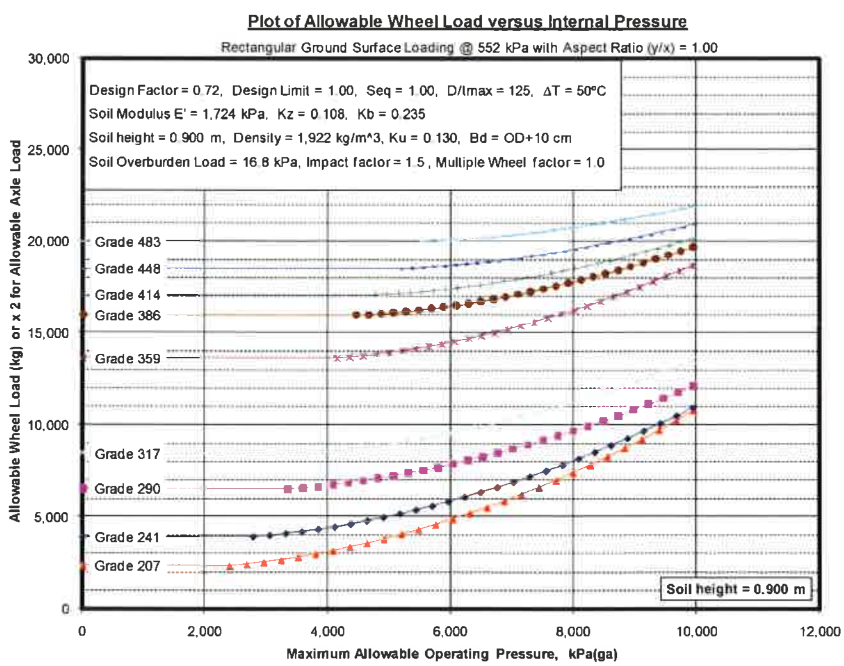

Figure C-1(b) – Soil Height = 0.90 meters, DF = 0.72

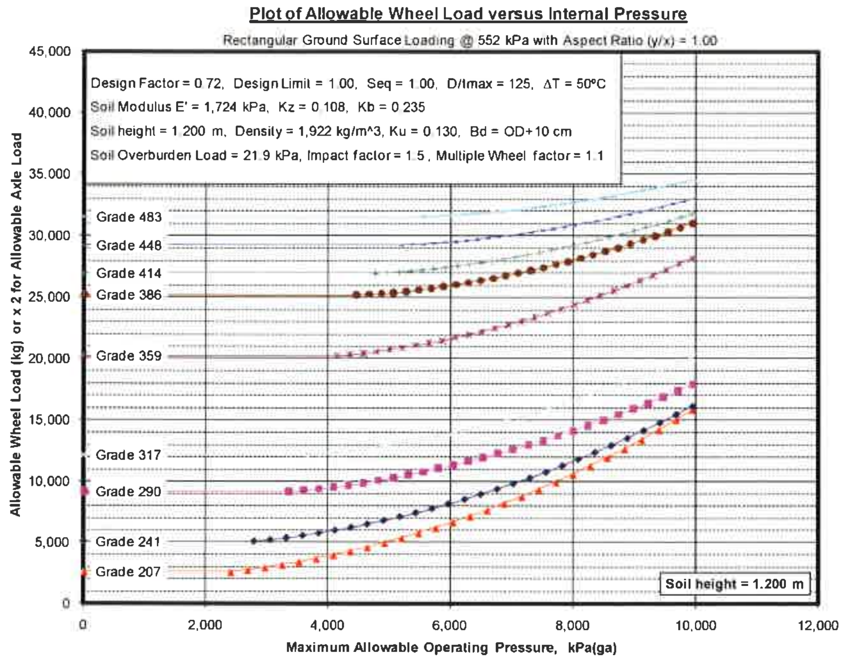

Figure C-1(c) – Soil Height = 1.2 meters, DF = 0.72

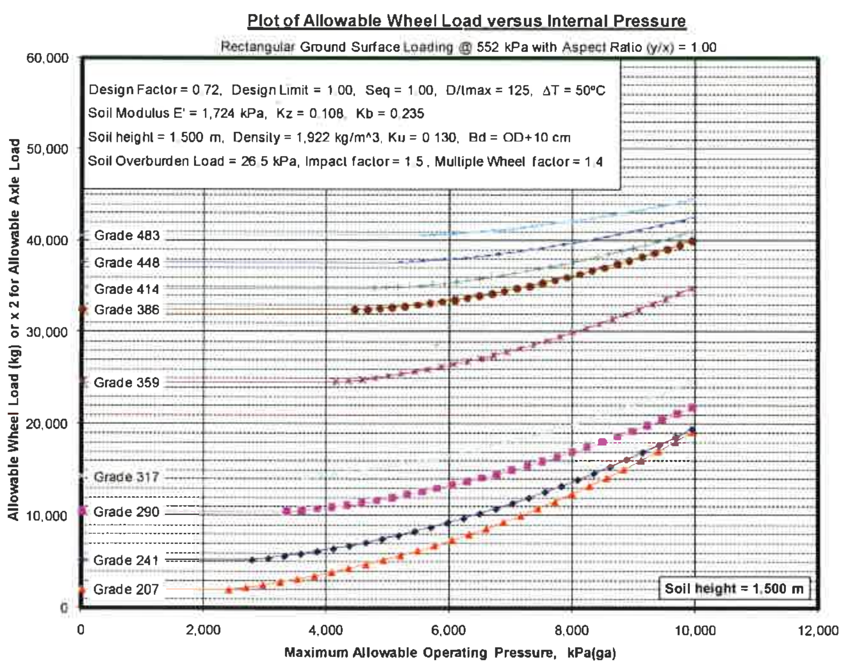

Figure C-1(d) – Soil Height = 1.5 meters, DF = 0.72

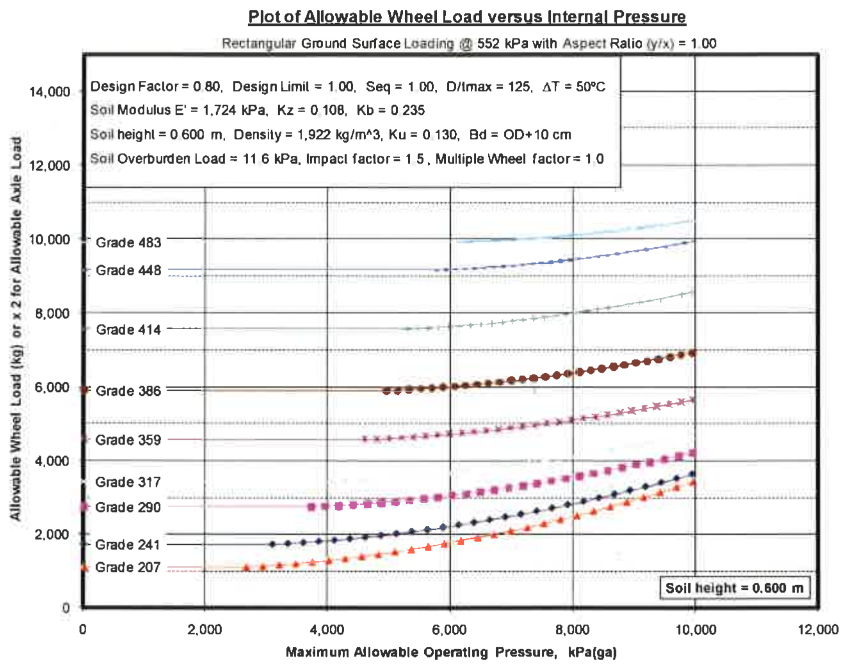

Figure C-1(e) – Soil Height = 0.6 meters, DF = 0.8

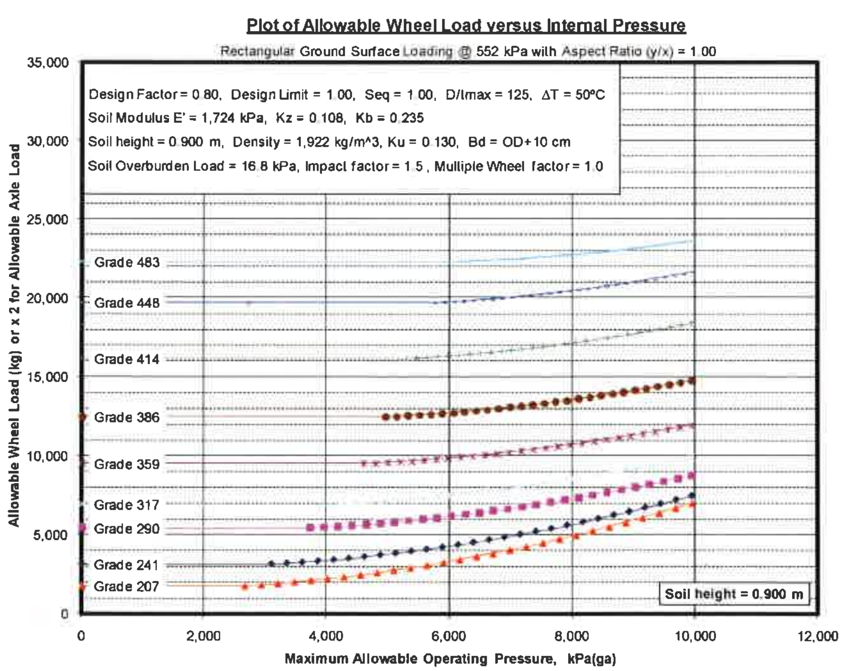

Figure C-1(f) – Soil Height = 0.9 meters, DF = 0.8

