



Research Article

Seismic and Surge-Induced Responses of Large-Diameter Buried Gas Pipeline Bends in Marshy Soil: A Multi-Hazard Framework

Vijay Kumar Khanna^{1, 2, *} ¹Department of Civil Engineering, Birla Institute of Technology & Science, Pilani, India²Refinery Projects Department, Engineers India Limited, New Delhi, India

Abstract

Large-diameter buried gas pipelines traversing marshy or potentially liquefiable soils may be exposed simultaneously to transient internal surge pressure, seismic ground motion and reduced soil restraint. Pipeline bends are particularly vulnerable because changes in direction generate local thrust, bending and non-uniform soil–pipe interaction. This technical paper presents a conceptual and parametric finite-element framework for evaluating these interacting effects at a 90 °buried pipeline bend. Surge pressure is estimated using the Joukowsky relation and applied with seismic excitation within a three-dimensional soil–pipe interaction model. Three progressively severe multi-hazard scenarios—Cases A, B and C—are considered by varying soil stiffness, burial depth, surge pressure rise and peak ground acceleration. Within each scenario, surge-only, seismic-only and simultaneous surge–seismic analyses are compared. The assessment indicates increasing stress concentration, ovalisation and relative soil–pipe displacement as soil restraint decreases and loading severity increases; under the severe scenario, partial uplift may also become significant. Combined loading produces greater demand than either single-hazard analysis and changes the location and distribution of critical response at the bend. The framework is intended primarily as a bid- and preliminary-design screening methodology for identifying vulnerable bends that warrant site-specific geotechnical investigation and detailed nonlinear analysis before final design. This approach provides a transparent basis for subsequent detailed engineering assessment.

Keywords

Finite Element Modelling, Pipeline–soil Interaction, Surge Loading, Seismic Loading, Soil Pressure Distribution, Multi-Hazard Analysis, Buried Pipelines

1. Introduction

Pipelines constructed in soft or marshy soils are particularly susceptible to multi-hazard scenarios involving both surge and seismic actions. Previous studies have largely treated these hazards independently, with limited insight into their com-

bined effects. This gap necessitates the development of advanced finite element (FE) models capable of simulating coupled load conditions while adequately representing soil–structure interaction.

*Correspondence: Vijay Kumar Khanna (intmica@yahoo.co.in)

Received: 10 September 2026; **Accepted:** 18 September 2026; **Published:** 29 September 2026



Copyright: © The Author(s), 2026. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

2. Background and Literature Review

In the Indian context, particularly in areas such as Kishangarh Park Sanctuary near Sharda River in Uttar Pradesh where marshy tracts of land are often encountered, preparing bid documents for large-diameter buried cross country gas pipelines often proceeds with geotechnical datasets as available from data banks of likewise/ nearly likewise areas without resorting to site specific data. Marshy soil conditions, high ground water levels, and uncertain liquefaction susceptibility are acknowledged, but quantitative inputs such as shear wave velocity, pore pressure response, and cyclic degradation properties are not always available. This creates difficulties for bidders, who must assume soil behaviour without site-specific testing.

Similarly, transient surge analysis is usually simplified or even omitted at the bidding stage, on the assumption that operational procedures such as provision of air valves will limit water-hammer / surge, which measures are not fool proof. However, when pipelines traverse soft, high-risk zones, ignoring the possible coincidence of surge events and seismic shaking, any short cut method adopted for the bid design can lead to unconservative design assumptions.

Whereas soil data at various locations on the route is included in the project report, specifics are left to the contracting agency to verify along the alignment. However, the zones for which this study has been aimed at need extra care.

Previous work provides the technical basis for the individual components of this problem. Liu and O'Rourke [1] summarised seismic design principles for buried and offshore pipelines, while Saberi et al. [2] examined the seismic behaviour of buried pipelines with bends under wave propagation. Vazouras and Karamanos [3] investigated the structural behaviour of buried pipe bends in fault-crossing areas, including soil-pipe interaction and internal pressure. Earlier work by Zhang [4] addressed the seismic response of buried pipelines in liquefiable soil. The American Lifelines Alliance guidelines [5] provide additional background on seismic design of buried pipelines. Further guidance on pipeline integrity and seismic design considerations is provided in ASME B31.8 [6] and ISO 13623 [7], which establish broader requirements relevant to the design and integrity assessment of gas pipeline systems. Together, these studies support consideration of seismic soil-pipe interaction, bend response, transient internal pressure and liquefiable-ground effects; the present study combines these aspects in a bid-level parametric screening framework for large-diameter bends in marshy soil. Recent studies further reinforce these themes. Choi et al. [8] developed a finite-element/Winkler-spring procedure for structural risk assessment of buried gas pipelines in liquefiable ground; Choudhury and Choudhury [9] reviewed earthquake-induced permanent

