

# Comparative Structural Integrity Assessment of Buried Gas Pipelines at Road Crossings Based API RP 1102 for Minimum Safe Burial Depth

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**Abstract:** The structural integrity of buried gas pipelines at road crossings is critically affected by external vehicular loads, particularly under shallow burial conditions. Existing studies predominantly rely on single analytical approaches, which may not adequately capture the complex soil pipe interaction and load transfer mechanisms. This study addresses this gap by proposing a comparative multi method framework to determine the minimum safe burial depth of pipelines. A 12 inch gas pipeline is evaluated using three complementary approaches, API RP 1102, CEPA analytical method, and three dimensional Finite Element Analysis (FEA). The analysis integrates realistic operational parameters, soil properties, and heavy vehicular loads up to 50 tons, with structural performance assessed against ASME B31.8 allowable stress criteria. Results reveal a consistent attenuation of stress with increasing burial depth across all methods. The CEPA method provides conservative predictions, indicating a maximum stress ratio of 69.9% SMYS at 0.7 m, while FEA captures more realistic stress redistribution, yielding lower stress ratios (59.55%). Notably, depths below 0.7 m exhibit significantly higher stress levels, approaching critical limits, particularly under combined loading scenarios. This study establishes 0.7 m as the minimum safe burial depth, validated through multi method agreement. Furthermore, it demonstrates that integrating analytical and numerical approaches enhances reliability in pipeline design. For shallow installations, structural protection systems are essential to mitigate load induced stress and vibration.

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buried gas pipeline, road crossing, structural integrity, API RP 1102, burial depth

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## INTRODUCTION

Buried gas pipelines are strategic energy infrastructure elements widely utilized in energy distribution and transmission systems due to their ability to efficiently and safely transport pressurized fluids. However, pipeline segments installed beneath the ground surface, particularly at road crossings, present significant technical challenges. Road crossing conditions impose not only static loads from soil weight and internal pipe pressure, but also dynamic loads induced by heavy vehicular traffic, construction related vibrations, and complex soil structure interactions (Tsamara & Puja, 2023). These conditions may lead to elevated stress levels, localized deformation, and potential structural failure if not properly addressed in the design and integrity assessment of the pipeline (Attia & others, 2024).

In pipeline engineering, API RP 1102 is widely recognized as a technical guideline for evaluating stresses and loads on buried pipelines at road crossings by considering the combined effects of internal and external loads. Meanwhile, the CEPA Kiefner method models soil pipe interaction using a beam on elastic foundation approach, providing an estimation of stress distribution induced by surface loads acting on the pipeline (Tong et al., 2025). However, such analytical approaches often require validation or supplementation through Finite Element Analysis (FEA), particularly under complex loading

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conditions and variable geotechnical parameters, in order to capture the structural response of the pipeline in greater detail (F. Li et al., 2024). Previous studies have generally examined these analytical and numerical approaches separately or focused on specific loading and burial-depth conditions, leaving limited comparative evidence on how API RP 1102, CEPA Kiefner, and FEA provide different assessments of pipeline structural integrity under the same road-crossing conditions.

The importance of such detailed analysis is supported by finite element studies showing that traffic loads and burial depth significantly affect the mechanical response of buried pipelines. Increasing burial depth generally reduces the effects of dynamic loading and pipeline deformation, while the magnitude and distribution of heavy vehicular loads strongly influence stress and strain within the pipeline. Experimental and numerical investigations have also demonstrated that surface pressure, load width, pipe type, wall thickness, and burial depth affect pipeline deflection and stress distribution, and have been used to develop predictions of maximum stress based on these parameters (Jia & others, 2024). Although these studies demonstrate the effects of individual loading and geometric parameters, they do not directly address whether different engineering assessment methods produce consistent safety evaluations for the same buried gas pipeline and road-crossing configuration. This issue is important because differences in modelling assumptions may lead to variations in predicted stress, deformation, and the resulting minimum safe burial depth.

For the buried gas pipeline case study in Jambi, the natural frequency characteristics of the pipeline system and its response to construction-induced vibrations suggest that actual dynamic conditions may differ from the conventional static assumptions commonly used in preliminary assessments. The API RP 1102 analysis produces a maximum stress of 7,636 psi, corresponding to 78.1% of the allowable stress. In contrast, the CEPA Kiefner method, evaluated at different burial depths, identifies the most critical condition at a depth of 0.5 m, with a stress ratio of 94.9%. The comparison of analytical and numerical approaches indicates that a minimum burial depth of approximately 0.7 m is required to satisfy the safety criteria for pipeline stress and deformation under the specified road-crossing conditions, consistent with ASME B31.8 requirements (Jalali & others, 2024). However, case-based evidence remains limited regarding whether the minimum safe burial depth obtained from analytical methods is consistent with results from finite element analysis (FEA) under identical loading and boundary conditions.

Given the stringent safety requirements of gas pipeline networks and the potentially widespread consequences of pipeline incidents, this study presents a comparative structural integrity assessment of buried gas pipelines at road crossings using three approaches: API RP 1102, CEPA Kiefner, and Finite Element Analysis (FEA) (Yang & others, 2024). The study addresses the limited comparative evaluation of these methods under a common pipeline road-crossing configuration, particularly regarding the consistency of their predicted stress, deformation, and safety margins. The novelty of this research lies in directly comparing the three approaches under identical loading, geometric, and boundary conditions to determine the minimum safe burial depth and identify differences in the resulting structural responses. Specifically, the study evaluates whether the three approaches provide consistent safety conclusions and determines the burial depth required to satisfy the applicable stress and deformation criteria. FEA is employed to complement the analytical methods by providing a more detailed assessment of pipeline structural response and by examining the potential limitations of static assumptions under the specified loading and geotechnical conditions.

## RESEARCH METHOD

### Research Methods

This study employs a comparative analytical and numerical approach to evaluate the structural integrity of buried gas pipelines, as illustrated in Figure 1, focusing on the road crossing segment in Jambi. As part of the construction of the Section 3 Tempino toll road access, and based on field inspection results, a 12 inch diameter pipeline owned by PT. XYZ is identified within the toll access area at KP 7+600 - KP 8+500, which is directly affected by the road crossing. To ensure the integrity and operational safety of the pipeline, a comprehensive risk assessment is required along the planned toll road access route. The evaluation is conducted using three approaches: API RP 1102, the CEPA Kiefner method, and Finite Element Analysis (FEA). The primary objective of this study is to determine the minimum safe burial depth based on maximum stress ratio, equivalent stress distribution, and the dynamic response of the pipeline system (Mohitpour et al., 2007).

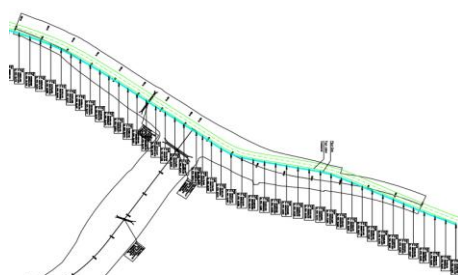


Figure 1. The road crossing segmentation in PT. XX2 and PT. XX3, Jambi

### Data Collection

The input data presented in Table 1 are obtained from pipeline technical parameters, fluid operating conditions, steel material properties, and geotechnical characteristics at the road crossing location. These parameters serve as the basis for the analyses using API RP 1102, the CEPA Kiefner method, and Finite Element Analysis (FEA).

