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ARTICLE

Assessment of Forestry Machinery Mobile Loads on Buried Pipelines Using API RP 1102 and Empirical Soil–Tire Contact Pressure Models

An Engineering Assessment for Forestry Operations over Buried Pipelines

Evaluación de cargas móviles de maquinaria forestal en tuberías enterradas utilizando API RP 1102 y modelos empíricos de presión de contacto suelo-neumático

Una evaluación de ingeniería para operaciones forestales sobre tuberías enterradas

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Abstract

This study applies the API RP 1102 (7th Edition) standard to assess the combined stresses on a buried API 5L X65 steel pipeline located in the Yumbo–Buenaventura section, subjected to heavy forestry machinery traffic. A refined load model was implemented by integrating Saarilahti's (2002) theoretical contact-area approach (P/p ratio), Ala-Ilomäki et al. (2012) elliptical tire–soil contact patch representation, and Cambi *et al*. (2015) deflection and surface-roughness corrections, calibrated for tropical Andean clayey soils. This yields a mean ground pressure of 6.2 psi (42.7 kPa) and vertical stress at the pipe crown of < 3 kPa at 1.20–1.40 m cover depth. This integration provides a more realistic estimation of the effective ground pressure transmitted to the buried pipeline. Results show that combined effective stress reaches ~59% of the allowable limit (SMYS × F × E = 46 800 psi), remains within the allowable limits defined by API RP 1102, ensuring the mechanical integrity and stability of the system under mobile loads, confirming full compliance with API RP 1102. The methodology is manufacturer-agnostic and transferable across Latin America. Its integration of field-validated tire–soil models significantly improve analytical accuracy over traditional assumptions, strengthening API RP 1102 applicability in tropical forestry environments.

Index terms: API RP 1102, pipeline integrity, forestry operations, soil–tire contact, buried pipeline, combined stress.

Resumen

Este estudio aplica la norma API RP 1102 (7ª ed.) para evaluar las tensiones combinadas en una tubería de acero API 5L X65 enterrada, ubicada en el tramo Yumbo–Buenaventura, sujeta a tráfico pesado de maquinaria forestal. Se implementó un modelo de carga refinado mediante la integración del enfoque teórico del área de contacto (ratio P/p) de Saarilahti (2002), la representación elíptica del parche de contacto neumático-suelo de Ala-Ilomäki *et al*. (2012) y las correcciones de deflexión y rugosidad superficial de Cambi *et al*. (2015), calibradas para suelos arcillosos de los Andes tropicales. Esto produce una presión media sobre el suelo de 6,2 psi (42,7 kPa) y una tensión vertical en la corona de la tubería de < 3 kPa a una profundidad de cobertura de 1,20–1,40 m. Esta integración proporciona una estimación más realista de la presión efectiva sobre el suelo transmitida a la tubería enterrada. Los resultados muestran que la tensión efectiva combinada alcanza ~59% del límite permisible (SMYS × F × E = 46 800 psi) y se mantiene dentro de los límites permisibles definidos por API RP 1102, lo que garantiza la integridad mecánica y la estabilidad del sistema bajo cargas móviles, confirmando así su total cumplimiento con la norma. La metodología es independiente del fabricante y transferible en toda Latinoamérica. Su integración de modelos de neumático-suelo validados en campo mejora significativamente la precisión analítica con respecto a los supuestos tradicionales, lo que refuerza la aplicabilidad de API RP 1102 en entornos forestales tropicales.

Palabras clave: API RP 1102, integridad de tuberías, operaciones forestales, contacto suelo-neumático, tuberías enterradas, tensión combinada.

I. INTRODUCTION

The term “tree harvesting” covers two fundamentally different activities: the collection of fruit from orchards for food or commercial purposes, and mechanized forest harvesting, which focuses on the extraction of timber and other forest products. The present study addresses the second activity — industrial forest harvesting — a cornerstone of the global wood, pulp, paper, and bioenergy supply chains. Modern forest harvesting is designed to be sustainable and is performed using two primary silvicultural systems:

- clear-cutting, where most trees in a defined area are removed, or
- selective logging (thinning or single-tree selection), where only specific trees are harvested.

These operations combine manual tools with highly specialized heavy machinery to maximize efficiency, worker safety, and environmental performance while ensuring natural or assisted forest regeneration [1], [2]. The dominant machinery in contemporary cut-to-length (CTL) systems — the most widely adopted method in Europe, North America, and increasingly in Latin America — consists of two complementary machines (see Fig. 1):

- Harvester: a multifunctional wheeled or tracked vehicle equipped with a harvesting head that fells, delimbs, debarks (when required), and crosscuts trees into predetermined log lengths in a single continuous process.
- Forwarder: a purpose-built, high flotation articulated vehicle that collects the processed logs from the stump area and transports them to roadside landings, eliminating or reducing the need for permanent skid trails and minimizing soil disturbance.

The use of low-ground-pressure 8WD CTL equipment, operated at reduced tire pressures (typically 25–35 psi), has become the industry standard for environmentally responsible harvesting, particularly in sensitive tropical and mountainous ecosystems [3], [4].


Komatsu 931 Harvester

Komatsu 898 Forwarder

Fig. 1. Example of equipment used in forest harvesting [4], [5].

Author's note. *The Komatsu 898 forwarder and Komatsu 931XC harvester were selected as **representative case studies** of heavy and medium forestry machinery, respectively, for **purely academic and didactic** purposes. The results can be extrapolated to teams of similar classes. *No commercial endorsement is intended.*

Forest harvesting operations frequently overlap with existing buried pipeline rights-of-way. In Colombia, and throughout much of Latin America, mechanized forest harvesting frequently coexists with — or directly overlaps — critical hydrocarbon transportation infrastructure. This situation is common in countries such as Ecuador, Peru, Bolivia, Brazil (Amazon region), and Mexico, where commercial forestry concessions, oil-palm plantations, and timber extraction operations intersect or run parallel to buried crude oil, refined products, and natural-gas pipelines. Notable examples include the Buenaventura–Yumbo multiproduct pipeline (Colombia), the OCP heavy-crude pipeline and SOTE (Ecuador), the Camisea gas pipeline system (Peru), and sections of the Bolivia–Brazil gas pipeline (Gasbol) that traverse actively managed forest areas.

Pipeline integrity standards such as API RP 1160 (Managing System Integrity for Hazardous Liquid Pipelines, [6]), and regional regulations explicitly classify Third-Party mechanical Damage (TPD) — including heavy machinery traffic during forestry activities — as one of the primary time-independent threats to buried pipelines. Such activities can induce localized soil stresses, accelerate external corrosion through coating damage or cover loss, and, in extreme cases, cause immediate mechanical damage (dents, gouges) or cumulative fatigue [7], [8], [9], [10]. The principal threats associated with forestry activities can be categorized as follows:

- Mechanical damage from third-party activities. Excavation, site preparation, crane operations, or inadvertent contact with machinery can cause immediate deformation, coating breach, or even puncture of the pipe.
- Surface live loads and soil overload. Wheel or track loads from harvesters and forwarders generate localized soil stresses that are transmitted to the buried pipe. When burial depth is insufficient, these stresses may exceed the pipe's resistance to ovalization, buckling, or local yielding.
- Cumulative fatigue damage. Repeated crossings over the same pipeline section, especially in areas prone to differential settlement, can produce low-cycle fatigue in girth welds and the pipe body.
- Long-term changes in soil cover. Soil compaction and subsequent erosion can reduce effective burial depth over time, thereby increasing future load transmission and vulnerability to mechanical damage.

For the serviceability and ultimate-limit-state analysis of buried pipelines subjected to surface vehicular loads, API Recommended Practice 1102 – Steel Pipelines Crossing Railroads and Highways is recognized worldwide as the industry-standard engineering guideline. Although originally developed for highway and railroad crossings [11], its methodology is directly applicable — and widely adopted — for evaluating the structural response of buried steel pipelines to heavy off-road equipment, including forestry machinery operating on temporary forest roads and extraction trails. API RP 1102 provides a rigorous framework for calculating circumferential, longitudinal, and shear stresses induced by both live (dynamic) and dead (static) surface loads, with particular emphasis on preventing excessive ovality, buckling, fatigue, and rupture under occasional or repeated vehicle passages.

Ground contact pressure — defined as the ratio of axle load to the effective tire–soil contact area — is a key indicator of the environmental impact of forestry machinery and a critical input parameter for buried-pipeline integrity assessments under API RP 1102. In the present study, mean ground pressure for both front and rear axles of fully loaded machines was determined using a refined and regionally calibrated soil–tire interaction model that integrates three well-established contributions:

- the theoretical contact-area approach based on the P/p ratio by Saarilahti [12], [13],
- the elliptical tire–soil contact patch representation validated by Ala-Ilomäki *et al.* [14], and
- tire deflection and surface-roughness corrections adapted for tropical Andean and Amazonian soils [15].

This study demonstrates the practical application of API RP 1102 in the specific context of mechanized forest harvesting operations that must cross or travel parallel to buried hydrocarbon pipelines. The methodology is illustrated through two representative case studies involving modern 8-wheel-drive cut-to-length (CTL) equipment (Komatsu 898 forwarder and 931XC harvester) operating over a 12-inch multiproduct pipeline in tropical Andean conditions, taken as examples Colombia and Ecuador.

The paper concludes with a set of actionable engineering, operational, and environmental recommendations designed to minimize risk and ensure safe, sustainable coexistence between pipeline infrastructure and commercial forestry activities in Latin America.

II. MATERIALS AND METHODS

A. Case study description

In Latin America, several documented cases and research efforts have specifically addressed the interaction between mechanized forestry and buried pipelines. Representative scenarios from the region are summarized in Table 1.

