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Research Article

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Posted Date: October 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11049270/v1>

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Additional Declarations: No competing interests reported.

Assessing Climate-Driven Ground Movement Effects on Buried Pipelines Using Efficient 2D and 3D Finite Element Modelling

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Abstract

Buried pipelines are critical components of UK infrastructure, but they are increasingly exposed to climate-driven soil movement, often resulting in differential settlement. There is therefore a need for computationally efficient tools to support large-scale risk assessment of buried pipelines under changing ground conditions. This study investigated whether a two-dimensional (2D) modelling approach can reproduce the key soil–pipe interaction behaviour predicted by a calibrated three-dimensional (3D) model under varying soil moisture conditions. A parametric analysis was carried out in PLAXIS 3D, which served as the high-fidelity reference model for the soil–structure interaction. The 3D model was first calibrated against experimental data for a concrete pipe and then used in a parametric study in which the water content within an active zone above and around the pipe was varied between 26% and 32%. In parallel, a two-dimensional (2D) finite element model (FEM) was developed in Python and can produce results within seconds. Comparative analysis indicates that the simplified model reproduces the displacement trends and magnitudes obtained from PLAXIS 3D simulations while reducing the computational cost by two orders of magnitude, highlighting its potential for large-scale climate resilience assessment of buried pipeline networks.

Highlights

- Developed a 3D PLAXIS modelling of a rigid concrete pipe is calibrated to experimental data.
- Developed a 2D finite element model (FEM) to simulate pipe-soil interaction, accounting for soil expansion due to water content variations.

- Validated model results against PLAXIS 3D simulations and experimental tests.
- Demonstrated the significant impact of soil expansion on pipeline displacement

Keywords

Pipe-soil interaction, Finite element modelling, Expansive soils, Buried pipelines, Water content variations, 2D FEM, 3D PLAXIS

1. Introduction

Climate-induced fluctuations in soil water content have a pronounced effect on the performance of buried pipelines in expansive soils by altering soil volume and strength. In expansive clay soils, periods of rainfall and drought drive cyclic swelling and shrinkage, which can lead to differential movement, thereby imposing significant bending and axial stresses on pipelines (Bouatia et al., 2020). Early field studies documented drastic pipeline damage due to lateral swelling pressures in reactive clays (Gallage et al., 2012, Liu and Vanapalli, 2017). Pipeline failures tend to spike after extreme dry spells in clay-rich regions, when desiccation-induced shrinkage reduces the support provided by the surrounding soil (Saadeldin et al., 2015). In contrast, these climate-related failure patterns are much less noticeable in non-expansive soils, such as sands or gravels (Saadeldin et al., 2015).

These mechanisms are now well recognised, particularly in expansive soils where climate-driven variations in water content and suction alter the soil strength, stiffness, and volume-change behaviour (Gallage et al., 2012, Wols and van Thienen, 2015, Oswell et al., 2019, Bai et al., 2020, Guo, 2025). Heavy rainfall and wetting can increase the water content, reduce soil strength and stiffness, and in expansive clays promote swelling, while prolonged drying can lead to shrinkage and loss of support around buried pipes. These moisture-driven ground movements may induce differential displacement and damage both above and below-ground infrastructure, including pipeline systems (Rajeev et al., 2012, Rajeev et al., 2013). However, these processes have not yet been translated sufficiently into computationally efficient tools for large-scale or network-level risk assessment. There is therefore a need for simplified modelling approaches that can capture the essential soil–pipe response under climate-driven ground movement while remaining suitable for rapid screening of extensive buried pipeline networks.

Modelling methods for soil–pipeline interaction range from high-fidelity numerical simulations to simplified analytical equations. Sophisticated finite element analysis (FEA), in which the soil is

represented as a three-dimensional domain with realistic stress–strain behaviour, enables detailed simulation of soil–structure interaction under varying moisture conditions. For instance, full three-dimensional FEA software such as PLAXIS 3D, ABAQUS and MIDAS FTS NX can capture unsaturated soil profiles and cyclic wetting–drying conditions near pipelines in considerable detail (Robert et al., 2020, Dave and Solanki, 2021, Al-Jeznawi et al., 2023, Priyom, 2025). However, such models generally require detailed soil characterisation, careful model setup and substantial computational effort, which can limit their practicality for large-scale assessments (Brinkgreve, 2005, Sung and Tuo, 2024).

At the other end of the spectrum, idealised models represent the soil support using Winkler- or Vlasov-type foundations, in which the pipeline is modelled as an elastic beam resting on an elastic foundation. In the classical Winkler model, soil reactions are represented by independent local springs that act in proportion to the pipe's local deflection. Although computationally efficient, this formulation neglects the continuity of the surrounding soil by assuming no interaction between adjacent springs and, in its basic form, does not explicitly represent plastic or irreversible soil deformation. As a result, it can lead to physically unrealistic responses, such as the absence of curvature under uniform loading (Ni, 2016). Two-parameter foundation models, such as the Vlasov model, extend the Winkler approach by incorporating shear interaction between adjacent springs, thereby providing a more continuous representation of soil support without substantially increasing computational cost. Pandey et al. (2023) reviewed a range of soil–foundation interaction models, including Winkler-type, continuum and modified formulations, and summarised their main assumptions and fields of application, while Çerezci (2021) further developed the Modified Vlasov foundation for nonlinear soil layers, showing how shear interaction can be retained while improving the representation of non-homogeneous and nonlinear soil behaviour (Noto et al., 2022). Although these formulations provide an efficient basis for soil–pipeline interaction analysis, most published applications still assume foundation properties are spatially uniform and independent of moisture-driven changes in soil stiffness and volume-change behaviour.

To address this gap, the present study develops a lightweight two-dimensional finite element model to simulate soil–pipeline interaction under climate-driven moisture variation. The model combines beam elements with a Modified Vlasov-type foundation and explicitly distinguishes between an active zone, where soil properties are updated as a function of moisture change, and a passive zone, where the initial soil conditions are preserved. This formulation enables the model

to capture the dominant mechanisms identified in the three-dimensional PLAXIS simulations, namely stiffness degradation, differential support conditions, and zone-dependent displacement response, while maintaining the computational efficiency required for parametric studies and network-scale assessment.

The novelty of the proposed 2D model lies in the development of a computationally efficient, climate-aware reduced-order formulation for soil–pipe interaction that preserves the key displacement mechanisms observed in high-fidelity three-dimensional analysis. Unlike classical Winkler-type idealisations, the model incorporates shear interaction between adjacent soil springs through a Modified Vlasov framework and explicitly distinguishes between active and passive zones with moisture-dependent properties. Furthermore, the formulation is systematically calibrated and verified against a validated three-dimensional finite element model, enabling it to reproduce complex soil–structure interaction behaviour while remaining suitable for rapid, large-scale infrastructure assessment.

The objective of this study is to develop and validate a computationally efficient reduced-order formulation that can reproduce the key displacement responses of buried pipelines under moisture-driven soil variability. The paper first establishes a high-fidelity three-dimensional reference model, including calibration against experimental data and a comprehensive parametric investigation. Building on this benchmark, a Python-based two-dimensional finite element model is formulated and systematically evaluated against the three-dimensional results. Through this coupled high-fidelity and reduced-order modelling framework, the study demonstrates that the essential mechanics of soil–pipe interaction can be captured with substantially reduced computational effort. The proposed approach, therefore, provides a practical and scalable tool for preliminary assessment, enabling its application to large-scale and network-level climate resilience and risk analysis.

2. 3D PLAXIS Model setup and validation

In this study, numerical simulations were performed using finite element (FEM) modelling using the PLAXIS 3D software package to investigate the potential impacts of climate change on existing buried pipes. The model was validated against a well-documented case study reported by MacDougall (2014). The previous study examined a concrete pipe with an inner diameter of 0.6 m and a wall thickness of 0.094 m. The concrete compressive strength was 66 MPa, which

corresponds to an elastic modulus of 38,450 MPa, and the Poisson's ratio of the pipe was 0.2 (Alzabeebee et al., 2018). The pipe was buried at varying depths, with backfill heights of 0.3 m, 0.6 m, and 0.9 m, and tested under an applied load of 110 kN (single-wheel-pair loading). Fig. 1 presents the FE mesh and geometry used during the validation process. The mesh size is consistent across all analysed cases. In terms of boundary conditions, the base boundary was fixed in all translational directions, and the vertical boundaries were fixed to their planes while remaining free in the other directions.