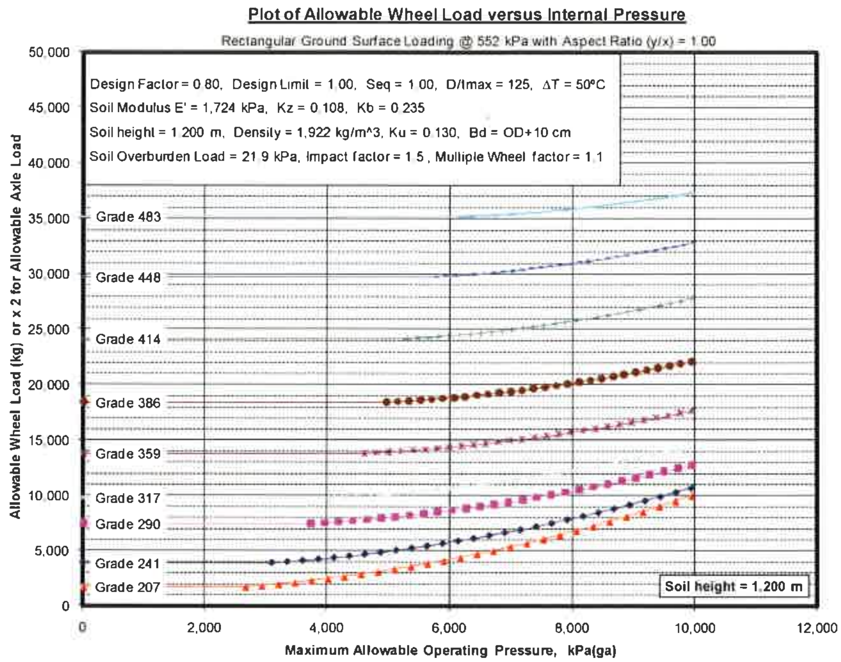

Figure C-1(g) – Soil Height = 1.2 meters, DF = 0.8

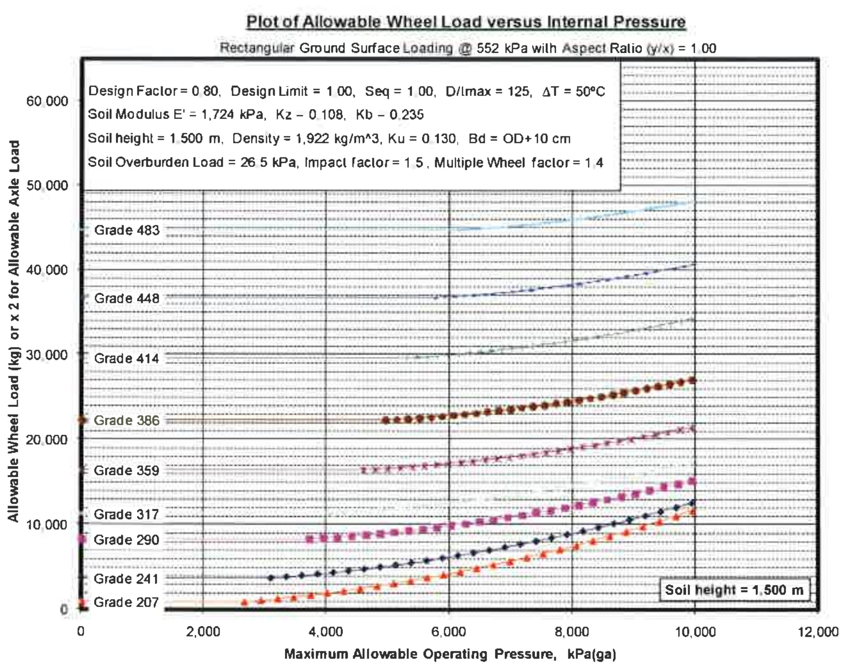

Figure C-1(h) – Soil Height = 1.5 meters, DF = 0.8

Surface Load Multiplier for Rectangular Footprint and Various Contact Pressure Figures C-2(a) through C-2(d)

Figures C-2(a) through C-2(d) 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). The figures apply for cover depths of 60 cm, 90 cm, 120 cm, and 150 cm (2ft, 3ft, 4ft, 5ft).

