Quarterly Report - Public

Date of Report: *5th Quarterly Report – December 31, 2023*

Contract Number: *693JK32210010POTA*

Prepared for: *DOT PHMSA*

Project Title: ***Risk-Based Decision Support for Rehabilitation of Natural Gas Distribution Pipelines***

Prepared by: *GTI Energy*

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For quarterly period ending: December *31, 2023*

1: Work Performed During this Quarterly Period

Task 3 – Evaluate Pipe Response to Threats: This task includes numerical analysis using the finite element program COMSOL Multiphysics to evaluate pipe deformations resulting from soil movement.

Deformations from the above analysis will determine the acceptable limits above which pipe rehabilitation or replacement should be performed. Various earlier studies evaluated limits of pullout displacement of cast iron joints before leak failure occurs. These studies showed that the upper bound for joints movement during traffic loadings was 0.5 to 1.0 degrees and maximum recommended value for joint pullout was from 0.03 to 0.1 inches. Details of these studies and the FE analysis are shown in the attached task report. Figure 1 shows the quarterly deliverables.

		Technical and Deliverable Milestone Schedule			
Item No.	**Task No.**	**Activity/Deliverable**	**Quarter No.**	**Expected Completion Date/Mos**	**Payable Milestone**
	(per proposal)	**ACTIVITY/DELIVERABLE**			**TITLE**
8	3	Estimate pipe movement and strains in a Finite Element Program	5	15 months	Report: 'Evaluation of Pipelines Response to Threats'
9	8	Quarterly Status Report	5	15 months	Submit 5th quarterly report
		Fifth Payable Milestone	**5**	**15 months**	**SUBTOTAL**

Figure 1 – 3rd Quarterly Deliverable

2: Project Technical Status

An Interim Report, in the Attachment, includes the quarterly technical report.

3: Project Schedule

Figure 3 shows the project schedule and progress as of the end of 5th Quarter. No time-related issues are reported in this quarter.

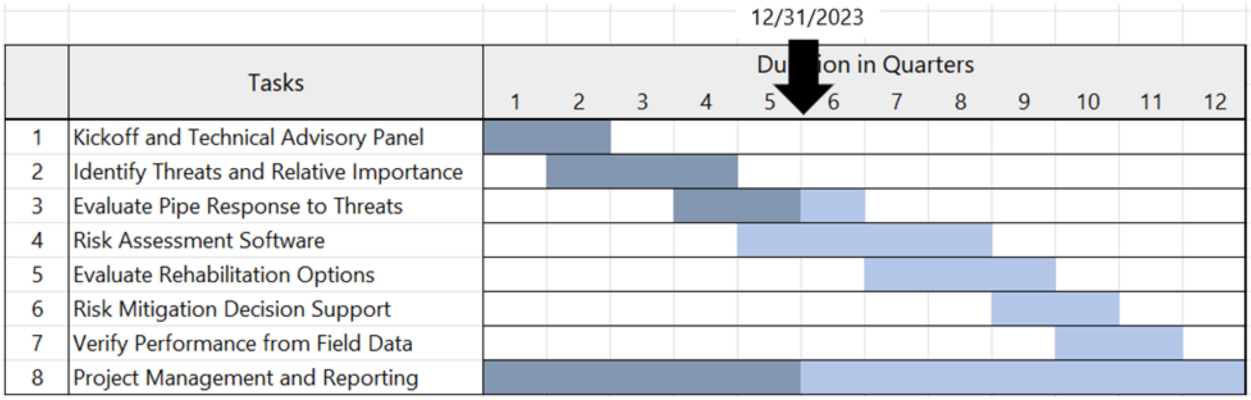

Figure 3 - Project time schedule

Task 3 - Pipeline Strains from Large Ground Movement

Introduction

Gas distribution pipelines may experience high strains in the events of soil movement resulting from external force, slope instability, flooding, and soil subsidence. Several guidelines provide recommended procedures and methods for the assessment of pipelines subjected to large soil deformation and seismic loading conditions [1, 2, and 3]. This task of the project focused on reviewing current procedures and analyzing pipeline-soil interaction with respect to axial, lateral and combined load effects on the pipe. The results of this analysis provide the limit strains under these loads for quantifying the risk factors due to outside force.