Table 1. Environmental parameters used in this study

| A. Line Pipa Data        |                   |                    |
|--------------------------|-------------------|--------------------|
| Parameter                | Unit              | Pipeline           |
| Pipe NPS                 | in                | 12                 |
| Pipe outside diameter    | in                | 12,75              |
| Pipe wall thickness      | mm                | 10,38              |
| Corrosion allowance      | mm                | 1,6 <sup>(1)</sup> |
| Steel density            | kg/m <sup>3</sup> | 7850               |
| B. Steel Material Data   |                   |                    |
| Parameter                | Unit              | Pipeline           |
| Manufacturer type        |                   | ERW-PSL 2          |
| Grade                    |                   | API 5L X52         |
| Yield stress             | psi               | 52000              |
| Tensile stress           | psi               | 66700              |
| Poisson ratio            |                   | 0,3                |
| C. Pipeline Process Data |                   |                    |
| Parameter                | Unit              | Pipeline           |

|                                  |                   |                        |
|----------------------------------|-------------------|------------------------|
|                                  |                   | 12" Under tool road    |
| Fluid type                       |                   | Process gas            |
| Design pressure                  | psi               | 947                    |
| Design temperature               | °F                | 150 <sup>(2)</sup>     |
| Ambient installation Temperature | °F                | 70 <sup>(1)</sup>      |
| Fluid density                    | kg/m <sup>3</sup> | 38,40 <sup>(2)</sup>   |
| D. Geotechnical Data             |                   |                        |
| Parameter                        | Unit              | Pipeline               |
|                                  |                   | 12" Under tool road    |
| Soil type                        |                   | Flat clay with sand    |
| Soil density                     | kg/m <sup>3</sup> | 1706 <sup>(1)</sup>    |
| Soil compaction                  | %                 | 95                     |
| Soil modulus elasticity          | kPa               | 9806                   |
| Road type                        |                   | Concrete road          |
| Concrete quality                 | kg/m <sup>2</sup> | 300 <sup>(1)</sup>     |
| Vibration information            | Hz                | 30 – 36 <sup>(1)</sup> |
| Seismic acceleration             | G's               | 0,2                    |

Pipeline Geometry and Specifications

The pipeline analyzed in this study is a carbon steel pipe with a specification of NPS 12 inch and an outside diameter of 12.75 inch. The pipe wall thickness is 10.38 mm, with an additional corrosion allowance of 1.6 mm. The material has a density of 7,850 kg/m<sup>3</sup>.

Steel Material Properties

The pipeline material is API 5L X52 steel with an ERW-PSL 2 manufacturing type. The primary mechanical properties used in the analysis include a yield strength (SMYS) of 52.000 psi, a tensile strength of 66.700 psi, and a Poisson's ratio of 0.3. The yield strength serves as the basis for determining the allowable stress in accordance with ASME B31.8 criteria.

Pipeline Operational Data

The pipeline transports process gas under a design pressure of 947 psi and a design temperature of 150°F. The ambient temperature during installation is assumed to be 70°F., while the fluid density is 38.40 kg/m<sup>3</sup>. These operating conditions provide the fundamental basis for subsequent analyses using API RP 1102, the CEPA Kiefner method, and Finite Element Analysis (FEA), ensuring that the structural integrity assessment reflects realistic service conditions (Gajdoš et al., 2022).

Geotechnical and Environmental Data

The pipeline is buried in soil classified as flat clay with sand, with a soil density of 1,706 kg/m<sup>3</sup> and a compaction level of 95%. The soil elastic modulus is 9,806 kPa. The road surface consists of concrete pavement with a strength of 300 kg/m<sup>2</sup>. Vibration data indicate a frequency range of 30-36 Hz, which serves as a critical parameter in the analysis of dynamic response and the potential for pipeline system resonance. In addition, a design seismic acceleration of 0.2 g is considered as an additional factor in the safety evaluation. These geotechnical parameters are utilized in the beam on elastic foundation model within the CEPA Kiefner method, as well as in defining soil properties for the Finite Element Analysis (FEA) simulations.

### Finite Element Analysis (FEA) Model

A three-dimensional Finite Element Analysis (FEA) was performed using ANSYS Mechanical to evaluate the structural response of a buried 12-inch gas pipeline subjected to vehicular loading. The numerical model comprised an API 5L X52 pipeline, surrounding soil, and a concrete road structure. The pipeline was modeled at a burial depth of 0.7 m and subjected to a total vehicle load of 50 tons, consisting of 10 tons (98,100 N) on the front axle and 40 tons (392,400 N) on the rear axle. The load was applied at three orientations relative to the pipeline axis: 0°, 30°, and 90°.

The material properties were defined according to the respective pipeline, soil, and concrete specifications. The API 5L X52 steel was assigned a density of 7,850 kg/m<sup>3</sup>, Young's modulus of  $3 \times 10^7$  psi, Poisson's ratio of 0.3, yield strength of 52,000 psi, and ultimate tensile strength of 66,000 psi. The surrounding soil was modeled with a density of 1,762 kg/m<sup>3</sup>, Young's modulus of 9.8 MPa, and Poisson's ratio of 0.3. The road structure was represented by K-300 concrete with a density of 2,400 kg/m<sup>3</sup>, Young's modulus of 23.453 MPa, and Poisson's ratio of 0.3.

The pipeline was discretized using three-dimensional solid elements to capture the local stress distribution, particularly in the pipe-soil contact region. The soil and concrete road were modeled using three-dimensional SOLID185/SOLID186 elements with tetrahedral meshing to represent their volumetric behavior and the load-transfer mechanism from the vehicle through the road and soil to the buried pipeline. The model incorporated the buried condition, surrounding ground, road structure, and soil-pipe interaction to provide a realistic representation of the pipeline response under vehicular loading.

The primary FEA outputs were von Mises stress, strain, and total deformation for each loading orientation. The computational domain had an estimated volume of approximately 5.4 m<sup>3</sup> and was discretized using element sizes ranging from approximately 20 to 50 mm. Local mesh refinement was applied to regions with potentially high stress gradients, particularly around the pipe-soil interface. Depending on the level of refinement, the model consisted of approximately 200,000–700,000 elements.

The FEA results were subsequently compared with the analytical results obtained using API RP 1102 and the CEPA Kiefner method. This comparison served as a numerical cross-check of the predicted stress response rather than as experimental validation. The allowable stress was evaluated in accordance with ASME B31.8. At a burial depth of 0.7 m, the maximum FEA stress ratio was approximately 59.55%, occurring at the 0° loading orientation, whereas the CEPA Kiefner method produced a maximum stress ratio of approximately 69.9%.

### Pipeline Stress Analysis

The initial stress analysis is conducted using CAESAR II software in accordance with the ASME B31.8 Gas transmission and distribution piping systems standard (American Society of Mechanical Engineers, 2018). The pipeline system is modeled along approximately 1 km of pipeline length, including the segment located beneath the road crossing. Several loading conditions (load cases) are considered in the analysis, including hydrostatic loads during pressure testing, operating loads (pressure and temperature), sustained loads, seismic loads, and occasional loads. The calculated stress results are then compared with the allowable stress limits specified in ASME B31.8 to verify the structural integrity of the pipeline system.

## Boundary Conditions

Boundary conditions are implemented in CAESAR II by assigning constraints at specific nodes to restrict translational and rotational degrees of freedom in the global or local coordinate system. These constraints are used to represent the support behavior of the pipeline.

## Pipeline Model Development Using CAESAR II

The pipeline models are developed and analyzed in CAESAR II by considering combinations of fundamental loading conditions, as summarized in Table 2, where each combination represents a distinct load case.