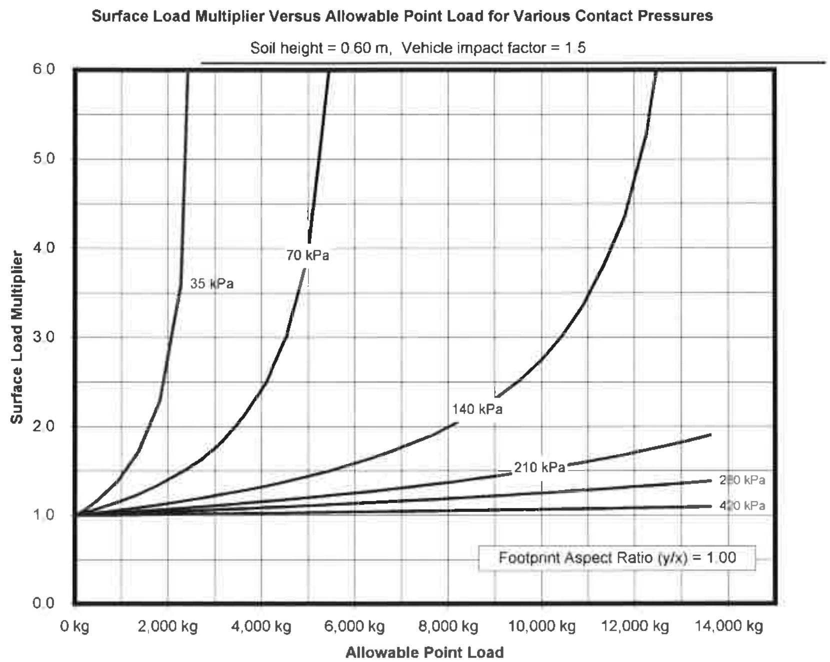

Figure C-2(a) – Soil Height = 0.6 meters

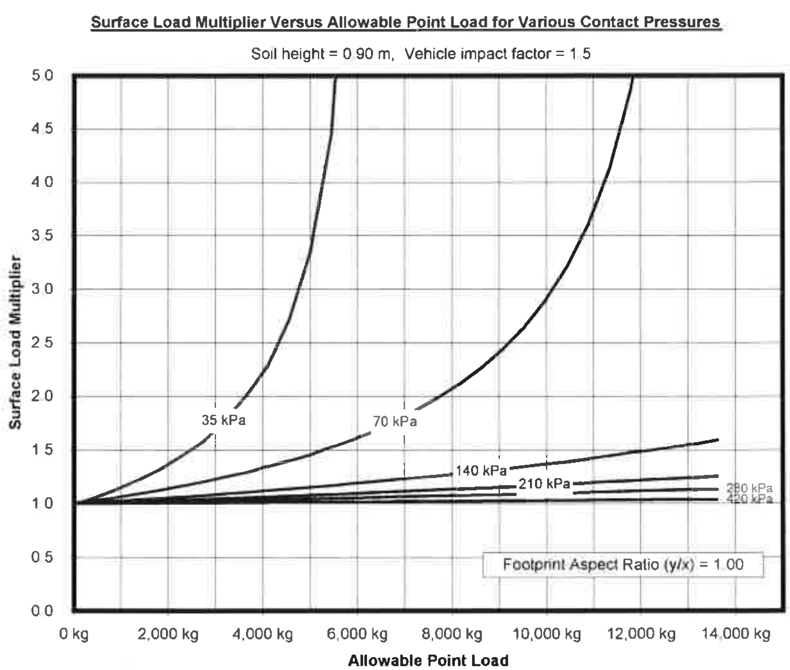

Figure C-2(b) – Soil Height = 0.9 meters

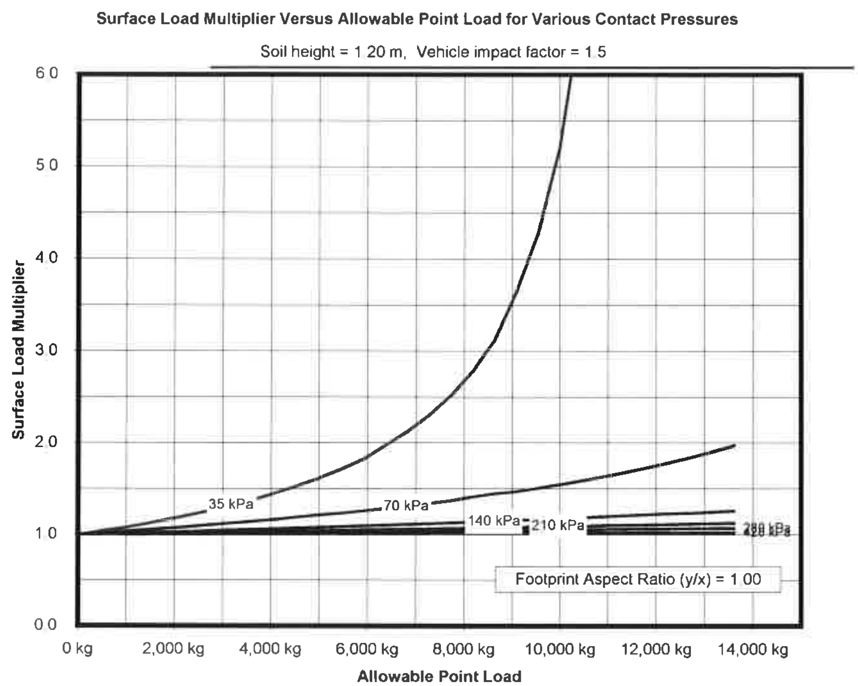

Figure C-2(c) – Soil Height = 1.2 meters

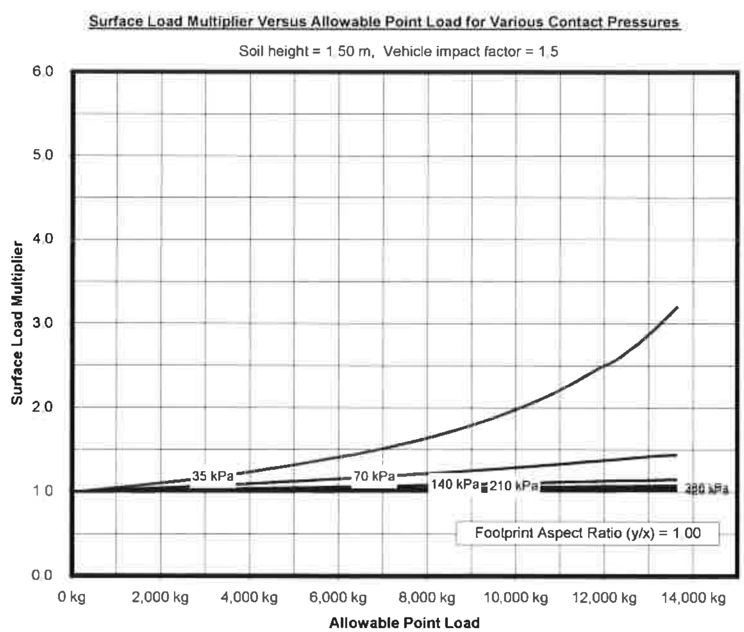

Figure C-2(d) – Soil Height = 1.5 meters

Surface Load Multiplier for Track Loads Figures C-3(a) through C-3(d)

Figures C-3(a) through C-3(d) present the Load Multiplier that can be applied to the previously determined allowable live surface "point" load for Track Loads. Track loads have been represented as surface loads applied over a rectangular footprint with an aspect ratio (Length/Width) of 4. The figures apply for cover depths of 60 cm, 90 cm, 120 cm, and 150 cm (2ft, 3ft, 4ft, 5ft).