Most of the soil-pipeline interaction analysis represents the pipe as a structural beam with the soil represented as spring elements in the axial (longitudinal), transverse horizontal, and transverse vertical directions as shown in Figure 1 [4]. This simplification is derived from the concept of sub-grade reaction originally proposed by Winkler (1867). The axial load on the pipe results mainly from the friction caused by soil shear stresses acting around the pipe circumference.

As the ground displacement is progressively increased, the pipe may reach their specified compressive or tensile strain limits. Additionally, the soil may yield and continue to move past the pipe with no increased pipe deformations. Soil displacement may be taken as the upper bound of pipe displacement.

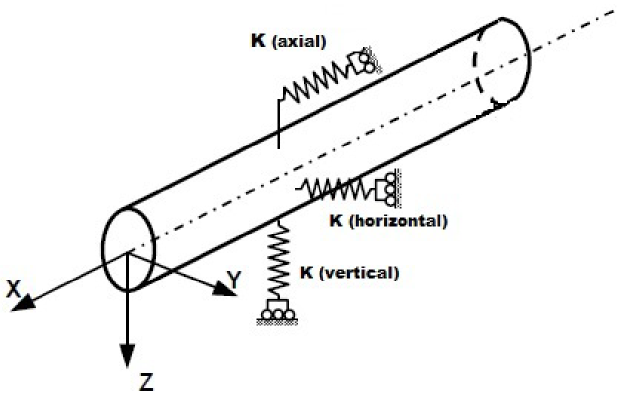

Figure 1 - Spring Elements Representation of Soil-pipe interaction

Differential soil settlement can result in significant deformation of buried pipes and above ground facilities such as gas meters. The ASME B31 code [5] indicates that large displacement stresses may be acceptable providing that excessive localized strains do not exceed their acceptable limits. Finite element analysis was performed in this task to estimate pipe strains from soil movement.

Finite Element Simulation of Pipe-Soil Interaction

Pipe-Soil interaction will be explored via a 3D finite element (FE) model in COMSOL Multiphysics®, that will consider multiple cases via design-of-experiment (DoE) methodology. The cases that are planned for simulation are shown in Table 6 below. The combination in the table requires up to 1428 simulations. The output of interest in each case is the strain in the pipe.

Table 6. Pipe-Soil Interaction DoE Parameters

Parameters	**Range of parameters for gas distribution lines**
Pipe Type	Steel mains (Grades A and X40) Plastic maines and services (PE) Case iron mains
Pipe Size	Plastic: 2-6 inch, SDR 11 Steel, 2-6 inch Cast iron: 4-12 inch
Soil Type	Loose sand Dense sand Clay
Length of Moving Soil Section	60-120 ft
Vertical & Horizontal Soil Movement	1-4 ft (all cases)

Table 5 – Allowable Stresses and Strains Due to Soil Loading

Loading Condition	Allowable Load or Stress	Allowable Deformation or Strain
Hoop stress from internal pressure and fluid transients	Code allowable for internal pressure	N/A
Through-wall bending from earth loads (static, live, surface impact)	Bending stress < 0.5 σ_y	N/A
Hoop compression from earth loads (static, live, surface impact)	Compressive stress < 0.5 σ_y	N/A
Ring buckling from earth loads (static, live, surface impact)	Compressive load < $\frac{1}{FS}\sqrt{32 R_W B' E' \frac{EI}{D^3}}$	Strain limits: Mortar-lined and coated = 2% D Mortar-lined & flexible coated = 3% D Flexible lining & coated = 5% D
Bending stress from buoyancy	Bending stress < σ_y[6]	Strain limits: Tension: 0.5% Compression: 0.5%
Thermal expansion	Code allowable for secondary loading[1]	N/A
Movement at bends	Code allowable for primary loading[1]	N/A
Longitudinal strain from ground movement due to earthquake, landslide, or mine subsidence, combined with thermal strain	N/A[2]	***Operable limits***[4,5] Tension strain limit 2% Compression strain limit $0.50\left(\frac{t}{D'}\right)-0.0025+3000\left(\frac{pD}{2Et}\right)^2$ $D'=\frac{D}{1-\frac{3}{D}(D-D_{min})}$ ***Pressure integrity limits***[4,5] Tension strain limit 4% Compression strain limit $1.76\frac{t}{D}$

