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Seismic analysis of a district heating pipeline

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Abstract

The effect of seismic loading is not contemplated in any of the current design standards of District Heating and Cooling (DHC) networks, since this technology has been originally adopted in northern Europe, characterized by low earthquake vulnerability. Nevertheless, an increasing number of countries, including those in seismic areas like Italy, Turkey, China, Japan, and Chile are using DHC solutions due to the higher energy efficiency, compared to individual heating systems.

Seismic regions are one of the most hostile environments for buried pipelines due to the effects of Transient Ground Deformation (TGD) caused by seismic wave propagation, and Permanent Ground Deformation (PGD), like faulting, landsliding, lateral spreading and buoyancy due to liquefaction.

Most of research publications on the seismic analysis and design of buried steel pipelines have been motivated by the need of safeguarding the integrity of hydrocarbon pipelines, and there are no actual studies on the seismic vulnerability of DHC pipelines. This highlights the need to carefully evaluate the seismic performance of DHC pipelines, considering their typical composite cross-section and soil-pipe interaction under service loading.

The present paper analyses the effect of diverse earthquake hazards on an operating District Heating (DH) pipe bend, usually susceptible to stress concentrations due to the greater flexibility, as well as the ability to accommodate thermal expansions, and absorb other externally-induced loading.

The response of the operating DH pipeline subjected to different seismic loading is evaluated taking into account the geometric and mechanical properties of the system, including the soil-pipeline interaction.

In conclusion, the obtained results give a better understanding on the seismic behavior of DH pipelines, highlighting important research ground for assessing their earthquake performance in operating conditions.

Keywords: Seismic analysis; Transient Ground Deformation; Permanent Ground Deformation; District Heating Pipeline

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1. Introduction

District Heating and Cooling (DHC) consist of an underground pipe network connecting buildings in an urban area to centralized plants or a number of distributed heat producing units, allowing for heat recycling and renewable energy supply. Due to the higher energy efficiency, an increasing number of countries including those in seismic areas like Italy, Turkey, China, Japan, are adopting district heating solutions. The effect of seismic loading is not contemplated in any of the current design standards of DH networks, since this technology has been originally adopted in northern European countries, characterized by low earthquake vulnerability.

Seismic regions are one of the most hostile environments for buried pipelines due to the effects of Transient Ground Deformation (TGD) caused by seismic wave propagation, and Permanent Ground Deformation (PGD), like faulting, landsliding, lateral spreading and buoyancy due to liquefaction [1].

Most of research publications on the seismic analysis and design of buried steel pipelines have been motivated by the need of safeguarding the integrity of hydrocarbon pipelines [2], and there are no actual studies on the seismic vulnerability of DHC pipelines. This highlights the need to carefully evaluate the seismic performance of DHC pipelines, considering their typical composite cross-section and soil-pipe interaction under service loading.

To minimize heat losses, DHC pipes have a composite cross-section of three different material layers, including the steel pipe for the water supply, the insulation foam of polyurethane (PUR), and an outer coating of High Density Polyethylene (HDPE), interacting with the surrounding soil. The stiffness of the PUR foam and its constant adhesion to the steel pipe are essential to properly transmit at the HDPE coating the friction stresses from the surrounding soil.

The axial expansion of the operating pipeline, is counteracted by the soil friction at the outer HDPE coating interface, until the total friction reaction equilibrates the pipe axial force at the anchor point, where the thermal expansion is fully restrained. Moreover, the thermal expansion is counteracted at the bend by the lateral soil reaction, inducing high stress levels in this critical region, as schematically illustrated in Fig. 1. Additionally, the PUR insulation is very sensitive to axial shear stress and lateral pressures, inducing high stresses associated with material failure and loss of the bond; in a worse case, it can lose its insulation effect if the steel service pipe cracks and the foam is moistured. [3].