Table 2. CAESAR II load case configuration

| Number | Load Combination          | Description                                                                                                    |
|--------|---------------------------|----------------------------------------------------------------------------------------------------------------|
| 1      | (HYD) WW+HP               | Hydrostatic Load Case 1 - the pipeline is fully filled with water for in-situ hydrostatic testing.             |
| 2      | (OPE) W+T1+P1             | Operating Load Case 2 - at design pressure and maximum operating temperature.                                  |
| 3      | (OPE) W+T1+P1+U1          | Operating Load Case 3 - at design pressure and temperature with seismic acceleration in the (+) X direction.   |
| 4      | (OPE) W+T1+P1-U1          | Operating Load Case 4 - at design pressure and temperature with seismic acceleration in the (-) X direction.   |
| 5      | (OPE) W+T1+P1+U2          | Operating Load Case 5 - at design pressure and temperature with seismic acceleration in the (+) Z direction.   |
| 6      | (OPE) W+T1+P1-U2          | Operating Load Case 6 - at design pressure and temperature with seismic acceleration in the (-) Z direction.   |
| 7      | (SUS) W+P1                | Sustained Load Case 7 - combination of internal design pressure and pipe weight.                               |
| 8      | (EXP) L9=L2-L8            | Expansion Load Case 8 - derived from operating load case, representing thermal expansion effects.              |
| 9      | (OCC) L10=L3-L2           | Occasional Load Case 9 - seismic acceleration in the (+) X direction.                                          |
| 10     | (OCC) L11=L4-L2           | Occasional Load Case 10 - seismic acceleration in the (-) X direction.                                         |
| 11     | (OCC) L12=L5-L2           | Occasional Load Case 11 - seismic acceleration in the (+) Z direction.                                         |
| 12     | (OCC) L13=L6-L2           | Occasional Load Case 12 - seismic acceleration in the (-) Z direction.                                         |
| 13     | (OCC) L14=L10,L11,L12,L13 | Occasional Load Case 13 - combined seismic acceleration in both X and Z directions.                            |
| 14     | (OCC) L15=L8+L14          | Occasional Load Case 14 - combined seismic acceleration in X and Z directions under sustained load conditions. |

Notes: WW is the dead weight including the fluid inside the pipeline, HP is the hydrostatic test pressure, P1 is the design pressure, U1 is the seismic load in the X-direction, T1 is the maximum operating temperature, U2 is the seismic load in the Z-direction, and WW is the weight of the pipe filled with water.

The Cartesian coordinate system adopted in CAESAR II, as illustrated in Figure 2, defines the 'Z' axis as the vertical direction, the 'Y' axis as the north direction, and the 'X' axis as the east direction.

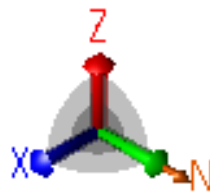


Figure 2. Coordinate axes of the CAESAR II model

### ASME B31.8 Acceptance Criteria and Maximum Stress Results

The pipeline stress analysis results are assessed against the allowable stress limits defined in ASME B31.8 to determine design compliance and identify any requirement for modification or revision (American Society of Mechanical Engineers, 2018). The maximum stress values for the 12 inch pipeline located beneath the toll road are summarized in Table 3.

Table 3. Maximum stress at 12 inch pipeline beneath the toll road

| No. | Load Combination          | Node | Code Stress (psig) | Allowable (psig) | Ratio (%) | Remarks |
|-----|---------------------------|------|--------------------|------------------|-----------|---------|
| 1   | (HYD) WW+HP               | 455  | 13940.7            | 39000            | 35.7      | PASS    |
| 2   | (OPE) W+T1+P1             | 250  | 37940.3            | 46800            | 81.1      | PASS    |
| 3   | (OPE) W+T1+P1+U1          | 250  | 37956.8            | 46800            | 81.1      | PASS    |
| 4   | (OPE) W+T1+P1-U1          | 250  | 37924.9            | 46800            | 81.1      | PASS    |
| 5   | (OPE) W+T1+P1+U2          | 250  | 37934.4            | 46800            | 81.1      | PASS    |
| 6   | (OPE) W+T1+P1-U2          | 250  | 37948.7            | 46800            | 81.1      | PASS    |
| 7   | (SUS) W+P1                | 66   | 14873.2            | 46800            | 31.8      | PASS    |
| 8   | (EXP) L9=L2-L8            | 420  | 3369.7             | 49300            | 6.9       | PASS    |
| 9   | (OCC) L10=L3-L2           | 134  | 290.7              | 39000            | 0,7       | PASS    |
| 10  | (OCC) L11=L4-L2           | 134  | 290.7              | 39000            | 0,7       | PASS    |
| 11  | (OCC) L12=L5-L2           | 135  | 211.2              | 39000            | 0,5       | PASS    |
| 12  | (OCC) L13=L6-L2           | 135  | 211.2              | 39000            | 0,5       | PASS    |
| 13  | (OCC) L14=L10,L11,L12,L13 | 297  | 345,8              | 39000            | 0,9       | PASS    |
| 14  | (OCC) L15=L8+L14          | 296  | 15216.9            | 39000            | 24.4      | PASS    |

For all load cases, the stress ratio, defined as the ratio of calculated stress to allowable stress, must remain below 100%. As presented in Table 3, the maximum stress in the pipeline system is observed at node 250 (KP 0+500), as illustrated in Figure 3, with a value of 37,956.8 psig.

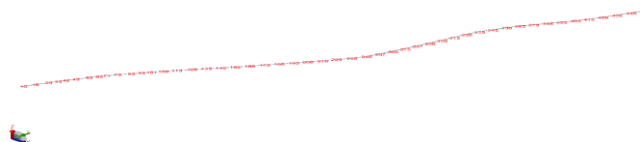


Figure 3. Maximum stress location

### Maximum Displacement

The maximum displacement of the 12 inch pipeline located beneath the toll road is summarized in Table 4.

Table 4. Maximum displacement assessment of the 12 inch pipeline – Jambi

| No | Load Case        | Displacement - X |            | Displacement - Y |            | Displacement - Z |            |
|----|------------------|------------------|------------|------------------|------------|------------------|------------|
|    |                  | Node             | Value (mm) | Node             | Value (mm) | Node             | Value (mm) |
| 1  | (HYD) WW+HP      | 460              | 1.574      | 10               | -3.801     | 13               | 0,178      |
| 2  | (OPE)<br>W+T1+P1 | 460              | 7.053      | 10               | -17.076    | 10               | 0,804      |
| 3  | (SUS) W+P1       | 460              | 1.050      | 10               | -2.537     | 13               | 0,117      |
| 4  | (EXP) L9=L2-L7   | 460              | 6.003      | 10               | -14.539    | 10               | 0,694      |

### Vibration Analysis

Resonance may occur when the excitation frequency approaches the pipeline's natural frequency, increasing vibration amplitude and the risk of fatigue and structural failure (J. Zhang et al., 2023). To avoid resonance, the natural frequency should be maintained below half or above twice the excitation frequency. The modal analysis gives a natural frequency of 26.895 Hz, while field observations recorded vibration levels of approximately 36 Hz during construction, indicating a potential resonance risk and the need for additional pipeline protection measures (Ma et al., 2023). Nevertheless, the stress analysis of the 12-inch pipeline in Jambi shows that the maximum stress remains below the allowable limit of ASME B31.8. For conservative assessment, the maximum operating temperature is adopted as the input parameter.