The FE model simulates the soil as 3D volume (Figure 7) and implements the Mohr-Coulomb soil plasticity constitutive model. The pipe is modeled with shell elements and implements an elastic-plastic strain-hardening constitutive model. The pipe's shell elements are directly "attached" to the respective coplanar soil elements, thereby disregarding any soil slippage on the pipe OD surface, which can be considered negligible [1].

The simulations are static, which assumes soil movement is slow and inertial effects are negatable; material behavior is also considered to be time-independent under static simulation. The mesh of the model is refined based on proximity to the pipe and moving soil regions (Figures 8 and 9). Linear elements are used throughout.

[1] O'Rourke, Michael J., Xuejie Liu, and Raul Flores-Berrones. "Steel pipe wrinkling due to longitudinal permanent ground deformation." Journal of transportation engineering 121.5 (1995): 443-451.

Soil movement is controlled via a prescribed displacement in the vertical or lateral direction, depending on the load case. Figure 10 shows an example of a lateral soil movement gradient. Gravity is included in all cases. Symmetry along the length of the pipe is utilized in the vertical loading case (Figure 11).

Figure 12 shows an example of a preliminary lateral soil movement case. In this figure total displacement is plotted on the soil surfaces and 1st principal strain is plotted on the pipe (shell) surfaces. The pipe displacement is completely driven by the displaced soil and as expected, the maximum pipe strain is located at end of the moving soil boundary. Figure 13 shows the maximum 1st principal strain of the entire pipe volume as a function of the peak soil displacement boundary condition.