ground deformation and highlighted the importance of pipe-soil interaction parameters. Nair et al. [10] examined horizontally bent buried pipelines subjected to strike-slip faulting, while Huang et al. [11] proposed and verified a pipe-soil interaction model for pipeline settlement. Yang et al. [12] investigated trench-material-pipeline interaction under fault displacement, and Darvishi et al. [13] developed predictive models for buried-pipeline response under seismic landslides. More recent work by Lai et al. [14] experimentally examined soil-pipeline interaction under localised subsidence, while Al-rubaye et al. [15] evaluated seismic soil-pipeline interaction through finite-element parametric modelling. These studies support the need to represent soil restraint, ground movement and pipeline geometry explicitly when screening buried pipelines for seismic and geotechnical hazards.

Framing for Innovation

The study proposes explicitly a conceptual framework that: (i) integrates transient surge pressure, seismic excitation, soil-pipe interaction and buoyancy within a single three-dimensional screening model; (ii) represents progressive loss of soil restraint through Cases A–C, including very soft or near-liquefiable conditions; (iii) compares surge-only, seismic-only and simultaneous surge-seismic loading through common response measures, including the combined-demand ratio (CDR); and (iv) identifies vulnerable bends that require site-specific geotechnical investigation and detailed nonlinear analysis before final design.

3. Materials and Methods

3.1. Finite Element Discretization and Software

ABAQUS was used for the finite-element analysis. The pipeline bend and adjacent straight segments are modelled using a three-dimensional finite-element (FE) mesh. The pipe wall may be represented either with 3D solid elements (e.g., 8-node bricks) for through-thickness stress resolution, or with shell elements for computational efficiency when ovalisation is likely to dominate. The surrounding marshy soil is modelled as a solid continuum with cyclic degradation represented by modulus reduction factors. Soil-pipe interaction is enforced through tied nodes or contact interfaces with appropriate normal and tangential stiffness (Coulomb friction). Boundaries are set far enough from the elbow to minimize spurious S-wave reflections; absorbing boundaries (dashpots) may be used at the outer faces. The conceptual configuration of pipeline bend under study is as shown in Figure 1.

The conceptual loading and soil-pipe interaction configuration adopted for the buried bend is shown in Figure 1.

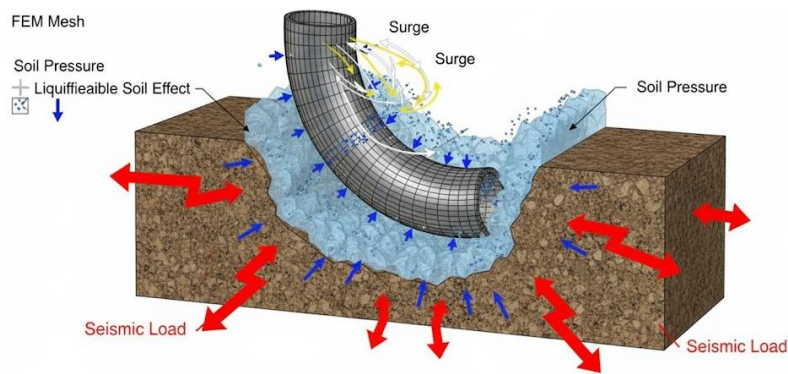


Figure 1. Conceptual loading schematic for a buried 90° pipeline bend in weak saturated soil, showing transient surge pressure, seismic loading, soil pressure and reduced confinement in potentially liquefiable ground.

3.2. Surge Load Modelling (Joukowsky Equation)

Surge-induced pressure rise is estimated using the Joukowsky relation, where ΔP is the pressure rise (MPa), ρ is the fluid density (kg/m^3), a is the acoustic wave speed in the fluid (m/s)—modified as needed to account for pipe wall elasticity—and ΔV is the instantaneous change in fluid velocity (m/s) from valve closure or compressor trip. The transient internal pressure at the elbow is then prescribed as a time-dependent load on the inner pipe wall. The resulting unbalanced thrust at the bend is transmitted to the surrounding soil through the soil–pipe interface. In the numerical cases, surge magnitudes of 1.5–3.0 MPa were paired with peak ground accelerations

(PGAs) of 0.20–0.35 g to explore multi-hazard interaction. In the marshy or near-liquefiable soil cases, the soil–pipe interaction parameters were reduced to represent loss of effective confinement during seismic excitation; soil pressure and stiffness degradation were therefore considered simultaneously within the interaction model.

$$\Delta P = \rho a \Delta V \quad (1)$$

Figure 3 shows the surge pressure time history at the pipeline bend following a sudden valve closure. The initial positive pressure spike reaches about 1.8 MPa, followed by alternating negative and positive oscillations that decay over time due to damping effects. This transient pressure rise provides the input load for subsequent structural analysis of the bend region under multi-hazard conditions.