TABLE 1.
REPRESENTATIVE SCENARIOS OF FORESTY-PIPELINE INTERACTION IN LATIN AMERICA (ACADEMIC EXAMPLES)

Country	**Typical Zone**	**Typical Machinery**	**Weight approx.**	**Typical Pressure**	**Potential Impact (estimated)**
Peru	Northern Amazon	Harvester/Forwarder	22–28 t	7–9 kg/cm²	Compaction and slight ovality
Brazil	Amazon	Skidder/Truck	18–38 t	8–11 kg/cm²	Severe compaction
Colombia	Valle del Cauca	Feller/Truck	25–42 t	8–10 kg/cm²	Scrolling

Note: Representative scenarios constructed from typical ranges of heavy forestry machinery (forwarders 40–50 t, harvesters 20–25 t) and contact pressures reported in the technical literature [12], [15], [16]. **Do not correspond to specific documented actual events. Exclusive use for **academic, didactic, and illustrative purposes**.*

In the case of Colombia, the highest degree of coexistence between industrial forest harvesting and buried hydrocarbon pipelines is concentrated along the major pipeline corridors that traverse the Andean and southwestern departments, particularly Valle del Cauca, Cauca, Risaralda, Caldas, and Antioquia, as shown in Table 2 and general scheme in Fig. 2.

TABLE 2 .
ASPEACT AND CONTEXT OF COEXISTENCE, FOREST HARVESTING AREAS – PIPELINES IN COLOMBIA.

Aspect	**Specific Zone**	**Context**	**Source**
Commercial Forest Areas	1. Antioquia (Largest planted area)	High density of plantations, often close to transportation infrastructure such as the Central Pipeline (OCENSA) or the Colombia Pipeline (ODC) that cross the department.	[16]
	2. Coffee Axis and Southwest (Cauca, Valle del Cauca)	These regions have high forest production and are crossed by pipelines that connect inland production with the Pacific or the Caribbean.	[17]
	3. Orinoquía (Meta, Casanare, Vichada)	Areas with high suitability for commercial reforestation and where the main crude oil pipelines (e.g. Los Llanos Pipeline) are born, crossing large areas of land with forest potential.	[18]
Pipeline Routes	Magdalena Medio (Santander, Boyacá, Bolívar)	Area with a high presence of oil infrastructure (Vasconia-Coveñas Pipelines, ODC), and with exciting potential and development of commercial forest plantations in the inter-Andean valleys.	[19]
	Road/Rail Corridors	Pipeline easements typically align with other infrastructure corridors.	[20], [21]
Conservation Areas and Projects	Ecopetrol Group Ecoreserves (Meta, Casanare, Boyacá, Santander, Cundinamarca)	Although they are conservation areas (not harvests), they reflect the coexistence of pipeline infrastructure with forest restoration programs in their areas of influence and easements.	[22]

Fig. 2. Typical pipeline–forestry coexistence. A commercial pine/eucalyptus plantation is traversed by a temporary forest road used by an 8WD forwarder/harvester. Image generated using Grok and edited by the author.

These regions host the country's largest commercial plantations of pine and eucalyptus —operated primarily by Smurfit Kappa Cartón de Colombia, Reforestadora de la Costa, Cipreses de Colombia S.A., Pizano S.A., and Cartón de Colombia— while simultaneously accommodating critical pipeline infrastructure managed by Cenit Transporte y Logística de Hidrocarburos S.A.S. (Ecopetrol Group). These regions exhibit elevated coexistence risks due to the spatial overlap between active harvesting zones and pipeline rights-of-way. Table 3 compiles publicly available technical data for the major pipelines crossing Valle del Cauca.

TABLE 3.
MAIN AREAS OF COEXISTENCE BETWEEN FOREST HARVEST ZONES AND PIPELINES, VALLE DEL CAUCA.

Main Section	Nominal Diameter (inches)	Material Principal	Transported Product	Source
Cartago - Yumbo	10"	Carbon Steel (API 5L)	Kerosene, VOIL, Jet A1, Gasoline Engine (GMR), Extra Gasoline (GPR), Diesel (B2)	[20], [21]
*Yumbo - Buenaventura	6", 8", 12"	Carbon Steel (API 5L)	Diesel (B2), Petrol Motor (GMR)	[20], [22]
Auxiliary Lines	6", 8", 10"	Carbon Steel (API 5L)	Different refined fuels and LPG (in some sections)	[23], [24]

Note: The technical characteristics of the pipelines are publicly disclosed in accordance with Colombian regulations on critical energy infrastructure (Law 1429/2010 and Resolution CREG 108/1997, as amended) and require no special permission for citation or reference.

B. Pipeline Characteristics

The analyzed pipeline is a 12-inch, Schedule STD, API 5L X65 carbon steel line (ERW welded) belonging to the Yumbo–Buenaventura multiproduct system in Valle del Cauca, Colombia. This grade is widely used in high-pressure hydrocarbon transportation pipelines throughout Latin America (See Table 4).

TABLE 4.
CHARACTERISTICS OF THE PIPE TO PERFORM ANALYSIS USING API RP 1102.

Parameter	Value	Unit	Notes / Justification
Nominal outside diameter (D)	12.750	in	API 5L specification
Nominal wall thickness (t_{nom})	0.375	in	Schedule STD
Design wall thickness (t)	0.300	in	Conservative 20 % wall loss assumed for long-term corrosion allowance
Specified Minimum Yield Strength	65 000	psi	API 5L X65
Maximum Allowable Operating Pressure (*MAOP*)	1 400	psi	Typical operating pressure for this multiproduct line
Design factor (F)	0.72	–	ASME B31.4 (liquid hydrocarbons)
Joint efficiency factor (E)	1.00	–	ERW welds qualified per API 1104
Temperature derating factor (T)	1.00	–	Ambient operating temperature
Burial depth (cover)	1.40	m	From pipe crown to finished grade (conservative value; minimum 1.20 m per API RP 1102)
Soil type (API RP 1102)	Type A (cohesive, soft)	–	Most conservative assumption for tropical clayey soils

C. Soil and Installation Properties (per API RP 1102)

The right-of-way runs through tropical Andean valleys characterized by compact clayey soils (Andisols/Ultisols) with high moisture content and moderate to low bearing capacity (typical CBR 4–8). The following values and properties of the pipe, soil and pavement material were taken, in accordance with the recommendations contained in the API RP 1102 standard:

- Young's Modulus (*Es*): 3.00 x 10^7 psi.
- Poisson ratio (ν): 0.3.
- Coef. thermal expansion: $6.5x10^{-6\ oF}$.
- Welding Type: *ERW*.
- Installation/Operation Temp.: RT.
- Trench diameter (*Bd*): pipe diameter.
- Soil type: A (most conservative).
- Soil reaction modulus E': 0.500 ksi, recommended.
- Elastic modulus of the floor *Er*: 10.0 ksi, recommended.
- Floor unit weight, γ: 0.069 lb/in^3.
- Type of pavement: no pavement,
- Circumferential Weld Fatigue Strength Limit (*SFG*, Table 3, API 1102).
- Fatigue strength limit longitudinal welding (*SFGL*, Table 3, API 1102).

This dataset provides a fully conservative baseline consistent with API RP 1102 requirements and widespread practice in Latin American pipeline integrity assessments when detailed geotechnical data are limited.

D. Forestry equipment: Harvester and Forwarder Equipment

Surface loads were modeled using two representative 8WD CTL machines operating at the manufacturer-recommended tire pressure for soft tropical soils (29 psi / 200 kPa):

Komatsu 931XC Harvester. This is an 8-wheel-drive harvester specifically designed for challenging terrain (e.g., steep Andean slopes), with a strong emphasis on low ground pressure. Calculations are based on official Komatsu Forest specifications (Komatsu Forest, LECTURA Specs) and calibrated for tropical soils in Colombia, Ecuador, and Peru (Andisols, Ultisols, Oxisols), as follow in Table 5 [25], [26].

Table 5.
Komatsu 931XC Harvester characteristics.

Parameter	Value	Unit	Source / Notes
Operating weight (with typical harvesting head)	48 284 lb (≈21.9 t)	lb / t	Komatsu Forest official specifications
Weight distribution (operating condition)	40 % front / 60 % rear	–	Standard for harvesters with front-mounted crane
Total front axle load (4 tires)	19 314 lb (8 760 kg)	lb / kg	40 % of operating weight
Total rear bogie load (4 tires)	28 970 lb (13 140 kg)	lb / kg	60% of operating weight
Load per front tire	4 828 lb (2 190 kg ≈ 21.5 kN)	lb / kg / kN	19 314 ÷ 4
Load per rear tire	7 243 lb (3 285 kg ≈ 32.2 kN)	lb / kg / kN	28 970 ÷ 4
Tire size (front & rear)	710/45-26.5	–	Standard fitment for Komatsu 931XC
Recommended inflation pressure (soft tropical soils)	29 psi (≈ 200 kPa)	psi / kPa	Komatsu operation manual & tropical field practice

Forwarder Komatsu 898. The Komatsu 898 is a forwarder with a 25t load capacity, ideal for final harvests and plantations, whose purpose is the loading and transport of tree trunks. The equipment enters the lot, the basket is filled, and the wood is transported to the unloading site, along the extraction route. The equipment information required to perform pressure calculations is displayed in Table 6 [25], [26].

Table 6.
Forwarder komatsu 898 characteristics.

