Multidiszciplináris Tudományok, 15. kötet, 3. sz. (2025) pp. 20–31. **https://doi.org/10.35925/j.multi.2025.3.3**

NUMERICAL MODELING OF PIPE-SOIL INTERACTION UNDER SURFACE LOADING

Attila Baksa
associate professor, Institute of Applied Mechanics, University of Miskolc
3515 Miskolc-Egyetemváros, e-mail: attila.baksa@uni-miskolc.hu

Erika B. Varga
associate professor, Institute of Informatics, University of Miskolc
3515 Miskolc-Egyetemváros, e-mail: erika.b.varga@uni-miskolc.hu

Abstract
Buried steel pipelines (BSPs) subjected to large surface-induced ground movements (e.g., fault displacements) exhibit complex behavior that is not yet fully understood. Such ground-induced deformations give significant risks to pipeline integrity, motivating detailed investigation into BSP response under extreme conditions. This study addresses the problem by numerically modeling pipe–soil interaction under a 1.0 m vertical fault displacement, illustrating the pipeline's stress–strain response and highlighting the challenges of this complex engineering scenario. The purpose of this paper is to demonstrate a robust simulation approach that captures the intricate BSP behavior under large ground shifts, thereby advancing understanding and aiding in the safe design of buried pipelines. The analysis employs a Pasternak elastic foundation model coupled with a finite element method (FEM) in Abaqus, using special pipe–soil interaction (PSI) elements to simulate the soil support and pipeline coupling. The numerical results provide detailed stress and displacement distributions along the pipeline, confirming an elastic–plastic deformation pattern. Permanent deformations (plastic yielding) develop primarily in the vicinity of the fault, while pipeline regions farther than roughly 100 m remain in the elastic region.

Keywords: *buried steel pipes (BSPs), surface load, pipe-soil interaction, numerical modeling*

1. Introduction

Oil, water, and gas pipelines are typically buried underground to provide both protection and structural support. These systems play a critical role in daily life and industrial operations, thanks to their simple beam-soil structure, ease of construction, and environmental friendliness. As a result, buried steel pipes (BSPs) have been widely adopted for the efficient transportation of various materials.

The pipes themselves are manufactured from high-strength steel with sufficient stiffness to withstand both internal and external loads. While the surrounding soil exerts pressure on the pipe, it also offers lateral support, contributing to the pipe's structural rigidity and helping it maintain its shape (Watkins, 2001).

Despite the importance of this pipe-soil interaction, it remains a complex and not fully understood phenomenon. In fact, it was not studied in detail until 2019, when Bildik and Laman (2019) conducted a comprehensive investigation into the behavior of buried steel pipes under such conditions.

Steel gas pipelines play an important role in urban energy distribution. Ground surface explosions are the main threat for urban buried steel pipelines in paper by Chi et al. (2023) the behavior of underground steel pipelines exposed to ground surface explosion was examined. Zhang et al. (2023) use Abaqus-based finite element simulations to analyze buried pipeline behavior under strike-slip faulting, evaluating influences such as crossing angle, ground motion characteristics, and soil–pipe interaction on deformation and failure mechanisms, including local buckling and tensile strain. Vilca et al. (2023) conduct a comprehensive FEM parametric study of thin-walled buried steel pipes subjected to heavy haul-road vehicle loading, identifying trench backfill height and lateral fill stiffness as key parameters governing pipe deflection and stress response.

To meet the continuously growing global demand for water supply and energy, large-diameter buried pipes have become increasingly popular and widely adopted in major water diversion and hydropower projects. Figure 1 illustrates the construction of a large-diameter buried steel pipe (BSP) at a project site, where the pipe diameter D is comparable to human height, while the wall thickness remains below 15 mm.

BSPs are generally characterized by significant flexibility, high internal pressure loads, and interaction with a wide range of soil types. These factors collectively complicate the accurate assessment of their mechanical performance and the behavior of pipe-soil interaction. Therefore, a detailed investigation into the influence of critical soil parameters on the structural behavior of BSPs is of great importance.