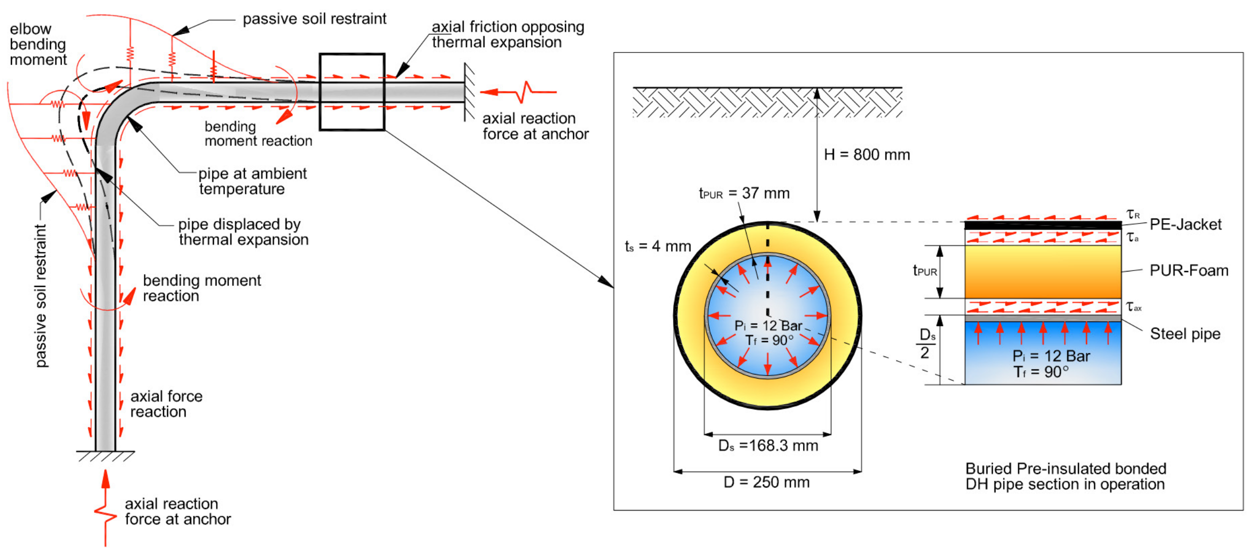

Fig. 1. Deformation of buried operating DH pipeline at the bend (adapted from [4] and [5])

Therefore, a correct design of DHC pipelines requires an accurate consideration of the elevated stresses and deformations due to the operating loads like internal pressure and temperature, as well as the evaluation of the soil-pipeline interaction.

Reported experimental research on the response of buried DH pipe systems subjected to ground movement is very limited, requiring further analysis of the soil-pipe interaction of buried DH pipes, while taking into account real operating conditions and modern pipe laying technologies [6-10]. On the other hand, the seismic response of buried pipelines has been investigated by many researchers in the last 50 years, using experimental investigations as well as simple analytical or more complex numerical approaches [11-17].

During extreme events like earthquakes, the pipeline needs to plastically stretch, bend and compress in order to accommodate local or global movement of the surrounding soil, requiring strain-based performance criteria for a safe and cost-effective pipeline design [18-19]. Evidently, stress-based performance limit states, like those recommended in European standard EN 13941 [20] or in the Eurocode 3 - Part 4-3 [21] are overconservative for pipelines constructed in harsh environments, like seismic regions.

The present paper analyses the effect of seismic induced ground movement on an operating District Heating (DH) pipe bend, typically susceptible to highest moments and stress concentrations due to the greater flexibility, as well as the ability to accommodate thermal expansions, and absorb other externally-induced loading. [22].

The response of the operating DH pipeline subjected to seismic loading is evaluated taking into account the geometric and mechanical properties of the system, including the soil-pipeline interaction. In conclusion, the obtained results give a better understanding on the seismic behaviour of DH pipelines, highlighting important research ground for assessing their earthquake performance in operating conditions.

Nomenclature

D_s	outer diameter of the steel pipe
t_s	thickness of the steel pipe
D	outer diameter of external HDPE coating
t_{PUR}	thickness of the PUR insulation
R_{bend}	radius of the pipe bend
L	length of the pipe legs
L_c	length of the expansion cushion at each bend leg
H	soil cover depth
E	elasticity modulus of the steel pipe
ν	Poisson's ratio of the steel pipe
σ_y	yield strength the steel pipe
α	linear thermal expansion coefficient of the steel pipe
ϕ	soil friction angle
γ	soil density
T_i, T_f	installation and operating temperature
P_i,	operating internal pressure in the steel pipe
U_g, ε_g, λ_g	earthquake induced ground displacement, ground strain, and seismic wave length
F_R	soil friction reaction
P_u	maximum lateral soil reaction
k	elastic lateral soil stiffness
k_c	equivalent lateral stiffness in the pipe corner with expansion cushion
M_y	yielding moment of the steel pipe section

2. Methodology

This paper investigates the performance of preinsulated bonded DH pipelines, subjected to TGD due to seismic wave propagation. Clearly, this hazard affects DH networks, considerably more than does PGD, threatening mainly transmission hydrocarbon pipelines.