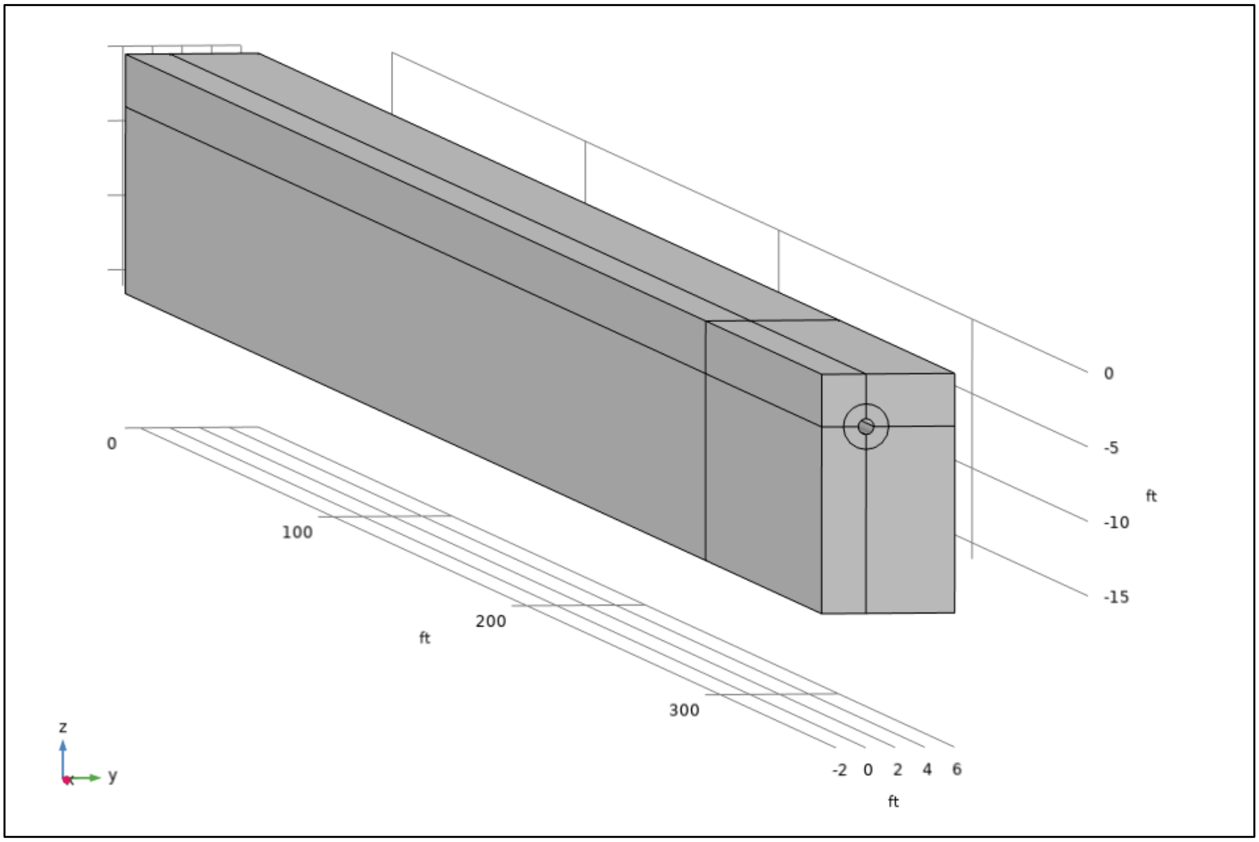

Figure 7 - FE Model Geometry, Lateral Soil Movement Case

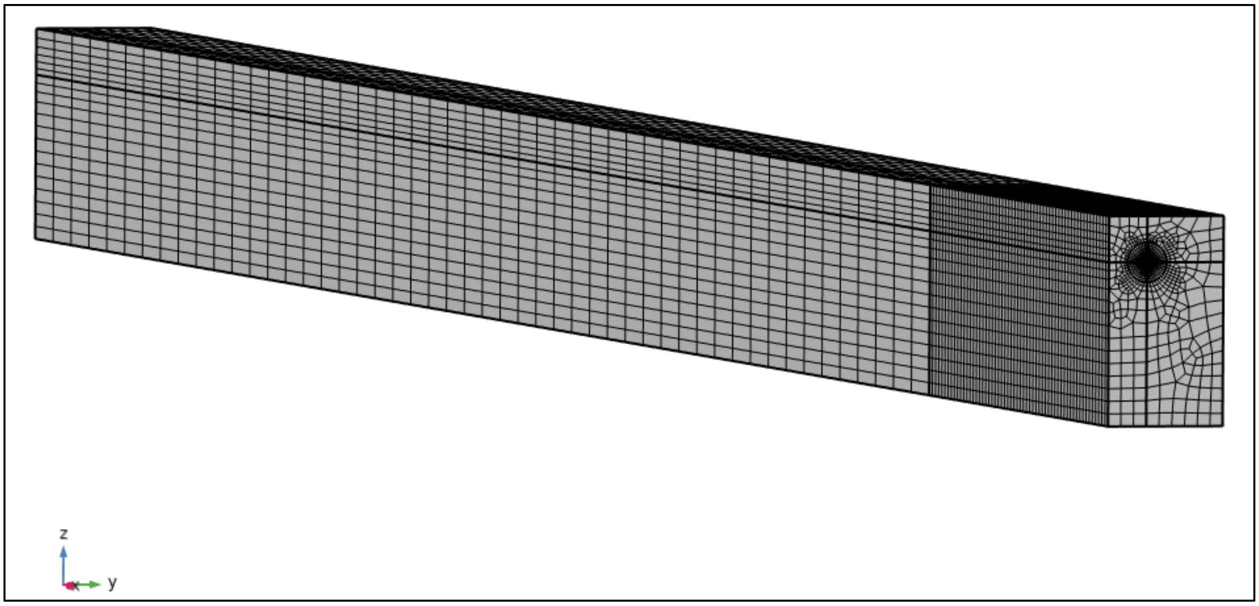

Figure 8 - FE Model Mesh, Lateral Soil Movement Case

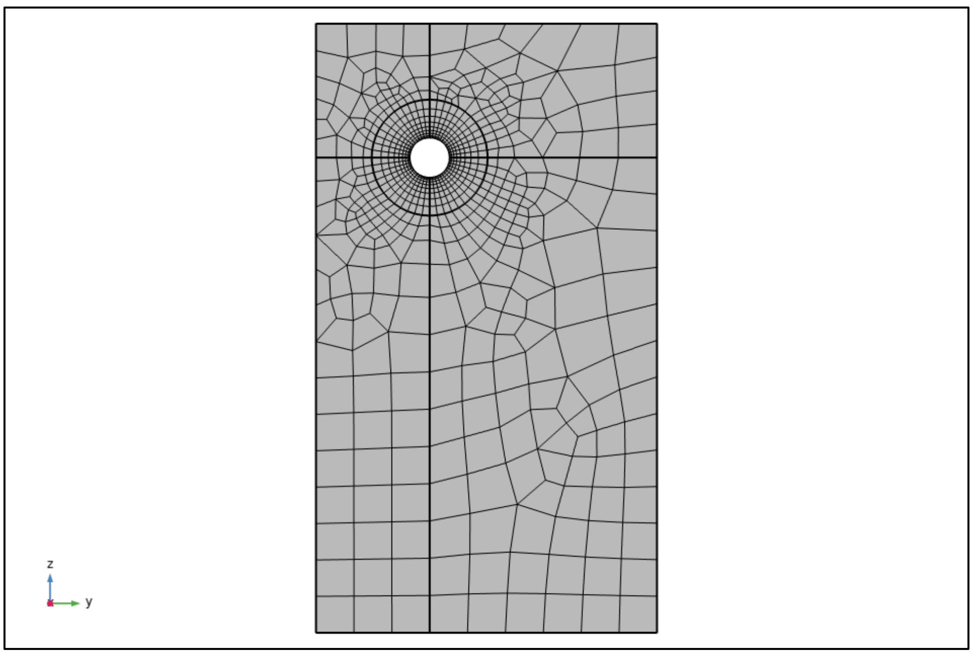