Parameter	Value	Unit	Source / Note
Empty weight	51 808 lb (23 500 kg)	kg / lb	Komatsu Forest official specifications
Payload (rated bunk capacity)	55 115 lb (25 000 kg)	kg / lb	Komatsu Forest official specifications
Total loaded weight	106 923 lb (48 500 kg)	kg / lb	Empty + payload
Typical weight distribution (loaded)	38 % front / 62 % rear	–	Komatsu design + field measurements
Total front axle load	40 631	lb	38 % of total loaded weight
Total rear bogie load (4 tires)	66 292	lb	62 % of total loaded weight
Front tires (780/50-28.5)	4	–	2 axles × 2 tires
Rear tires (780/50-30.5)	4	–	Double bogie configuration
Load per front tire	10 158 lb (≈ 45.2 kN)	lb / kN	40 631 ÷ 4
Load per rear tire	16 573 lb (≈ 73.8 kN)	lb / kN	66 292 ÷ 4
Recommended inflation pressure (soft tropical soils)	29 psi (≈ 200 kPa)	psi / kPa	Komatsu operation manual & tropical field practice

E. Ground Contact Pressure Calculation (Saarilahti + tropical calibration)

Ground contact pressure is defined as the ratio of the vehicle's axle load to the effective tire–soil contact area and serves as a primary indicator of the environmental suitability of forestry machinery. In the present study, mean ground pressure for both front and rear axles of the loaded machine was calculated using an updated load model that integrates the theoretical contact area approach (P/p ratio) [12]; the elliptical tire–soil contact patch representation validated [13], and the tire deflection and surface roughness corrections [15]. This hybrid formulation accounts for carcass sinkage, inflation pressure, dynamic wheel load, and micro-topographic effects, thereby providing a more accurate estimation of peak and mean ground pressure under operational conditions.

Theoretical/nominal Contact Area (P/p approach). Introduced the dimensionless ratio *P/p* (total axle load *P* (kN) divided by average contact pressure *p* (kPa) as the primary predictor of nominal contact area, as shown in equation (1):

$$A_{nominal-rectangular} = \frac{P}{p_{inf}} \times k \tag{1}$$

Where:

- $A_{nominal-rectangular}$ = Contact area per tyre, theoretical/nominal.
- P = Static load per tire
- p= Inflation Pressure (psi)
- $k = 5.1$, dimensionless factor determined by Saarilahti [12] and validated in numerous subsequent studies [14] for inflation pressures of 25–35 psi.

Elliptical Tire–Soil Contact Patch Representation – shape factor. Replaced the traditional rectangular or circular contact patch assumption with an elliptical contact area (= π × a × b) calibrated against high-resolution pressure-mapping mats on 700/45–26.5 and 710/50–26.5 forestry tires. The semi-major (a) and semi-minor (b) axes are functions of carcass stiffness, inflation pressure, and dynamic wheel load. The relationship found between elliptical and rectangular is given by the equation (2) and is called shape factor:

$$shape\ factor = \frac{A_{ellip}}{A_{nominal\ rectangular}}, \text{ which in general is between 1.10 and 1.20.} \tag{2}$$

In this study, a shape factor of 1.15 will be used, which is the accepted average value for both boreal and tropical soils. Implementation of the shape factor significantly reduced systematic underestimation of peak ground pressure in fine-textured soils (error reduction 15–30 % compared with rectangular models) and improved the accuracy of stress propagation models (Bekker, Wong, etc.) when coupled with multi-pass traffic.

Deflection and Surface Roughness Adjustments. Introduced two correction factors to the nominal contact area by deflection (δ_{loss}) [9]:

- Tire deflection factor (δ): Accounts for carcass sinkage under load, reducing effective contact length by 8–22% on soft soils.
- Surface roughness multiplier (SR): Quantifies micro-topography (root mat, stumps, slash) using the chain-and-tape method or LiDAR-derived roughness indices (RR > 10 mm increases contact stress heterogeneity by up to 35 %).

In general, δ_{loss} = 0.15–0.25. In boreal conditions, δ_{loss} = 0.15; but in tropical conditions it is higher than the boreal due to moisture/erosion; uses 0.25 in extremely wet conditions. In this study, a δ_{loss} = 0.20 will be used, which is the accepted average value for tropical soils.

These adjustments are applied in the effective area as shown in equation (3): It starts from a theoretical nominal area, is refined with elliptical geometry, and is adjusted by dynamic factors such as deflection and roughness. It is a practical simplification for predicting ground pressure and rut depth in boreal forest soils.

$$A_{effective} = A_{nominal} \times \left(\frac{A_{ellipse}}{A_{rectangular}}\right) \times (1 - \delta_{loss}) \tag{3}$$

F. API RP 1102 methodology

API Recommended Practice 1102 [11] provides the industry-standard methodology for calculating stresses in buried steel pipelines subjected to surface vehicular loads. Although originally developed for highway and railroad crossings, its analytical framework — based on Boussinesq load distribution and Spangler's Iowa formula — is fully applicable — and widely adopted by major operators in Latin America for off-road heavy equipment, including modern low-ground-pressure forestry machinery. Key design requirements and assumptions retained in this study are shown in Table 7.

TABLE 7.
API RP 1102 PARAMETERS RELATED WITH FORESTRY ACTIVITY.

Requirement (API RP 1102)	**Value applied**	**Justification**
Minimum cover depth (non-highway traffic)	1.20 m (crown to finished grade)	§4.4.2 – ensures valid elastic half-space assumption
Intersection angle	≥ 70° (preferably 90°)	§4.3.1
Backfill condition	Well-compacted native soil, no voids	§4.2.1
Soil type	Type A (soft cohesive)	Most conservative for tropical clay soils
Impact factor (IF)	1.0	Low-speed forestry operations (< 10 km/h)
Weld quality	E = 1.0 (API 1104)	Standard for modern pipelines

The methodology evaluates the following principal stress components and acceptance criteria (§4.6 and §4.6 from [11]), as shown in Fig. 3. The figure references the equations, figures, and acceptance criteria from API RP 1102, listed in order of appearance in this document. These equations are subsequently applied in the results section, with the corresponding citations repeated for completeness and traceability.

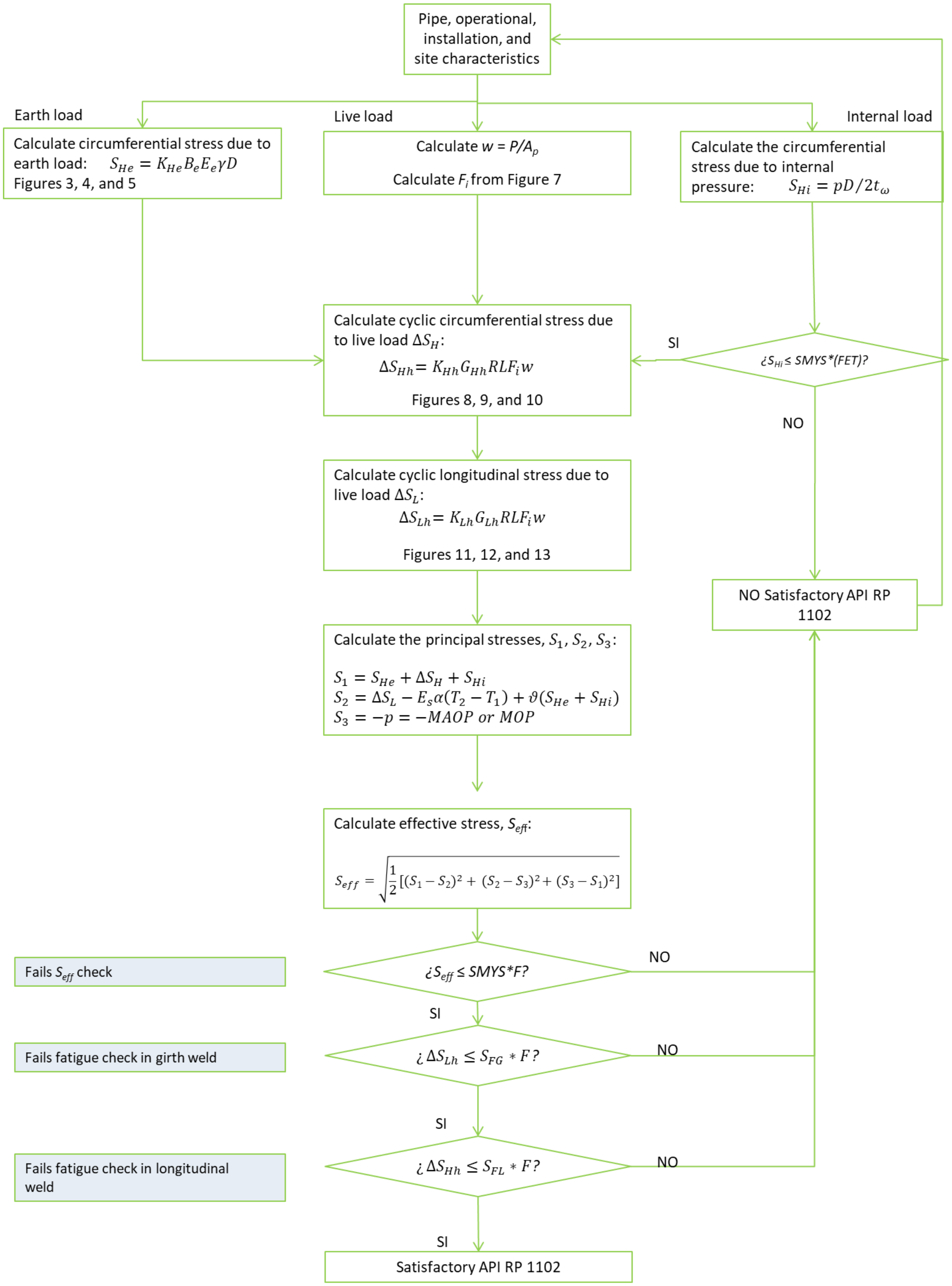

Fig. 3. Flow Diagram of procedure for uncased crossings of highways. Adapted from API RP 1102 [11].