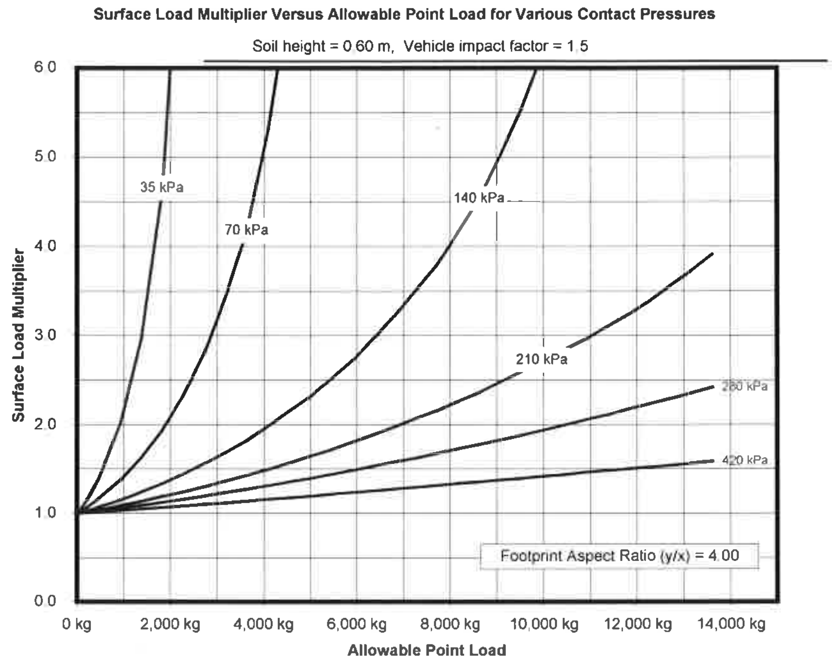

Figure C-3(a) – Soil Height = 0.6 meters

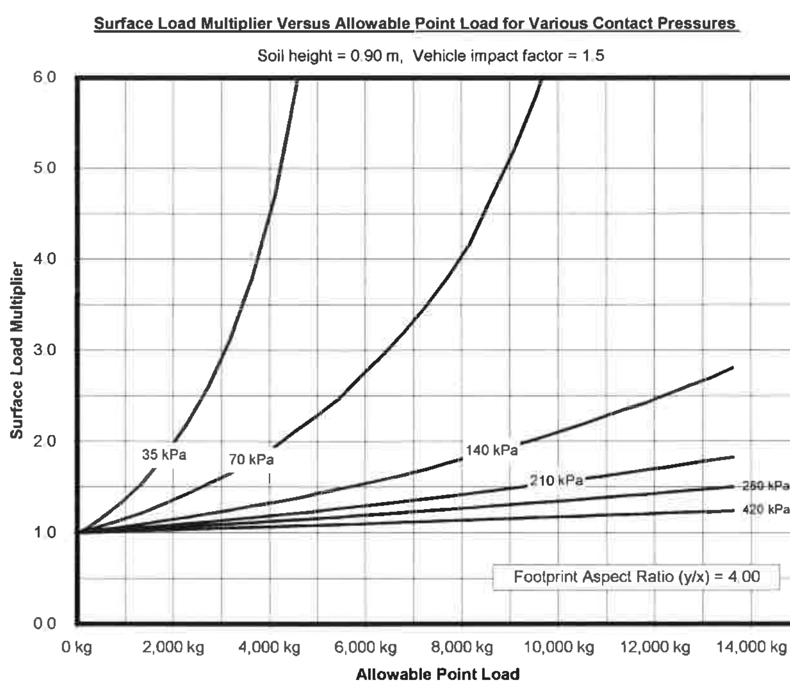

Figure C-3(b) – Soil Height = 0.9 meters

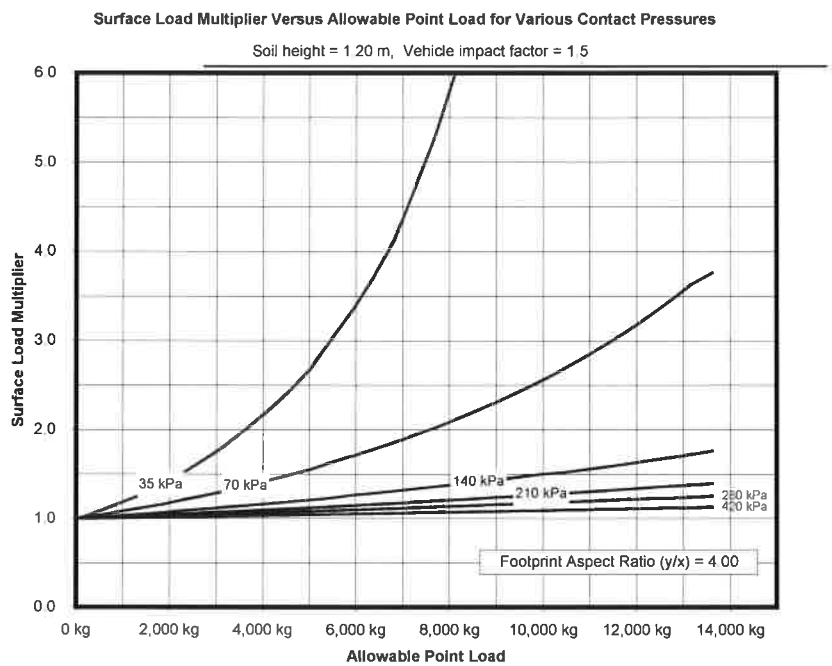

Figure C-3(c) – Soil Height = 1.2 meters

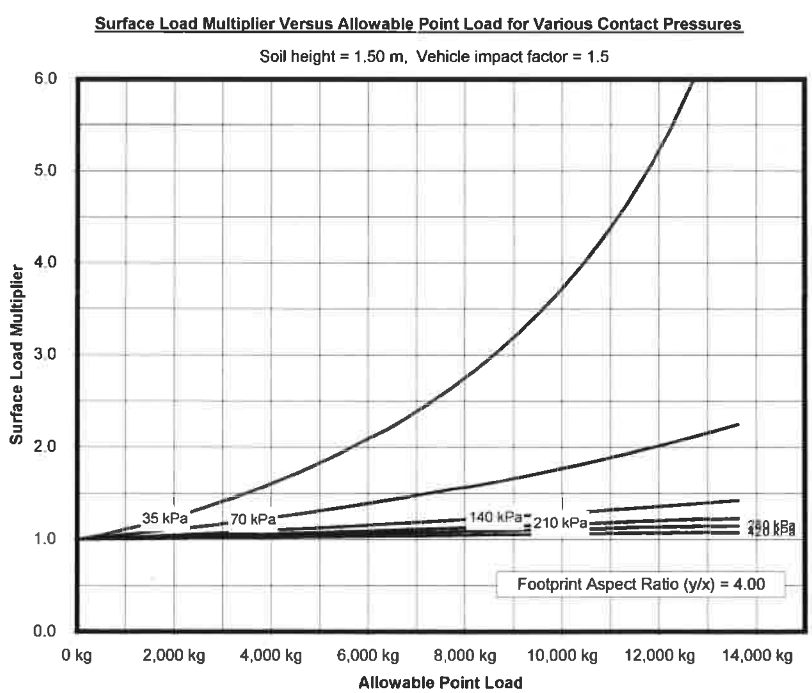

Figure C-3(d) – Soil Height = 1.5 meters

Surface Load Multiplier for Concrete Slab Figures C-4(a) through C-4(d)

Figures C-4(a) through C-4(d) present the effects of placing a concrete slab on the surface as a mitigative measure to increase the allowable surface "point" load. The figures apply for cover depths of 60 cm, 90 cm, 120 cm, and 150 cm (2ft, 3ft, 4ft, and 5ft).