### Road Crossing Analysis Using API RP 1102

The road-crossing assessment follows API RP 1102 and considers the combined effects of internal pressure, soil loads, and vehicular loading (American Petroleum Institute, 2022). The evaluated stresses include circumferential stress from internal pressure and soil load, cyclic circumferential and longitudinal stresses from vehicle loads, welded-joint fatigue, and combined effective stress. The calculated stresses are compared with allowable limits based on SMYS and ASME B31.8. Both circumferential and longitudinal stresses from soil loads, highway traffic, internal pressure, and fatigue at girth and longitudinal welds are systematically assessed to verify pipeline structural integrity under road-crossing conditions (Mosadegh & Nikraz, 2021).

### Internal Pressure Stress Check (Barlow)

The internal pressure stress check is performed using the following equation:

$$S = SMYS \times F \times E \times T \quad (1)$$

where  $S$  is the circumferential stress due to internal pressure (psi),  $F$  is the design factor in accordance with ASME B31.8,  $E$  is the longitudinal joint factor in accordance with ASME B31.8,  $T$  is the temperature derating factor in accordance with ASME B31.8, and  $SMYS$  is the Specified Minimum Yield Strength ( $Psi$ ).

### Circumferential Stress Due to Internal Pressure ( $S_{Hi}$ )

The circumferential stress induced by internal pressure is determined and compared with the allowable limit.

$$S_{Hi} = \frac{p(D - t_w)}{2t_w} \quad (2)$$

where  $S_{Hi}$  is the circumferential stress due to internal pressure ( $Psi$ ),  $P$  is the internal pipe pressure, assumed equal to the design pressure ( $Psi$ ),  $tw$  is the pipe wall thickness ( $inch$ ), and  $D$  is the pipe outside diameter ( $inch$ ).

### Circumferential Stress Due to Earth Load

The circumferential stress at the invert of the pipe caused by earth load is calculated using the following equation:

$$S_{He} = K_{He} B_{He} E_{He} \gamma D \quad (3)$$

where  $S_{He}$  is the circumferential stress due to earth load ( $Psi$ ),  $K_{He}$  is the stiffness factor for circumferential stress due to earth load, as defined in API RP 1102,  $B_{He}$  is the burial factor for earth load in accordance with API RP 1102,  $E_{He}$  is the excavation factor for earth load,  $\gamma$  is the soil unit weight ( $lb/in^3$ ), and  $D$  is the pipe outside diameter ( $inch$ ).

### Surface Live Load

Vehicular load ( $w$ ) is applied at the road crossing surface. Based on API RP 1102 and Indonesian Regulation No. 2 of 2022, the recommended maximum axle load for vehicles operating on Class I highways is  $P_t = 10$  tons (Tandem axle) (Huang *et al.*, 2022). However, for the purpose of this analysis, a total vehicular load of 50 tons is adopted as a conservative design loading scenario, distributed as 10 tons on the front axle and 40 tons on the rear axle. This same 50-ton loading condition is applied in the FEA, API RP 1102, and CEPA analyses to maintain consistency among the assessment methods. The applied design surface pressure ( $w$ ) is determined as follows:

$$w = \frac{P}{A_p} \quad (4)$$

where  $P$  is the design single wheel load ( $Ps$ ) or design tandem wheel load ( $P_t$ ) ( $lb$ ), and  $A_p$  is the contact area over which the load is applied ( $in^2$ ).

### Cyclic Circumferential Stress ( $\Delta S_{Hh}$ ) and Longitudinal Stress ( $\Delta S_{Lh}$ ) due to Dynamic Loads

The cyclic circumferential and longitudinal stresses induced by dynamic vehicular loading are calculated based on the appropriate impact factors. For highway crossings, these stresses are determined as follows:

$$(\Delta S_{Hh}) = K_{Hh} G_{Hh} R L F_i w \quad (5)$$

$$(\Delta S_{Lh}) = K_{Lh} G_{Lh} R L F_i w \quad (6)$$

where  $\Delta S_{Hh}$  is cyclic circumferential stress due to highway vehicular loading ( $Psi$ ),  $\Delta K_{Hh}$  is stiffness factor for cyclic circumferential stress due to vehicular loading,  $\Delta G_{Hh}$  is geometric factor for cyclic circumferential stress due to vehicular loading,  $\Delta S_{Lh}$  is cyclic longitudinal stress due to highway vehicular loading ( $Psi$ ),  $\Delta K_{Lh}$  is stiffness factor for cyclic longitudinal stress due to vehicular loading,  $\Delta G_{Lh}$  is geometric factor for cyclic longitudinal stress due to vehicular loading,  $R$  is pavement type factor,  $F_i$  is impact factor,  $w$  is applied design surface pressure ( $Psi$ ).

### Fatigue Weld Check

The fatigue assessment for road crossing conditions is performed in accordance with API RP 1102 using the following criteria:

$$\Delta S_{Hh} \leq S_{FL} \times F \quad (7)$$

$$\Delta S_{Lh} \leq S_{FG} \times F \quad (8)$$

where  $\Delta S_{Hh}$  is the cyclic circumferential stress due to highway vehicular loading (*psi*),  $\Delta S_{FL}$  is the longitudinal weld fatigue limit (*psi*),  $\Delta S_{Lh}$  is the cyclic longitudinal stress due to highway vehicular loading (*psi*),  $\Delta S_{FG}$  is the girth weld fatigue limit (*psi*), and  $F$  is the design factor in accordance with ASME.

### Effective Stress Check

The effective stress is evaluated using the following criterion:

$$S_{eff} = \sqrt{\frac{1}{2} \{S_1 - S_2\}^2 + \{S_2 - S_3\}^2 + \{S_3 - S_1\}^2} \leq SMYS \cdot F_c \quad (9)$$

with the principal stresses defined as:

$$\begin{aligned} S_1 &= S_{He} + \Delta S_{Hh} + S_{Hi} \\ S_2 &= \Delta S_L - E_S \alpha_T (T_2 - T_1) + v_s (S_{He} + S_{Hi}) \\ S_3 &= -p \end{aligned}$$

where  $S_{eff}$  is Total effective stress (*Psi*) ,  $S_1, S_2, S_3$  is Principal stresses acting on the pipeline (*Psi*),  $S_1$  is Maximum circumferential stress (*Psi*) ,  $S_2$  is Maximum longitudinal stress (*Psi*),  $S_3$  is Maximum radial stress (*Psi*) ,  $F_c$  is Effective stress design factor (0.9), in accordance with ASME B31.8,  $SMYS$  is Specified Minimum Yield Strength (*Psi*).

The results of the road crossing analysis for an uncased pipeline at a burial depth of 0.7 m, as presented in Table 5, demonstrate that the installation of a casing pipe is not required. The analysis evaluates the ability of the uncased pipeline to safely resist the induced stresses and deformations under road crossing conditions, considering both pressurized (design pressure) and unpressurized (zero internal pressure) scenarios (D. Zhang *et al.*, 2022).