3.3. Bid-Level Parametric Modelling

Table 1. Bid Level Parametric Ranges for Buried Pipeline Analysis: These can be normally adopted for Bid-Documents (as in the table).

Parameter	Range/Value	Notes/assumptions	Remarks
Soil Shear Modulus (G_{max})	5 – 20 MPa	Very soft soil to medium-stiff alluvial/marshy soil	
Liquifaction Resistance (SPT-N)	5 – 10 blows / 30 cm	Loose silty sand; high Liquefaction susceptibility	
Groundwater table depth	depth 1.0 – 2.0 m below ground surface	Shallow, consistent with marshy condition	
Burial depth (to pipe crown)	1.5 – 3.0 m	Typical for oil / gas pipelines	
Internal surge pressure rise (ΔP)	1.5 – 3.0 MPa	MPa Calculated via Joukowsky equation; mild to severe surge scenarios	
Peak ground acceleration (PGA)	0.20 – 0.35 g BIS Zone IV seismicity	representative range for northern India	
Pipe diameter (D)	800 – 1200 mm (example range)	Large-diameter gas transmission pipeline	
Pipe wall thickness (t)	20 – 30 mm	API 5L X65 grade (illustrative)	

4. Example Case

For the analysis carried out for the example case, following parameters and features have been considered.

Table 2. Pipeline and soil parameters adopted in the analysis.

Parameter	Value
Pipeline Diameter (D)	1000 mm
Wall Thickness (t)	25 mm (API 5L X65)
Burial Depth (to crown)	1.5–3.0 m
Soil Shear Modulus (Gmax)	5–20 MPa
Groundwater Table	1–2 m

Table 3. Bid-level parametric ranges for marshy soil pipeline analysis.

Parameter	Range / Value	Notes
Soil shear modulus (Gmax)	5 – 20 MPa	Soft to medium marshy soils
Liquefaction resistance (SPT-N)	5 – 10	Loose silty sands
Groundwater table depth	1 – 2 m	Consistent with marshy conditions
Burial depth (pipe crown)	1.5 – 3.0 m	Typical practice
Surge pressure rise (ΔP)	1.5 – 3.0 MPa	Mild to severe surge
Peak ground acceleration (PGA)	0.20 – 0.35 g	BIS Zone IV seismicity

5. Results

5.1. Figure-Based Results

(a) FE mesh with soil continuum & boundary conditions (b) Soil pressure contours in soil continuum

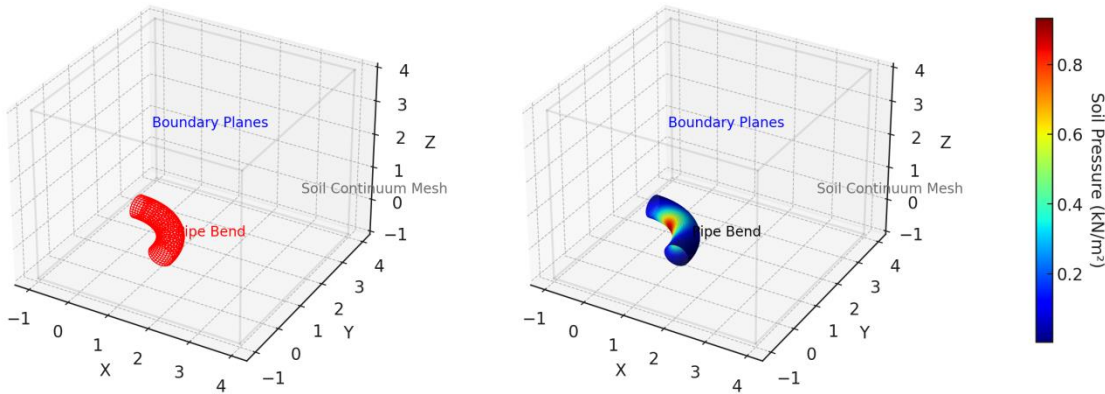


Figure 2. Pipeline bend embedded in the soil continuum: (a) finite-element mesh with far-field boundary planes; (b) representative soil-pressure contours around the bend.

Figure 2 shows pipe embedded in soil continuum and pressure contours:

Figure 2(a) is 3D finite element mesh of the pipe bend embedded in a soil continuum with outer boundary planes defining far-field conditions.

Figure 2(b) shows soil pressure contours around pipe bend in red-to-blue gradient, representing high to low soil pressures. The surrounding soil is rendered semi-transparent for clarity. A colour bar provides the pressure scale (kN/m^2). The highest pressures are concentrated near the intrados of the bend, where surge and seismic effects overlap, and progressively reduce with distance into the soil continuum. This demonstrates that marshy soils, being relatively soft, allow greater spread of stresses, thereby increasing the extent of soil–pipe interaction compared with stiff soils.