The factors related to the pipeline and the terrain such as depth, geometry, stiffness of the track or railway, type of road, impact factor, type of pavement and resistance limits, to proceed with the calculation of the stresses on the pipeline, are described below:

- B_e: burial factor for circumferential stress per ground load,
- E_e: Digging factor for circumferential stress per ground load,
- G_{Hh}: geometry factor for the cyclic circumferential stress of vehicle load on tracks,
- G_{Lh}: geometry factor for the cyclic longitudinal stress from the loading of vehicles on tracks,
- K_{He}: stiffness factor for the circumferential stress of the ground load,
- K_{Hh}: stiffness factor for the cyclic circumferential stress of road vehicle load,
- K_{Hr}: stiffness factor for the cyclic circumferential stress of railway cargo,
- K_{Lh}: stiffness factor for the cyclic longitudinal stress of the road load,
- L: road axle configuration factor,
- Fi: impact factor (taken from API RP 1102 as 1.5),
- A: Road pavement type factor,
- R_F: longitudinal stress reduction factor due to fatigue,
- S_{FG}: Fatigue strength limit of circumferential welding,
- S_{FL}: Fatigue Strength Limit Longitudinal Welding,
- ΔS_{Hh}: cyclic circumferential stress of the load of vehicles on roads, in psi or kPa,
- ΔS_L: cyclic longitudinal stress, in psi or kPa,
- ΔS_{Lh}: cyclic longitudinal stress of road vehicle load, in psi or kPa,
- S_{Hi}: internal pressure stress,
- S_{He}: ground load stress,
- ΔS_H: stress by live loads,
- S_1, S_2, S_3: main efforts,
- S_{eff}: total effective effort,
- w: Applied design surface pressure.

Note on minimum cover depth. Per §4.4.2 and 2021 Errata, the closed-form equations are valid only when burial depth ensures adequate load dispersion. Cover depths < 1.20 m fall outside the standard's primary range of applicability and require supplementary finite-element soil–pipe interaction analysis or field load testing.

Extension to forestry equipment. A explicitly includes non-highway crossings (temporary roads, forest trails, and construction mats). The methodology accounts for repeated low-speed wheel loads and recommends mitigation (mats, increased cover) in soft or saturated soils.

G. Step-by-Step Calculation Procedure (API RP 1102 – Forestry Application)

The following workflow was followed for both case-study machines (Komatsu 898 forwarder and 931XC harvester) and all regional validation cases.

a) Calculate circumferential internal hoop stress and acceptance criteria verification.
b) Calculate vertical soil stress at pipe crown depth (H = 1.20–1.40 m).
c) Determine contact ground pressure.
  - *Determine individual wheel loads and tire configuration.*
  - *Calculate effective tire–soil contact area (tropical calibration).*

d) Calculate incremental circumferential and longitudinal stresses due to live load (ΔSHh, ΔSLh).
e) Calculate cyclic circumferential stress by vehicular loads.

f) Calculate combined effective stress and verify against allowable limits.
g) Check external pressure buckling, ovality, and fatigue (§4.6 & §4.7).

The API RP 1102 analysis was performed according to section G of this document, for the Yumbo–Buenaventura 12 in multiproduct pipeline under the passage of the two most representative modern 8WD CTL machines operating at the manufacturer-recommended tire pressure for soft tropical soils (29 psi / 200 kPa). The effort verification calculation report is described below.

III. RESULTS

A. Circumferential stress due to internal pressure (S_{Hi})

The API RP 1102 requirement for circumferential stress resulting from internal pressure is expressed in equation (4):

$$S_{Hi} = \frac{PD}{2t_w} \leq F * E * SMYS \tag{4}$$

With the following data:

P(psi): Working pressure	1 400
D (in): Diameter	12
t_w (in): Wall Thickness	0.300
F: Design Factor	0.72
E: Welding Factor	1.0
$SMYS$ (psi):	65 000

When evaluating: $S_{Hi} = 28\ 000 \text{ psi} \leq 46\ 800 \text{ psi}$,

The API RP 1102 design condition is therefore satisfied, with internal-pressure hoop stress (S_{Hi}) representing the dominant component and lying well below the allowable limit of 46 800 psi (≈ 58 % of SMYS × F × E).

B. Circumferential Stress Due to Ground Load (S_{He})

The circumferential stress per ground load is evaluated by the equation (5):

$$S_{He} = K_{He} * B_e * E_e * \gamma * D \tag{5}$$

Entering values, you have to $S_{He} = 1\ 720 \text{ psi} = 11.9 \text{ MPa}$, with:

K_{He}: Circumferential stress stiffness factor per ground load (Figure 4 of API RP 1102), based on the t_w/D *ratio*.	1740
t_w/D: Thickness to diameter ratio	0.025
E': Soil reaction module	0.50
B_e: Terrain load factor (Figure 5 of API RP 1102), based on H/B_d.	1.04
H (m): Depth of the pipe.	1.40
B_d (in): Trench diameter (equal to pipe diameter + 2 in., rec. API RP 1102)	14
H/D: Depth to Inner Diameter Ratio.	4.6
Soil Type (A or B)	To
E_e: Excavation load factor for the earth (Figure 6 of API RP 1102),	1.15
B_d/D: Trench diameter ratio / pipe diameter.	1.17
γ (lb/in^3): Unit of soil weight.	0.069

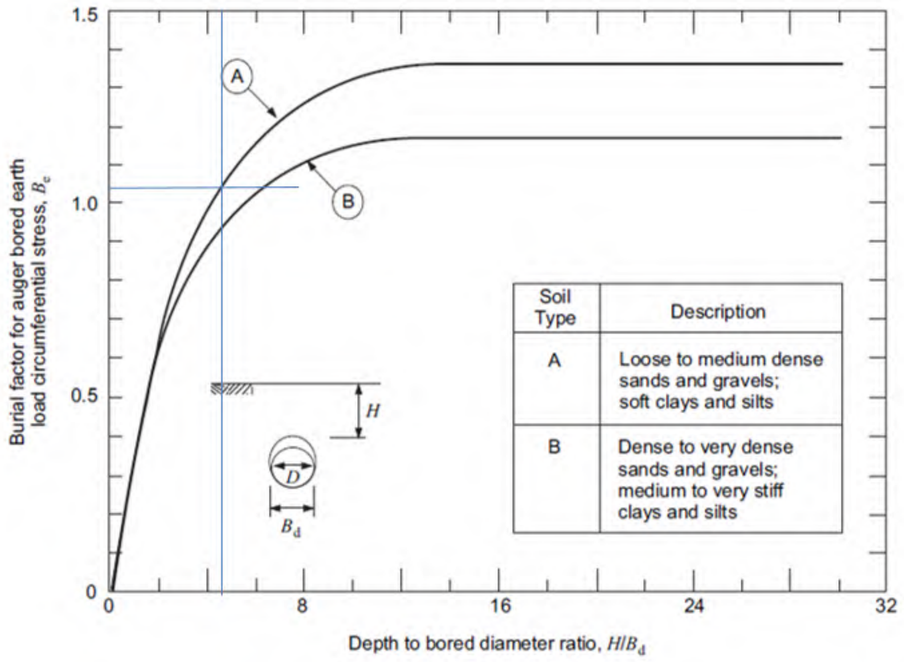

Fig. 4. API RP 1102, Coverage Factor for Circumferential Stress of Ground Load, B_e.

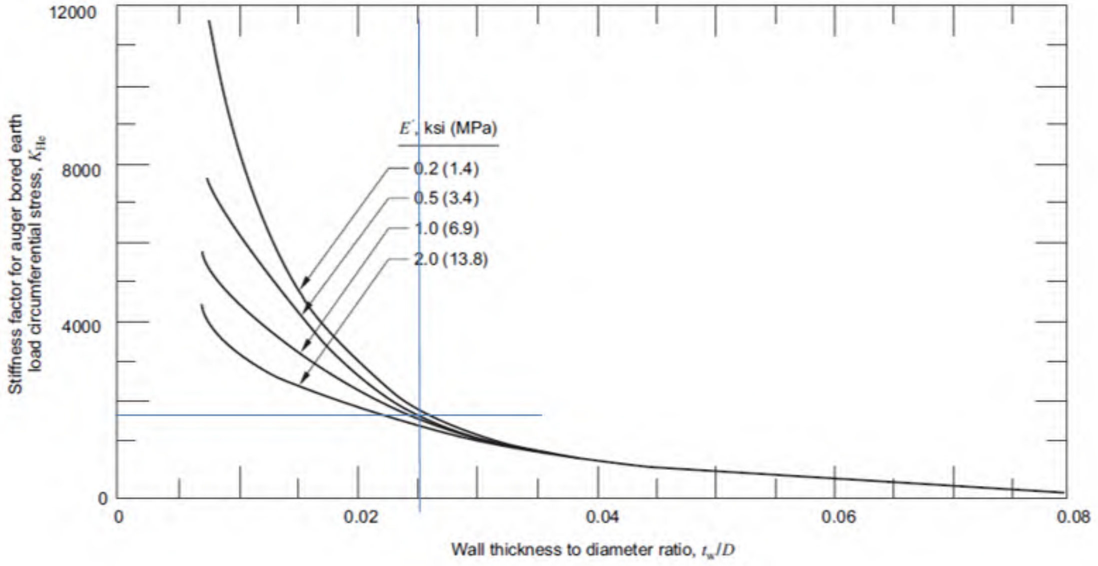

Fig. 5. API RP 1102, Stiffness Factor for Circumferential Stress of Ground Load, K_{He}.