Table 5. Road crossing calculation for a 12 inch uncased pipeline

| Parameter                     |                                                   | Value    | Unit       |
|-------------------------------|---------------------------------------------------|----------|------------|
| Stress Check (100% Corroded)  |                                                   |          |            |
| Hoops (Barlow)                |                                                   | 17.646   | <i>Psi</i> |
| Stress due to earth load      |                                                   | 899,6    | <i>Psi</i> |
| Stress due to highway         | Cyclic circumferential stress ( $\Delta S_{Hh}$ ) | 7.635,6  | <i>Psi</i> |
| Vehicular load                | Cyclic longitudinal stress ( $\Delta S_{Lh}$ )    | 5.249,5  | <i>Psi</i> |
| Principal stress              | $S_1$                                             | 25.707,6 | <i>Psi</i> |
|                               | $S_2$                                             | -328,92  | <i>Psi</i> |
|                               | $S_3$                                             | -947,0   | <i>Psi</i> |
| Effective combined stress     |                                                   | 26.351,0 | <i>Psi</i> |
| Allowable                     |                                                   | 46.800,0 | <i>Psi</i> |
| Stress check                  |                                                   | OK       |            |
| Fatigue Check (100% Corroded) | $SFG$                                             | 21.000   | <i>Psi</i> |

|                                                                              |                 |        |     |
|------------------------------------------------------------------------------|-----------------|--------|-----|
| Fatigue endurance limit of girt weld                                         | $SFG \times Fd$ | 8.400  | Psi |
| Fatigue check - girt weld ("OK" if $\Delta S_{Hh} < SFG \times Fd$ )         |                 | OK     |     |
| Fatigue endurance limit of longitudinal weld                                 | $SFL$           | 21.000 | Psi |
|                                                                              | $SFL \times Fd$ | 8.400  | Psi |
| Fatigue check - longitudinal weld ("OK" if $\Delta S_{Hh} < SFG \times Fd$ ) |                 | OK     |     |

The results of the road crossing analysis indicate that a 12 inch pipeline installed at a burial depth of 0.7 m or greater does not require additional protection (Chaudhuri & Choudhury, 2023). Nevertheless, if pipeline protection is deemed necessary by the project authority, particularly for highway crossings, appropriate protective measures shall be implemented by the contractor in accordance with the specified requirements and designated locations.

### Road Crossing Analysis Using the CEPA Method

The CEPA method evaluates pipe-soil interaction under internal pressure, soil, and vehicular loads, including Boussinesq-transmitted stress, circumferential and longitudinal stresses, and equivalent stress based on Tresca or von Mises criteria (Alshibany *et al.*, 2023). Vehicle-induced loads depend mainly on burial depth, vehicle weight, and tire contact area (Saber *et al.*, 2022), while pipe deformation is governed by external loads, pipe stiffness, internal pressure, and soil restraint (He *et al.*, 2024; Shi *et al.*, 2022).

Unlike the Spangler and Iowa equations, CEPA integrates internal pressure and lateral soil restraint into the circumferential bending-stress formulation. It reduces to the Iowa equation without internal pressure and to the Spangler equation when soil restraint is negligible. This study applies CEPA to determine circumferential bending stress from surface loading (Chen *et al.*, 2023).

### Pressure at Pipe Depth

The pressure acting on the pipeline at burial depth due to surface loading is calculated using the Boussinesq equation:

$$P_{live} = \frac{W_{live}}{D} = \frac{3.F}{2\pi H^2 \left[ 1 + \left( \frac{d}{H} \right)^2 \right]^{2.5}} \quad (10)$$

where  $P_{live}$  is the pressure acting on the pipeline due to dynamic loading (psi),  $W_{live}$  is the dynamic load acting on the pipeline (lb/in),  $D$  is the pipe diameter (inch),  $F$  is the point load applied at the surface (lb),  $H$  is the soil cover depth (inch), and  $d$  is the offset distance from the pipeline to the load application point (inch).

Using this approach, tires, tracks, or any surface load with a known contact area can be represented as a series of point loads at the surface, and the total load acting on the pipeline is obtained by superimposing the effects of these individual loads. As recommended by Moser, the soil load above the pipeline is calculated as the weight of a soil prism with a width equal to the pipe diameter and a height equal to the burial depth:

$$P_{soil} = \frac{W_{soil}}{D} = \rho . H \quad (11)$$

where  $P_{soil}$  is the pressure acting on the pipeline due to soil load (psi),  $W_{soil}$  is the soil load acting on the pipeline (lb/in),  $\rho$  is the soil density (lb/in<sup>3</sup>), and  $H$  is the burial depth (inch).

### CEPA Equation for Stress Determination

The CEPA formulation combines the effects of internal pressure stiffening and lateral soil restraint into a single expression to determine the circumferential bending stress induced by dynamic (live) loads and soil loads:

$$\sigma_{H_{live}} = \frac{3 \cdot K_b \cdot P_{live} \cdot \left(\frac{D}{t}\right)^2}{1 + 3 \cdot K_z \cdot \frac{P}{E} \cdot \frac{D^3}{t} + 0,0915 \cdot \frac{E'}{E} \cdot \frac{L}{t}} \quad (12)$$

where  $\sigma_{H_{live}}$  is the circumferential bending stress due to dynamic (live) loading (psi),  $K_b$  is the soil parameter (inch),  $t$  is the pipe wall thickness (inch),  $K_z$  is the soil parameter,  $P$  is the internal pressure (psi),  $E$  is Young's modulus of steel ( $30 \times 10^6$  psi), and  $E'$  is the modulus of soil reaction (psi).

And similarly, the circumferential bending stress due to soil load is expressed as:

$$\sigma_{H_{soil}} = \frac{3 \cdot K_b \cdot P_{soil} \cdot \left(\frac{D}{t}\right)^2}{1 + 3 \cdot K_z \cdot \frac{P}{E} \cdot \frac{D^3}{t} + 0,0915 \cdot \frac{E'}{E} \cdot \frac{D^3}{t}} \quad (13)$$

where  $\sigma_{H_{soil}}$  is the circumferential bending stress due to soil load (psi). The circumferential (hoop) stress due to internal pressure is expressed as:

$$\sigma_{H_{internal}} = \frac{P \cdot D}{2 \cdot t} \quad (14)$$

where  $\sigma_{H_{internal}}$  is the circumferential (hoop) stress due to internal pressure (psi).

The total circumferential stress  $\sigma_{H_{Total}}$ , is defined as the sum of the circumferential bending stress and the circumferential stress due to internal pressure. This total stress is then compared with the allowable stress limit. The internal pressure acting on a buried pipeline also induces longitudinal stress, which is expressed as:

$$\sigma_{L_{internal}} = \nu \cdot \sigma_{H_{internal}} \quad (15)$$

where  $\sigma_{L_{internal}}$  is the longitudinal stress due to internal pressure (psi), and  $\nu$  is Poisson's ratio for steel (0.3). Similarly, soil loading induces longitudinal stress of the same form:

$$\sigma_{L_{soil}} = \nu \cdot \sigma_{H_{soil}} \quad (16)$$

where  $\sigma_{L_{soil}}$  is the longitudinal stress due to soil load (psi).