Because Figure 2 illustrates the central soil–pipe interaction mechanism examined in this study, its observations are also mapped to the relevant code-oriented design considerations below.

Code-Oriented Mapping of Figure 2(b) Observations:

The elevated and non-uniform soil contact pressures observed at the 90° bend are consistent with the recognition in ASME B31.8 [6] that changes in direction introduce additional bending stresses beyond those present in straight pipe.

While code equations are primarily based on straight-pipe assumptions, fittings and bends are implicitly treated as stress-intensified regions, requiring additional scrutiny when subjected to combined loads.

The asymmetric pressure distribution around the bend circumference aligns with ISO 13623 [7] soil–pipe interaction concepts, which recognise that curved pipelines mobilise non-uniform passive soil resistance due to bending-induced deformation.

This behaviour is not captured by simplified uniform overburden or Winkler-spring assumptions used for straight pipelines.

The presence of internal pressure (5.5 MPa) increases axial membrane stress and influences cross-sectional ovalisation.

In accordance with the combined-loading considerations of ASME B31.8 [6], the interaction of axial force, bending moment, and pressure becomes critical at bends, justifying explicit numerical evaluation rather than closed-form checks.

ISO 13623 [7] explicitly requires consideration of ground movement, seismic loading, and buoyancy where relevant.

Figure 2(b) shows that these actions lead to direction-dependent mobilisation of soil resistance, producing localized pressure peaks at the bend crown and springline, which are not addressed by pressure-only or gravity-only load combinations.

The rapid reduction of soil pressure away from the curved segment confirms that stress amplification is geometry-driven.

This supports the continued applicability of straight-pipe checks in ASME B31.8 [6] for tangent sections, while reinforcing the need for special assessment of bends.

Figure 3 presents the surge-pressure time history used to represent the transient loading at the bend.

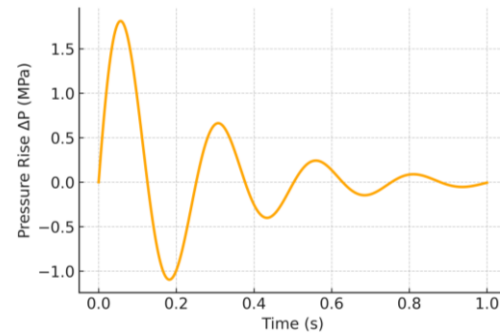
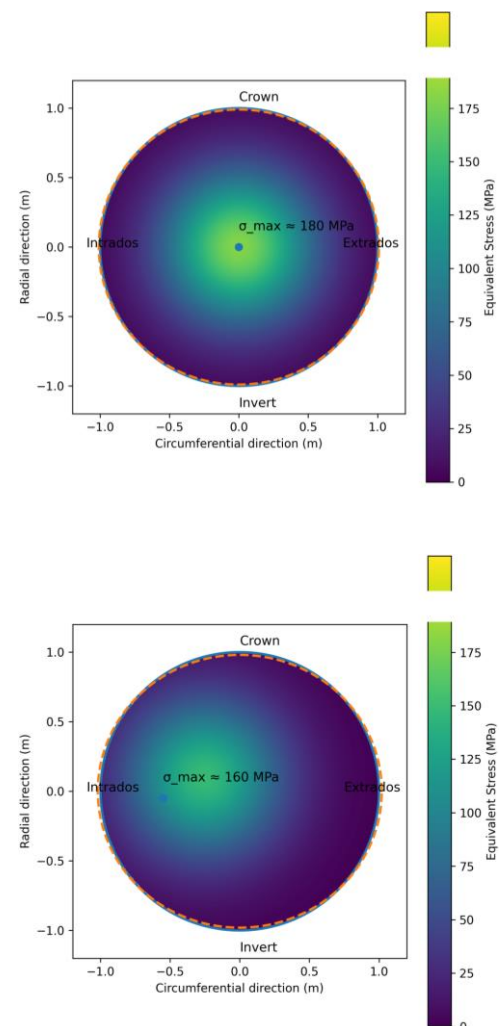


Figure 3. Surge-pressure time history at the pipeline bend following a sudden valve-closure event.

Figure 4 shows conceptual stress-contour patterns at the elbow for surge-only, seismic-only and simultaneous surge–seismic loading. Surge loading produces a predominantly pressure-driven response, whereas seismic excitation introduces asymmetric bending through soil–pipe relative movement. The combined case illustrates how the two actions can shift and intensify the critical response at the bend. The contours are illustrative and should be interpreted together with the parametric response ratios reported in Table 3.