Figure 9 - FE Model Mesh, Cross-Section View, Lateral Soil Movement Case

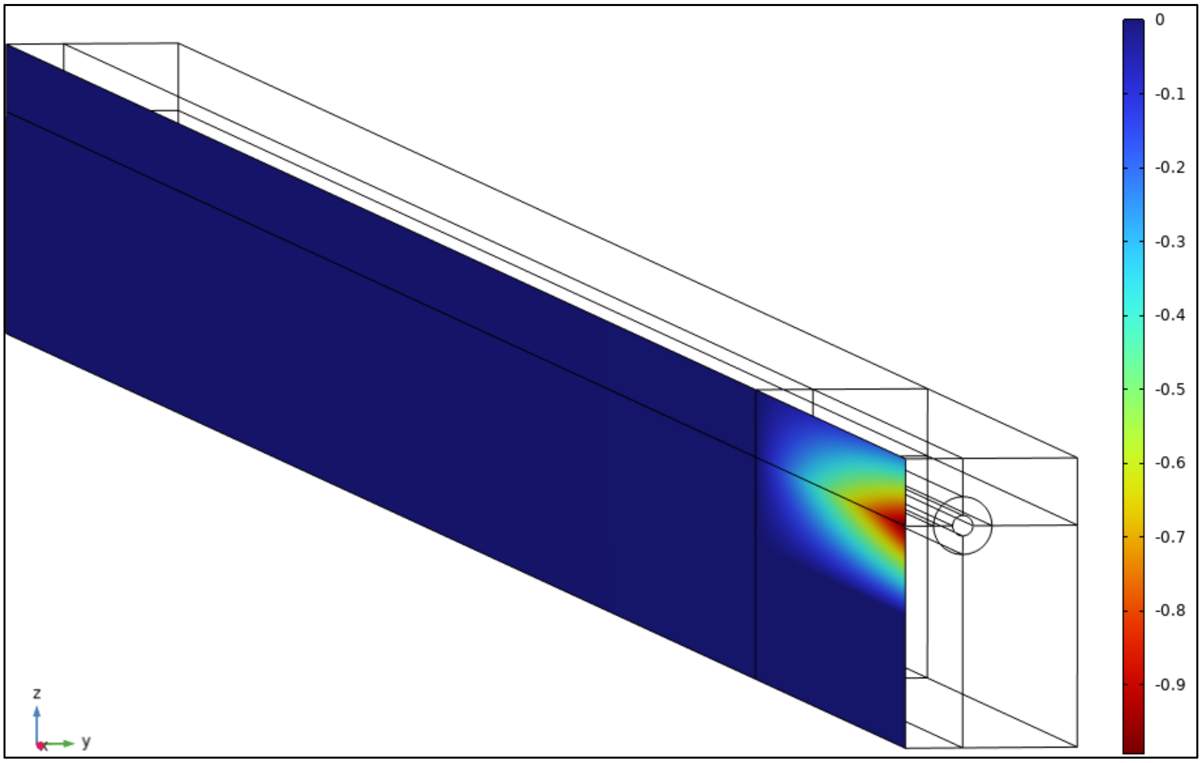

Figure 10 - FE Model Boundary Conditions, Lateral Soil Movement Case

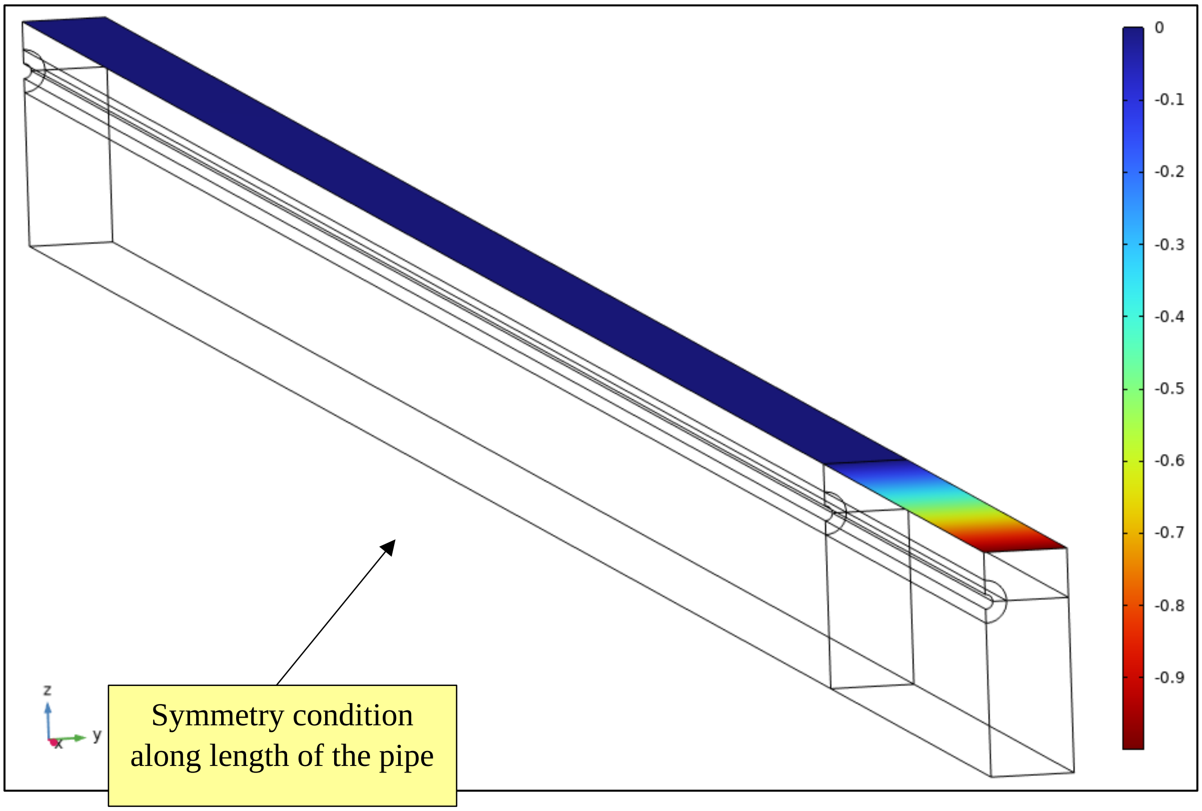