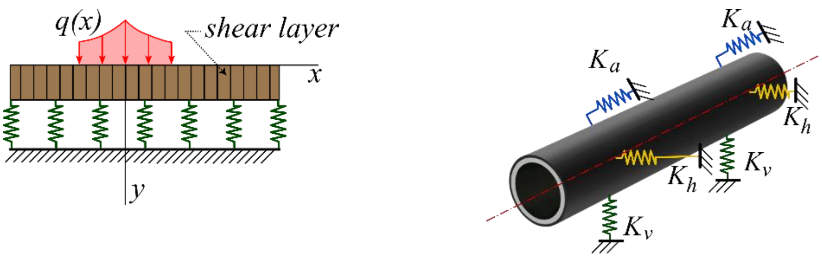
Figure 1. *A large-diameter BSP in site*

The aim of this paper is to demonstrate how special-purpose finite elements, implemented in a commercial numerical modeling software, can be used to effectively simulate buried pipeline behavior. These pipelines are often subjected to significant loads due to relative ground displacements along their alignment. Such displacements can result from fault movements, landslides, slope failures, earthquake-induced ground deformation, or other seismic hazards (Achilleas et al., 2019). These permanent ground movements pose a serious threat to pipeline integrity, potentially causing large axial and bending strains that may ultimately lead to rupture-either due to tensile failure or buckling (O'Rourke and Liu, 1999).

2. Mechanical Analysis

Buried pipelines can be analyzed using the Winkler elastic foundation beam model or the more advanced Pasternak foundation model (Pasternak, 1954). In this study, it is assumed that the pipeline exhibits uniform rigidity along its axial direction, and the effects of pipe-to-pipe joints are neglected, treating the pipeline as a continuous, monolithic structure.

The Pasternak foundation model extends the basic Winkler model by introducing shear interaction between adjacent spring elements. This shear coupling is realized by connecting the individual vertical spring elements through a shear layer that can deform transversely but remains incompressible. As a result, the Pasternak model better captures the continuous nature of the soil's response compared to the independent springs in the Winkler model.



a.) b.)

Figure 2. *a.) Pasternak foundation vs. b.) Winkler type model*

In a two-dimensional formulation, the Pasternak foundation model can be mathematically expressed as follows:

$$G_P \frac{\mathrm{d}^2 w(x)}{\mathrm{d}x^2} + q(x) = kw(x). \tag{1}$$

In this model, $q(x)$ represents the reaction force exerted by the foundation, k is the foundation modulus (reaction coefficient), $w(x)$ is the deflection of the buried pipeline, and G_P denotes the shear stiffness of the foundation. When the shear stiffness is neglected (i.e., $G_P = 0$), *Equation (1)* simplifies to the classical Winkler model, where no shear interaction exists between adjacent spring elements.

The Pasternak model, as a two-parameter foundation model, is characterized by the constants k and G_P. These parameters can be related to the soil's elastic properties, namely the modulus of elasticity E_s and the Poisson's ratio ν. An empirical relationship proposed in (Yao, 2010) provides a more representative connection between these values and can be expressed as:

$$G_P = \frac{E_S H}{6(1+\nu_S)}. \tag{2}$$

In the above expressions, E_s is the elastic modulus of the foundation soil, ν is the Poisson's ratio of the soil, and H denotes the thickness of the elastic layer.

The buried pipeline is assumed to behave as a beam resting on an elastic foundation. Under this assumption, the relationship between the pipe's deflection $w(x)$, the applied load $q_1(x)$, and the resulting foundation reaction force $p(x)$, can be expressed as:

$$EI\frac{\mathrm{d}^4w}{\mathrm{d}x^4} = q_1 - p, \tag{3}$$

where E is the elastic modulus of steel, I is the section moment of inertia of the pipe.

According to the Pasternak foundation model, *Equation (3)* can be written as

$$EI\frac{\mathrm{d}^4w}{\mathrm{d}x^4} + kDw = G_P D\frac{\mathrm{d}^2w}{\mathrm{d}x^2} + q_1. \tag{4}$$

In *Equation (4)*, D represents the outer diameter of the pipe, k is the elastic coefficient of the soil, and G_P denotes the shear stiffness of the foundation.

Based on the equations presented above, it is possible to derive expressions for key structural responses at any section of the pipeline, including the rotation angle θ, the bending moment M, and the shear force Q.

$$\theta(x) = \frac{\mathrm{d}w}{\mathrm{d}x} \tag{5}$$

$$M(x) = -EI\frac{\mathrm{d}^2w}{\mathrm{d}x^2} \tag{6}$$

$$Q(x) = -EI\frac{\mathrm{d}^3w}{\mathrm{d}x^3} \tag{7}$$

3. Finite element analysis

The pipe–soil interaction (PSI) elements available in `Abaqus/Standard` can be used to simulate the connection between a buried pipeline and the surrounding soil. The pipeline itself is modeled using beam elements, which may incorporate either linear or nonlinear constitutive behavior depending on the analysis requirements.