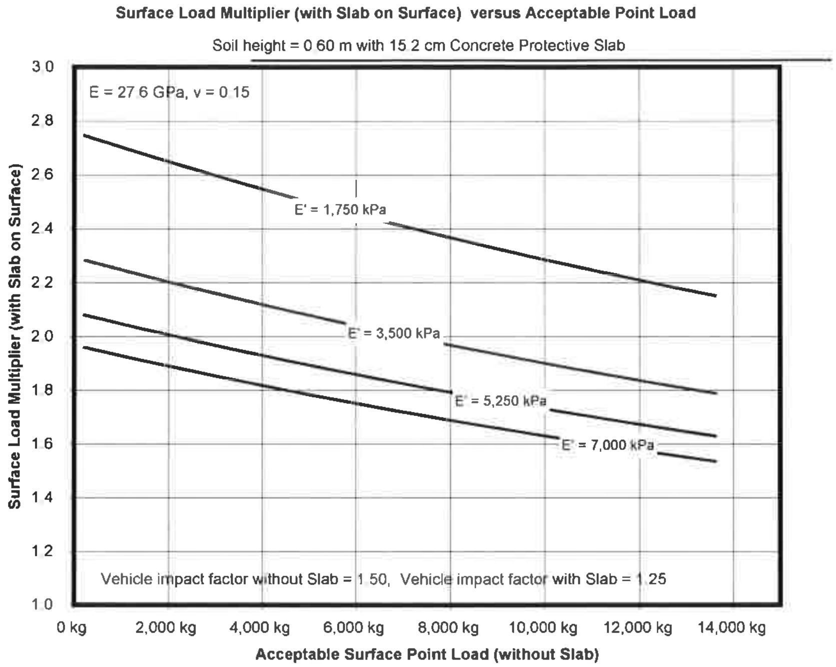

Figure C-4(a) – Soil Height = 0.6 meters

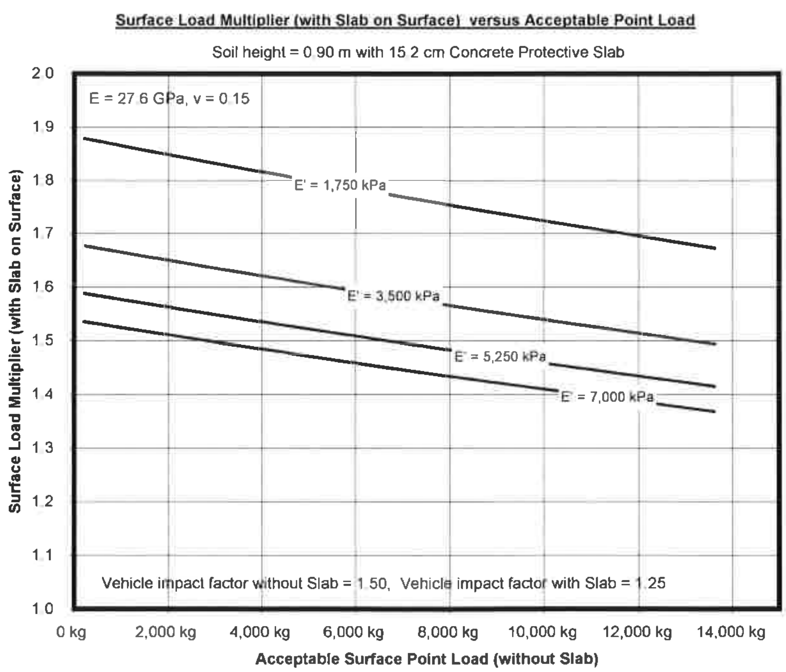

Figure C-4(b) – Soil Height = 0.9 meters

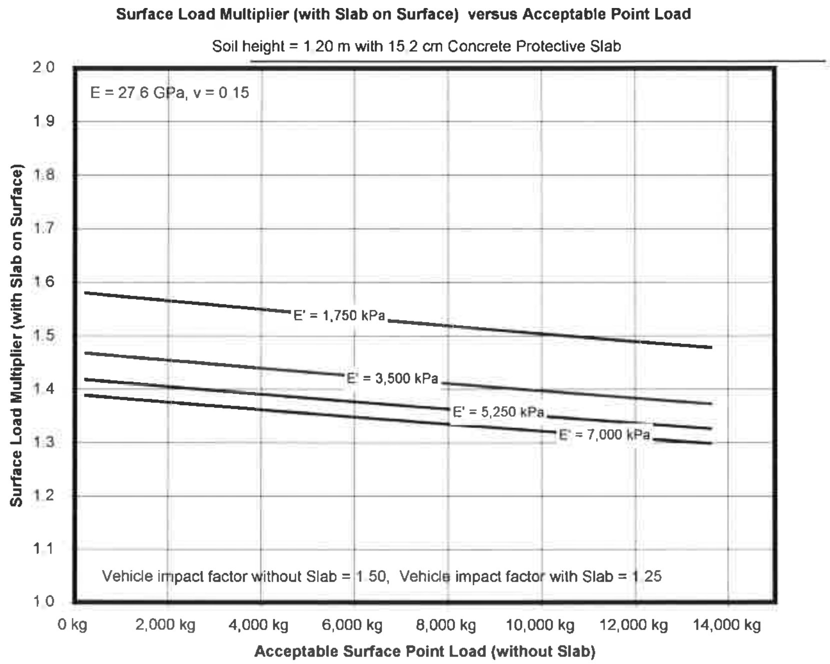

Figure C-4(c) – Soil Height = 1.2 meters

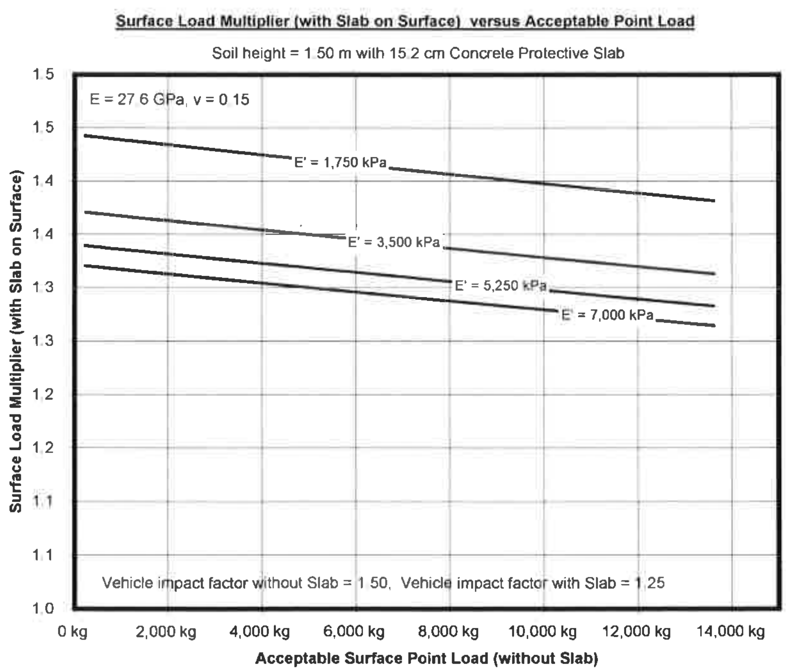

Figure C-4(d) – Soil Height = 1.5 meters

Surface Load Multiplier for Timber Mats Figures C-5(a) through C-5(d)

Figures C-5(a) through C-5(d) present the effects of placing a 20 cm (8-inch) thick timber mat on the surface as a mitigative measure to increase the allowable surface "point" load. The figures apply for cover depths of 60 cm, 90 cm, 120 cm, and 150 cm (2 ft, 3 ft, 4 ft, 5 ft).

Note:	It is important to note that the individual timbers within the mat must be tied in a manner that provides for a uniformly transfer of load between timbers making up the mat.