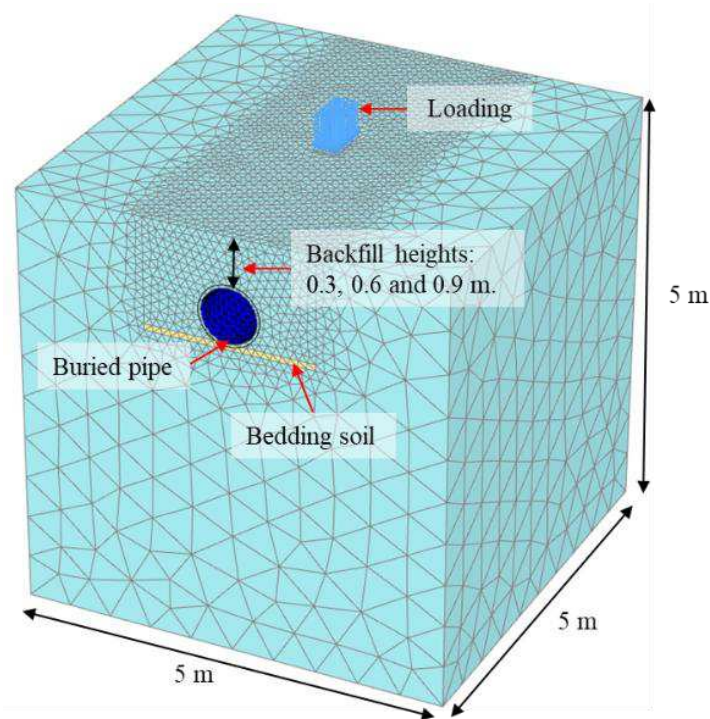
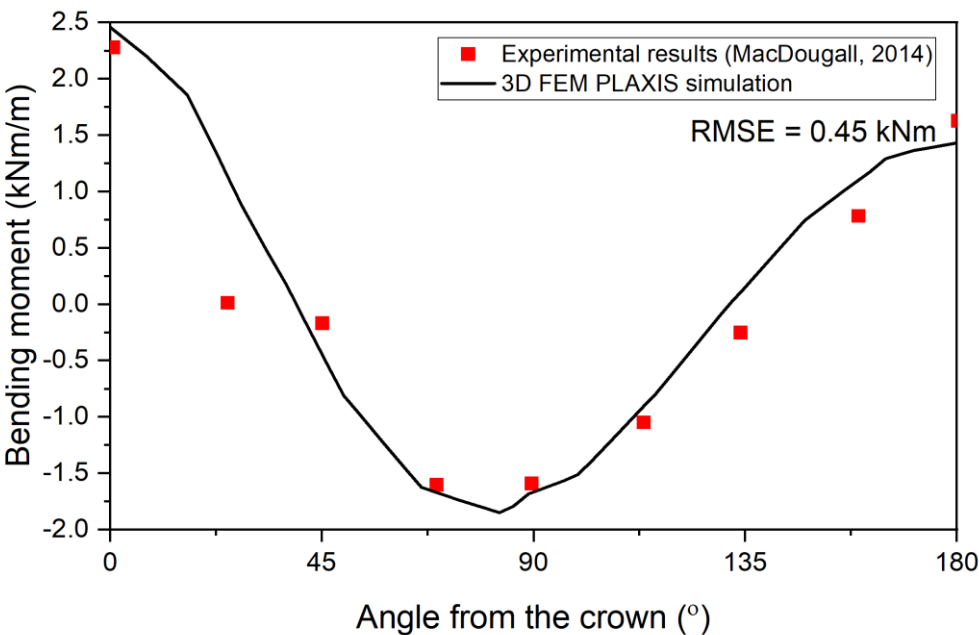


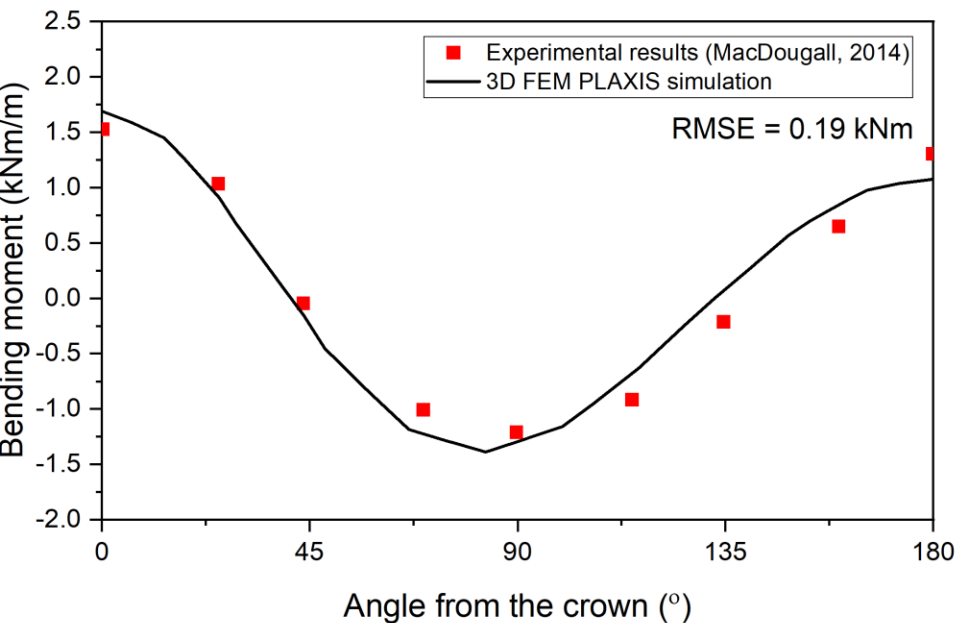
Fig.1 FE mesh and geometry for model validation against (MacDougall, 2014)

Fig. 2 (a)–(c) presents a comparison between the bending moments measured experimentally from the mounted strain gauges on the pipe's surface arranged from 0 – 180 degrees from the crown to invert level, and those computed by the simulations for backfill soil heights of 0.3 m, 0.6 m and 0.9 m, respectively. The results indicate that the bending moments predicted by the FE simulations closely match the experimental data, with Root Mean Square Errors (RMSEs) of 0.45, 0.19, and 0.22 kNm for backfill soil heights of 0.3 m, 0.6 m, and 0.9 m, respectively. Based on this agreement, the 3D finite element method is a reliable tool for predicting the impact on buried pipes, thereby supporting confidence in the analysis approach. In terms of computation time, each

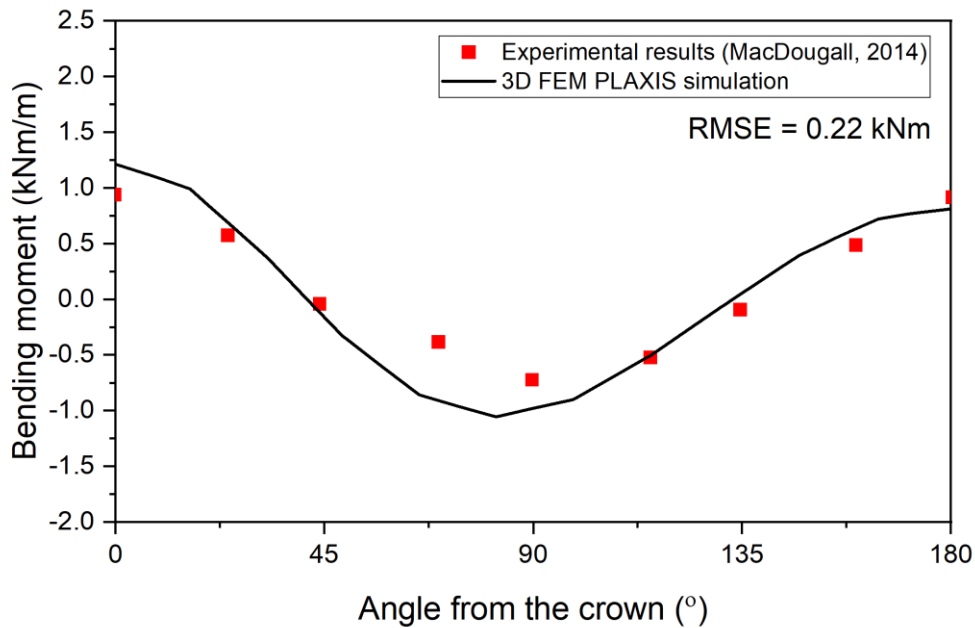
137 scenario took approximately 30 minutes for non-expansive soils and approximately 40-45 minutes
138 for expansive soils, excluding the time to build the model.