Figure 11 - FE Model Boundary Conditions, Vertical Soil Movement Case

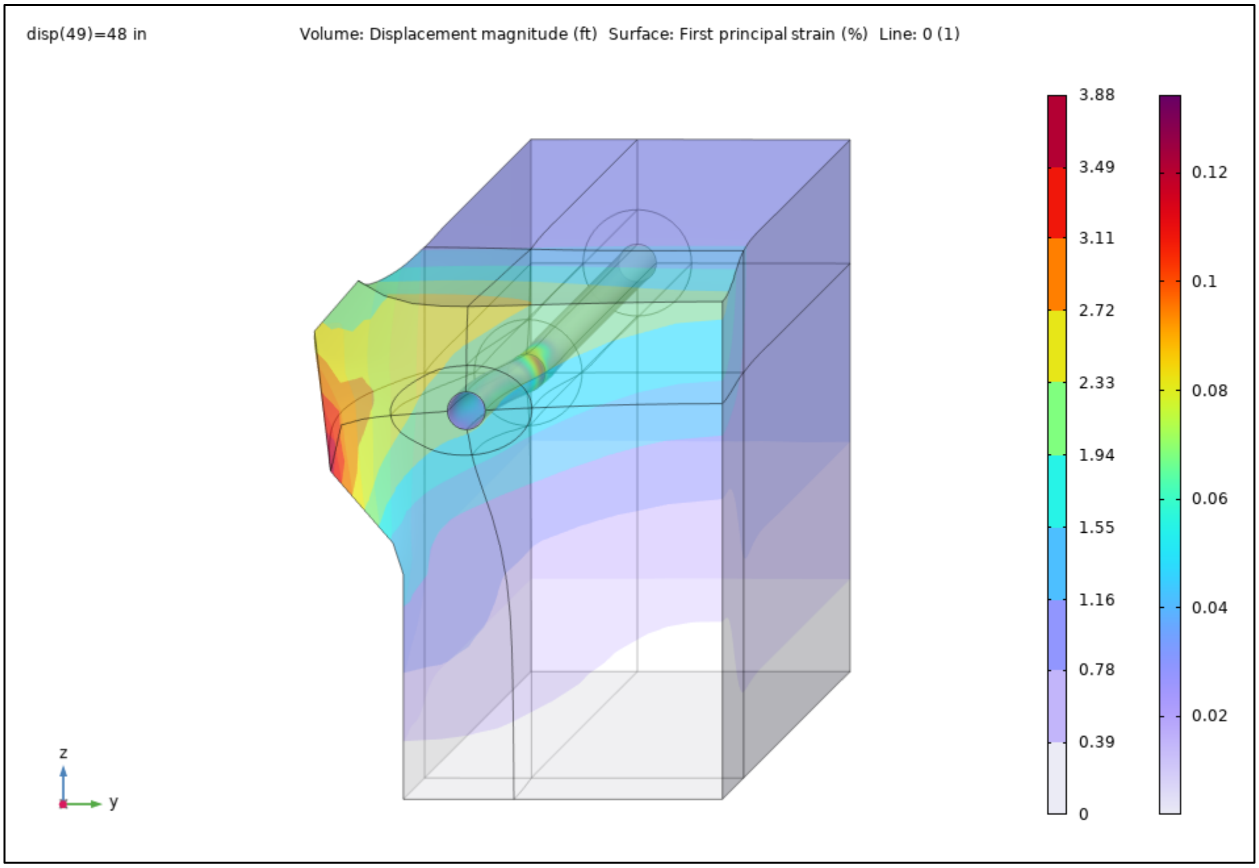

Figure 12 - Preliminary Model Result, Lateral Soil Movement Case

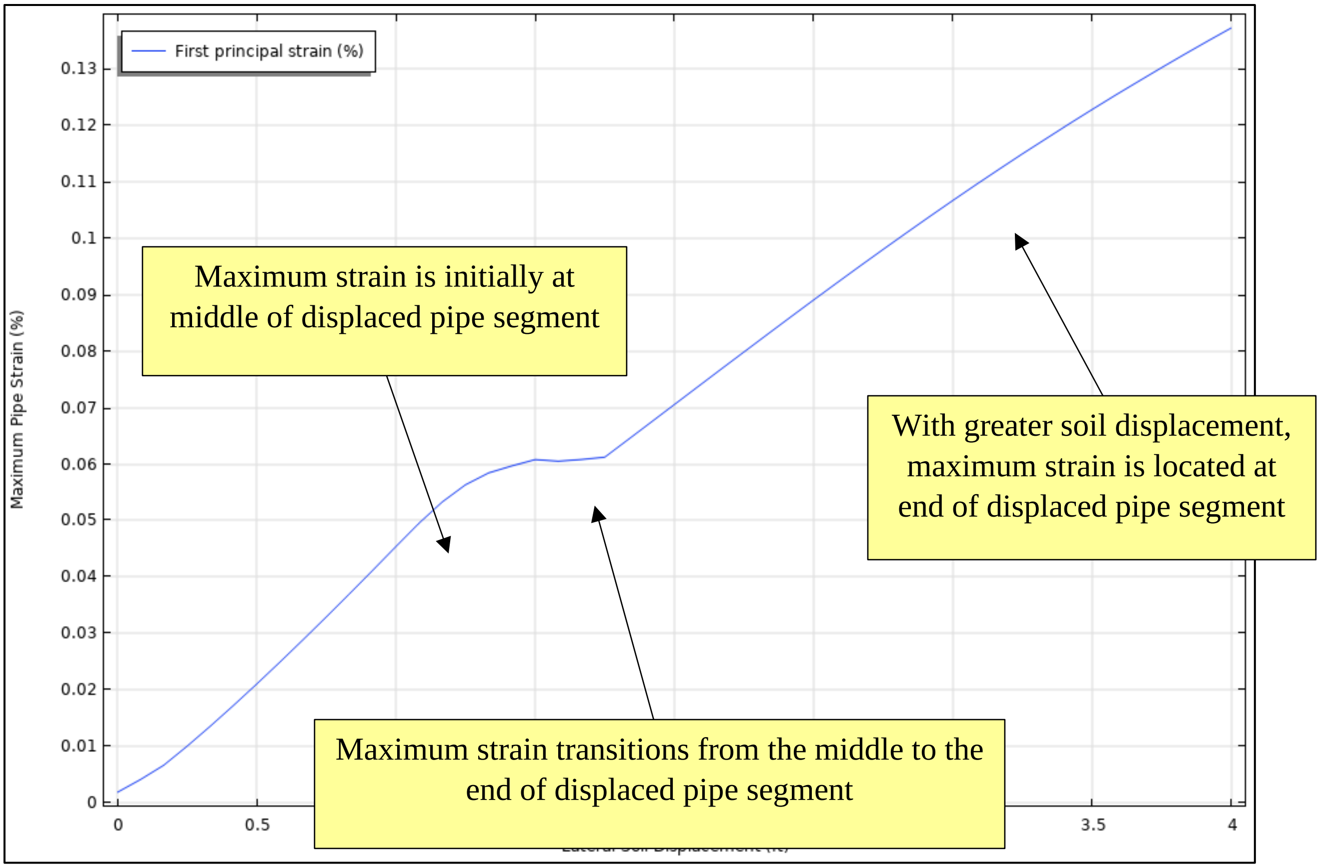

Figure 13 - Steel Pipe Maximum 1st Principal Strain, Lateral Soil Movement Case

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10. O'Rourke, M.J., El Hmadi, K. (1988), "Analysis of continuous buried pipelines for seismic wave effects", Earthquake Engineering and Structural Dynamics, Vol. 16, No. 6, pp. 917-929.
11. Evaluating Service Life of Anaerobic, Joint Sealing Products and Techniques, Cornell University, Gas Technology Institute, Report GRI-96/0318, 1996.

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