The investigated pipe bend DN 150/250 is composed of a central P235GH steel pipe of external diameter D_s = 168.3 mm and thickness t_s = 4 mm, a foam insulation of thickness t_{PUR} = 37 mm, and external plastic mantle with outer diameter D = 250 mm. The radius of the pipe bend is R_{bend} = 1 m, the length of the expansion cushion at the corner is L_c = 2 m, while the length of both bend legs is L = 40 m, anchored at the ends. The pipe is assumed buried in loose sand soil with a cover depth H = 0.8 m, as schematically illustrated in Fig. 1.

The soil-pipeline system subjected to seismic loading has been analyzed numerically within beam on Winkler foundation theory, using the finite element software ABAQUS/Standard [23].

The pipeline is modeled using the PIPE31 beam element type, allowing the possibility to specify external or internal pressure. The soil-pipeline interaction is modeled with the spring-like pipe-soil interaction elements PSI34, representing the soil reaction to the soil movement in the axial, lateral, and vertical direction. One edge of the element shares nodes with the underlying pipe element while the nodes on the other edge are assigned the far-field ground motion through the boundary conditions.

The P235GH steel pipe material model is defined within the von Mises plasticity theory with nonlinear hardening. The material parameters are determined as a function of the operating temperature T, according to EN 13941 [19]. The elasticity modulus, yield strength, and the linear thermal expansion coefficient at the operating temperature T = 90°C are E = 208857 MPa , σ_y = 215.8 MPa and α = 12.098 10^{-06} 1/K respectively, while the Poisson's ratio is ν = 0.3. A loose sand material is assumed as soil backfill, with the same properties reported in the calculation example of the German standard FW 401 [4], characterized by a friction angle ϕ = 32.5°, and a soil density γ = 18 kN/m^3. The force-displacement relationship is considered bilinear elasto-plastic, and evaluated according to FW 401 [5]. Specifically, the calculated soil friction reaction is F_R = 3944 N/m, while the maximum lateral soil reaction is P_u = 49750 N/m, with an elastic lateral soil stiffness k = 35 MPa beyond the expansion cushion, where the equivalent elastic lateral stiffness is k_c = 0.247 MPa [5].

The seismic-induced ground movement is applied at the free nodes of the pipe-soil interaction elements, as a sinusoidal wave propagating horizontally in the direction of the longitudinal leg.

The numerical analysis for assessing the seismic performance of the operating DH pipeline are conducted in two consecutive steps. At first, a static analysis is performed to establish the stress and strain state in the soil-pipeline system in operating conditions with internal pressure P_i = 12 Bar, installation and service temperature T_i = 10°C and T_f = 90°C, respectively. In the second step, a horizontal displacement is applied quasi-statically at the free nodes ends of the pipe-soil interaction elements, matching the sinusoidal pattern defined by:

$$U_g(x) = \varepsilon_g \left(\frac{\lambda_g}{2\pi} \right) \sin\left(\frac{2\pi y}{\lambda} \right) \tag{1}$$

where ε_g = 0.0041 is the soil strain and λ = 500 m is the seismic wave length. Thus, the maximum value of the ground displacement results U_g = 0.33 m

On each loading step, the global equilibrium equations are solved iteratively by the Newton-Raphson method permitting to assess the pipe and soil deformation state at each increment.

3. Results and discussion

This section presents the structural response of the buried DH pipeline evaluated using the proposed methodology. Firstly, the pipeline response is investigated in operating conditions, under the effect of internal pressure and temperature variation. Then the seismic performance of the pipeline is analyzed in terms of loading and deformations, for different values of the maximum seismic-induced ground displacement U_g, as discussed further in this section.

3.1. Structural response of the pipeline in operating conditions

The expansion of the operating pipeline is counteracted by the beneficial effect of the soil friction, and the bearing force on the transverse leg (Fig. 1). The maximum axial elongation of the pipeline in operation conditions, calculated numerically (31.1 mm) is consistent with the theoretical value of the maximum axial elongation u_{max}, according to the formula reported in the standards FW 401 [5] and EN 13941 [20]:

$$u_{\max} = \left(\alpha_T \Delta T + \frac{(1-2\nu)}{EA_s} \frac{P_i D_s}{4t_s} \right) \cdot L - \left(\frac{7}{10} \cdot \frac{F_R}{EA_s} \right) \cdot L^2 \approx 29.4 \ mm \tag{2}$$

Clearly, the first addend in Eq. (2) indicates the pipeline expansion due to the positive temperature variation ΔT = 80°C, and internal pressure P_i = 12 Bar, while the second negative term represents the pipeline contraction due to the soil resistance at the outer HDPE coating.
The aforementioned values of the maximum axial elongation are consistent with the estimations using the method proposed in [22, 24-26], considering the bend either rigid (30.8 mm) or flexible (31.4 mm).