(a)



(b)



(c)

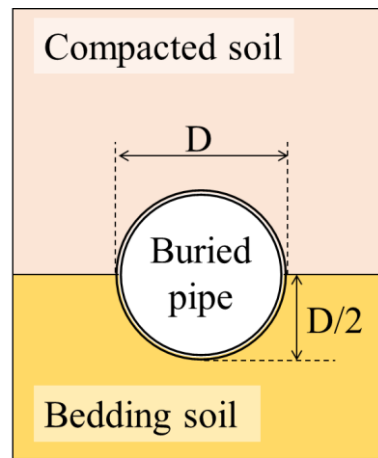
Fig. 2 Bending moments along the circumference of the pipe for the different backfill height of: (a) 0.3 m (b) 0.6 m and (c) 0.9 m comparing numerical modelling results with experimental data from the literature

2.1 Finite element modelling for climatic change investigation on buried pipe

To investigate the impact of climate change on the ground, an extended geometry was employed, enabling the pipe and surrounding soil to be divided into two distinct zones: the active and passive zone. The active zone represents the region where soil conditions (i.e., soil moisture content, soil strength and stiffness) fluctuate in response to climatic changes, whereas the passive zone represents the region where the ground conditions remain stable. The extended geometry consists of a domain measuring 20 m in depth, 30 m in length, and 10 m in width. Additionally, a road structure was modelled to include a 0.1 m thick asphalt pavement, a 0.15 m subbase layer, and a 0.1 m base layer, representing the realistic above-ground structure. The pipe diameter remained unchanged at 600 mm, with a backfill height of 0.9 m, as adopted from the validation process.

Fig. 3 shows a cross-sectional layout of a concrete pipe bedded in the ground consistent with bedding Class B [18] comprising the excavated soil, backfill and bedding material (Card, 2012).

160 By implementing this bedding class, the bedding soil was placed at the bottom half of the pipe,
161 while the top half was filled with compacted backfill soil.



D = Pipe diameter

162

163 **Fig.3** Schematic of the buried pipe's cross-section with bedding class B (Card, 2012)

164 Fig. 4 shows the mesh, geometry, and boundary conditions employed in the FE model. The 20 kPa
165 surcharge loading (BD37/01) was applied across all analysed cases to simulate the traffic surcharge
166 loading. In the FE model, the original soil was divided into two primary zones: the active and
167 passive zones. The active zone had dimensions of 5 m wide, 30 m long, and 4.5 m deep. A fixed
168 depth of 4.5m for the active zone was considered, based on the assumption that water penetrates
169 the soil to the full depth of influence, which was previously validated against the study by
170 MacDougall (2014), as shown in Fig. 1. In contrast, the passive zone (of similar dimensions to
171 the active zone) remains unaffected by these external factors, maintaining a constant water content.
172 Furthermore, the properties of the original soil, backfill, and bedding materials were implemented
173 to reflect typical conditions in the United Kingdom. London Clay was selected to represent the
174 native soil because data on its strength and expansive behaviour, which are driven by variations in
175 water content, are available, and because it is consistent with ground conditions in the United
176 Kingdom.

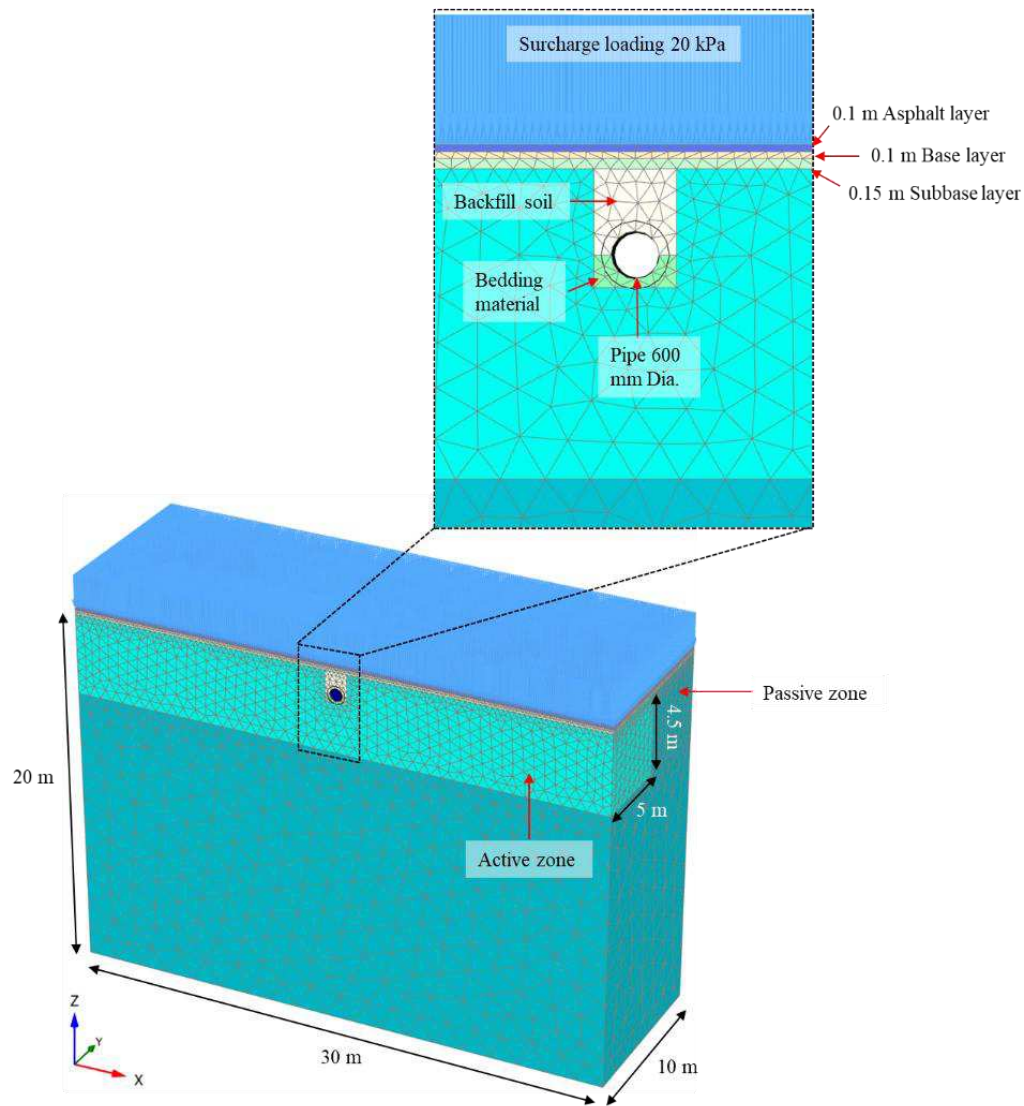


Fig. 4 FE modelling geometry and mesh

Fig. 5 illustrates the relationship between soil water content and undrained shear strength, as reported by (Skempton and Northey, 1952). This relationship was employed as a framework for simulating variations in soil water content. Water content values ranging from 26% to 32% were adopted, based on observational data reported by Standing (2020) for the first 30 m of London clay. With these ranges of water content and the relationship presented by Standing (2020) the undrained shear strength varied between 170 kPa and 35 kPa, respectively.