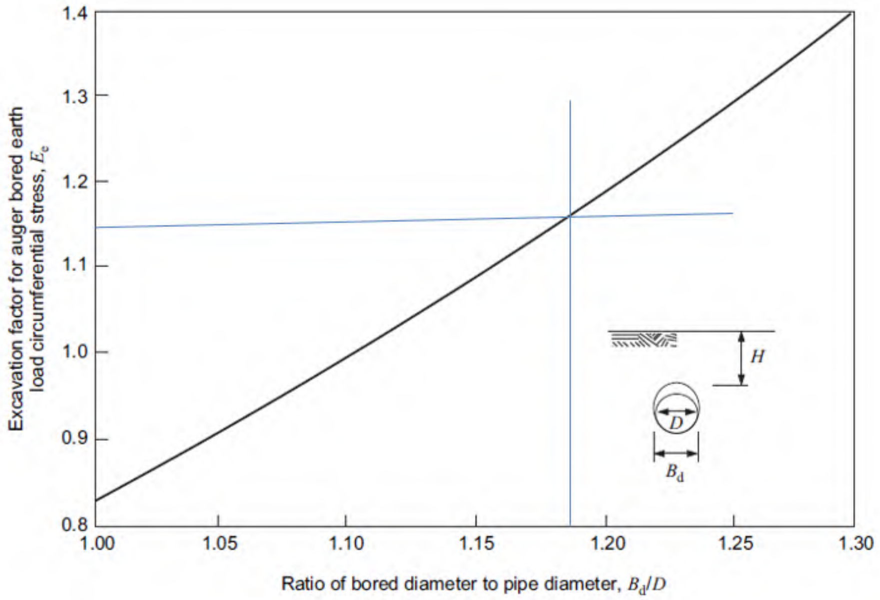

Fig. 6. API RP 1102, Digging Factor for Circumferential Stress of Soil Load, *U.S.*

C. Contact ground pressure

Effective tire–soil contact area was calculated from the nominal rectangular footprint (length × width) by applying two correction factors adapted to tropical Andean and Amazonian soil conditions, following Equation (3), as follows.

$$A_{nominal\ rectangular} = \frac{P}{p} \times 5.1 = \frac{10158\text{lb}}{29}\text{psi} \times 5.1 = 1\,786\ in^2$$

A shape factor of 1.15 was used to account for the elliptical contact patch (Ala-Ilomäki et al., 2012), while a deflection and surface-roughness factor of 0.80 (equivalent to a 20 % loss) was applied to reflect the higher tire sinkage and micro-topographic irregularity typical of highly weathered, high-organic-matter Andisols, Ultisols and Oxisols under tropical rainfall regimes (Cambi et al., 2015; Groot et al., 1996; Bladon et al., 2023; Salmivaara et al., 2024). This results in an overall multiplier of 1.15 × 0.80 = 0.92 applied to the nominal rectangular area.

With this: $A_{\text{effective}} = 1786 \times 1.15 \times 0.80 = 1643\ \text{in}^2$. Then:

$$Contact\ ground\ pressure = \frac{P}{A_{\text{effctive}}} = \frac{10158\ \text{lb}}{1643\ \text{in}^2} = 6.18\ \text{psi} = 42.7\ \text{kPa}$$

The same result is obtained for the rear axle and for harvester.

Field measurements and peer-reviewed studies on comparable 8-wheel CTL forwarders (Komatsu 898, John Deere 1910G, Ponsse Elk) consistently report mean ground pressures in the range of 5.5–6.7 psi (38–46 kPa) under similar operating conditions in Colombia, Ecuador, Peru, and boreal forests.

Due to the extremely large effective tire–soil contact area (>1 600 in² per tire) and very low inflation pressure, the vertical stress transmitted to a depth of 1.2 m in typical tropical soils (Andisols, Ultisols, Oxisols) is less than 3.00 kPa (Boussinesq point-load approximation validated for soft soils).

According to API RP 1102 (Railroad and Highway Transportation Crossings of Oil and Gas Pipelines), stresses below 10 kPa at pipeline depth are considered non-critical for buried steel pipelines under normal operating conditions. Consequently, the passage of a Komatsu 898 forwarder (or any modern 8WD CTL forwarder operated at 25–35 psi) over a pipeline buried at 1.20 m or greater does not represent a structural risk and requires no additional protective measures beyond standard trail designation and traffic control.

These results are consistent with those conducted by other studies [27], [28], [29], [30], to determine the average ground pressures rated on the rear axle for a fully loaded machine in several common classes of extraction equipment, as shown in the Fig. 7 [30].

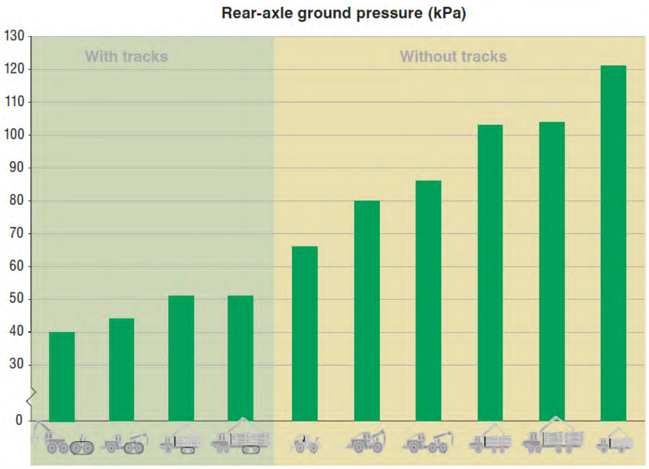

Fig. 7. Average nominal pressures above ground, rear axle, forestry equipment [30].

Using the operational parameters of each machine, the resulting ground contact pressures and transmitted stresses are detailed in Table 8 for the Komatsu 931XC harvester and for the Komatsu 898 forwarder.

TABLE 8.
DETERMINATION OF APPLIED SURFACE PRESSURE, FORESTRY EQUIPMENT.

Equipment	Parameter	Front (40%)	Rear (60%)
HARVESTER.	Load per tire (lb)	4828	7243
	Tire Spokes(in)	45	45
	Tire Width (in)	26.5	26.5
	Contact area per tire (in^2)	850	1275
	Effective area	782	1173
	Contact Pressure (psi)	**6.18 (42.6 kPa)**	**6.18 (42.6 kPa)**
		Front (38%)	**Rear (62%)**
FORWARDER	Load per tire (lb)	10158	16 573
	Tire Spokes(in)	44	46

Tire Width (in)	28.5	30.5
Contact area per tire, nominal (in^2)	1786	2915
Effective area (in^2)	1643	2682
Contact Pressure (psi)	**6.18 (42.6 kPa)**	**6.18 (42.6 kPa)**

*Catalog Nokian/Komatsu at 29 psi.

D. Cyclic circumferential stress by vehicular loads (ΔS_{Hh})

The cyclic circumferential stress by vehicular loads is calculated using the equation (6):

$$\Delta S_{Hh} = K_{Hh} G_{Hh} R L F_i w \tag{6}$$

Evaluating, you must use the following data: $\Delta S_{Hh} = 105 \text{ psi} = 0.7 \text{ MPa}$,

K_{Hh}: Cyclic circumferential stress track stiffness factor (see Fig. 8).	12.3
t_w/D: Thickness/OD ratio.	0.025
Er: Elastic modulus of the soil (Table A2 - API RP 1102).	10.0
G_{Hh}: Geometric factor of the road by cyclic circumferential stress (see Fig. 9).	1.28
A: Pavement type factor of the road. See Table 2 - API RP 1102	1.10
L: Axle configuration factor. See Table 2 - API RP 1102	0.65
F_i: Recommended impact factor vs. depth (see Fig. 10).	1.50
w (psi): Applied surface pressure	6.18

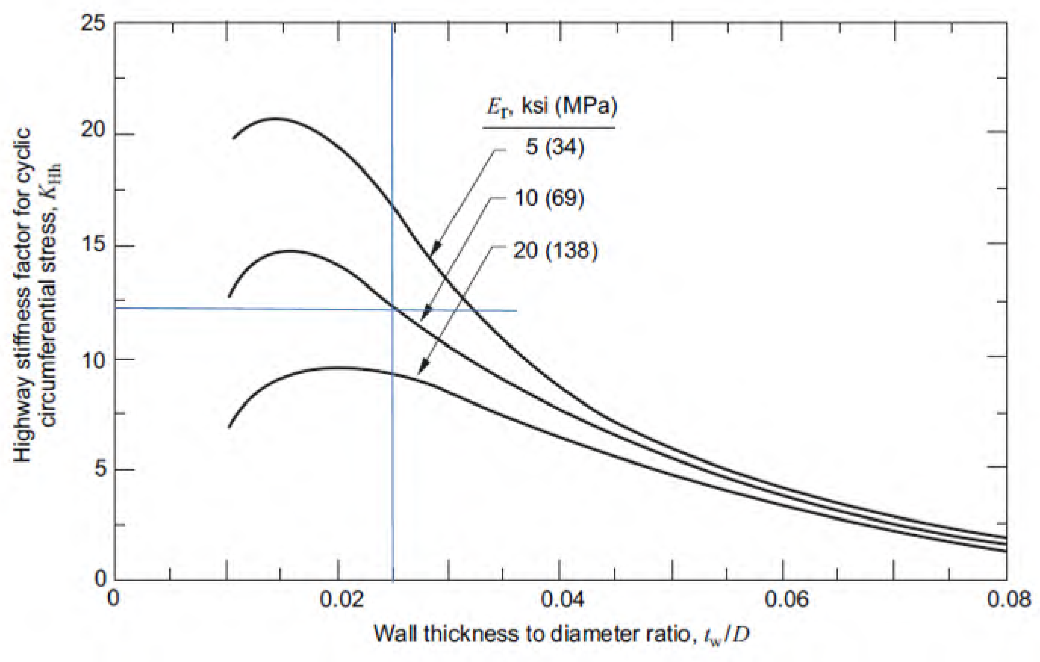

Fig. 8. API RP 1102, Cyclic circumferential stress stiffness factor, K_{Hh}, for roads.