The pipeline response in terms of longitudinal deformations does depend on the geometrical and mechanical parameters of the system, like the operating temperature T_f, the pipe length L, and the bend radius R_{bend}.

Clearly, the maximum longitudinal strain in operating conditions occurs at the elbow (ε_{max} = 0.42%, for T_f = 90°C, L = 40 m and R_{bend} = 1 m). A small parametric study has shown that the pipeline deformation is accentuated for greater operating temperatures (ε_{max} = 1.03%, for T_f = 130°C), larger pipe length (ε_{max} = 0.91%, L = 80 m), smaller bending radius (ε_{max} = 0.68%, for R_{bend} = 0.5 m), all other parameters remaining the same, as shown in Fig. 2. These critical factors need to be carefully evaluated in the design phase in order to avoid excessive stress-strain concentration in the operating pipeline, associated with material damage.

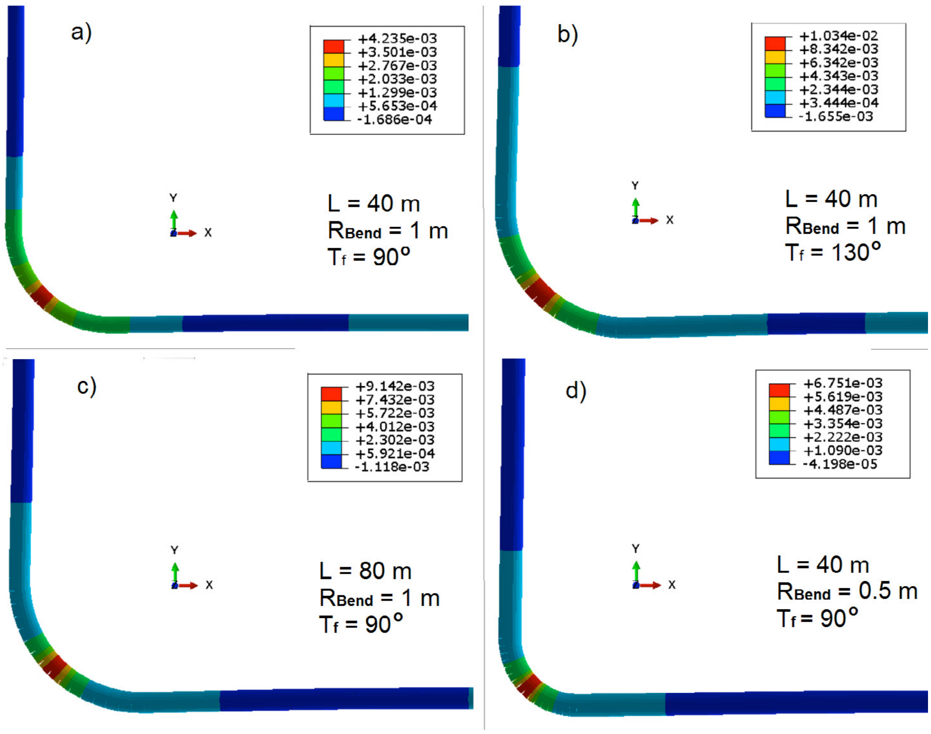

Fig. 2. Longitudinal strain contour and deformed shape of pipeline at the bend region, under operating conditions, for different values of the system parameters: a) T_f = 90°C, L = 40 m, R_{bend} = 1 m; b) T_f = 130°C, L = 40 m, R_{bend} = 1 m; c) T_f = 90°C, L = 80 m, R_{bend} = 1 m; d) T_f = 90°C, L = 40 m, R_{bend} = 0.5 m.

Evidently, the axial force in operating conditions is compressive and in the elastic range, with its magnitude increasing linearly along the pipeline from the bend region towards the anchor points, where it reaches its maximum value (162507 N). The observed linear variation of the axial force beyond the bend region is caused by the constant soil friction (F_R = 3944 N/m) opposing the thermal expansion. Instead, close to the bend, the pipe axial force decreases due to the bearing force on the transverse leg (Fig. 3a).