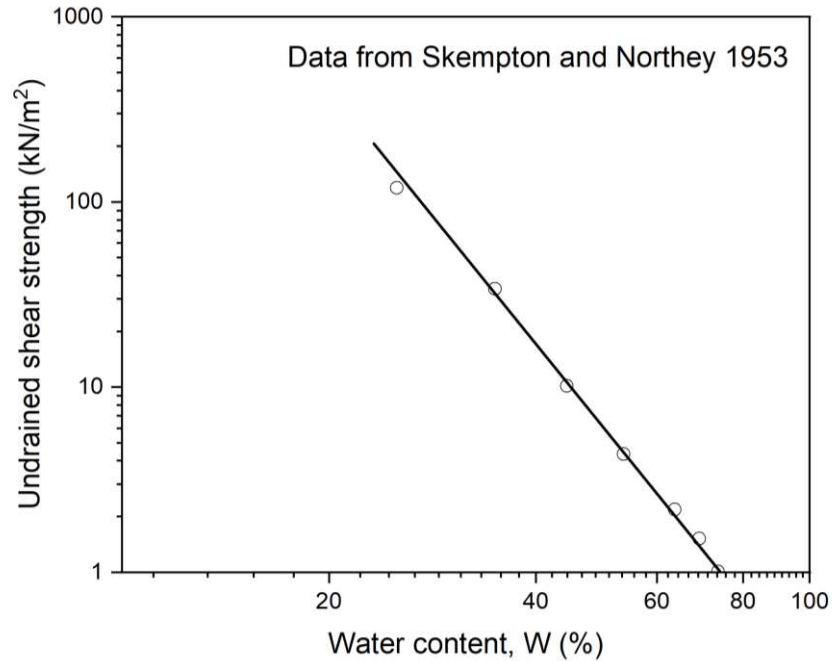
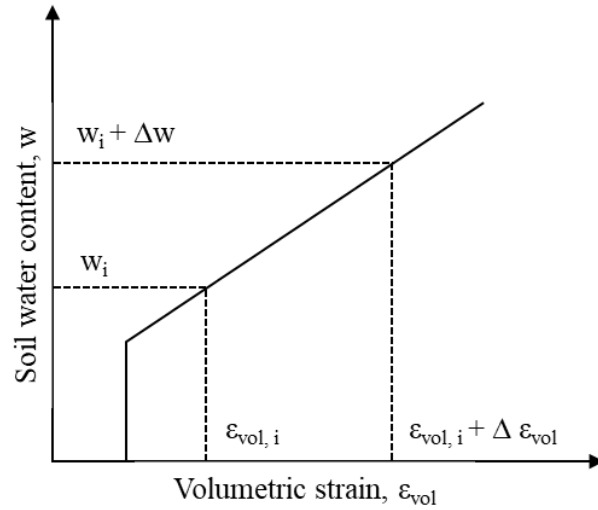


Fig. 5 The relationship between water content in soil and undrained shear strength (Skempton and Northey, 1952)

In the context of expansive soil behaviour, Briaud et al. (2003) reported that the soil's water content directly influences changes in soil volume. Their study further indicated that an increase in water content contributes to variations in volumetric strain, as illustrated in Fig. 6. Based on these findings, a volumetric strain (ϵ_{vol}) was applied to simulate volume changes in expansive soil behaviour corresponding to increases in soil water content.

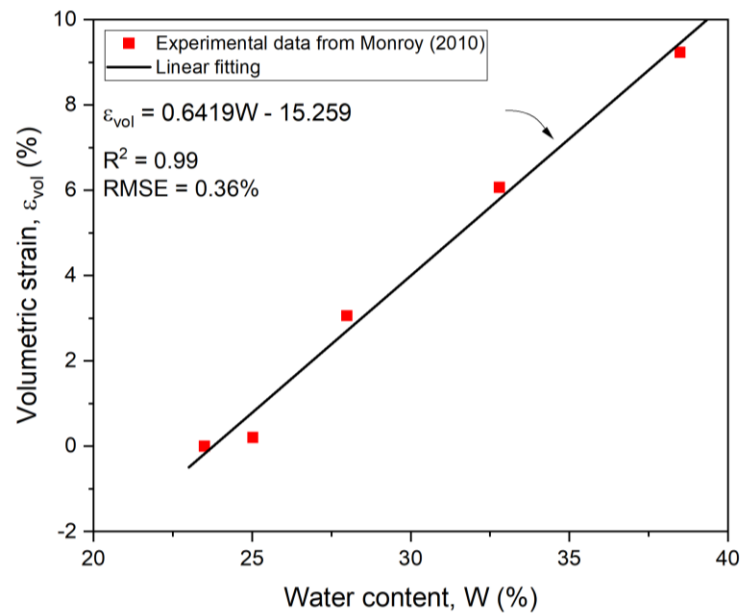
For London clay, an increase in water within the voids affects the volumetric strain, as observed through oedometer experiments (Monroy et al., 2010). Building on their findings, Fig. 7 illustrates the relationship between the water content of London clay and changes in volumetric strain, calculated from the data reported by Monroy et al. (2010), where the volumetric strain is positive for swelling. Table 1 summarises the material properties implemented in this study.



w_i = Initial water content
 Δw = Change in water content
 $\epsilon_{vol, i}$ = Initial Volumetric strain
 $\Delta \epsilon_{vol}$ = Change in Volumetric strain

198

199 **Fig. 6** Schematic relationship between soil water content and volumetric strain observed from
 200 physical modelling (Briaud et al., 2003)



201

202 **Fig. 7** The relationship between water content of London clay and volumetric strain calculated
 203 from the experimental tests (Monroy et al., 2010).

2.2 Parametric study

Two sets of parametric studies were conducted to investigate the impact of climate change-induced variations in soil water content on the performance of existing buried pipes. Two soil conditions within the active zone were considered, including non-expansive and expansive soil.

For the non-expansive soil analysis, the variation of the water content within the active zone, which influences changes in the elastic modulus and undrained shear strength of the original soil, was examined. The parameters used in the model are summarised in Table 1. The initial condition was set at a water content of 26%, with increases to 28%, 30%, and 32% (maximum), respectively, representing the soil's response to climatic change in the active zone. Fig. 8 illustrates the results for the different cases implemented in the parametric study.

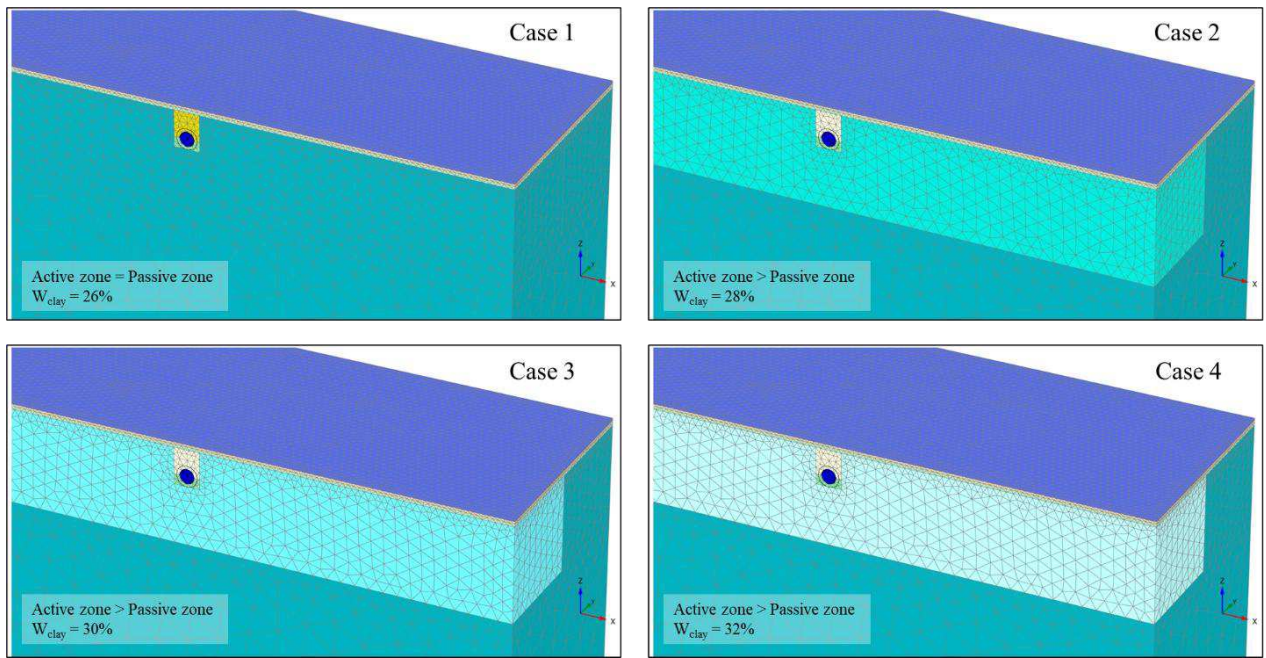


Fig. 8 FE model with varying water content (WC) of Case 1 (WC = 26%), Case 2 (WC=28%), Case 3 (WC =30%) and Case 4 (WC = 32%).

In the context of an expansive soil, an additional parameter, volumetric strain, was incorporated into the analysis of the active zone, alongside changes in the elastic modulus and undrained shear strength, to evaluate the impact of soil expansion. The applied volumetric strains were derived from the relationship presented in Fig. 7.

The initial condition, corresponding to a water content of 26%, was assumed to exhibit no volumetric strain. For water contents ranging from 28% to 32%, incremental volumetric strains of 1.41%, 2.75%, and 4.04% were applied, respectively, as summarised in Table 2.