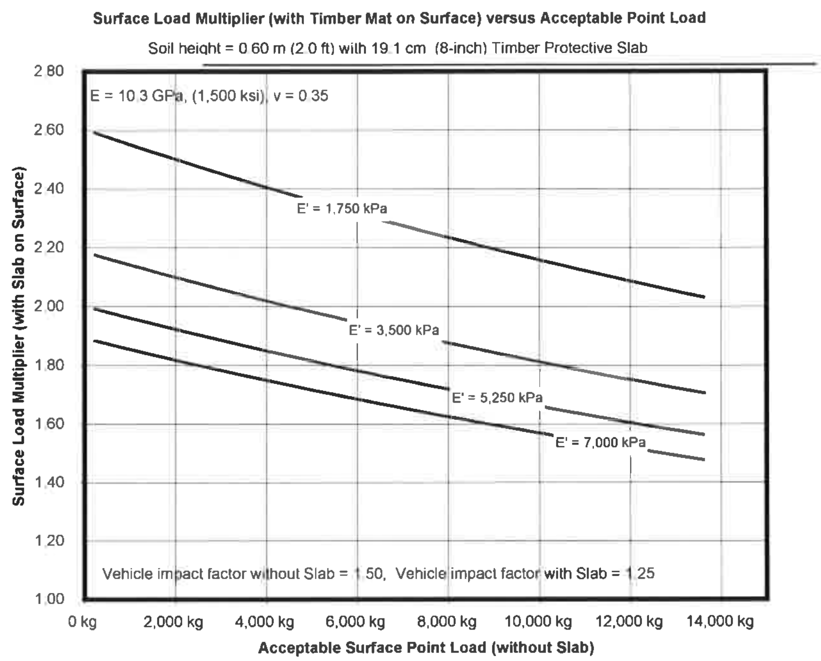

Figure C-5(a) – Soil Height = 0.6 meters

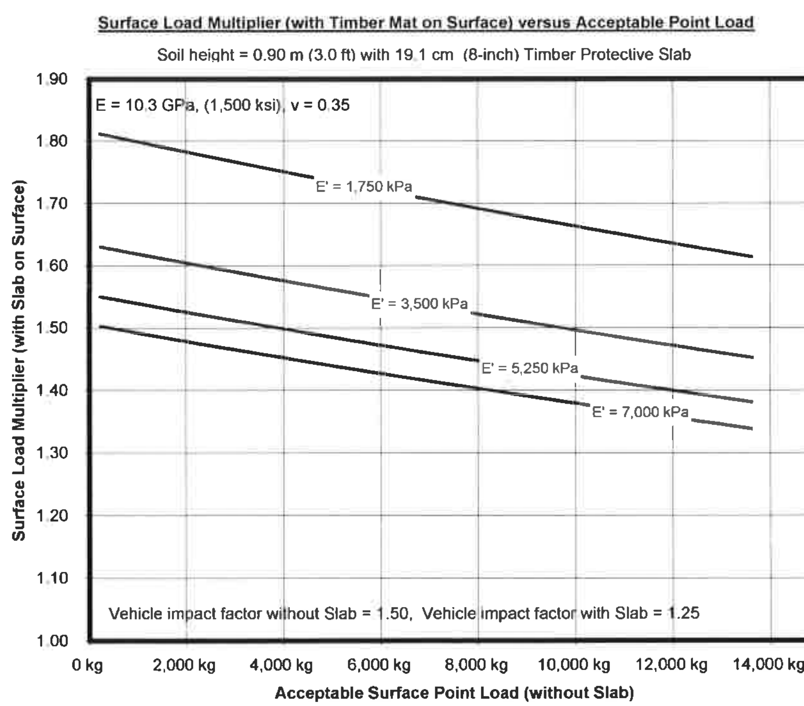

Figure C-5(b) – Soil Height = 0.9 meters

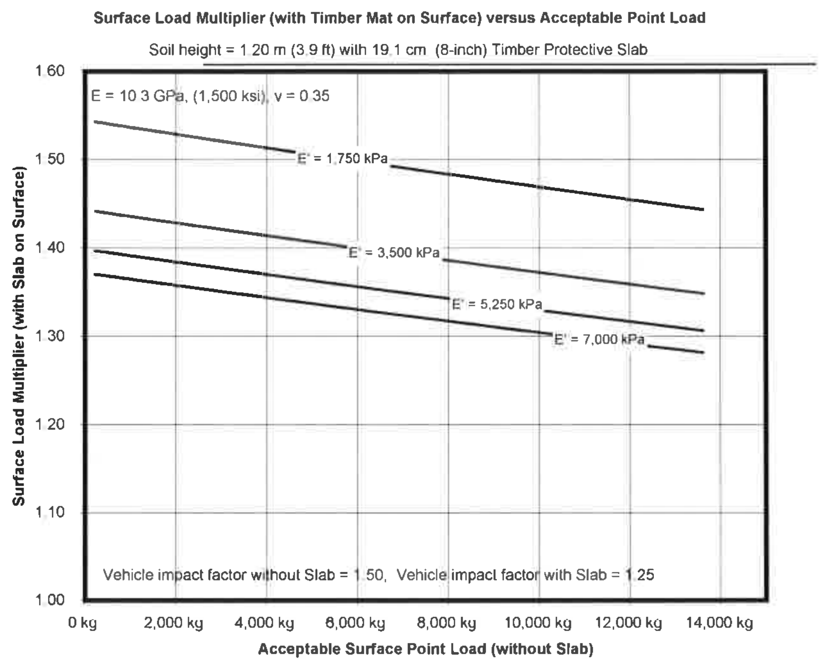

Figure C-5(c) – Soil Height = 1.2 meters

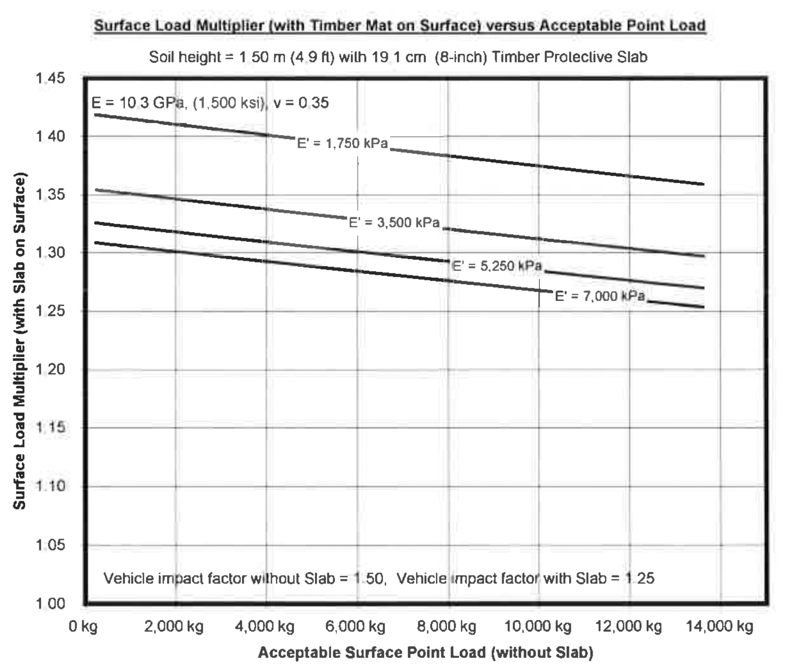

Figure C-5(d) – Soil Height = 1.5 meters

Appendix D:

Proposed Guideline – 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) through D-1(f).

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

Note: Figures D-1(a) thru D-1(f) 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) thru D-1(f) 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)

Figures D-1(a) through D-1(f)

Figure D-1(a) through D-1(f) present the maximum live surface "point" load in kilograms for cover depths of 60cm, 90 cm, 120 cm & 150 cm and design operating pressures of 72% SMYS and 80% SMYS.

Notes applicable to Figures D-1(a) through (f):

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:
   - Depth of cover as indicated
   - Maximum hoop stress of 72% or 80% percent SMYS as indicated
   - Maximum combined circumferential stress of 100 percent SMYS
   - Surface loading based on a contact pressure of 207 kPa (30 psi) applied over a rectangular area with aspect ratio (y/x) = 1
   - Fluctuating stress limitation of 82.7 MPa (12 ksi) based upon 2,000,000 cycles
   - Maximum D/t ratio of 125.
   - Soil Modulus E' = 1,724 kPa at pipe.
   - Soil Density = 1,922 kg/m^3
   - Loading criteria includes an impact factor of 1.25.
   - Maximum combined effective stress of up to 100 percent SMYS.
   - A temperature differential of $\Delta T = 50°$ C or the maximum temperature limitation as per CSA Clause 4.6.2.1 (section 2 above) whichever is the lower is included in the calculated the longitudinal stress.
   - A 60 degree bedding angle has been utilized reflecting a mature pipeline where the soil has re-consolidated around the pipeline providing additional support.
   - Multiple wheel influence factor (if applicable)