Conversely, the bending moment under service loads is maximum at the bend (22163 Nm), exceeding the yielding moment of the pipe section (M_y = 18804 Nm), associated with plastic bending strains (Fig. 4), leading to compressive plastic longitudinal strains (-0.3%). The latter must be carefully verified in order to prevent the onset of local buckling limit state in the operating pipeline.

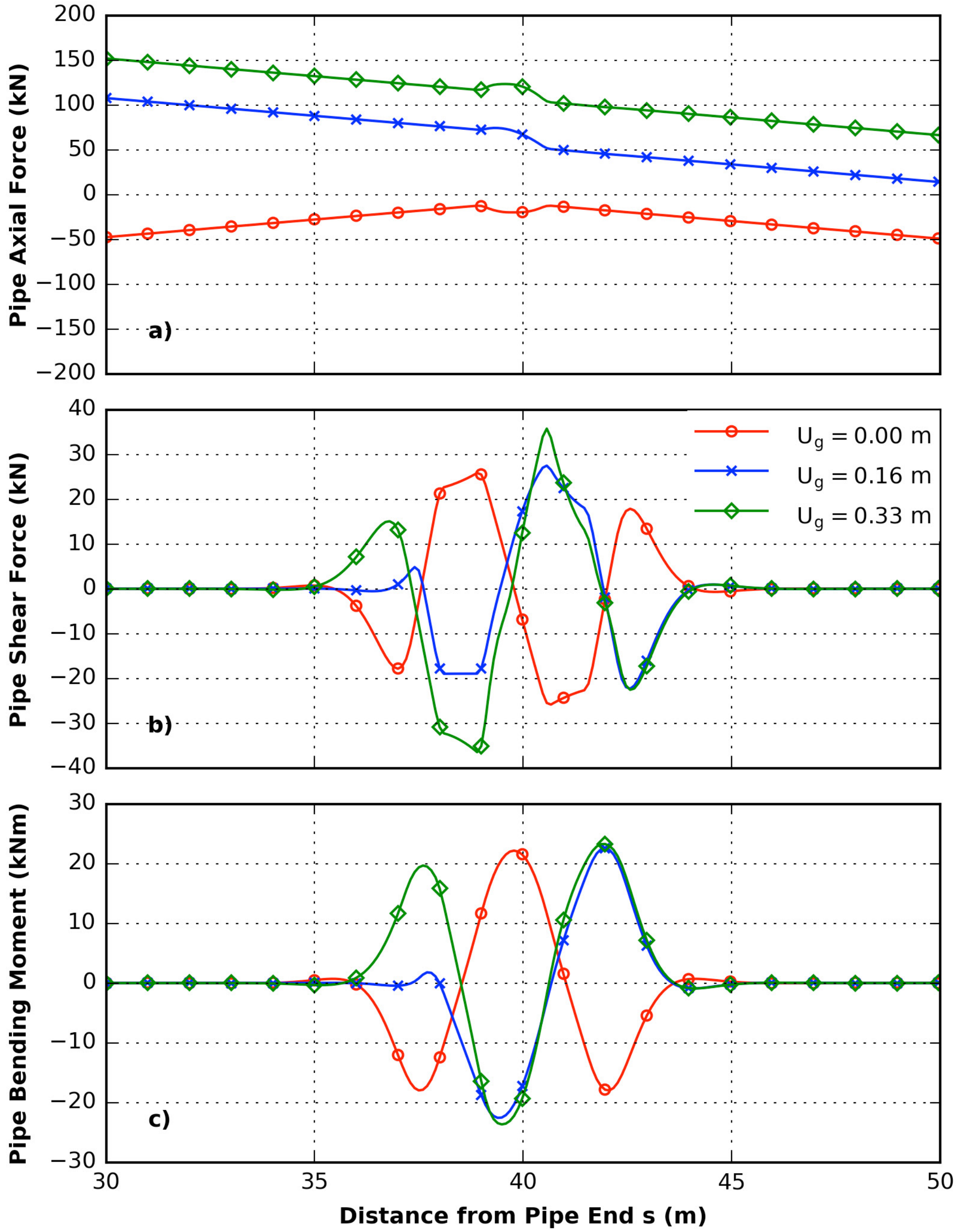

Fig. 3 Variation of the loads along the pipeline axis for different values of the ground displacement U_g: a) axial force; b) shear force; c) bending moment.