3. 3D PLAXIS FEM results

This section presents the results and discussion of the parametric study conducted using FE analysis. The results mainly focus on the influence of varying the water content in the soil to induce movement of the existing buried pipe. The discussion is divided into two parts, addressing non-expansive and expansive soil behaviour separately.

3.1 Non expansive soil

Fig. 9 illustrates the computed vertical pipe deformation at the crown resulting from varying the water content of the soil from 26% to 32% . At the initial condition, corresponding to a water content of 26%, the induced deformation is relatively small at 1.41 mm along the entire length of the pipe, with no differential deformation. This uniformity is attributed to the identical properties of the soil in both the active and passive zones.

However, when the water content in the active zone increases by 2% (to 28%), the maximum induced deformation rises slightly to 1.67 mm, accompanied by a small differential deformation of 0.2 mm observed at the two ends of the pipe. Further increases in water content to 30% (a 4% increase from the initial condition) result in a maximum settlement of 2.47 mm at the edge of the pipe within the active zone, contributing to a differential settlement of 0.93 mm. Finally, at a water content of 32%, the maximum settlement reaches 5.26 mm, leading to an increase in differential settlement to 3.61 mm between the pipe's ends. The pattern of vertical pipe displacement, distinguishing between the active and passive zones, is summarised in Fig. 10.

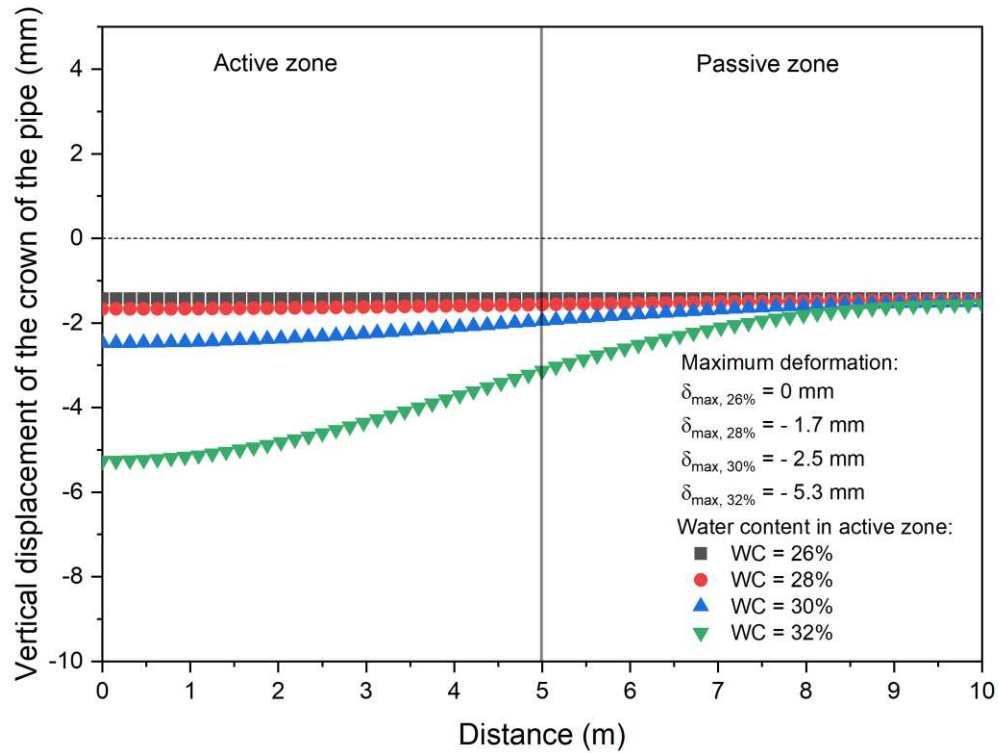


Fig. 9 Vertical pipe movements due to non-expansive soil

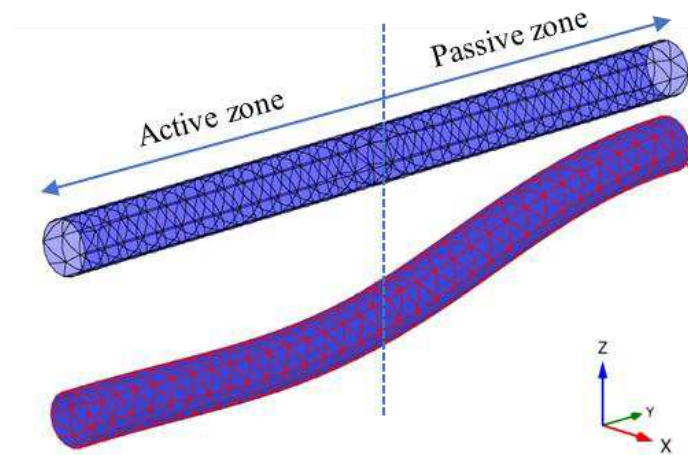


Fig. 10 Predicted pipe displacement due to changing soil water content in active zone (not to scale)

3.2 Expansive soil

In the investigation of expansive soil behaviour, Fig. 11 presents the results for vertical displacement at the pipe crown, influenced by soil expansion due to increased water content. A

water content of 26% was designated as the initial condition, with no volumetric strain applied, and the maximum settlement remained consistent with the non-expansive analysis.

However, when the water content increased to 28%, the soil's strength and stiffness decreased, and an additional volumetric strain of 1.41% was observed. This increase in soil volume led to heave movement in the active zone, with the maximum displacement observed at the edge of the pipe (at crown level), reaching 36.33 mm. The resulting differential displacement was modelled as 34.48 mm.

Notably, further increases in water content to 30% and 32% led to significant increases in both maximum heave and differential displacement. At a water content of 30%, the maximum pipe heave was 82.22 mm, corresponding to a maximum differential settlement of 79.30 mm. Similarly, at a water content of 32%, the maximum pipe heave movement was 129.00 mm, accompanied by a differential settlement of 127.22 mm.

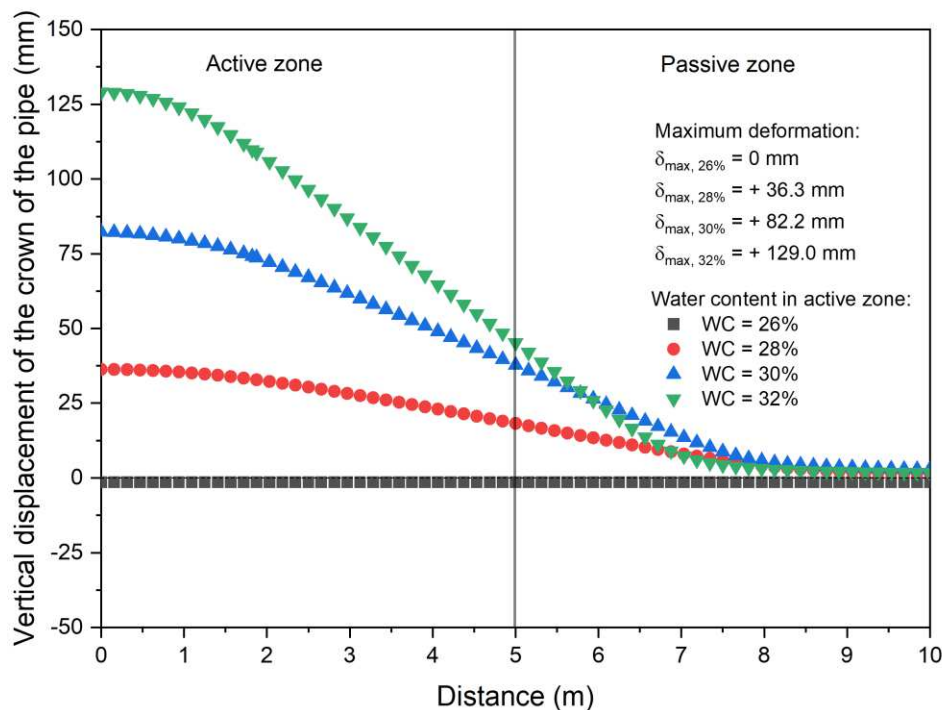


Fig. 11 Vertical pipe movements due to expansive soil behaviour

4. 2D Efficient FEM model using Python

4.1 Motivation for a Reduced-Order 2D Soil-Pipeline Model

PLAXIS 3D simulations were used as the high-fidelity reference for soil-pipeline interaction under climate-driven moisture variation. Although 3D continuum modelling captures the full stress field and geometric detail, its computational demand is high: each scenario required approximately 30 min on a 64-bit workstation using all 12 CPU cores, excluding geometry preparation, meshing, and pre-processing. For large pipeline systems, where hundreds to thousands of segments and multiple environmental scenarios must be assessed, this cost becomes prohibitive for routine engineering screening and network-scale risk assessment.