The ground response and the interaction between the soil and the pipe are represented using PSI elements. These elements possess only translational degrees of freedom at their nodes. One side of each PSI element shares nodes with the underlying beam elements that model the pipeline. The opposite side represents the far-field (e.g., ground surface) and is used to define far-field ground motion through boundary conditions, which may include time-dependent amplitude references as necessary.

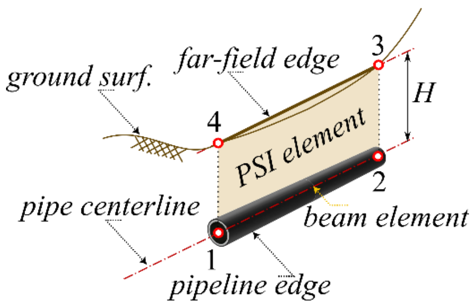


Figure 3. *Pipe-soil interaction element*

The far-field side and the side that shares nodes with the pipeline are defined by the element connectivity. It is essential to ensure that the pipeline is attached to the correct edge of the PSI element, as the connectivity determines the element's local coordinate system and the depth, H, of the pipeline below the ground surface. This depth is measured along the vertical edge of the PSI element, as illustrated in *Figure 3*, and is dynamically updated during geometrically nonlinear analysis.

It is important to emphasize that PSI elements do not discretize the physical domain of the surrounding soil. Instead, the extent and influence of the soil medium are captured through the stiffness properties assigned to the PSI elements, which are defined by the constitutive model.

Furthermore, the PSI model does not include the mass of the surrounding soil. If inertial effects are to be considered, concentrated mass elements may be applied at the nodes of the PSI elements to represent the influence of the soil's mass.

Kinematics and local coordinates

The deformation of the pipe-soil interaction (PSI) element is characterized by the relative displacements between its two edges. When the element undergoes "strain" due to these relative displacements, corresponding reaction forces are applied to the pipeline nodes. These forces may follow a linear (elastic) or nonlinear (elastic–plastic) constitutive relationship, depending on the material model assigned to the element.

Positive strain in the local coordinate direction is defined as:

$$\varepsilon_{ii} = \Delta\boldsymbol{u} \cdot \boldsymbol{e}_i \tag{8}$$

where $\Delta\boldsymbol{u} = \boldsymbol{u}^f - \boldsymbol{u}^p$ is the relative displacement vector between the two sides of the PSI element. Here, u^f denotes the displacement at the far-field side, and u^p represents the displacement at the pipeline side. The vectors e_i $(i = 1,2,3)$ define the local coordinate directions of the element.

In two-dimensional analysis, only the in-plane strain components ε_{11} and ε_{22} are considered. In contrast, for three-dimensional elements, all three strain components ε_{11}, ε_{22}, and ε_{33} are computed.

The local orientation system of the pipe-soil interaction element is defined by three orthonormal vectors: e_1, e_2, and e_3. By default, e_1 represents the axial direction along the pipeline, e_2 is oriented normal to the plane of the element in the transverse horizontal direction, and e_3 lies within the plane of the element and characterizes the transverse vertical response.

The default positive orientation is such that e_1 points from the first pipeline node toward the second, while e_3 points from the pipeline edge of the element toward the far-field edge. This local coordinate system establishes the reference for computing directional deformations and forces within the PSI element, and its alignment is illustrated in *Figure 3*.

Constitutive model

The constitutive behavior of a pipe-soil interaction element is defined in terms of the force per unit length-referred to as the "stress" q_i, that develops at each point along the pipeline due to the relative displacement, or "strain", ε_{jj} between that point and the corresponding location on the far-field surface.

$$q_i = q_i(\varepsilon_{jj}, s_\alpha, f_\beta, \ldots) \tag{9}$$

This behavior may also depend on additional state variables, such as accumulated plastic strain s_α, as well as on temperatures f_β, and other field variables.

These constitutive relationships can be defined in a general and customizable way by implementing a user-defined material model through the `UMAT` subroutine. Alternatively, `Abaqus/Standard` allows the behavior to be specified directly through input data, under the assumption that the response of the foundation is separable along the local coordinate directions.