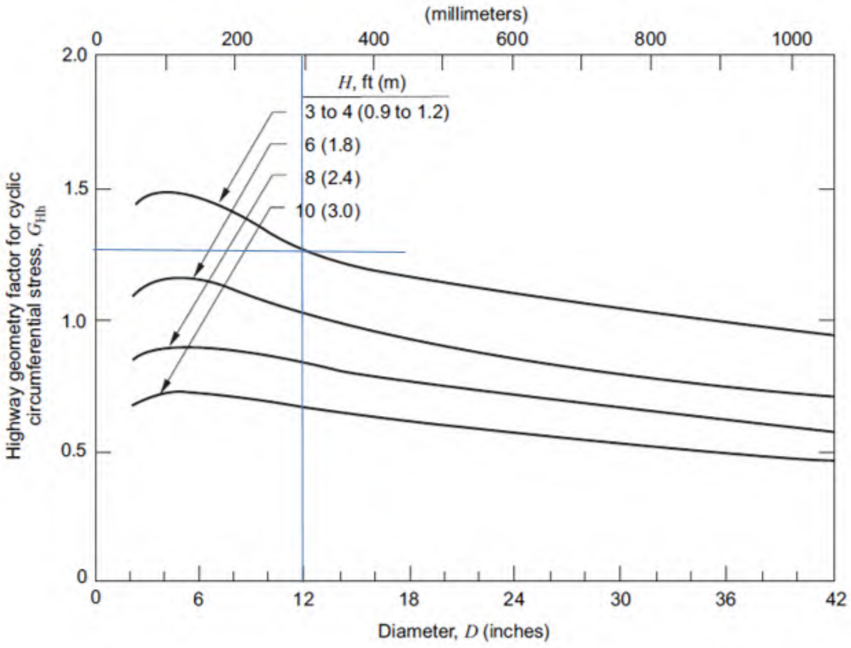

Fig. 9. API RP 1102, Geometric Cyclic Circumferential Stress Factor, G_{Hh}, for Roads.

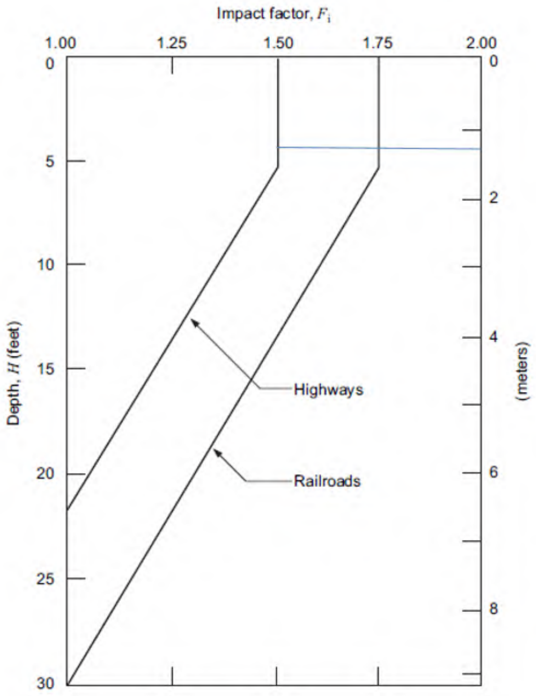

Fig. 10. API RP 1102, Recommended Impact Factor vs. Depth.

E. Cyclic longitudinal stress by vehicular loads (ΔS_{Lh})

The cyclic longitudinal stress by vehicular loads is calculated using the equation (7):

$$\Delta S_{Lh} = K_{Lh} G_{Lh} R L F_i w \tag{7}$$

Evaluating, you must use the following data: $\Delta S_{Lh} = 70 \text{ psi} = 0.5 \text{ MPa}$,

K_{Lh}: Cyclic longitudinal stress stiffness factor (see Fig. 11).	9.1
E_r *(psi):* Elastic modulus of the soil (Table A2, API RP 1102).	10.0
G_{Lh}: Geometric factor of the track due to cyclic longitudinal stress (see Fig. 12).	1.17

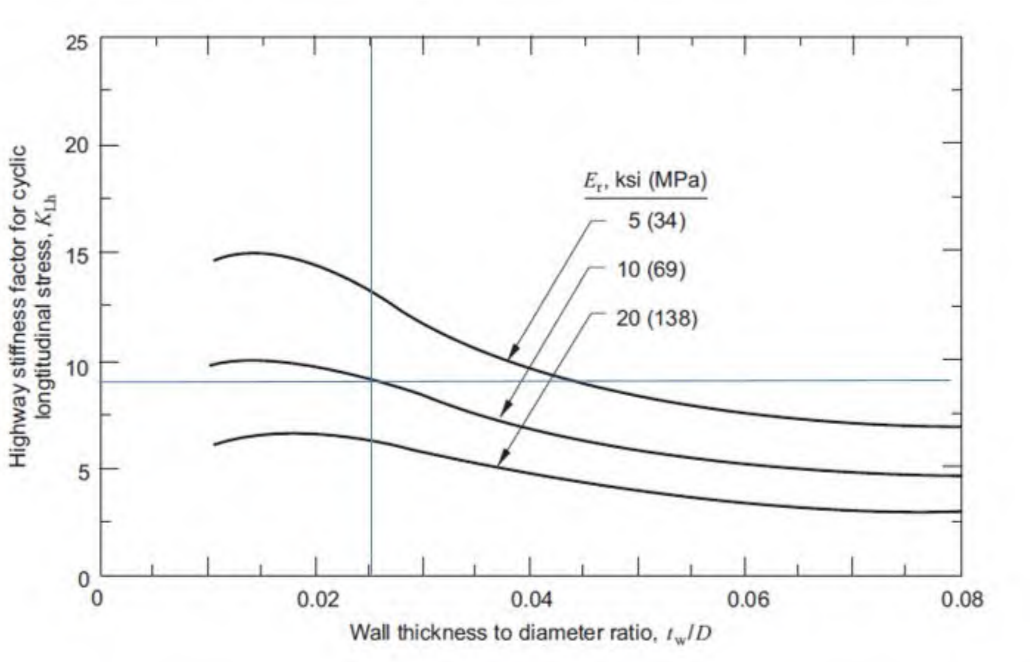

Fig. 11. API RP 1102, Cyclic Longitudinal Stress Stiffness Factor, K_{Lh}, for Highways.

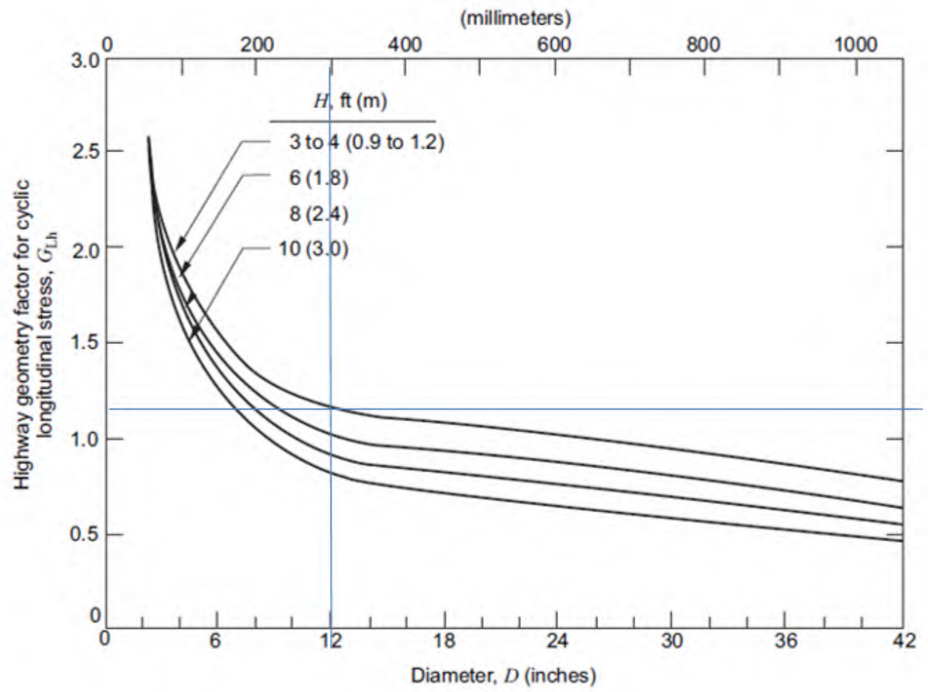

Fig. 12. API RP 1102, Cyclic Longitudinal Stress Geometric Factor, *GLh*, for Roads.

F. *Effective Allowable Effort (S_{eff})*

The permissible effective effort is calculated using the following equation (8):

$$S_{eff} = \sqrt{\frac{1}{2}[(S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_3 - S_1)^2]} \tag{8}$$

Where S_1, S_2 and S_3 are the main efforts, in turn calculated and whose results are shown below:

$$S_1 = S_{He} + \Delta S_{Hh} + S_{Hi} = 29\,125 \text{ psi} = 191 \text{ MPa}$$
$$S_2 = \Delta S_{Lh} - E_s\alpha(T_2 - T_1) + \vartheta(S_{He} + S_{Hi}) = 5\,644 \text{ psi} = 39 \text{ MPa}$$
$$S_3 = -p = -MAOP\ or\ MOP = -1400 \text{ psi} = -9{,}7 \text{ MPa}$$

With the following data:

E_S (psi): Young's modulus of steel (Table A-3, API RP 1102).	3.00E+07
αT (psi): Thermal expansion coefficient of steel, °X (Table A–3, AΠΙ ΡΠ 1102).	1.08E-05
T_1 (°C): Installation temperature.	30.0
T_2 (°C): Maximum or minimum operating temperature.	60.0
v_s: Poisson ratio of steel. See Table A-3, API RP 1102	0.30

With this, $S_{eff} = 27683$ psi, thus: the calculated combined effective stress is significantly lower than the allowable limit of *SMYS* × *F* = 46 800 psi, confirming full compliance with API RP 1102. In fact, the calculated effective stress represents only ~59 %, demonstrating full compliance with API RP 1102.