The bending moment decreases monotonically beyond the bend, inverting its direction until reaching two local peaks (17981 Nm) in the elastic range, located symmetrically at a distance of 2.5 m from the bend. Afterwards, the magnitude of the bending moment decreases rapidly to zero, so that beyond a distance of 5m from the bend, the pipeline undergoes only axial loading (Fig. 4).

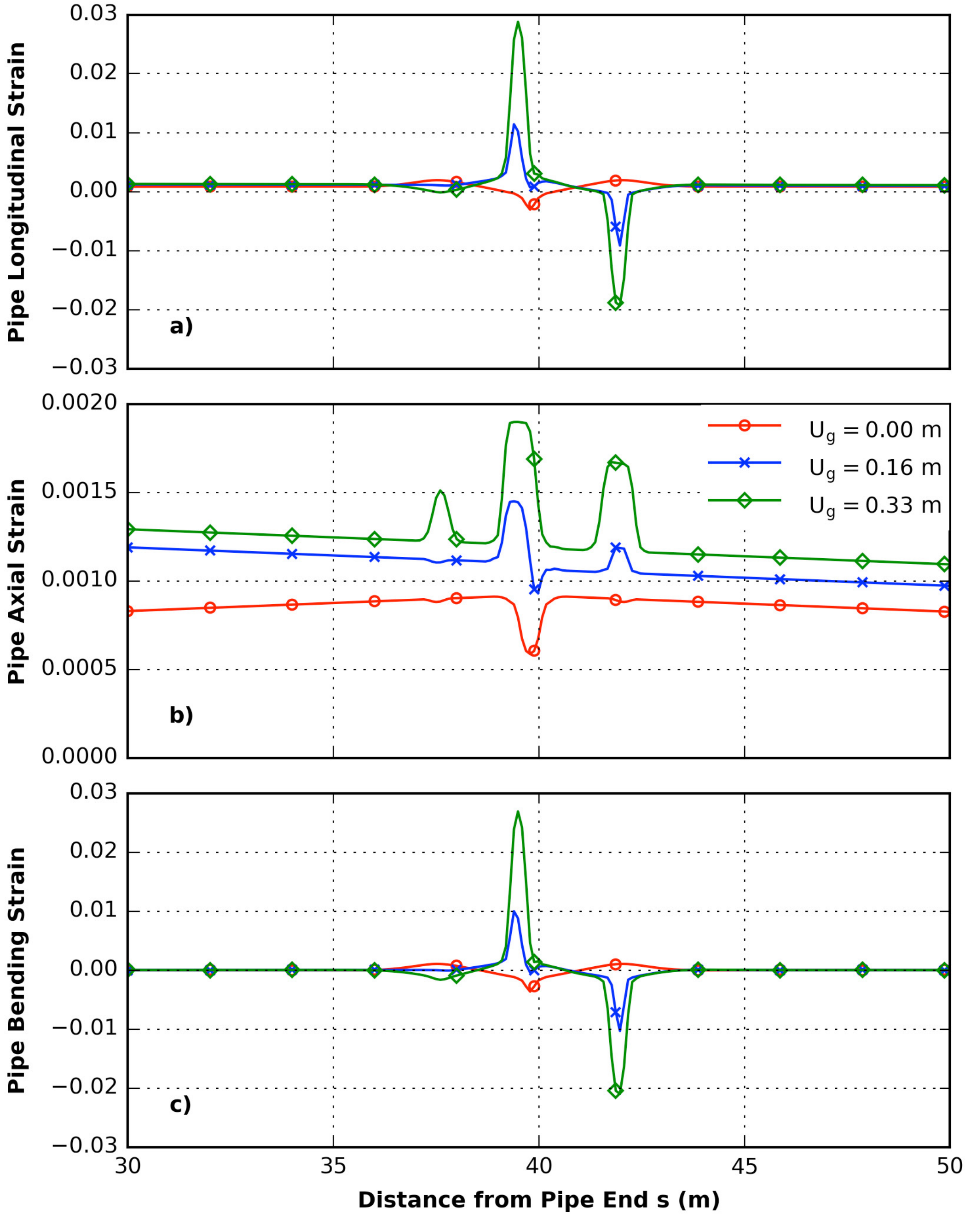

Fig. 4 Variation of the strains along the most stressed generator of the pipeline for different values of the ground displacement U_g: a) longitudinal strain; b) axial strain; c) bending strain.