In the separable case, each of the directional force-displacement relationships (axial, transverse horizontal, and transverse vertical) must be defined independently. By default, `Abaqus` assumes that these relationships are symmetric with respect to the origin, which is typically appropriate for axial and horizontal motions. However, non-symmetric behavior may also be specified when necessary, for example, in the vertical direction where the pipeline is shallowly buried and experiences different responses in tension versus compression.

In all cases, the PSI model assumes that positive strain induces a force on the pipeline acting in the positive direction of the corresponding local axis.

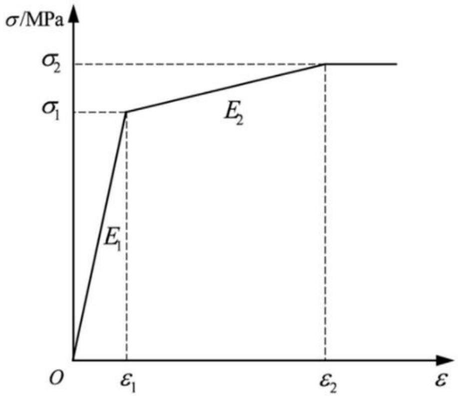


Figure 4. *Constitutive relationship of the pipe tree-fold line model*

For a nonlinear material model, the force-displacement relationship is defined as a function of positive and negative relative displacement (referred to as "strain"), temperature, and any relevant field variables. The data must be specified in ascending order of relative displacement, and the input range should be wide enough to capture the full behavioral response of the material. Outside this specified range, the force is assumed to remain constant.

To distinguish between tensile and compressive behavior, the data must include a point at the origin of the force-displacement diagram, which separates the positive and negative branches of the response. The model provides linear elastic behavior as long as the following conditions are satisfied:

$$F_n = q - \overline{q}_n\left(\overline{\varepsilon}_n^{pl}\right) \geq 0 \qquad F_p = q - \overline{q}_p\left(\overline{\varepsilon}_p^{pl}\right) \leq 0 \tag{10}$$

where $\overline{\varepsilon}_n^{pl}$ and $\overline{\varepsilon}_p^{pl}$ are the equivalent plastic strains associated with negative and positive relative displacements, respectively. Inelastic deformation occurs once the relative force exceeds these initial elastic limits.

The model allows for independent hardening in tension and compression through the evolution of $\overline{q}_n(\overline{\varepsilon}_n^{pl})$ and $\overline{q}_p(\overline{\varepsilon}_p^{pl})$. During loading, the plastic strain in the opposite direction remains constant; that is, $\overline{\varepsilon}_p^{pl}$ does not evolve when the relative displacement is decreasing, and $\overline{\varepsilon}_n^{pl}$ does not evolve when the relative displacement is increasing.

Relative pipe-soil displacement

Buried pipelines may be subjected to significant bending and tensile forces due to surface-induced ground movements or large operational loads, such as those caused by thermal expansion or contraction. Common sources of ground movement include differential soil settlement, fault displacement, and lateral spreading during seismic events. Evaluating the structural response of pipelines under such conditions typically requires the use of finite element analysis that incorporates both nonlinear soil behavior and nonlinear material response of the pipeline. This approach allows for a more accurate assessment of deformation patterns, internal forces, and potential failure mechanisms in complex loading environments.

4. Numerical example

The purpose of this example is to evaluate the stress distribution along the length of an infinitely long buried pipeline subjected to a large fault displacement of $1.0\ m$, as illustrated in Figure 5. The pipeline intersects the fault at an angle of $90.0°$.

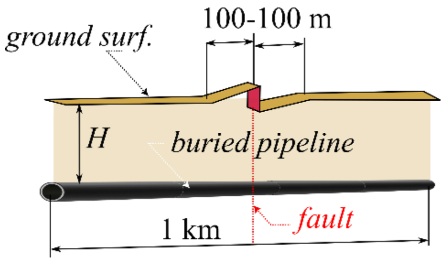


Figure 5. *Pipe with fault motion*

The problem involves an idealized, infinitely long pipeline buried at a depth of 5.0 m below the ground surface. For computational efficiency, only a 1000.0 m segment of the pipeline is modeled. The pipe has an external radius of D with three different values $508 - 609.6 - 762$ mm and a wall thickness of 12.7 mm. The pipeline is discretized using 100 first-order `PIPE21` elements, arranged in a nonuniform mesh that concentrates finer elements in the region near the fault to improve resolution.