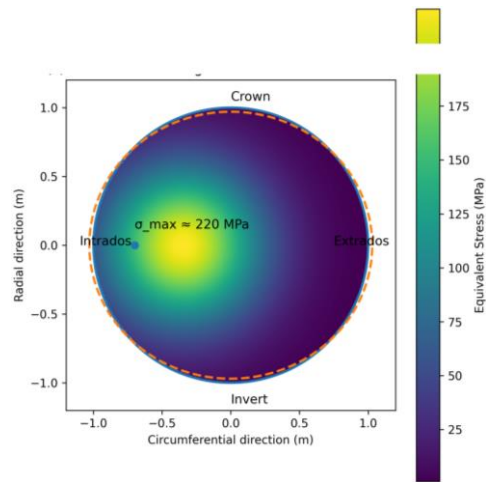


Figure 4. Conceptual stress contour patterns at a 90 °pipeline elbow under different loading conditions: (a) Surge-only, showing predominantly hoop-stress-dominated response with near-axisymmetric distribution around the cross-section; (b) Earthquake-only, illustrating bending-dominated behaviour with stress concentration shifted toward the intrados and adjacent crown region, and reduced demand at the extrados; (c) Combined surge + earthquake loading, demonstrating amplified and non-uniform stress localisation at the intrados–crown transition due to interaction between internal pressure and seismic bending effects. (Contours are illustrative and shown on a normalised scale).

The consistent stress scale across all three cases highlights the progressive amplification from surge-only to combined loading.

The stress patterns in Figure 4 are consistent with the soil–pipe interaction behaviour shown in Figure 2. Reduced soil stiffness permits greater relative displacement and less uni-

form restraint around the elbow, thereby increasing the susceptibility to ovalisation, bending and localised strain under combined loading.

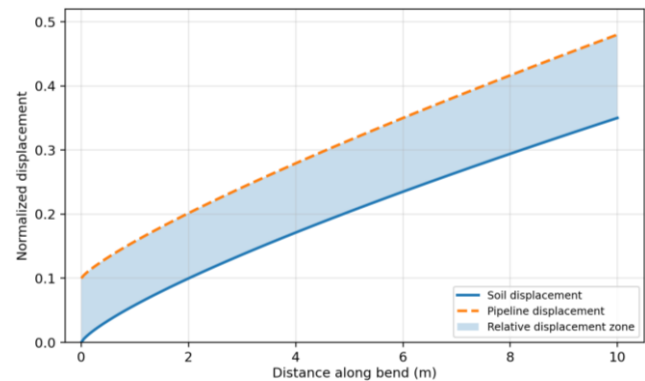


Figure 5. Conceptual soil–pipe relative displacement in marshy soil: normalized soil (solid orange) and pipeline (dashed blue) displacements along the bend length, with shaded zone showing relative displacement.

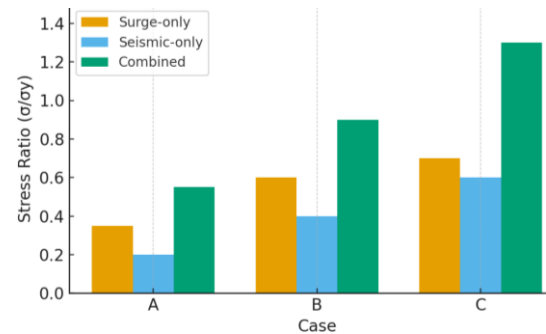


Figure 6. Comparative stress ratios during surge-only, seismic-only, and combined loading for Cases A–C.

5.2. Peak Stresses, Deformations and Combined-Demand Ratios

Table 4. Summary of peak stresses and deformations (Cases A–C).

Case	Surge-only σ/σ_y	Seismic-only σ/σ_y	Combined σ/σ_y	Ovalization (%)
A	0.35	0.20	0.55	1.0
B	0.60	0.40	0.90	3.0
C	0.70	0.60	1.30	5.0
Notes	Response ratio normalised to yield stress	Response ratio normalised to yield stress	Simultaneous loading run	Conceptual FE response

Table 5. Combined-demand ratios (CDR) for Cases A–C.

Case	CDR = Combined / max (Surge, Seismic)	CDR
A	0.55 / max (0.35, 0.20)	1.57
B	0.90 / max (0.60, 0.40)	1.50
C	1.30 / max (0.70, 0.60)	1.86

6. Discussion

6.1. Definition of Load Cases

Based on the parametric ranges summarised in Tables 1 and 2, three progressively severe multi-hazard scenarios were analysed for bid-level screening. Each scenario was evaluated under three loading runs: (i) surge-only, (ii) seismic-only and (iii) simultaneous surge + seismic. Thus, Cases A–C describe ground/load severity; they do not denote the loading type.

Case A – Moderate / relatively favourable ground:

Medium-stiff soil ($G_{max} \approx 20$ MPa, SPT-N = 10), burial depth = 3.0 m, shallow surge ($\Delta P = 1.5$ MPa), PGA = 0.20 g.

This represents the lower-severity multi-hazard screening scenario.