3.2. Structural response of the pipeline in operating conditions

The seismic wave propagating parallel to one longitudinal leg, reverses the direction of the activated soil friction under service loads (Fig. 5), subjecting the pipeline to increasing tensile forces, as shown in Fig. 4 (a).

Evidently, pipe axial force varies linearly along the pipeline axis beyond the bend region, due to the soil friction reaction (F_R = 3944 N/m), that is assumed constant throughout the analysis, despite the cyclic loading.

The pipe axial force is maximum at the anchor point in the longitudinal leg, parallel to the direction of the seismic wave propagation, decreasing linearly thereupon, until the bend region where it increases slightly, due to the lateral soil reaction in transverse leg. The linear variation of the axial force along the pipe axis is due to the soil friction reaction (F_R = 3944 N/m), that is assumed constant throughout the analysis, despite the cyclic loading.

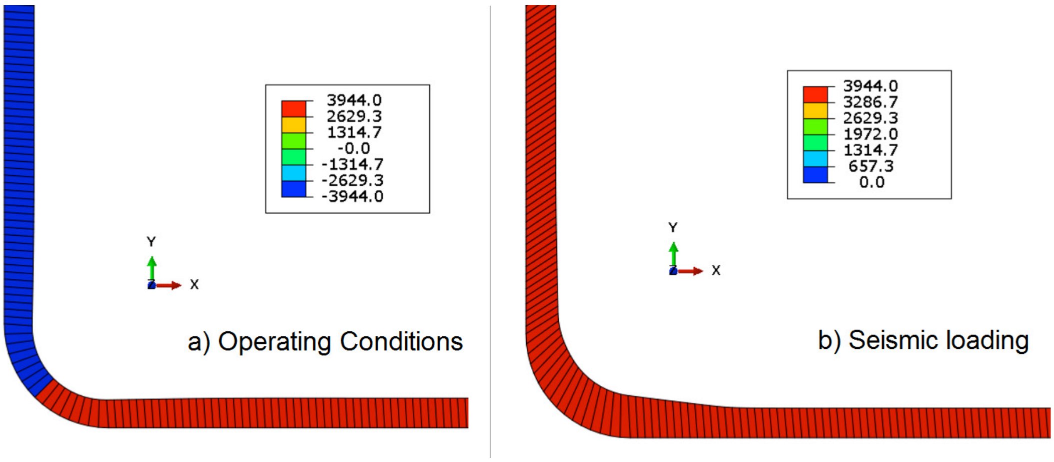

Fig. 5. Contour of the soil friction reaction along the pipeline (N/m): a) in operating conditions; b) under seismic loading.

The bending moment along the pipeline inverts its direction with respect to the operating conditions (Fig. 4), exceeding the elastic limit (M_y = 18804 Nm), at the bending point in the transverse leg, located at 2.4 m from the bend. Consequently, two plastic hinges develop at these bending points during seismic loading, characterized by a localization of excessive bending and longitudinal strains, as shown in Fig. 4 and Fig. 6.