A reduced order model is therefore required to preserve the governing mechanics while substantially reducing runtime. The proposed 2D finite element model provides this compromise by representing the pipe as beam elements and the soil-pipe interaction through calibrated stiffness components for active and passive zones. This formulation retains the dominant mechanisms that control the bending response (soil support stiffness, stiffness contrast between zones, and moisture-dependent degradation) while avoiding the full computational overhead of 3D meshing and solution procedures.

The 2D model isn't meant to replace detailed 3D analysis for final design verification. Instead, it allows for quick parametric studies, climate scenario testing, and network prioritisation. In this process, the 2D model serves as an effective predictive tool, calibrated and validated against PLAXIS 3D and experimental data. Critical cases can then be analysed further using comprehensive 3D simulations. Section 4.2 presents the numerical formulation of this simplified model, including element-level stiffness assembly, soil-reaction representation, and the implementation of moisture-driven stiffness variation.

4.2 Numerical Formulation of the Lightweight 2D FEM Model

The 2D FEM model developed in this study simulates the interaction between buried pipelines and the surrounding soil, incorporating both structural and geotechnical components. The pipeline is discretised into beam elements, while soil-pipe interaction is modelled using stiffness matrices derived from soil parameters, pipeline material properties, and environmental loading. Key parameters include soil stiffness, represented by Poisson's ratio and Young's modulus, as well as

pipeline characteristics such as external diameter, burial depth, Young's modulus, and moment of inertia. Expansive soil behaviour is incorporated through parameters such as volumetric strain and soil expansion coefficients, enabling the assessment of stress and deformation across diverse soil conditions. The framework also accommodates variable loading scenarios, particularly those driven by changes in soil moisture content, to simulate realistic environmental effects. Soil reaction is modelled using a combination of bearing stiffness, shear layer resistance, and Winkler Spring representations, applied through element-specific stiffness matrices.

Fig. 12 illustrates the modelling approach for a buried pipeline section, with the surrounding soil modelled as discrete spring elements. The two interaction zones indicate the length of pipe subject to changes in water content (active zone) and the section of pipe where the water content remains constant (passive zone). At both pipe ends, roller-type boundary conditions are imposed, such that horizontal displacement is restrained, vertical displacement is permitted, and rotation remains free. These boundary conditions are intended to represent the modelled pipe segment as part of a longer continuous pipeline, allowing vertical deformation while preventing rigid-body translation in the horizontal direction. Model predictions of the pipeline's displacement and stress are validated against PLAXIS 3D simulations and available experimental data, confirming the model's reliability and robustness. This FEM framework offers an efficient and effective tool for evaluating the stability and long-term performance of buried pipelines under variable geotechnical and environmental conditions.

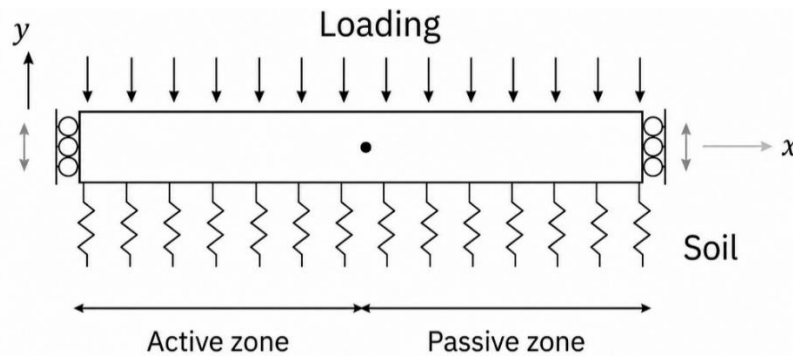


Fig. 12 Schematic of the model of a pipe section indicating the two different zones and the representation of the soil in form of springs

The transverse vertical deflection of the pipe axis (centroidal line) v_x due to applied distributed load q_x is provided by following equation:

$$\frac{d^2}{dx^2} \left(\frac{E_p I d^2 v_x}{dx^2} \right) + p_x = q_x \quad (1)$$

where E_p and I are, respectively, the Young's modulus and the moment of inertia of the pipe, q_x is the external load applied in the vertical direction to the pipe axis and typically represents the overburden (soil) weight, surcharge loads (traffic and surface loads) and any vertical actions; and p_x is the soil reaction (in N/m) on the components of the pipes, expressed according to the Modified Vlasov Model MVM, as follows:

$$p_x = k_w \cdot v_x - \frac{k_s d^2 v}{dx^2} \quad (2)$$

where k_w is the coefficient of the subgrade reaction (equivalent to the Winkler coefficient in N/m^2), and k_s is the shear coefficient (in N). Their values are based on the research by (Elachachi et al., 2012) as given in Eqs. (3) to (6).

$$k_w = \frac{(1 - \nu_s) E_s D_{ext}}{(1 + \nu_s)(1 - 2\nu_s) H_s} \psi_k \quad (3)$$

$$k_s = \frac{E_s D_{ext} H_s}{2(1 + \nu_s)} \psi_s \quad (4)$$

$$\psi_k = \frac{\gamma (\sinh \gamma \cosh \gamma + \gamma)}{2 \sinh^2 \gamma} \quad (5)$$

$$\psi_s = \frac{1}{\gamma} \frac{(\sinh \gamma \cosh \gamma - \gamma)}{2 \sinh^2 \gamma} \quad (6)$$

where, D_{ext} is the external pipe diameter, E_s and ν_s are the Young's modulus and the Poisson coefficient of the bedding material respectively and H_s is the thickness of the soil layer beneath the pipe. The normalised stiffness soil-pipe parameter γ was assumed equal to 0.39 based on the research by (Elachachi et al., 2012).

The soil-pipe interaction stiffness matrices based on the research by Elachachi et al. (2012) is defined as:

$$[K^e] = [K_b^e] + [K_w^e] + [K_s^e] \quad (7)$$

Where $[K_b^e]$ is the elementary stiffness matrix of the beam (Eq. 8), $[K_w^e]$ is the soil stiffness matrix related to the Winkler part and expressed by Eq. (9) and $[K_s^e]$ is the soil stiffness matrix related to the shear contribution, as given in Eq. (10).

$$[K_b^e] = \frac{E_p I}{l_e^3} \begin{bmatrix} 12 & 6l_e & -12 & 6l_e \\ 6l_e & 4l_e^2 & -6l_e & 2l_e^2 \\ -12 & -6l_e & 12 & -6l_e \\ 6l_e & -2l_e^2 & -6l_e & 4l_e^2 \end{bmatrix} \quad (8)$$

$$[K_w^e] = \frac{k_w D_{ext} l_e}{420} \begin{bmatrix} 156 & 22l_e & 54 & -13l_e \\ 22l_e & 4l_e^2 & 13l_e & -3l_e^2 \\ 54 & -3l_e & 156 & -22l_e \\ -13l_e & -3l_e^2 & -22l_e & 4l_e^2 \end{bmatrix} \quad (9)$$

and

$$[K_s^e] = \frac{k_s D_{ext}}{30l_e} \begin{bmatrix} 36 & 3l_e & -36 & 3l_e \\ 3l_e & 4l_e^2 & -3l_e & -l_e^2 \\ -36 & -3l_e & 36 & -3l_e \\ 3l_e & -l_e^2 & -3l_e & 4l_e^2 \end{bmatrix} \quad (10)$$

The volumetric strain (ε_{vol}), representing the volume changes of the soil due to variations in water content, was explicitly defined as a parameter within the soil properties. An expansion coefficient (β_{ex}) was introduced to quantify the induced stress resulting from this volumetric change.

Mathematically, the induced additional load (Δq) from the soil volumetric expansion was calculated as:

$$\Delta q = -\varepsilon_{vol} \cdot \beta_{ex} \quad (11)$$

where ε_{vol} was considered equal to 6.6% and the β_{ex} was considered equal to $1e7$ based on the research by (Monroy et al., 2010) which represent London clay as a worst case scenario (Briaud et al., 2003). This additional load was superimposed onto the original vertical load acting on the pipe, thereby modifying the resultant loading condition. The finite element formulation

incorporated this modified loading scenario in the calculation of the displacements and stresses, allowing for an accurate representation of the pipe behavior under expansive soil conditions.