Case B – Intermediate / representative weak ground:

Soft soil ($G_{max} \approx 10$ MPa, SPT-N = 7), burial depth = 2.0 m, moderate surge ($\Delta P = 2.0$ MPa), PGA = 0.25 g.

This represents an intermediate bid-level scenario for marshy terrain.

Case C – Severe / very soft or near-liquefiable ground:

Very soft soil ($G_{max} \approx 5$ MPa, SPT-N = 5), burial depth = 1.5 m, severe surge ($\Delta P = 3.0$ MPa), PGA = 0.35 g.

This represents the upper-severity screening scenario.

6.2. Stress Response at Pipeline Bend

6.2.1. Stress Response for Loading Cases

Refer Table 4.

Surge-Only vs. Seismic-Only:

For Case B, the surge-only and seismic-only response ratios are approximately 0.60 and 0.40, respectively. These values represent separate loading runs within the same intermediate ground scenario.

Combined Loading:

When surge and seismic inputs are applied simultaneously in Case B, the response ratio increases to approximately 0.90. The combined result is therefore greater than either single-hazard result, demonstrating why the bend should be checked under simultaneous actions rather than inferred from a single governing hazard.

Combined-Demand Ratio:

For screening purposes, the combined-demand ratio (CDR) is defined as the combined response divided by the larger of the two corresponding single-hazard responses:

The combined-demand ratio is calculated as:

$$CDR = \sigma_{combined} / \max(\sigma_{surge}, \sigma_{seismic}) \quad (2)$$

Table 5 lists the CDR values. This ratio measures the increase in combined demand relative to the governing single-hazard analysis; it is not presented as a nonlinear interaction or code calibration factor.

6.2.2. Explanation of Stress Pattern in Figure 2(b)

Figure 2(b) shows the distribution of soil contact pressure acting on the pipeline surface in the vicinity of the single 90° bend, obtained from the three-dimensional soil–pipe interaction analysis. The observed stress pattern is a direct consequence of pipeline curvature, soil confinement, and imposed loading, and may be interpreted as follows.

1) Concentration of soil pressure at the bend region

Compared to the adjoining straight segments, the bend exhibits higher and more non-uniform contact pressures. This occurs because curvature introduces radial deformation demands, forcing the pipe wall to mobilise additional soil resistance in order to satisfy compatibility between the pipe and surrounding ground.

2) Asymmetric pressure distribution around the pipe circumference

The pressure contours are not uniform circumferentially. Higher pressures typically develop on the intrados and adjacent zones of the bend, where the pipe tends to push into the soil under combined axial force, internal pressure, and bending effects. Lower pressures (or partial relief) may occur on the opposite side, reflecting local separation or reduced confinement.

3) Influence of bending-induced ovalisation

Internal pressure combined with curvature promotes ovalisation of the pipe cross-section in the bend region. This ovalisation alters the local contact condition with the soil, leading to localized peaks in soil reaction, which are captured in the contour plot.

4) Effect of seismic and buoyancy actions

Seismic excitation and buoyancy introduce additional vertical and horizontal components of relative displacement between the pipe and soil. These effects further accentuate non-

uniform soil pressure, particularly near the bend crown and springline, where uplift and lateral inertia demands are highest.

5) Rapid decay of pressure away from the bend

Moving away from the curved segment into the straight portions, the pressure contours become more uniform and of lower magnitude. This confirms that the bend acts as a local stress amplifier, while straight segments primarily transmit loads without significant local interaction effects.

6.2.3. Engineering Significance

The stress pattern in Figure 2(b) demonstrates that pipeline bends are critical locations for soil–pipe interaction, where local pressure concentrations can develop under multi-hazard loading. For a conceptual screening study, this supports explicit three-dimensional assessment of bends where surge, seismic, soil and buoyancy effects may act together; site-specific final design requires project-specific geotechnical and loading data.

6.3. Soil–Pipe Interaction in Marshy Soil

In Case A, representing comparatively stiffer soil conditions, lateral and vertical restraint limited pipe deformation,

6.4. Comparative Summary

Table 6. Comparative summary of soil stiffness, burial depth, surge pressure, PGA, peak response and combined-demand ratio for Cases A–C.

Case	Soil Stiffness (MPa)	Burial Depth (m)	Surge ΔP (MPa)	PGA (g)	Peak Stress / Yield (σ/σ_y)	Combined-Demand Ratio (CDR)
A	20	3.0	1.5	0.20	0.55	1.57
B	10	2.0	2.0	0.25	0.90	1.50
C	5	1.5	3.0	0.35	1.30	1.86

6.5. Implications

Combined-load screening: Across Cases A–C, simultaneous loading produces a higher response than either corresponding single-hazard run. The CDR ranges from about 1.50 to 1.86 for the adopted conceptual cases.

Bid stage risk: Even without site-specific data, the parametric approach highlights that elbows in marshy soil at shallow burial depths are critical design locations.