The pipe-soil interaction behavior is modeled using `PSI24` elements. These elements are defined such that one edge is connected to the nodes of the underlying pipe element, while the opposite edge represents a far-field surface where prescribed ground motion is applied. The orientation of each PSI element, including which edge corresponds to the pipeline and which to the far-field, is determined by the element connectivity.

To verify the accuracy of the two-dimensional model, a corresponding three-dimensional simulation is also performed using `PIPE31` and `PSI34` elements.

Table 1

Pipe (X65) material parameters

Density [kg/m^3]	Young's modulus [GPa]	Poisson's ratio [–]	Elastic yield stress [MPa]	Elastic yield strain [–]	Plastic yield stress [MPa]	Plastic yield strain [–]
7850	210	0.3	498	2.4e-3	565	30e-3

The pipeline is composed of an elastic–perfectly plastic metal with a Young's modulus of $E = 210.0$ GPa, a Poisson's ratio of $\nu = 0.3$, and the corresponding stress-strain data is given by Table 1.

Figure 6. *Finite element model of PSI*

The pipe-soil interaction behavior is also modeled as elastic-perfectly plastic, using a nonlinear constitutive model to define the interaction response. The vertical and axial directions are treated independently, with differing behavioral assumptions. It is assumed that the pipeline is buried deep enough beneath the ground surface for the interaction response to be symmetric about the origin. However, `Abaqus` also supports non-symmetric behavior in any direction, which may be applicable in cases where the burial depth is shallow, particularly in the vertical direction.

In this example, the ultimate force per unit length in the axial direction is specified as $1{,}200.0\ \mathrm{N/m}$, and in the vertical direction as $1{,}500.0\ \mathrm{N/m}$. The corresponding ultimate relative displacement for axial directions is $5\ \mathrm{mm}$, and for vertical direction is $350\ \mathrm{mm}$ beyond which the force remains constant.

Since the loading occurs in the axial-vertical plane, the properties associated with pipe-soil interaction in the transverse horizontal direction are not considered relevant for this analysis. The loading on the pipeline is induced by a relative vertical displacement of $1.0\ \mathrm{m}$ along the fault line. It is assumed that the effect of this vertical ground motion decreasing linearly over a distance of $100.0\ \mathrm{m}$ from the fault origin, see *Figure 5*.

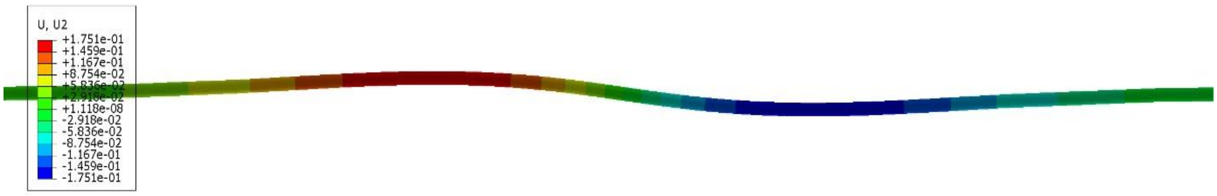


Figure 7. *Pipe with fault vertical motion (scale = 20x)*

Since the loading occurs in the axial-vertical plane, the properties associated with pipe-soil interaction in the transverse horizontal direction are not considered relevant for this analysis. The loading on the pipeline is induced by a relative vertical displacement of 1.0 m along the fault line. It is assumed that the effect of this vertical ground motion decreases linearly over a distance of 100.0 m from the fault origin.

5. Results

The simulations include three pipe diameters (508 mm, 609.6 mm, 762 mm). The results show that (1) vertical force per unit length is only slightly affected by diameter, (2) axial stress variation is minimal between diameter cases, and (3) differences are attributed to variations in bending stiffness (EI). These small differences are physically realistic and indicate that numerical noise or mesh irregularities are not dominating the results.