4.3 Verification of the 2D FEM model against PLAXIS 3D

To validate the theoretical framework and numerical model, simulations were conducted using PLAXIS 2D, a robust finite element software for geotechnical engineering. The simulations were designed to replicate real-world conditions, focusing on the interactions between buried pipelines and expansive soils under varying water contents due to climatic changes.

Figs. 13 and 14 present the transverse vertical deflection of the pipe axis (centroidal line) along the buried pipeline under varying soil gravimetric water contents, comparing the predictions of the developed 2D finite element model with those of the PLAXIS 3D simulation. Fig. 13 shows results for a non-expansive soil at water contents of 26%, 28%, and 30%, while Fig. 14 illustrates results for expansive soil under the same water conditions. In both cases, the solid lines represent the outputs of the 2D FEM model, and the dotted markers indicate the results obtained from the PLAXIS 3D simulations. A strong agreement is observed between the two modelling approaches.

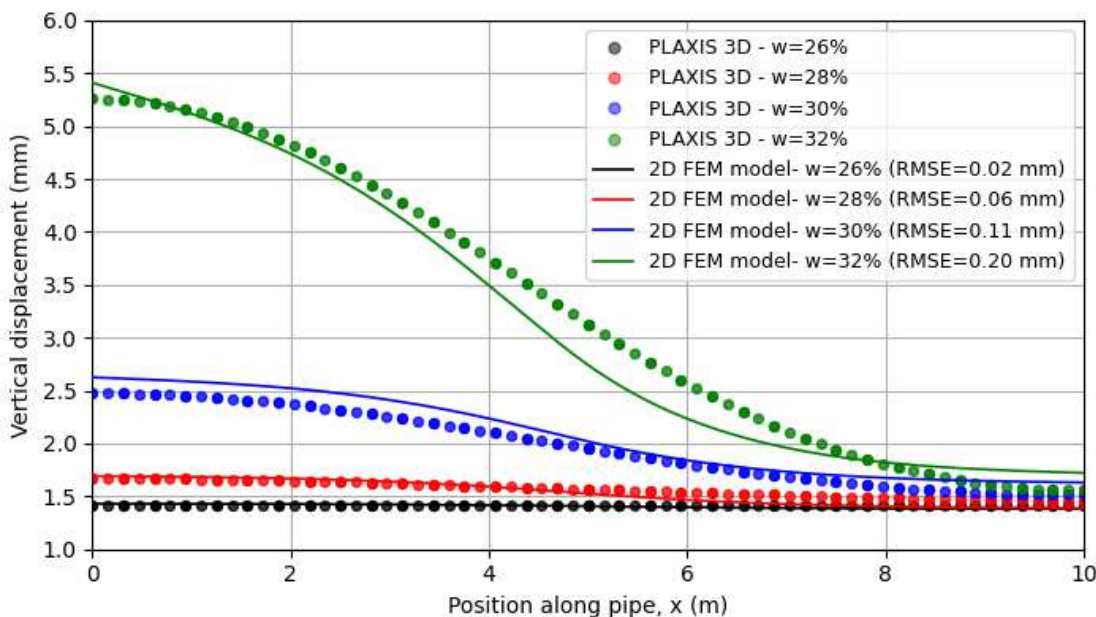


Fig. 13 Absolute value of vertical settlement from 2D and 3D modelling along the buried pipe in a non-expansive soil with water contents of 26%, 28%, 30% and 32% in the active zone (in the passive zone a constant value of 26% is used).

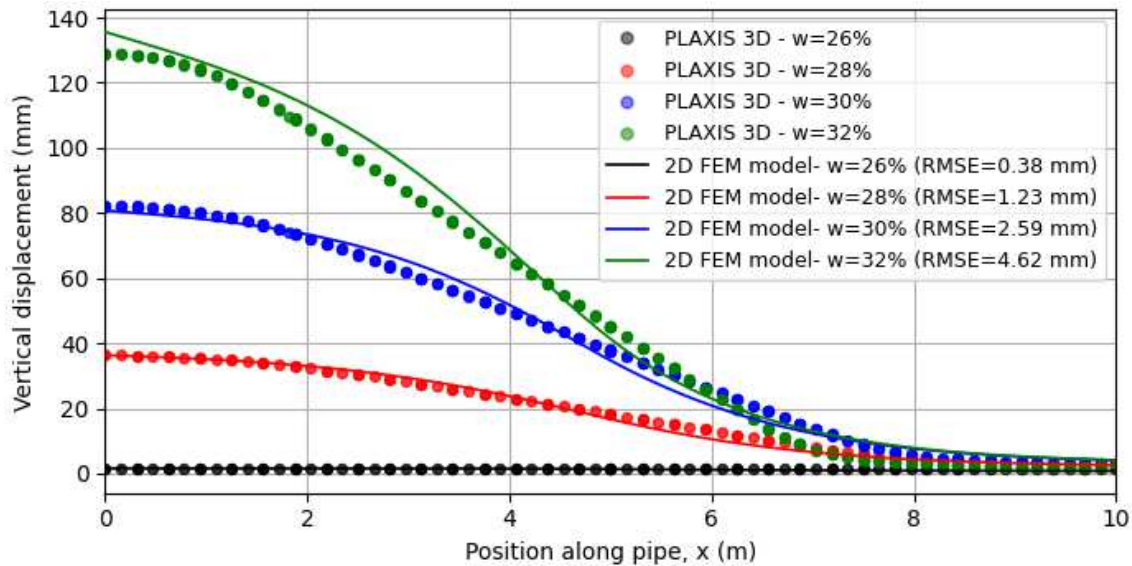


Fig. 14 Vertical displacement from 2D and 3D modelling along the buried pipe in an expansive soil at water contents of 26%, 28%, 30% and 32 % in the active zone (in the passive zone a constant value of 26% is used).

4.4 Model comparison, computational efficiency and discussions.

The comparison presented in Figs. 13 and 14 demonstrates that the developed 2D Python FEM model can reproduce the key displacement behaviour predicted by the PLAXIS 3D simulations for both non-expansive and expansive response scenarios. In the non-expansive case, the model captures the gradual increase in downward vertical displacement associated with reductions in soil stiffness and undrained shear strength as water content increases. In the expansive case, the model also successfully represents the significantly larger upward movements driven by moisture-dependent volumetric strain within the active zone.

Although minor local discrepancies are observed, primarily arising from the simplified representation of soil continuity and the absence of full three-dimensional stress redistribution, the overall displacement magnitudes and longitudinal deformation profiles from the 2D beam–Winkler model are in close agreement with the PLAXIS 3D reference solutions for both soil types. For non-expansive conditions, profile RMSE values were 0.02 mm ($w = 26\%$), 0.06 mm ($w = 28\%$), 0.11 mm ($w = 30\%$) and 0.20 mm ($w = 32\%$), with a mean RMSE of 0.10 mm across all moisture scenarios. Peak settlement differences at $x = 0$ m were 0.9%, 1.4%, 6.1% and 3.0%, respectively, generally below 5%, with a maximum of approximately 6% at $w = 30\%$. Normalised

against the PLAXIS peak settlement (1.4, 1.7, 2.5 and 5.3 mm), profile RMSE remained below 4% of the reference peak in all cases. The largest deviation occurred at $w = 32\%$ (RMSE = 0.20 mm), where settlement was slightly overestimated near the pipe ends ($x \approx 0$ and $x \approx 10$ m), with a modest local underprediction in the mid-span region ($x \approx 4$ –8 m). Nevertheless, all compared points lay within ± 0.4 mm of the PLAXIS solution, and the two models showed nearly identical trends along the pipe length, including the reduction in settlement from the active zone towards the passive zone and convergence towards similar values at $x = 10$ m.