The longitudinal stress induced by dynamic loading is determined as a combination of local bending stress and beam type deflection (Shan & Li, 2025). The local longitudinal stress caused by surface loading is estimated using the *Bijlaard* solution for localized loading on pipes, as presented in *Roark's* formulas for stress and strain:

$$\sigma_{L\_local} = \frac{0,153}{1,56} \cdot \beta^4 \cdot \sigma_{H\_live} \quad (17)$$

where  $\sigma_{L\_local}$  is the local bending stress (psi). The parameter  $\beta$  is defined as:

$$\beta = [12 \cdot (1 - \nu^2)]^{1/8} \quad (18)$$

Vehicular loading induces axial deflection of the pipeline, which contributes to longitudinal stress in addition to the effects of internal pressure and temperature variations. When the pipeline is modeled as a beam on an elastic foundation, the maximum bending moment is expressed as:

$$M = \frac{P_{pipe} \cdot D}{4\lambda^2} (2e^{-\lambda x} \sin \lambda x) \quad (19)$$

where  $M$  is the bending moment (in-lb),  $P_{pipe}$  is the pressure acting on the pipe due to an equivalent point load (psi),  $\lambda$  is the characteristic length (in<sup>-1</sup>), and  $x$  is the distance along the pipeline (inch). The characteristic length is defined as:

$$\lambda = \sqrt[4]{\frac{E' \cdot D \cdot \theta}{4 \cdot E \cdot I}} \quad (20)$$

where  $\theta$  is the installation angle of the pipeline (°),  $I$  is the moment of inertia of the pipe (in<sup>4</sup>), and  $P_{pipe}$  is derived from the equivalent surface point load distributed through the soil at an assumed load dispersion angle of 29.9°. The longitudinal bending stress is given by:

$$\sigma_{L\_bend} = \frac{M \cdot D}{2I} \quad (21)$$

where  $\sigma_{L\_bend}$  is Longitudinal bending stress (Psi). The total longitudinal stress due to temperature variation is expressed as:

$$\sigma_{L\_thermal} = E \cdot \alpha \cdot \Delta T \quad (22)$$

where  $\sigma_{L\_thermal}$  is the longitudinal thermal stress (psi),  $\alpha$  is the coefficient of thermal expansion for steel ( $6.67 \times 10^{-6}/^{\circ}F$ ), and  $\Delta T$  is the temperature difference between the installation temperature and the operating temperature. The total longitudinal stress  $\sigma_{L\_Total}$ , is defined as the sum of stresses arising from internal pressure, soil load, surface load, axial deflection, and temperature variation. The total longitudinal stress is then compared with the allowable stress limit. The combined equivalent stress is calculated as:

$$\begin{aligned} \sigma_E &= \max (|\sigma_{H\_Total}|, |\sigma_{L\_Total}|, |\sigma_{H\_Total} \\ &\quad - \sigma_{L\_Total}|) \\ \sigma_E &= \sqrt{\sigma_{H\_Total}^2 - \sigma_{H\_Total} \cdot \sigma_{L\_Total} + \sigma_{L\_Total}^2} \end{aligned} \quad (23)$$

where  $\sigma_E$  is combined equivalent stress (Psi).

## RESULTS AND DISCUSSION

The calculated equivalent stress is subsequently compared with the allowable stress limit to assess pipeline safety. If surface loading is expected to occur frequently, fatigue effects must be considered. Reference can be made to Table 5 “Fatigue Endurance Limits,  $S_{FG}$  and  $S_{FL}$ , for Various Steel” Grades in API Recommended Practice 1102, which provides standard guidelines for fatigue assessment (Zapata-García *et al.*, 2022). Based on the results of the road crossing analysis for the pipeline at a burial depth of 0.7 m, the corresponding calculations are presented in Table 6.

Table 6. Calculation results

| Angle (°) | Maximum Circumferential Stress Ratio (%) | Maximum Longitudinal Stress Ratio (%) | Maximum Equivalent Stress Ratio (%) | Remarks |
|-----------|------------------------------------------|---------------------------------------|-------------------------------------|---------|
| 0°        | 56,7                                     | 50,1                                  | 69,9                                | Pass    |
| 30°       | 53,1                                     | 46,4                                  | 59,3                                | Pass    |
| 60°       | 50,3                                     | 44,2                                  | 50,3                                | Pass    |
| 90°       | 48,5                                     | 43,0                                  | 48,5                                | Pass    |
| 120°      | 47,5                                     | 42,2                                  | 47,5                                | Pass    |
| 150°      | 46,9                                     | 41,7                                  | 46,9                                | Pass    |
| 180°      | 46,8                                     | 41,4                                  | 46,8                                | Pass    |

The results indicate that the maximum stress ratio occurs at an angle of 0° and a burial depth of 0.7 m, with a value of 69.9%, which is below the allowable limit of 0.9 SMYS as specified in ASME B31.8. Pipelines installed at depths shallower than 0.7 m require additional protection to mitigate excessive stress and potential failure, whereas pipelines buried deeper than 0.7 m demonstrate adequate structural safety under the evaluated loading conditions.

### Finite Element Analysis (FEA) Simulation

In pipeline engineering, the application of Finite Element Analysis (FEA) is a critical methodology for assessing structural integrity and the performance of pipeline crossings. This subsection provides a comprehensive overview of a general FEA approach specifically developed for a 12-inch pipeline crossing beneath a toll road, offering insights into the analytical procedures and modeling considerations. To validate the analytical results, numerical simulations are conducted using FEA to evaluate the structural behavior of the pipeline buried beneath the ground surface. The FEA model consists of the pipeline geometry with API 5L X52 material properties, the surrounding soil as the supporting medium, and the concrete road structure above the pipeline.

The pipeline is modeled at a burial depth of 0.7 m, subjected to a total vehicular design load of 50 tons, distributed as 10 tons on the front axle and 40 tons on the rear axle. This 50-ton load is adopted as a conservative design loading scenario to represent heavy vehicular traffic at the toll road crossing, rather than as the maximum axle load specified by the applicable road regulation. The same total vehicle load and axle distribution are applied consistently in the FEA, API RP 1102, and CEPA assessments. Simulations are performed under three loading orientations relative to the pipeline, namely 0°, 30°, and 90°. The simulation results provide distributions of von Mises stress, strain, and total deformation. These FEA results are subsequently compared with the analytical outcomes

obtained from API RP 1102 and the CEPA method to ensure consistency and reliability of the analysis (Ávila *et al.*, 2023).

### Boundary Conditions and Analysis Setup

In this study, the pipeline is modeled at a constant burial depth of 0.7 m. Loading conditions are applied at three different orientations ( $0^\circ$ ,  $30^\circ$ , and  $90^\circ$ ) to represent various vehicle positions relative to the pipeline. For all three loading orientations, the total applied vehicular load is maintained at 50 tons, consisting of 10 tons on the front axle and 40 tons on the rear axle. The same 50-ton loading condition is used as the reference vehicle load in the comparative assessment with API RP 1102 and CEPA. The geometric configuration of the model is presented in the figure below.

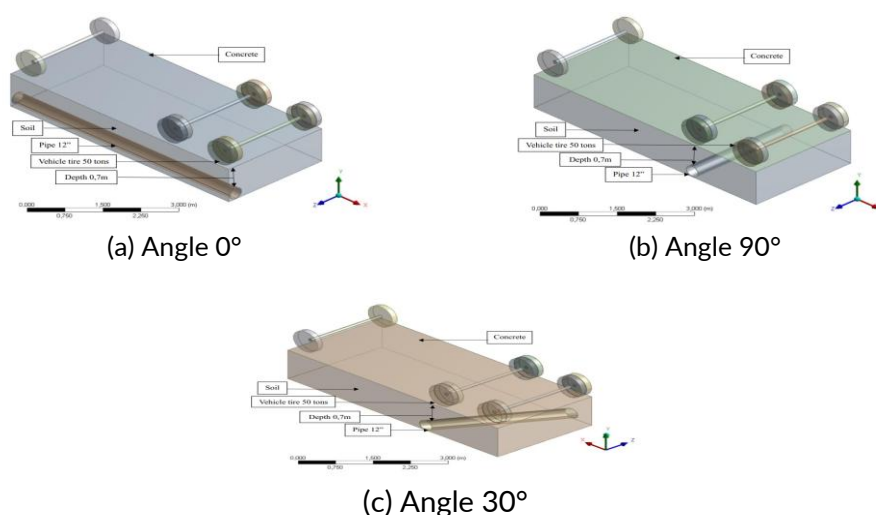


Figure 4. Pipeline loading under different angular orientations

The material properties used in the simulation are shown in Table 7.