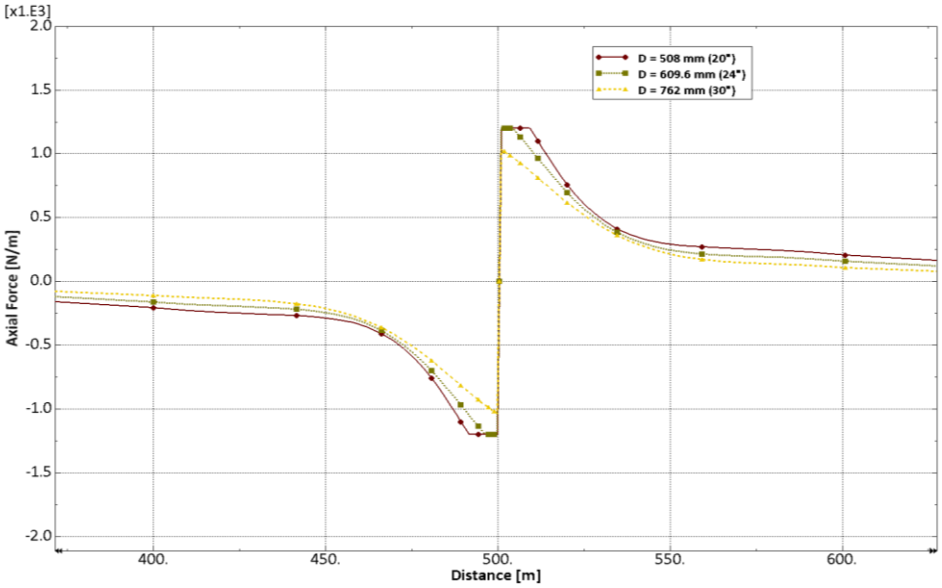


Figure 8. *Applied load along the pipeline from the soil elements (axial force/unit length)*

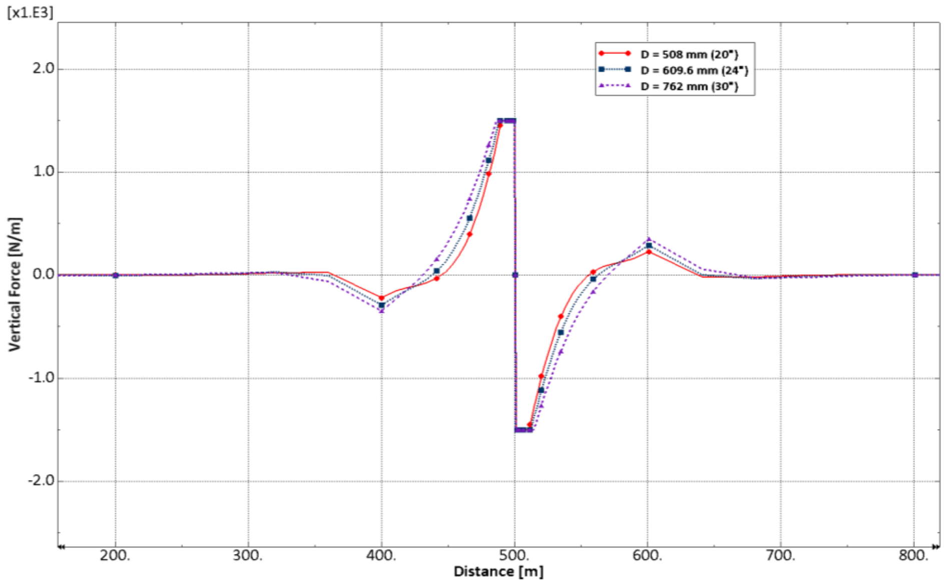


Figure 9. *Applied load along the pipeline from the soil elements (vertical force/unit length)*

Although explicit convergence testing is not detailed, the mesh refinement near the fault (nonuniform element size) and use of 100 PIPE21 elements in 2D, and confirmation via a corresponding 3D simulation (PIPE31 + PSI34 elements), indicate that the model was tested for dimensional consistency and robustness. Agreement between 2D and 3D results enhances confidence in numerical accuracy and stability.

The paper supports its claim of good agreement through. Reproduction of physically expected deformation modes (elastic–plastic transition, symmetry). Agreement of stress and displacement profiles with theory. Minor, explainable variation across parameter changes (diameter). Cross-checking with a 3D model for verification.

While there is no formal error analysis or experimental validation in this work, the consistency with mechanics theory and internal checks (e.g., comparing diameters, dimensions) provide credible support for the model's numerical accuracy and mechanical realism.

Figures 8 and *9* illustrate the axial and vertical forces per unit length acting on the pipeline because of vertical ground displacement. The variation in pipeline geometry (specifically, the outer diameter) has a relatively minor effect on the vertical force and causes only slight changes in the axial force distribution.