For expansive conditions, profile RMSE values were 0.38 mm ($w = 26\%$), 1.23 mm ($w = 28\%$), 2.59 mm ($w = 30\%$) and 4.62 mm ($w = 32\%$), yielding a mean RMSE of 2.21 mm. Agreement was strongest at low moisture and remained within 2.59 mm at $w = 30\%$, with the largest discrepancy at $w = 32\%$ (RMSE = 4.62 mm), associated with an intentional, conservative calibration of heave near the pipe centre. Peak heave errors at $x = 0$ m were approximately 0% ($w = 26\%$), 1% ($w = 28\%$), 1.8% ($w = 30\%$) and +5% ($w = 32\%$). For $w = 28$ –32%, peak heave agreed within 5% of PLAXIS, while normalised RMSE remained below 4% of the reference peak heave. Slightly larger local discrepancies of up to approximately 8–10% were observed in regions of maximum curvature (mid-span, $x \approx 3$ –5 m), where the 2D model did not fully capture three-dimensional stress redistribution; this was most evident at $w = 32\%$, where heave was slightly overestimated near $x = 0$ but underestimated between $x \approx 4$ and 8 m. Despite these local effects, the 2D model captured the overall profile shape, including the peak at the pipe centre and the transition from the active to the passive zone.

In both cases, RMSE increased with moisture content but remained small relative to the reference displacement magnitudes, indicating that the simplified formulation retains the dominant mechanics governing soil–pipeline interaction under climate-induced moisture variation.

A key advantage of the proposed approach lies in its computational efficiency. The PLAXIS 3D simulations required approximately 30 to 45 minutes per scenario, even when executed on a multi-core workstation, excluding the additional time associated with geometry generation, meshing, and model calibration. While such high-fidelity models are essential for understanding detailed soil–structure interaction mechanisms, their computational cost makes them impractical for large-scale applications. This limitation becomes particularly significant in the context of national infrastructure systems, where hundreds of thousands of kilometres of buried pipelines must be

assessed under multiple climate scenarios. For example, in England and Wales alone, wastewater and water distribution assets extend over very large distances (approximately 500,000 km of sewers and 425,000 km of water mains), and climate-resilience assessments may require evaluation across multiple soil types, temporal scenarios, and probabilistic conditions. In this context, reliance solely on 3D finite element simulations would lead to prohibitive computational demands (Calafati et al., 2025, Hall and Gray, 2025).

In contrast, the developed 2D Python FEM model completes each simulation in less than 30 seconds on standard computing hardware, with minimal memory requirements. This represents a reduction in computational time of several orders of magnitude while maintaining sufficient accuracy for screening-level assessment. Such performance enables integration within large-scale risk assessment frameworks where soil moisture data, climate projections, and infrastructure datasets must be combined to evaluate network-wide vulnerability. The ability to rapidly evaluate thousands of pipeline segments under varying environmental conditions makes the proposed model particularly suitable for probabilistic analysis, asset management, and decision-support tools. Therefore, the combination of high-fidelity 3D modelling for validation and a fast 2D surrogate for large-scale application provides a practical and scalable approach for climate resilience assessment of buried pipeline infrastructure.

Several limitations remain and point to future work. First, the lightweight 2D model was verified primarily against PLAXIS 3D outputs; although this provides a high-fidelity numerical benchmark, it is still largely model-to-model verification, and broader independent validation against laboratory and field datasets is needed. Second, the present study considers a single soil formation (London Clay), one pipe type, and one installation class, and represents moisture variation through discrete water-content and volumetric-strain states rather than fully coupled hydro-mechanical processes driven by site-specific climate time series. Third, soil behaviour in the 2D model is represented through equivalent linear stiffness, without explicit plasticity, large-strain stiffness degradation, or detailed pipe-joint modelling. Future developments will therefore expand the Python tool to include a wider library of soil types and moisture-dependent parameter relationships, additional loading actions (e.g., traffic and seismic loading), and probabilistic treatment of soil variability and climate projections. Despite these simplifications, the combined use of high-fidelity 3D modelling and a computationally efficient 2D implementation provides a practical basis for climate-resilience assessment of buried pipeline infrastructure.

5. Conclusions

This study investigated how buried rigid pipelines respond to climate-induced variations in soil moisture by combining detailed three-dimensional finite element modelling in PLAXIS 3D with an efficient two-dimensional numerical model developed in Python. London Clay was used as the representative parent material, and realistic installation and loading conditions were considered. To capture spatially variable climate effects, the soil domain was divided into an active zone, where water content and associated soil properties were varied, and a passive zone, where the initial soil conditions were maintained. The 3D simulations provided a high-fidelity reference for soil–pipeline interaction, while the 2D model was designed as a computationally efficient surrogate for large-scale applications.

The PLAXIS 3D parametric study showed that variations in water content within the active zone strongly influence pipe behaviour. Under non-expansive conditions, increasing the water content from 26% to 32% reduced undrained shear strength and stiffness, leading to gradual increases in settlement and differential displacements, primarily affecting serviceability. When expansive soil behaviour was represented by changes in the moisture-dependent volumetric strain, the response became much more severe, with heave of the order of 100 millimeters and large differential displacements between the active and passive zones.

The 2D beam-on-elastic-medium model, incorporating Modified Vlasov-type soil stiffness, reproduced the displacement profiles predicted by the PLAXIS 3D simulations with strong quantitative agreement across all investigated scenarios. For expansive response cases, differences in peak displacement between the two models were generally within 5–10%, with slightly higher deviations in regions of maximum curvature, where three-dimensional stress redistribution effects are more pronounced. In non-expansive response scenarios, the agreement was even closer, with differences typically below 5% and nearly identical displacement trends along the pipe length. In addition to capturing peak magnitudes, the 2D model accurately reproduced the spatial distribution of deformation and the transition between active and passive zones. This level of agreement was achieved while reducing computational time from approximately 30 minutes per scenario for the PLAXIS 3D simulations, even on a multi-core system, to less than 30 seconds on standard computing hardware. Overall, the results demonstrate that the simplified 2D model retains the dominant mechanics governing soil–pipeline interaction while offering a substantial reduction in

computational demand. This makes it particularly suitable for integration into large-scale, probabilistic, and network-level climate resilience and risk assessment frameworks, where rapid evaluation of numerous pipeline segments under varying environmental conditions is required.

Code availability

The developed computational code will be made available upon reasonable request, subject to any institutional or project-related restrictions

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable. This study is based entirely on numerical modelling and analysis of previously published experimental data. No human participants, personal data, or identifiable individuals were involved.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Nikolaos Reppas: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Original draft writing, Visualization. Xilin Xia: Methodology, Supervision, Review & editing. Phatharaphong Yensri: Methodology & editing. Soroosh Sharifi: Review & editing. Asaad Faramarzi: Supervision, Project administration, Review. Nicole Metje: Supervision, Review & editing.

Funding

This work was supported by UK Research and Innovation under the Data & Analytics Facility for National Infrastructure (DAFNI) Centre of Excellence for Resilience Infrastructure Analysis [grant number ST/Y00406X/1].

Acknowledgements

The authors gratefully acknowledge the support of UK Research and Innovation under the Data & Analytics Facility for National Infrastructure (DAFNI) Centre of Excellence for Resilience Infrastructure Analysis (ST/Y00406X/1) (Matthews et al., 2023). The authors also acknowledge the use of the BlueBEAR High Performance Computing service at the University of Birmingham.

Tables

Table 1. Material properties used in the analysis

Material	Constitutive Model	Water content (%)	Unit weight (kN/m ³)	S _u (kPa)	Cohesion (kPa)	Friction angle (deg)	Poisson's ratio	Secant stiffness, E ₅₀ (MPa)	Tangent stiffness, E _{oed} (MPa)	Unloading stiffness, E _{ur} (MPa)
London clay	HS	26	19.0	170	5.0	25.0	0.30	25.50	25.50	76.50
		28		125				18.75	18.75	56.25
		30		80				12.00	12.00	36.00
		32		35				5.25	5.25	15.75
Backfill soil	HS	-	19.5	-	0	40.0	0.35	10.00	10.00	30.00
Bedding soil	HS	-	20.0	-	0	46.7	0.30	22.00	22.00	66.00
Base	MC	-	21.2	-	0	50.0	0.38	214.00	-	-
Subbase	MC	-	19.0	-	0	40.0	0.35	93.00	-	-
Asphalt	LE	-	22.8	-	-	-	0.35	3,140.00	-	-
Concrete pipe	LE	-	24.5	-	-	-	0.20	38,450.00	-	-

(Soil models: HS = Hardening soil, MC = Mohr-Coulomb, LE = Linear)

520 **Table 2. Applied volumetric strains due to different water content in soil**

Case	Water content of soil (%)	Volumetric strain, ϵ_{vol} (%)	Incremental volumetric strain, $\Delta\epsilon_{vol}$ (%)
Case 1	26	1.5 (baseline)	0.0
Case 2	28	2.9	1.4
Case 3	30	4.3	2.8
Case 4	32	5.5	4.0

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