Table 7. API 5L material properties

| No. | Property                  | Value      | Unit       |
|-----|---------------------------|------------|------------|
| 1   | Density                   | 7850       | $kg/m^3$   |
| 2   | Young's Modulus           | 3E+07      | <i>Psi</i> |
| 3   | Poisson's Ratio           | 0,3        |            |
| 4   | Bulk Modulus              | 1.7237E+11 | <i>Pa</i>  |
| 5   | Shear Modulus             | 7,9555E+10 | <i>Pa</i>  |
| 6   | Yield Strength            | 52000      | <i>Psi</i> |
| 7   | Ultimate Tensile Strength | 66000      | <i>Psi</i> |

Table 8. Concrete road material properties (K-300)

| No. | Property        | Value      | Unit       |
|-----|-----------------|------------|------------|
| 1   | Density         | 2400       | $kg/m^3$   |
| 2   | Young's Modulus | 23453      | <i>MPa</i> |
| 3   | Poisson's Ratio | 0,3        |            |
| 4   | Bulk Modulus    | 1.9544E+10 | <i>Pa</i>  |
| 5   | Shear Modulus   | 9,0204E09  | <i>Pa</i>  |

|   |                      |    |     |
|---|----------------------|----|-----|
| 6 | Compressive Strength | 24 | MPa |
|---|----------------------|----|-----|

Table 9. Soil material properties

| No. | Property         | Value       | Unit              |
|-----|------------------|-------------|-------------------|
| 1   | Density          | 1762        | kg/m <sup>3</sup> |
| 2   | Young's Modulus  | 9,8         | MPa               |
| 3   | Poisson's Ratio  | 0,3         |                   |
| 4   | Bulk Modulus     | 8,1667E+06  | Pa                |
| 5   | Shear Modulus    | 3.7692 E+06 | Pa                |
| 6   | Tensile Strength | 0,0158      | MPa               |

In the following section, the results obtained from the Finite Element Analysis (FEA) simulation provide a comprehensive assessment of the structural behavior of the buried pipeline under loading conditions with varying orientations of 0°, 30°, and 90°. The simulation is conducted with careful consideration of a total load of 50 tons, distributed between the front and rear axles (Shi *et al.*, 2022). The front axle carries a load of 10 tons (equivalent to 98,100 N), while the rear axle supports 40 tons (equivalent to 392,400 N) at a burial depth of 0.7 m. The FEA results offer detailed insights into stress distribution, deformation patterns, and the overall structural response of the pipeline under the specified loading scenarios. A summary of the results is presented in Table 10 and Figure 5.

Table 10. FEA simulation results

| Angle (°) | Pipeline Operating Stress (MPa) | Allowable Pipeline Stress (MPa) | Stress Ratio (%) | Remarks |
|-----------|---------------------------------|---------------------------------|------------------|---------|
| 0°        | 213,49                          | 358,53                          | 59,55            | Pass    |
| 90°       | 189,81                          | 358,53                          | 48,92            | Pass    |
| 30°       | 157,76                          | 358,53                          | 44               | Pass    |

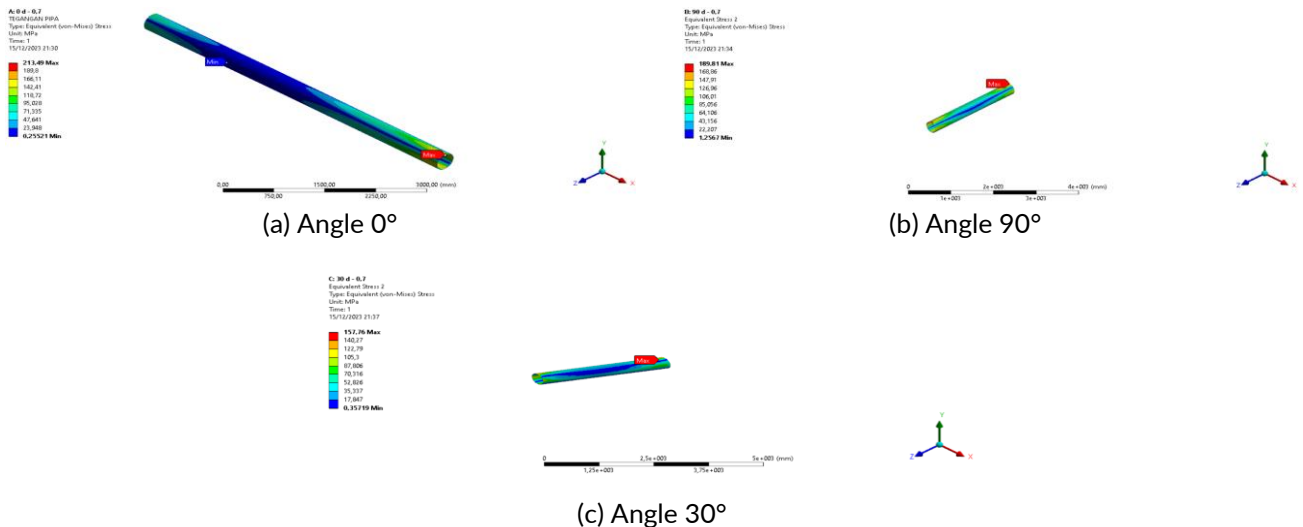


Figure 5. FEA Stress Simulation Results

The FEA results show that the highest stress occurs at the 0° loading orientation, with a maximum stress of 213.49 MPa. Given an allowable stress of 358.53 MPa, the corresponding stress ratio is 59.55%, which remains well below the allowable limit. This result indicates that the pipeline

satisfies the applicable stress criterion under the specified loading condition in accordance with ASME B31.8 (Chaudhuri & Choudhury, 2023).

The comparison of the three assessment approaches shows differences in the predicted stress ratios. The CEPA method produces the highest stress ratio, reflecting its analytical formulation for traffic loading, soil cover, pipe geometry, and soil response through simplified and relatively conservative assumptions. API RP 1102 also uses standardized analytical relationships and prescribed parameters to estimate the response of buried pipelines subjected to highway loading. Consequently, local variations in soil-pipe interaction and load transfer may not be represented in the same detail as in numerical analysis. In contrast, FEA models the pipeline and surrounding soil as an interacting system, enabling the applied vehicle load to be transferred through the soil and redistributed around the pipe according to the specified contact and boundary conditions (He et al., 2024).

The lower stress ratio obtained from FEA should not be interpreted as evidence that FEA is inherently more conservative or that the analytical methods are inaccurate. Instead, the differences primarily result from variations in modeling assumptions, calculation procedures, and spatial discretization. FEA provides a more detailed representation of stress distribution by evaluating the structural response at multiple locations within the pipe-soil system and explicitly accounting for the spatial distribution of external loads and deformation. Consequently, local stress concentrations and stress redistribution may be represented differently from those obtained using simplified analytical formulations. The CEPA results indicate a reduction in stress ratio with increasing burial depth, whereas the API RP 1102 and FEA analyses in this study were conducted at the specified design depth of 0.7 m (J. Zhang et al., 2023).