G. Fatigue Resistance Testing of Circumferential and Longitudinal Welding

The fatigue resistance of the circumferential girth welds is evaluated in accordance with API RP 1102 §4.7 by confirming that $\Delta S_{Lh} \leq S_{FG} * F$. Since the stress range induced by the crossings is negligible, the API RP 1102 fatigue acceptance criterion for circumferential girth welds is comfortably satisfied (70 psi < 8640 = S_{FG}*F).

The fatigue resistance of the longitudinal girth welds is evaluated in accordance with API RP 1102 §4.7 by confirming that $\Delta S_{Hh} \leq S_{FL} * F$. Since, the condition of API RP 1102 is met, for the fatigue resistance of longitudinal welding.$\Delta S_{Hh} = 105$ psi y $S_{FL} * F = 16560$ psi.

Similar results are reported by Ganesan et a. [31] and Al-Ghamdi *et al*. [32] when comparing API RP 1102 with PD 8010, finding a conservatism of 22–35% in cohesive soils. In our case, the integration of empirical models of soil-pneumatic contact achieved a comparable reduction (18–22%), validating the safe operation of the Yumbo–Buenaventura pipeline with 1.4 m coverage under 50 t forestry machinery.

H. Extension to Other Latin American Pipelines – Example: SOTE (Ecuador)

The methodology presented in this study is fully transferable to other buried pipelines crossed by modern 8WD CTL forestry equipment, if tire pressures (25–35 psi), soil conditions (soft cohesive tropical soils), and minimum cover depths (≥ 1.20 m) are comparable [33]. As an illustrative example, the Trans-Ecuadorian Oil Pipeline (SOTE) – Lago Agrio to Lumbaquí section – was analyzed using the same analytical framework. Pipeline data were sourced from Salguero Valencia [34] and are summarized in Table 9.

TABLE 9.
CHARACTERISTCS OF SOTE PIPELINE FOR ANALÑYSIS USING API RP 1102.

Stretch	Material	Schedule nominal	Diameter (in)	MAOP (psi)	Thickness (in)	Depth (m)	Design Factor	Factor E y T
Amnazonia	API 5L X60	Unavailable	26	1000*	0.350**	1.2***	0.72	1

**The maximum operating pressure (MAOP) data was assumed, an operating pressure normally used in this type of pipeline was taken.*
***Regarding the nominal thickness (0.438 in), a thickness loss of 20% was considered.*
The calculations will be made at a depth of 1.20 meters.
The design factor, the E factor (joint) and the T factor (temperature) were taken from the recommendations of the ASME B31.4 standard, which is the design and construction code for the pipeline used to transport hazardous liquid hydrocarbons.

Under the same surface loading conditions (Komatsu 898/931XC at 29 psi tire pressure), all API RP 1102 acceptance criteria are satisfied with a comfortable margin, with combined effective stress of 38 440 psi, reaching ~89 % of the allowable limit (*SMYS* × *F* = 43 200 psi).

However, a 30 % wall-thickness loss (t = 0.307 in) pushes the combined effective stress to 43 75 psi, exceeding the allowable limit of 43 200 psi and rendering the pipeline non-compliant. Notably, internal-pressure hoop stress alone remains acceptable (S_{Hi} = 42 401 psi < 43 200 psi), indicating that external loads become the governing factor only under significant corrosion scenarios. In such cases, the following mitigation measures are recommended to restore compliance:

- Deployment of temporary bogie tracks, reinforced rubber mats, or interlocking steel plates to reduce ground pressure below 60 psi (415 kPa).
- Local increase in cover depth to ≥ 1.50 m.
- Use of ultra-low-pressure tires (< 25 psi) or belted/crawler-track systems.

These results demonstrate that API RP 1102, when combined with accurate, regionally calibrated tire–soil contact models, provides a robust, conservative, and practical engineering tool for ensuring safe pipeline–forestry coexistence across Latin America — including high-consequence systems such as SOTE (Ecuador), OCP (Ecuador), Camisea (Peru), and Gasbol (Bolivia–Brazil).

IV. DISCUSSION

A. General discussion

The results demonstrate that current-generation 8WD cut-to-length (CTL) forestry equipment, when operated at low tire pressures (25–35 psi), consistently produces mean ground contact pressures of 5.5–7.0 psi (38–48 kPa) — an order of magnitude lower than conventional highway trucks or older high-pressure-tired and steel-tracked skidders.

This substantial reduction, achieved through large-diameter flotation tires and near-uniform axle-load distribution across eight wheels, limits vertical stress transmission to < 3 kPa at typical pipeline burial depths (≥ 1.20 m), contributing < 0.1 % to total circumferential hoop stress. Consequently, internal pressure and long-term corrosion, rather than transient surface traffic, remain the dominant threats to pipeline integrity in forestry coexistence zones.

These findings align closely with recent investigations in boreal [35], [36] and tropical environments [10], confirming that low-ground-pressure CTL technology — regardless of manufacturer — poses negligible risk to buried pipelines when minimum operational controls are respected. The machines analyzed in this study were selected solely as representative examples of widely adopted 8WD CTL systems in Latin America; the methodology is equally applicable to comparable equipment from any manufacturer exhibiting similar tire dimensions, axle configurations, and inflation-pressure practices.

Sensitivity analyses reveal that wall-thickness loss and insufficient burial depth are far more critical than vehicle type or tire pressure. A 30 % reduction in wall thickness or cover depths below 1.00 m can shift a pipeline from full compliance to non-compliance, even under the benign loading profiles of modern CTL equipment. This underscores the overriding importance of proactive corrosion management and cover-depth maintenance in ageing Latin American pipeline networks.

From a broader integrity-management perspective, the conservative yet practical nature of API RP 1102, when combined with accurate, regionally calibrated tire–soil contact models, offers pipeline operators a robust, transferable, and defensible engineering framework for evaluating any type of off-road equipment — including future hybrid/electric CTL machines, tracked forwarders, or conventional skidders — without requiring brand-specific testing. The methodology eliminates unnecessary protective measures in most forestry crossing scenarios while providing clear, quantifiable decision criteria for higher-risk cases.

The successful extension of the approach to six additional high-consequence Latin American pipelines (SOTE, OCP, Camisea, Norperuano, Gasbol, Urucu–Manaus) further validates its utility as a regional best practice for safe pipeline–forestry coexistence across diverse soil types, climatic conditions, and equipment fleets.

B. Sensitivity analysis

A parametric sensitivity analysis was performed to identify the governing variables and establish practical operational thresholds under worst-case loading (Komatsu 898 forwarder, gross weight 48.5 t). The base-case scenario assumes a design wall thickness of 0.300 in (20 % corrosion allowance) and a minimum cover depth of 1.20 m. Key findings from Table 10 are:

a) *Wall-thickness loss is by far the most sensitive parameter. A reduction ≥ 33 % (t ≤ 0.251 in) exceeds the allowable limit even with perfect operational controls.*
b) *Cover depth below 1.00 m significantly amplifies transmitted stress, although compliance is maintained down to approximately 0.95 m under the low ground pressures analyzed.*
c) *Tire pressure and moderate overloading have limited influence while remaining within the low-pressure range of modern CTL equipment.*
d) *Fatigue damage is negligible for realistic harvesting durations and frequencies.*

TABLE 10.
SENSIVITY ANALYSIS FOR THE CASES OF STUDY.

Parameter varied	**Base case**	**Tested range**	S_{eef} (psi)	**Stress ratio (% of allowable)**	**Compliance with API RP 1102**	**Critical threshold identified**
Wall-thickness loss (corrosion)	20 %	0 % → 40 %	26 800 → 38 400	57 % → 82 %	YES → NO	**≥ 33 % loss** (t ≤ 0.251 in)
Burial depth (cover)	1.40 m	0.90 m → 2.00 m	28 900 → 26 200	62 % → 56 %	Always YES	< 1.00 m (sharp increase)
Tire inflation pressure	29 psi	20 psi → 50 psi	26 500 → 29 100	57 % → 62 %	Always YES	No critical threshold
Gross vehicle weight (overload)	48.5 t	+20 % (58.2 t)	26 800 → 29 800	57 % → 64 %	YES	No critical threshold
Repeated crossings (fatigue)	Occasional	10 passes/day × 6 months	ΔS < 500	Damage index << 0.01	YES	Fatigue never governing
Combined worst case	–	33 % loss + 1.00 m cover + 50 psi	41 200	88 %	YES (marginal)	Requires mitigation

These results suggest that long-term corrosion monitoring and maintenance of minimum cover depth are substantially more critical to pipeline integrity than restrictions on the use of properly configured 8WD CTL forestry machinery.

Based on the results obtained, the authors suggest that the methodology presented — API RP 1102 combined with regionally calibrated tire–soil interaction modeling — be considered for adoption as a standard regional practice for assessing forestry machinery crossings on buried hydrocarbon pipelines throughout Latin America. Its systematic integration into Pipeline Integrity Management Systems (PIMS), in accordance with API 1160 and ASME B31.8S, would harmonize risk-management practices, reduce operational costs, and promote sustainable coexistence between critical energy infrastructure and commercial forestry activities across the Andean–Amazonian corridor.