Code consideration: ASME B31.8 [6] and ISO 13623 [7] address relevant pressure, ground-movement and seismic design requirements, but the present conceptual study identifies a need to examine explicitly how simultaneous surge and seismic actions should be treated at bends in weak soils.

resulting in modest ovalization ($< 2\%$) and negligible uplift at the bend. The surrounding soil provided sufficient confinement to restrict curvature-induced distortion.

In Case B, corresponding to intermediate soil stiffness, a measurable reduction in restraint was observed. The pipe experienced increased relative displacement within the soil matrix, with ovalization rising to approximately 3–4%. While uplift remained limited, stress redistribution toward the intrados–crown region became more pronounced, indicating the onset of deformation amplification as soil stiffness decreased.

In Case C, representing very soft marshy or near-liquefiable soil conditions, significant loss of effective restraint permitted substantial relative movement between the pipe and surrounding soil. Ovalization exceeded 5%, accompanied by partial uplift of the bend segment. The reduction in confinement intensified curvature effects and localised strain demand at the elbow.

These results demonstrate that progressive reduction in soil stiffness—from Case A to Case C—systematically increases deformation demand, confirming that soft soil conditions and shallow burial depth are dominant drivers of critical bend behaviour, even prior to the inclusion of surge loading effects.

7. Code Implications

The present conceptual analysis is intended to highlight a multi-hazard design issue for buried bends in weak ground. ASME B31.8 [6] and ISO 13623 [7] contain requirements relevant to pressure effects, ground movement and seismic design; however, the present study does not attempt a clause-by-clause code validation. Instead, it asks whether separate single-hazard evaluations are sufficient to screen a bend when a transient surge and earthquake-induced soil movement can occur concurrently.

For each of the three ground/load scenarios (Cases A–C), three loading runs were considered: surge-only, seismic-only and simultaneous surge + seismic. The resulting response ratios are 0.35, 0.20 and 0.55 for Case A; 0.60, 0.40 and 0.90 for

Case B; and 0.70, 0.60 and 1.30 for Case C. In every scenario, the simultaneous-loading response exceeds the larger corresponding single-hazard response. Expressed as $CDR = \sigma_{Combined} / \max(\sigma_{Surge}, \sigma_{Seismic})$, the ratios are approximately 1.57, 1.50 and 1.86 for Cases A, B and C, respectively.

The trend is physically consistent with the reduced restraint represented in the softer-soil scenarios: surge pressure and bend thrust act while seismic ground movement changes the direction and magnitude of soil reaction around the elbow. The numerical values should be regarded as conceptual screening results rather than universal amplification factors because the model has not yet been calibrated against site-specific field or experimental data.

Accordingly, the study supports explicit consideration of simultaneous actions at vulnerable bends during bid and preliminary design. It does not propose a new code factor. Site-specific geotechnical characterisation, transient analysis and validated nonlinear soil–pipe modelling remain necessary before final design recommendations or code provisions can be established.

8. Conclusions

This conceptual and parametric technical study examined the multi-hazard response of large-diameter buried gas pipeline bends in marshy soils, with emphasis on simultaneous seismic ground motion and surge-induced internal pressure transients. The following conclusions are drawn:

- 1) Simultaneous loading warrants explicit screening. In all three conceptual scenarios, the combined surge-seismic response exceeded the larger corresponding single-hazard response. The calculated CDR values ranged from approximately 1.50 to 1.86; these are scenario-specific screening indicators, not universal amplification factors.
- 2) Soil conditions dominate vulnerability. Marshy or potentially liquefiable soils with low stiffness and high groundwater levels permit greater pipe-soil relative displacement, leading to larger ovalisation and uplift, particularly at shallow burial depths.
- 3) The three severity scenarios - moderate, intermediate and severe - provide a practical bid-level framework for flagging vulnerable bends and identifying where soil improvement, surge suppression, flexible detailing or more rigorous analysis may be warranted.
- 4) The study identifies a design-assessment gap rather than proposing a new code rule. Existing pipeline standards contain requirements relevant to pressure and seismic or ground-movement effects, but simultaneous surge-seismic response at bends in weak soil merits explicit project-specific assessment.
- 5) Practical recommendations for pipelines traversing marshy terrain include:
 - Preliminary screening for multi-hazard interaction.
 - Local assessment of burial depth and soil improvement requirements near bends.

Surge-suppression measures where transient pressure demand is significant.

Project-specific combined surge-seismic analysis for bends identified as critical during screening.

9. Future Work

The present results are conceptual and parametric. Future work should use site-specific geotechnical data and measured pore-pressure response, validate the soil–pipe model through centrifuge or full-scale testing, and extend the assessment across a broader range of soils, bend geometries and burial conditions. Probabilistic treatment of uncertainty in soil stiffness, surge magnitude and seismic intensity would further strengthen the screening framework. Only after such validation should simplified design charts, interaction guidance or proposals for future code provisions be developed.