The differences among the three approaches should therefore be interpreted in terms of their respective modeling assumptions rather than solely by comparing the magnitude of the calculated stresses. CEPA and API RP 1102 provide relatively direct and efficient procedures for standardized engineering assessments, while FEA offers greater spatial resolution for evaluating the interaction among the pipeline, surrounding soil, and traffic loading. The consistent trend of decreasing stress ratio with increasing burial depth provides supporting evidence for the observed structural response, while differences in stress magnitude reflect the distinct formulations and assumptions of each method.

Based on the comparative assessment using API RP 1102, CEPA, and FEA, the 12-inch pipeline installed beneath the toll road at a burial depth of 0.7 m or greater satisfies the specified safety criteria under the maximum vehicular load of 50 tons, consisting of 10 tons on the front axle and 40 tons on the rear axle. The results from both analytical and numerical approaches indicate that the pipeline can withstand the specified loading condition at this burial depth. For burial depths below 0.7 m, additional protective measures should be considered based on the results of analytical assessments using CEPA and API RP 1102. These assessments can be used to determine the required level of protection while accounting for variations in loading orientation between the pipeline and vehicular traffic, consistent with applicable engineering standards (American Society of Mechanical Engineers, 2018). Although the pipeline meets the specified safety criteria at the evaluated depth, appropriate protective measures and compliance with relevant standards remain necessary for shallower installations to maintain structural integrity and operational reliability. A comparative evaluation of the pipeline crossing conditions based on the different assessment methods and burial depths is presented in Figure 6.

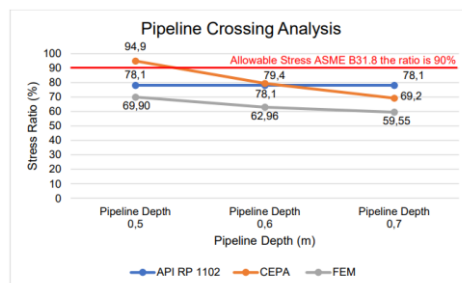


Figure 6. Pipeline road crossing analysis

Figure 6 presents a comparative evaluation of the analytical and numerical assessment results at different burial depths. The highest stress ratio, 94.9%, occurs at a burial depth of 0.5 m based on the CEPA method. Although a burial depth of 0.6 m produces stress ratios below the allowable limit of 90% SMYS for all three approaches, the relatively small margin to the allowable stress provides less tolerance for variations in soil properties, loading conditions, and modeling assumptions. Therefore, although 0.6 m satisfies the calculated stress criterion, it is not selected as the minimum design burial depth. A depth of 0.7 m is adopted because it provides a greater safety margin and is supported by the consistent decrease in stress ratios observed across the assessment methods (Mosadegh & Nikraz, 2021).

Accordingly, a minimum burial depth of 0.7 m is established for the pipeline road-crossing configuration evaluated in this study. This value applies specifically to the pipeline dimensions, material properties, soil conditions, vehicle loading, geometric configuration, and other parameters considered in the present case study and should not be interpreted as a universal minimum depth for all pipeline road crossings. Additional calculations for burial depths greater than 0.7 m indicate that increasing burial depth further reduces the stress ratio, thereby providing a greater margin relative to the allowable stress criterion. Thus, deeper burial may provide additional structural margin under the conditions examined in this study (Saberi et al., 2022).

For installations with burial depths below 0.7 m, additional protective measures should be considered to reduce the effects of external loading and potential structural risks. Such measures may include dedicated pipeline protection systems designed to limit stress and deformation caused by vehicular loads. The selection and design of these protective measures should be based on the specific loading conditions, soil characteristics, pipeline properties, and applicable engineering standards. This approach complements the determination of an appropriate burial depth and provides additional protection against variations between modeled and actual field conditions (D. Zhang et al., 2022).

The findings are consistent with previous studies on buried pipeline behavior under road-crossing conditions. Roy et al. reported that increasing burial depth reduces vehicle-induced pipeline stresses because traffic loads are dispersed through the soil before reaching the buried pipe. This behavior is consistent with the Boussinesq stress distribution theory, which describes the reduction of vertical stress with increasing depth (Chaudhuri & Choudhury, 2023). Previous studies of pipeline crossing assessments have also indicated that analytical methods such as API RP 1102 may produce relatively conservative results because they incorporate standardized or empirical factors to account for uncertainties in soil and loading conditions (Huang et al., 2022). A similar difference is observed in the present study, in which the CEPA method produces higher stress estimates than FEA. Recent FEA-

based investigations have demonstrated that numerical modeling can provide greater detail in representing soil-pipe interaction, spatial load distribution, deformation, and boundary conditions (Gajdoš et al., 2022). In the present study, FEA produces lower stress values than the analytical approaches. This difference is attributed to the modeled load-transfer mechanism and stress redistribution within the coupled soil-pipe system and should not be interpreted as evidence that FEA systematically produces lower stresses. Nevertheless, analytical methods such as API RP 1102 and CEPA remain useful in engineering practice because of their relatively simple procedures, computational efficiency, and standardized application in the oil and gas industry. The combined use of analytical and numerical approaches therefore provides a more comprehensive basis for assessing the structural response of buried pipelines at road crossings (He et al., 2024).

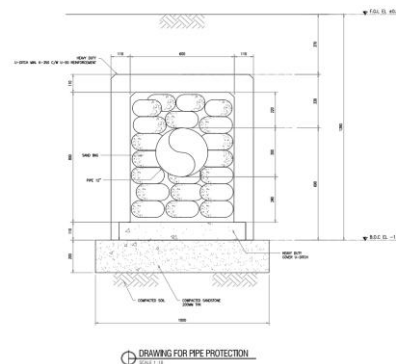


Figure 7. Pipeline protection recommendations

For the 12-inch pipeline installed beneath the toll road at burial depths below 0.7 m, a U-shaped trench system is recommended as an additional protection measure (Y. Li et al., 2025). The trench should provide adequate clearance above the pipeline to minimize direct transfer of traffic loads to the pipe (Ma et al., 2023). As illustrated in Figure 7, the trench has internal dimensions of 600 × 800 mm. Along the 200 m section with burial depths below 0.70 m (KP 0+425–KP 0+625), reinforced concrete with a minimum K-350 grade, U50 reinforcement, and a thickness of 110 mm is specified. For vibration protection along the remaining 400 m section (KP 0+025–KP 0+425), the same trench dimensions are maintained using concrete with a minimum K-175 grade (Alshibany et al., 2023). Detailed design calculations and drawings are provided in Appendix M (DNV GL, 2019). The proposed U-shaped trench functions as a protective barrier that reduces direct traffic-load transmission to the pipeline and provides additional structural protection under the specified road-crossing conditions.

## CONCLUSION

This study evaluated the minimum safe burial depth of buried gas pipelines at road crossings using API RP 1102, CEPA, and FEA. All methods showed that increasing burial depth reduces pipeline stress, with CEPA providing the most conservative results and FEA capturing soil-structure interaction more realistically. At 0.7 m burial depth, the stress ratios remained below the ASME B31.8 limit of 0.9 SMYS, establishing 0.7 m as the minimum safe burial depth under the specified loading conditions. Depths below 0.7 m produced substantially higher stresses and increased safety risks. Where 0.7 m cannot be achieved, reinforced U-ditch or equivalent structural protection is recommended. Vibration

assessment and soil characterization should also be incorporated during construction and operation to maintain pipeline integrity.

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