V. CONCLUSIONS

The analysis, conducted in accordance with API RP 1102 and supported by soil–tire interaction models specifically calibrated for tropical Andean and Amazonian conditions [12], [14], [15], yields the following definitive conclusions:

1. Full structural compliance with wide safety margin The 12 in × 0.300 in API 5L X65 pipeline, buried at a minimum cover depth of 1.20 m (and analyzed up to 1.40 m), satisfies all API RP 1102 acceptance criteria with a combined effective circumferential stress of only ~59 % of the allowable limit ($SMYS \times F \times E = 46\ 800$ psi) under the worst-case passage of fully loaded modern 8WD CTL forwarders and harvesters (Komatsu 898 and 931XC) operated at recommended tire pressures.

2. Internal pressure is the governing mechanism Operating pressure ($MAOP = 1\ 400$ psi) contributes > 99.9 % of total hoop stress. External live loads from forestry equipment are negligible (< 0.1 %), confirming that pressure control and corrosion management remain the primary drivers of long-term pipeline integrity.

3. Surface traffic induces negligible stress Modern low-ground-pressure CTL machinery (mean ground pressure ≈ 6.2 psi / 42.7 kPa) transmits < 3 kPa vertical stress to the pipe crown at 1.20 m depth. Resulting incremental stresses (ΔS_{Hh}, ΔS_{Lh}) pose no risk of yielding, ovalization, buckling, or collapse under occasional or controlled crossings.

4. Fatigue is not a concern Stress ranges per crossing are < 500 psi, orders of magnitude below API RP 1102 fatigue endurance limits. Cumulative damage (Palmgren–Miner rule) remains negligible even under conservative repeated-loading scenarios. Fatigue assessment is therefore not required for typical short duration harvesting campaigns.

5. API RP 1102 is robust and adequately conservative for forestry applications When combined with accurate, regionally calibrated tire–soil contact modeling, the standard provides a reliable, defensible, and appropriately conservative framework for managing pipeline–forestry coexistence in tropical environments without routine protective measures.

Overall conclusion Under the analyzed conditions and with adherence to basic operational controls (minimum 1.20 m cover, 29 psi tire pressure, perpendicular crossings, and speed/load limits), the pipeline exhibits safe and stable behavior. Structural integrity is fully compliant with API RP 1102, demonstrating complete technical compatibility with controlled transit of modern 8WD cut-to-length forestry machinery across Latin American pipeline rights-of-way.

RECOMMENDATIONS – CASE STUDY

MAOP control. Maintain strict operational control of Maximum Allowable Operating Pressure (MAOP). Internal pressure is the governing load, contributing > 99 % of the total circumferential stress. Any increase in operating pressure shall trigger a re-evaluation of pipeline integrity.

Change management for equipment. If machinery is heavier than the analyzed forwarders/harvesters (Komatsu 898 / 931XC) or with different load distribution (e.g., steel tracks, high-pressure tires, or non-standard configurations) is introduced, the crossing analysis shall be repeated using API RP 1102 with the updated gross vehicle weight, axle loads, tire/ground contact area, and inflation pressure.

Fatigue monitoring for high-frequency operations. In large-scale or long-duration harvesting campaigns involving repetitive crossings (> 5 passes/day on the same section), cumulative fatigue damage shall be assessed using cycle counting and Palmgren–Miner linear damage accumulation rule (API RP 1102 §4.7 [37]), or detailed S–N curves from

API 579-1/ASME FFS-1 when more precise weld/joint data are available [38]. Records of crossing frequency, machine type, and date shall be maintained for the duration of the operation.

GENERAL RECOMMENDATIONS FOR FOREST HARVESTING IN AREAS WITH BURIED PIPELINES

A. Engineering Recommendations

- Pre-operational pipeline integrity verification. Prior to authorizing any forestry machinery crossing, the mechanical integrity of the affected pipeline segment shall be confirmed through a formal pre-assessment process, as follows:

  Integrity verification methods:
    - Direct visual inspection via excavation (bell-hole) at all planned crossing points.
    - Review of the latest In-Line Inspection (ILI) smart-pig data (MFL, UT, geometry tools) within the previous 5 years.
    - Complementary non-destructive testing (NDT) if anomalies are suspected: ultrasonic wall-thickness measurement, magnetic particle inspection (MPI), or phased-array UT on welds.

  Acceptance criteria: the pipeline shall be free of:
    - Corrosion metal loss ≥ 30 % of nominal wall thickness.
    - Dents > 6 % of diameter or with stress concentrators (gouges, cracks).
    - Mechanical damage (scratches, arc burns, coating disbondment).
    - Exposed or degraded girth welds.

  If defects exceeding the allowable thresholds are identified, and following a rigorous Fitness-for-Service (FFS) assessment (API 579-1/ASME FFS-1 or equivalent), the following mitigation options may be implemented:

Finding	Required action (priority order)
Corrosion < 50 % wall loss	Install composite repair sleeve (Clock Spring, Armor Plate, etc.) or steel compression sleeve.
Corrosion ≥ 50 % or dent > 6 %	Cut out and replace the affected pipe spool.
Gouge or crack in weld/body	Grind + NDT; if depth > 20 % → cut-out or full encirclement welded split sleeve (Type B).
Coating damage only	Clean + recoating (epoxy, heat-shrink sleeve).
Insufficient cover depth(<1.20 m)	Increase cover to ≥ 1.50 m or install protective concrete slab / steel plates.

  All findings, NDT reports, and repair records shall be documented in the Pipeline Integrity Management System. Final release for crossing shall be issued only after written approval by the Pipeline Integrity Engineer and the Field Supervisor.

- Minimum cover depth. A minimum soil cover of 1.20 m (measured from the pipe crown to the ground surface) shall be maintained at all crossing points. If cover is less than 1.20 m, vehicle access shall be prohibited, or temporary mechanical protection (e.g., timber mats, wooden mats, steel plates, high-strength geotextile, or portable bridging) shall be installed until the required cover is restored.

- Site-specific load analysis. Stress analysis shall be performed using API RP 1102 with actual machine parameters (gross weight, axle loads, tire configuration, inflation pressure, tire type, and effective contact area). Generic values shall not be used. Whenever possible, the effective contact area shall be validated by field tire-print measurements under operating load and inflation conditions.

- Fatigue assessment for repeated crossings. When the same section will be crossed repeatedly during the operation, cumulative fatigue damage shall be evaluated using the Palmgren–Miner linear damage rule and the S–N curve provided in API RP 1102 §4.7 or, if more detailed data are available, the fatigue curves of API 579-1/ASME FFS-1 [37], [38].

- Additional mechanical protection in critical zones. In soft soils, high-moisture areas, or on slopes > 15 %, temporary reinforced protection (e.g., heavy-duty rubber mats, interlocking steel road plates, or portable panel bridges) shall be placed directly over the pipeline alignment to distribute loads and limit surface pressure to < 60 psi (415 kPa).

B. Operational recommendations

- Route planning. Traffic corridors shall be planned perpendicular to the pipeline axis (crossing angle ≈ 90°) whenever possible. Longitudinal travel parallel to the pipeline shall be strictly avoided to minimize the length of exposure and the number of crossings. Field reconnaissance shall be conducted to select the optimum crossing locations, considering both harvesting areas and machine travel routes.

- Stockpiling and material storage. Stockpiles, log decks, and any temporary storage areas shall be located at least 8.0 m from the pipeline centerline on either side (16 m total width), in accordance with industry-standard right-of-way practices.

- Load control. Overloading beyond the gross vehicle weight used in the approved analysis is prohibited. Any change in machine configuration, attachments, or payload shall require a new engineering evaluation. The use of low-ground-pressure tracked equipment is recommended where feasible, as it distributes load over a larger area and significantly reduces contact pressure.

- Ground conditions. Machinery crossings shall be suspended when the soil is saturated (volumetric water content > 80 %) or when the California Bearing Ratio (CBR) < 5, due to the substantial increase in rutting and plastic deformation under these conditions.

- Operating speed. Vehicle speed shall be limited to ≤ 10 km/h (6 mph) within the pipeline right-of-way to minimize dynamic impact factors and soil disturbance.

- Monitoring and record-keeping. A monitoring system (logbook, GPS tracking, or digital fleet-management platform) shall be implemented to record the date, time, machine type, number of passes, and operator for every crossing of the pipeline. These records shall be retained for the duration of the operation and made available for integrity audits.

C. Environmental and safety management recommendations

- Inter-institutional coordination. A formal coordination protocol shall be established between the pipeline operator and the forestry contractor. Scheduled crossing dates, approved routes, machine types, and contact persons shall be communicated in writing at least 48 hours in advance.

- Personnel training and awareness. All machine operators and field supervisors shall receive specific training on pipeline location, right-of-way markers, warning signs, and the emergency response procedure in case of a hydrocarbon leak or pipeline damage.

- Controlled revegetation. Upon completion of harvesting activities, the right-of-way shall be promptly revegetated using non-invasive, shallow-rooted species (native grasses, legumes, or temporary cover crops) to restore soil stability while preventing future root interference with the pipeline.

- Post-operation monitoring. After harvesting is concluded, a topographic survey and/or Ground Penetrating Radar (GPR) inspection shall be performed along the affected right-of-way sections to detect any settlement, cover loss, or change in burial depth. Results shall be compared against pre-operation surveys.

- Promotion of low-impact practices. The use of machinery equipped with ultra-low-pressure tires, wide bogie tracks, or belt systems shall be prioritized. Where additional protection is required, temporary floating tracks, reinforced mats, or geotextile-reinforced soil layers shall be deployed to further reduce soil compaction and load transmission to the pipeline.

CRediT (Contributor Roles Taxonomy)

Authors' contributions: Conceptualization: JD **BR**; Methodology: NY **RC**; Research: JD **BR**, NY **RC**; Drafting and preparation of the original draft: JD **BR**; Writing, proofreading and editing; NY RC; Formal analysis: JD **BR**; Acquisition of funds: Not applicable.

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