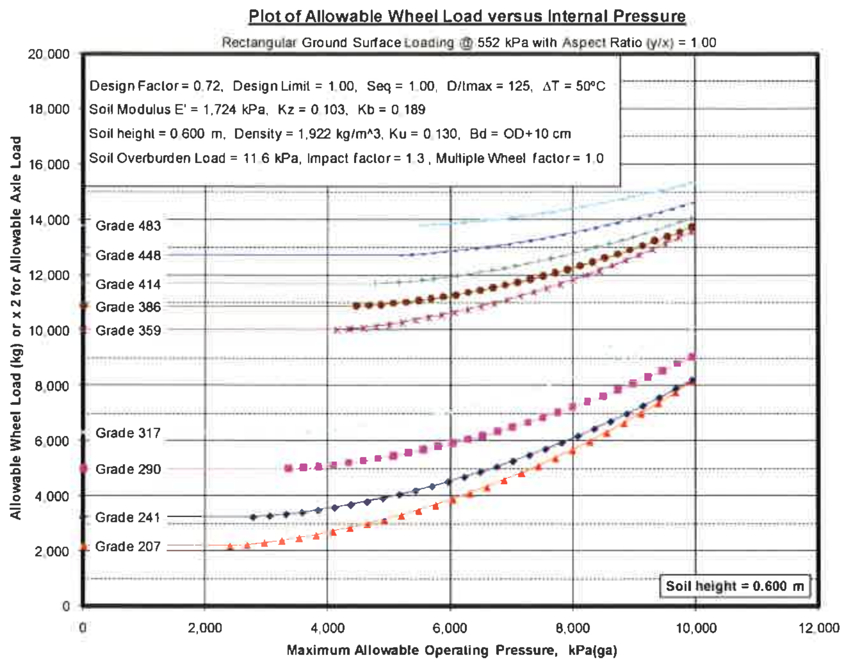

Figure D-1(a) – Soil Height = 0.60 meters, DF = 0.72

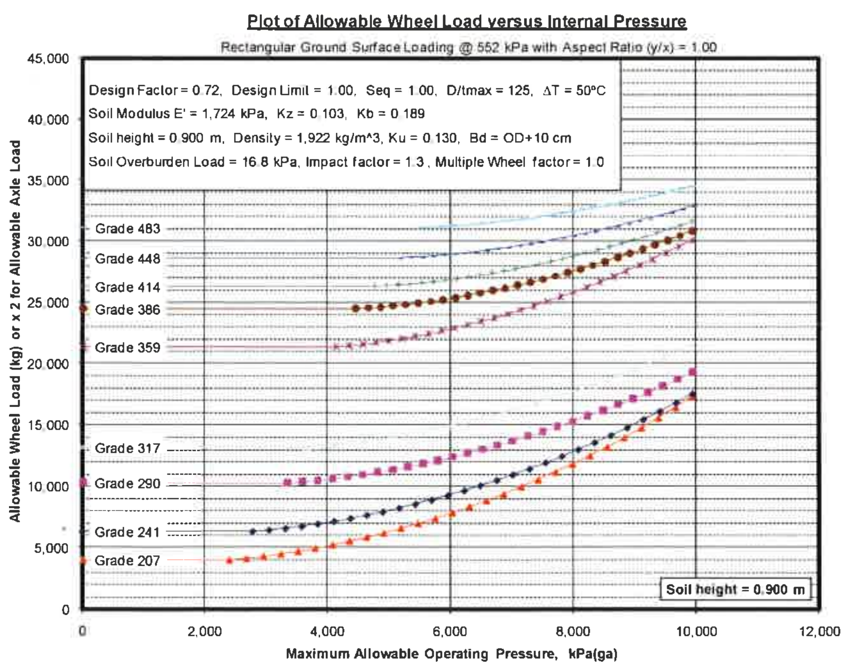

Figure D-1(b) – Soil Height = 0.90 meters, DF = 0.72

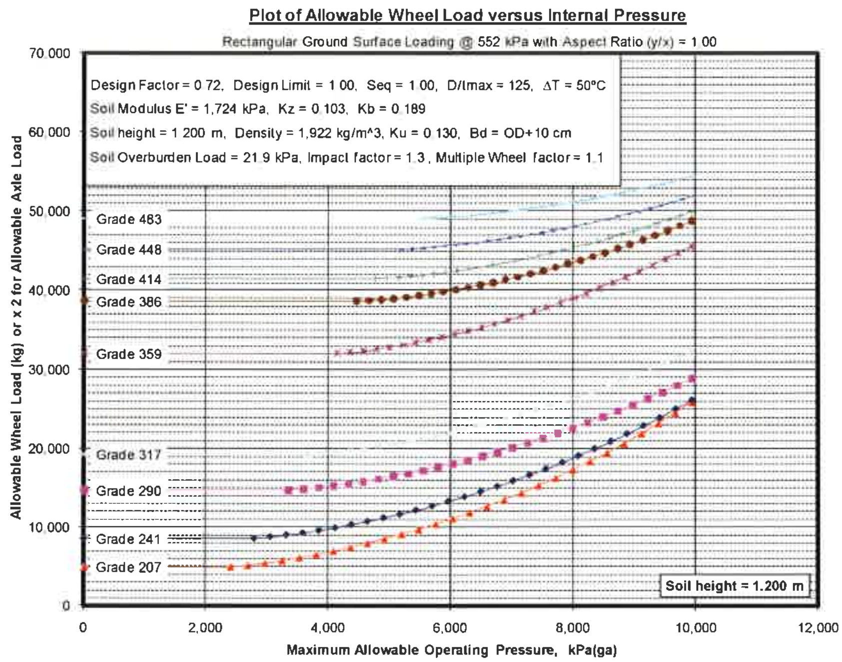

Figure D-1(c) – Soil Height = 1.2 meters, DF = 0.72

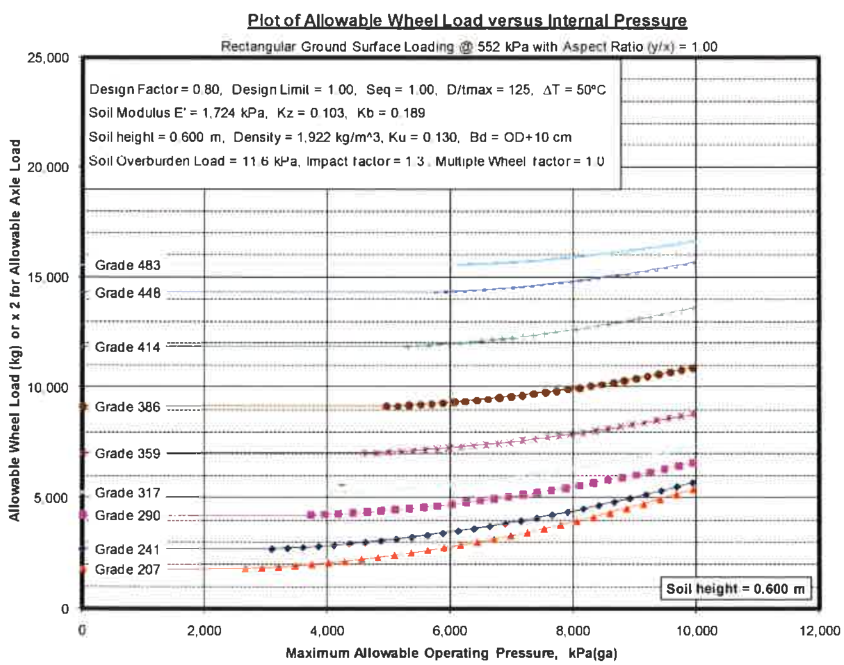

Figure D-1(d) – Soil Height = 0.6 meters, DF = 0.8

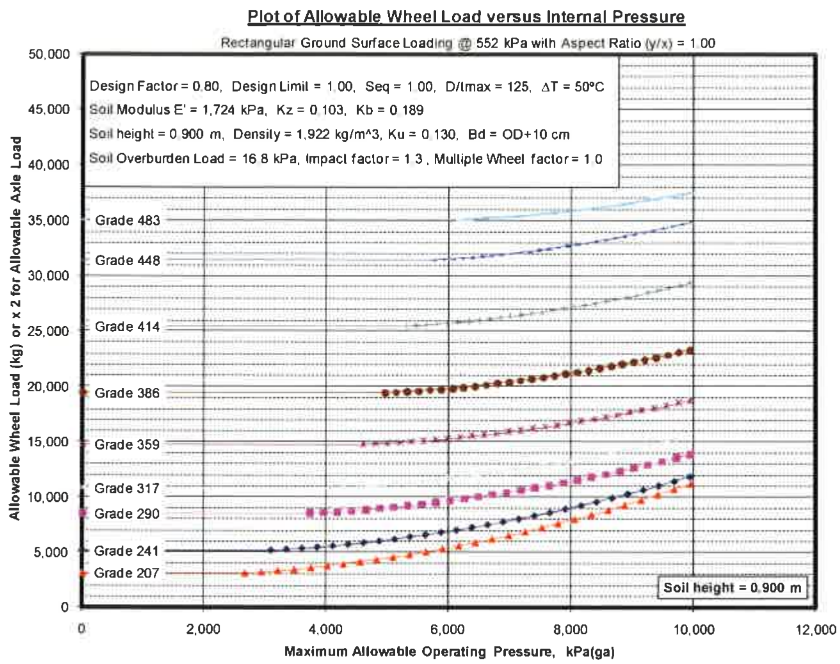

Figure D-1(e) – Soil Height = 0.9 meters, DF = 0.8

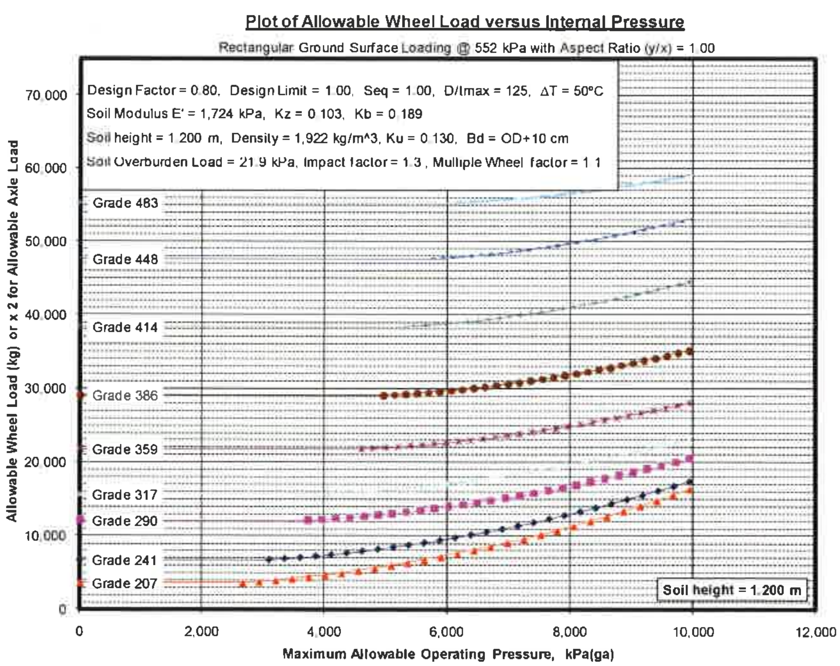

Figure D-1(f) – Soil Height = 1.2 meters, DF = 0.8

Surface Load Multiplier for Rectangular Footprint and Various Contact Pressure Figures D-2(a) through D-2(d)

Figure D-2(a) through D-2(d) present the Load Multiplier that can be applied to the previous determined allowable live surface load for surface loads applied over a square footprint with contact pressures ranging from 35 kPa through 420 kPa (5 psi through 60 psi). The figures apply for cover depths of 60 cm, 90 cm, 120 cm, and 150 cm (2ft, 3ft, 4ft, 5ft).