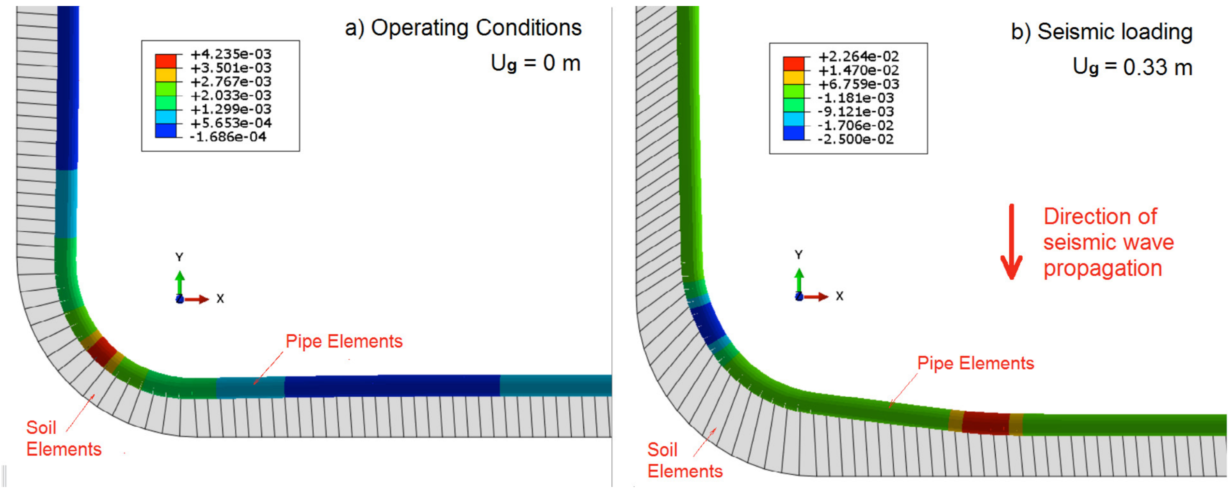

Fig. 6 Longitudinal strain contour and deformed shape of the pipeline at the bend region: a) in operating conditions; b) under seismic loading.

Particularly, the large compressive strains at the plastic hinges may lead to local buckling and consequent pipe failure, requiring proper mitigation measures in the design phase.

Furthermore, the axial strains vary linearly along the pipeline in the elastic range, apart two local peaks developing at the bending points (Fig. 4). The latter are produced by the interaction between bending and axial strains as a result of the elastoplastic response of the pipe section [27, 28]. Once the maximum longitudinal strain exceeds the yielding limit, axial strains increase locally so that the integral of the corresponding longitudinal stresses is equal to the continuously increasing axial force due to the ground displacement.

Evidently, the critical pipe region undergoing excessive plastic deformations is determined by the large bending moment, dissipating within a few pipe diameters around the bend (5 m), while beyond it the pipeline is subjected only to axial loading in the elastic range.

4. Conclusions

The present paper analyses the performance of an operating DH pipeline subjected to seismic loading within the finite element methodology, taking into account the geometric and mechanical properties of the system, including the soil-pipeline interaction.

The analyzed pipeline bend suffered plastic strains due to predominant bending induced by the imposed seismic ground displacement, leading to large compressive strains associated with local buckling in a brittle failure mode.

The pipeline performance depends on the geometrical and mechanical properties of the system, like the operating temperature, the pipe length, and the bend radius, requiring accurate evaluation in the design phase, in order to prevent material damage, under service and seismic loading.

Moreover, despite the simplistic assumptions regarding the adopted numerical model, including the representation of seismic loading as a sinusoidal wave, the obtained results give a better understanding on the earthquake response of operating DH pipelines. The latter is characterized by a cyclic soil-pipe interaction during seismic wave propagation (Fig. 7), requiring proper consideration in the engineering design practice.

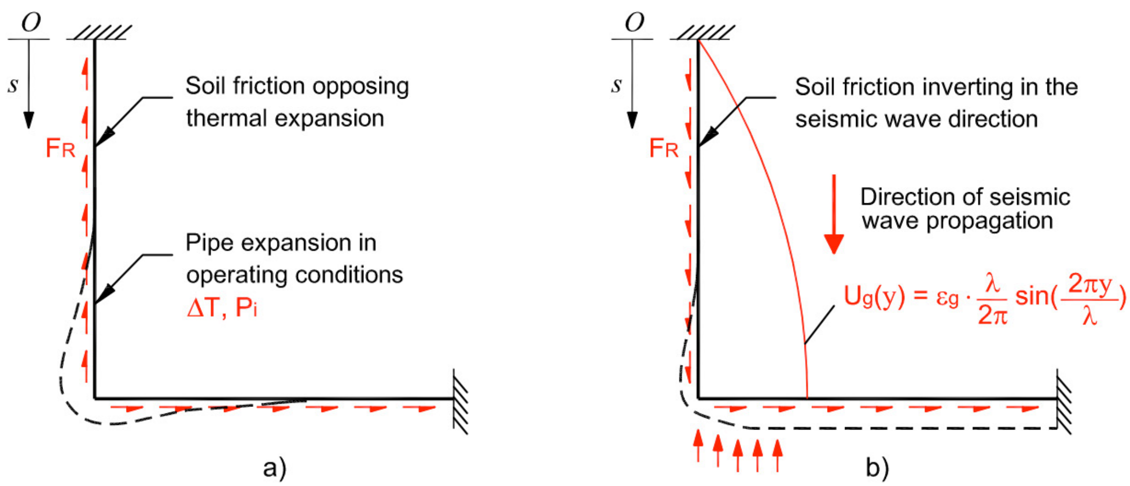

Fig. 7 Pipeline behaviour during: a) operating conditions; b) seismic ground deformation.

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