Figure 10 compares the axial stress in the bottom wall of the pipeline for different outer diameters. Stress distribution along the pipe is shown to be approximately linear *(Figure 10)*, which is consistent with beam theory under gradually varying loads. The figure demonstrates that the pipeline response is approximately linear across the cases considered. *Figure 11* shows the vertical displacement along the pipeline near the failure zone, for different pipe diameters. Vertical displacements around the fault *(Figure 11)* match the shape expected for a beam on an elastic foundation subjected to localized loading, i.e., the maximum deformation at the fault, changing symmetrically with distance.

The results indicate that permanent deformation develops in the pipe-soil interaction zone near the fault, both in the axial and horizontal directions, while regions farther from the fault exhibit purely elastic behavior.

The small discrepancies between the solutions can be attributed to variations in bending stiffness. Additionally, the reaction forces at the pipeline boundaries and the maximum displacements show good agreement with expected mechanical behavior.

This match suggests that the finite element model reproduces the expected structural behavior under such load conditions, validating its reliability.

6. Conclusions

This study demonstrated the effectiveness of using special-purpose pipe-soil interaction (PSI) elements in Abaqus to model the behavior of buried steel pipelines subjected to large vertical ground displacements. The comparative analysis using varying pipeline geometries revealed that axial and vertical forces are only moderately influenced by the pipe's outer diameter, while stress and displacement fields remain consistent with expected elastic-plastic behavior.

The results highlight that permanent deformation occurs primarily in the vicinity of the fault, while the pipeline responds elastically in regions farther from the fault plane. This localized plasticity is consistent with analytical solutions for buried beams where maximum bending and axial strains occur near sudden ground movements. The localized yielding followed by elastic zones further confirms the correctness of the material modeling and boundary conditions.

The near-linear stress distribution and close agreement in boundary reaction forces across models confirm the robustness of the numerical approach. Overall, the Pasternak-type PSI modeling approach provides a reliable framework for assessing pipeline performance under large-scale ground movement. Future work will consider dynamic loading and more complex soil behaviors to further refine the predictive capabilities of the model.