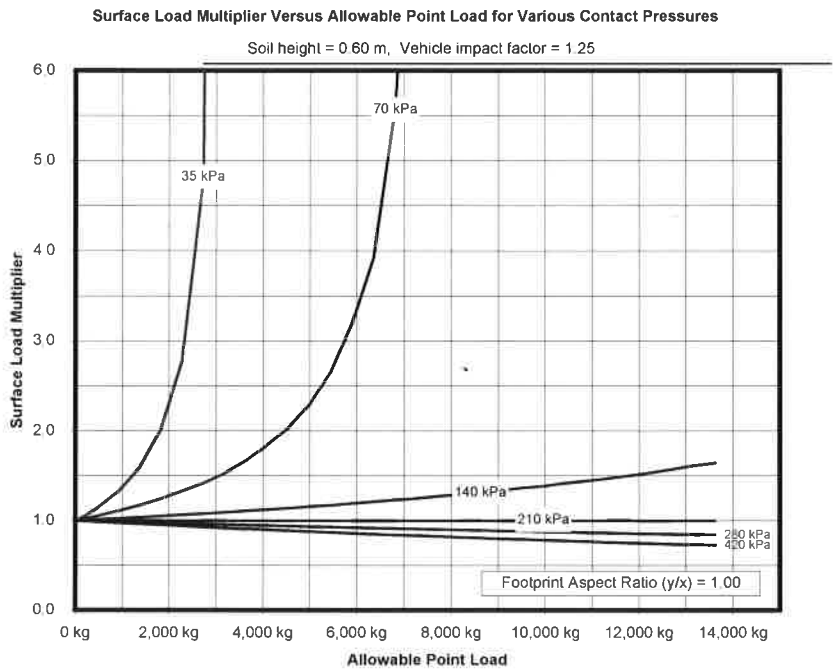

Figure D-2(a) – Soil Height = 0.6 meters

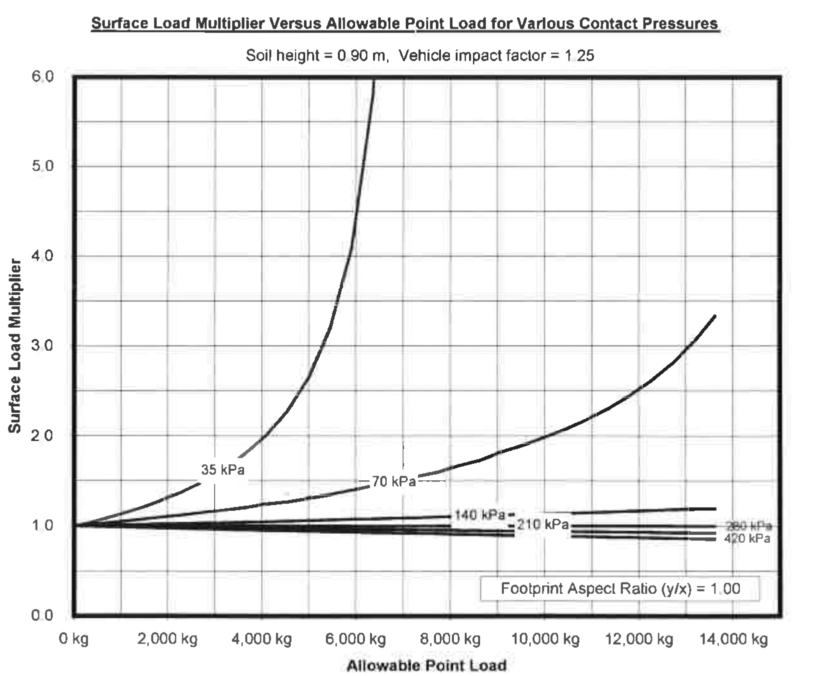

Figure D-2(b) – Soil Height = 0.9 meters

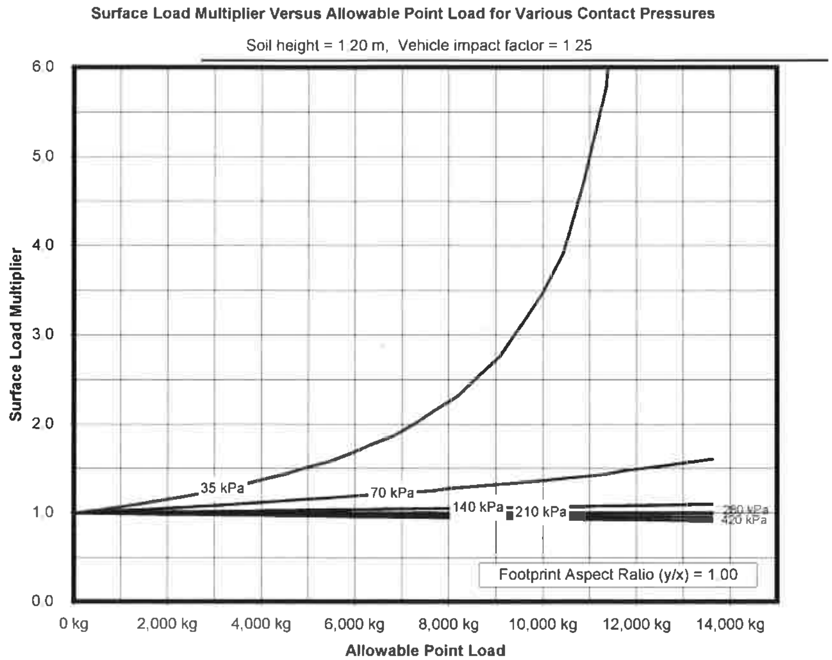

Figure D-2(c) – Soil Height = 1.2 meters

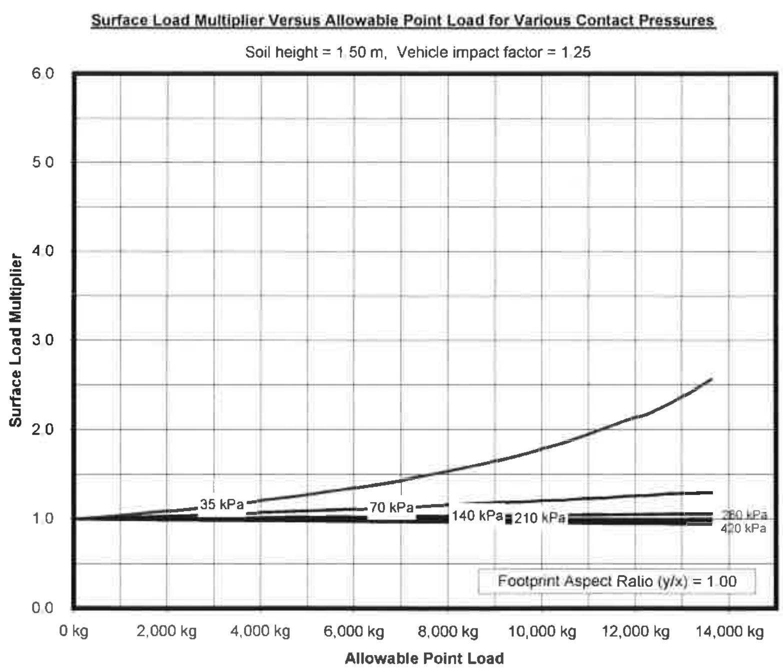

Figure D-2(d) – Soil Height = 1.5 meters