Abbreviations

CDR	Combined-demand Ratio
FE	Finite Element
FEM	Finite Element Modelling
Gmax	Maximum Shear Modulus
PGA	Peak Ground Acceleration
SPT-N	Standard Penetration Test N-value

Author Contributions

Vijay Kumar Khanna: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Conflicts of Interest

The author declares no conflicts of interest.

References

- [1] Liu, X. and O'Rourke, T. D. (2012) Seismic Design of Buried and Offshore Pipelines. MCEER Monograph 3, University at Buffalo, NY.
- [2] Saberi, M., Arabzadeh, H. and Keshavarz, A. (2011) Numerical Analysis of Buried Pipelines with Right Angle Elbow under Wave Propagation. *Procedia Engineering*, 14, pp. 3260–3267. <https://doi.org/10.1016/j.proeng.2011.07.412>
- [3] Vazouras, P. and Karamanos, S. A. (2017) Structural behavior of buried pipe bends and their effect on pipeline response in fault crossing areas. *Bulletin of Earthquake Engineering*, 15, pp. 4999–5024. <https://doi.org/10.1007/s10518-017-0148-0>

- [4] Zhang, H. (1992) Seismic Response of Pipeline Systems in a Soil Liquefaction Environment. PhD dissertation, Civil & Environmental Engineering, Old Dominion University.
<https://doi.org/10.25777/168t-tt44>
- [5] American Lifelines Alliance (2005) Seismic Guidelines for Water Pipelines. FEMA/NIBS, Washington, D. C.
- [6] ASME (2020) ASME B31.8 - Gas Transmission and Distribution Piping Systems. American Society of Mechanical Engineers, New York.
- [7] ISO (2017) ISO 13623 - Petroleum and Natural Gas Industries - Pipeline Transportation Systems. International Organization for Standardization, Geneva.
- [8] Choi, Y., Choi, Y., Kwon, K., Baek, W. and Kong, J. (2023) Preventive Structural Risk Assessment of Buried Gas Pipelines in Liquefaction of Ground. KSCE Journal of Civil Engineering, 27(3), pp. 1224–1235.
<https://doi.org/10.1007/s12205-023-1209-3>
- [9] Choudhury, D. and Chaudhuri, C. H. (2023) A critical review on performance of buried pipeline subjected to pipe bursting and earthquake induced permanent ground deformation. Soil Dynamics and Earthquake Engineering, 173, 108152.
<https://doi.org/10.1016/j.soildyn.2023.108152>
- [10] Nair, G. S., Dash, S. R. and Mondal, G. (2024) Response of Horizontally Bent Buried Pipelines Subjected to Strike-Slip Faulting: A Numerical Investigation. Journal of Pipeline Systems Engineering and Practice, 15(3).
<https://doi.org/10.1061/JPSEA2.PSENG-1480>
- [11] Huang, Z., Yu, X., Lv, Z., Chen, C., Shuai, J., Li, Y. and Liu, Q. (2024) Mechanical response analysis of pipeline under settlement based on pipe-soil interaction model. Applied Ocean Research, 151, 104162.
<https://doi.org/10.1016/j.apor.2024.104162>
- [12] Yang, M., Wang, D., Jia, H., Hu, W., Zhao, Y. et al. (2024) Research on the interaction between trench material and pipeline under fault displacement. Scientific Reports, 14, 12439.
<https://doi.org/10.1038/s41598-024-57936-9>
- [13] Darvishi, R., Lashgari, A. and Jafarian, Y. (2024) Predictive models for assessment of buried pipeline response under seismic landslides in Iran. Transportation Geotechnics, 45, 101208.
<https://doi.org/10.1016/j.trgeo.2024.101208>
- [14] Lai, D.-L., Xu, L., Chen, F.-Q. and Chen, H.-B. (2025) Soil-Pipeline interaction under localized soil Subsidence: Experimental Investigation. Measurement, 242, 116175.
<https://doi.org/10.1016/j.measurement.2024.116175>
- [15] Alrubaye, M., Şengör, M. and Almusawi, A. (2026) Pseudo-Static Finite-Element Assessment of Seismic Soil–Pipeline Interaction in Multi-Line Buried Pipelines. Processes, 14(3), 491.
<https://doi.org/10.3390/pr14030491>

Biography



Vijay Kumar Khanna has diverse professional experience spanning 56 years in civil/structural engineering, engineering and project management in the oil and gas sector, and technical marketing of process instruments and non-destructive evaluation tools for civil/structural applications. He is currently engaged in engineering consultancy, technical writing and independent research. He has authored eighteen technical publications across journals, industry publications and conference proceedings. He holds a B.E. in Civil Engineering and a PGDBM.