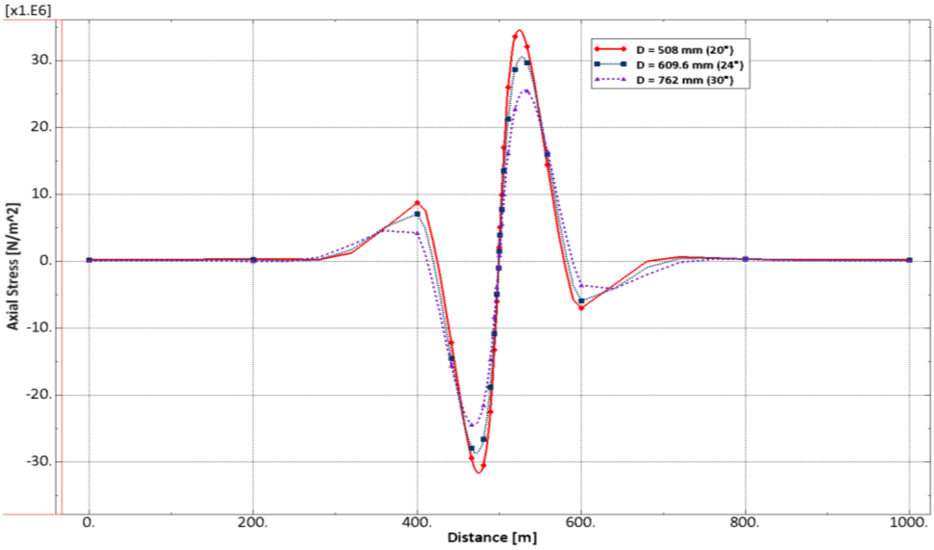


Figure 10. *Axial stress along the bottom of the pipeline*

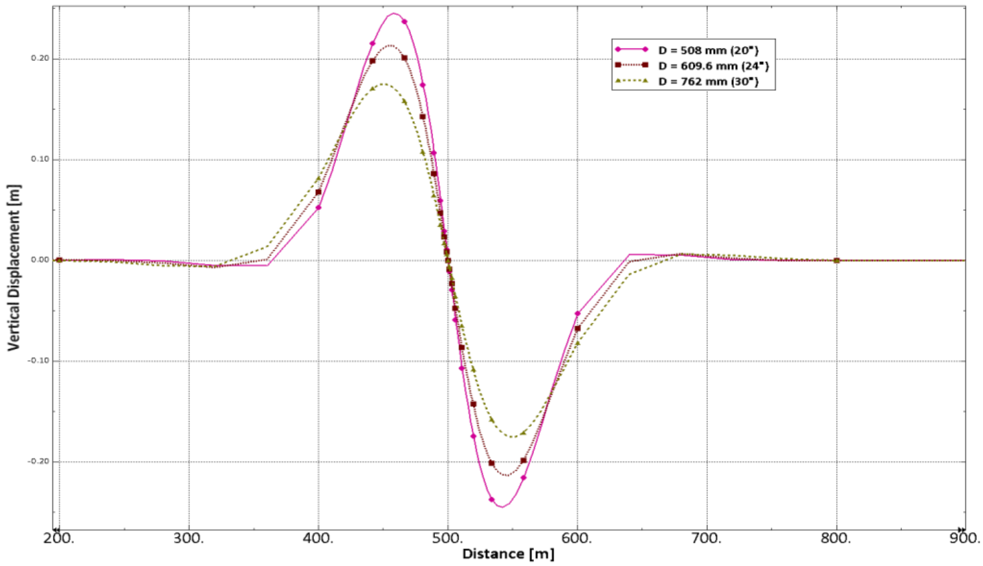


Figure 11. *Vertical displacement along the pipeline near the failure*

References

[1] Bildik, S., Laman, M. (2019). Experimental Investigation of Soil – Structure – Pipe Interaction. *KSCE Journal of Civil Engineering*, 23 (9), pp. 3753–3763. **https://doi.org/10.1007/s12205-019-0134-y**

[2] Audibert, J. M. E., Nyman, D. J., and O'Rourke, T. D. (1984). Differential ground movement effects on buried pipelines. *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems, ASCE publication*, pp. 151–180.

[3] Dezfooli, M. S., Abolmaali, A., Razavi, M. (2015). Coupled nonlinear finite element analysis of soil-steel pipe structure interaction. *International Journal of Geomechanics*, 15 (1), p. 04014032. **https://doi.org/10.1061/(ASCE)GM.1943-5622.0000387**

[4] Watkins, R. K.: *Non-elastic behavior of buried pipes*, 2001 Pipeline division specialty conference, July 15–18, San Diego, CA, USA. **https://doi.org/10.1061/40574(2001)46**

[5] O'Rourke, M. J., Liu, X. (1999). *Response of buried pipelines subject to earthquake effects*. Monograph Series. Multidisciplinary Center for Earthquake Engineering Research (MCEER).

[6] Pasternak, P. L. (1954). *Fundamentals of a new method of analyzing structures on an elastic foundation by means of two foundation moduli*. (Gosudarstvennoe Izdatelstro Liberaturi po Stroitelstvu i Arkhitekture, Moscow).

[7] Yao, W.-J. et al. (2010). Numerical simulation of a super-long pile group under both vertical and lateral loads. *Advances in Structural Engineering*, 13 (6), pp. 1139–1151. **https://doi.org/10.1260/1369-4332.13.6.1139**

[8] Papadimitriou, Achilleas G., Bouckovalas, George D., Nyman, Douglas J., Valsamis, Alexandros I. (2019). Analysis of buried steel pipelines at watercourse crossings under liquefaction-induced lateral spreading. *Soil Dynamics and Earthquake Engineering*, 126. **https://doi.org/10.1016/j.soildyn.2019.105772**

[9] Chi, K., Li, J., and Wu, C. (2023). Numerical simulation of buried steel pipelines subjected to ground surface blast loading, *Thin-Walled Structures*, 186, p. 110716. **https://doi.org/10.1016/j.tws.2023.110716**

[10] Zhang, R., Wang, C., Li, S., and Zhang, J. (2023). Numerical simulation study on the performance of buried pipelines under the action of faults. *Applied Sciences*, app132011266. **https://doi.org/10.3390/app132011266**

[11] Vilca, N. S., Gómez-Amador, A. M., and Jiménez de Cisneros Fonfría, J. J. (2024). Soil–structure Interaction analysis using the finite element method in thin-walled steel pipes buried under haul roads. *Applied Sciences*, 14 (1), 167. **https://doi.org/10.3390/app14010167**