Upheaval Buckling of Onshore Buried Steel Pipelines with Flexible Joints

Vasileios E. Melissianos*, Charis J. Gantes[a],

*National Technical University of Athens
Institute of Steel Structures, Zografou Campus, 9 Iroon Polytechneiou Str., GR-15780 Athens, Greece
melissia@mail.ntua.gr

[a]National Technical University of Athens

Abstract

Buckling and post-buckling behavior of beams resting on nonlinear foundation is addressed in the present study, as a decisive step towards investigating upheaval buckling of onshore buried pipelines. The adopted mechanical model is that of a beam with fixed boundary conditions supported laterally by uniformly distributed uniaxial springs that model vertical downward and upward pipeline movement in the trench. An internal hinge equipped with an elastic rotational spring in the beam middle span models the introduced flexible joint. The beam under investigation is subjected to constant compressive axial force over its length. Linear Buckling Analyses (LBAs) are initially conducted to obtain eigenmodes that are then adopted as imperfection shapes. Then, geometrically and materially nonlinear analyses with imperfections (GMNIAs), incorporating soil nonlinearity, are carried out, indicating unstable post-buckling behavior. Obtained results are of importance regarding the use of flexible joints in pipelines crossing areas prone to large ground differential movement.

Keywords: buried pipeline, upheaval buckling, beam on foundation, nonlinear analysis

1. Introduction

The construction of new buried pipelines throughout the world meets the rising energy demands to transport fuel to even greater distances. Crossing seismic areas that comprise active tectonic faults is then often inevitable. Thus, considering that earthquakes and the associated fault displacements may highly affect pipeline integrity, buried pipelines have to be designed against potential large ground differential deformations that cause combined axial and bending actions along the pipeline (O' Rourke and Liu [12]). Possible failure modes triggered by ground deformation are tensile fracture at girth welds between adjacent pipeline parts, local shell buckling due to compressive strains and upheaval buckling (UHB) due to compressive axial forces. According to Yun and Kyriakides [17] shallowly buried pipelines with low diameter to thickness ratio are more prone to upheaval buckling compared to those buried deeper and having high diameter to thickness ratio.

In recent years there is ongoing research effort on assessing the advantages of flexible joints in pipelines' seismic performance. Flexible joints placed between adjacent continuous parts of steel pipelines aim at concentrating strains at the joints and retain the steel pipe virtually undeformed (Bekki *et al.* [4]). This design approach drastically reduces the risk of failure due to local shell buckling or tensile fractures at the welds, which are both directly associated with developing normal stresses. However, it should not be overlooked that limited bending stiffness of flexible joint may result to mitigation of the pipeline's global stiffness. The latter is likely to bring out upheaval buckling as the critical failure mode, even for deeper buried pipelines with relatively high diameter to thickness ratio.

Research on upheaval buckling of pipelines has been carried out since the 1970s. Hobs [6] was the first to analytically investigate thermal buckling of offshore pipelines resting on rigid foundation. Then, Yun and Kyriakides [16] proposed advances on Hobs model by modeling pipeline as a long heavy beam resting on rigid foundation and they extracted formulae for bending moments and axial forces. Taylor and Gan [14] presented an analytical approach employing 2nd order statics on submarine pipeline buckling accompanied by imperfection studies. Then, Maltby and Calladine [8],[9] conducted extensive experimental research on pipeline upheaval buckling on elastic soil. Later, Andreuzzi and Perrone [3] presented an extensive analytical solution on pipeline upheaval buckling by modeling pipeline as a simply-supported elastic beam of finite length under steady temperature gradient and by incorporating in their analysis friction forces between pipeline and the underlying soil. A study on upheaval buckling of onshore pipelines was presented by Matheson *et al.* [10] who analytically extracted a limit state function for the case of pipeline passing over a hill and constructed with cold formed bends. However, soil conditions either in seabed or onshore are apart from being assumed as rigid or elastic. So, recently Wang *et al.* [15] adopted the model of a beam resting on elastic or plastic foundation to investigate thermal global buckling of buried pipelines. Additionally, Shi *et al.* [13] dealt with global thermal buckling of offshore pipelines by incorporating soil through nonlinear soil springs and extracted results concerning the effects of dominant parameters regarding upheaval buckling, while Karampour *et al.* [7] adopted the formerly introduced model of heavy beam on rigid foundation to demonstrate that upheaval buckling of subsea pipeline subjected to thermal expansion is very sensitive to initial imperfections, while soil stiffness play a rather minor role.

Upheaval buckling is investigated in the present study extending an advanced numerical modeling approach, employed already by the authors for the case of buried pipelines without internal flexible joint (Gantes and Melissianos [5]) and for a simply-supported beam resting on Winkler soil with internal flexible joint (Melissianos and Gantes [11]). The mathematical model adopted is that of a long beam resting on deformable foundation with an internal hinge equipped with a linear rotational spring to model the flexible joint located in the middle of the beam. For reasons of simplicity, the case of a fixed-fixed beam subjected to concentrated axial compression load is considered. The beam is bilaterally supported by uniformly distributed transverse springs modeling upward and downward movement of the pipeline in the trench according to ASCE-ALA [2].

2. Numerical modeling

Consider the fixed-fixed beam of length L and flexural rigidity EI, resting in soil characterized by stiffness k_u for upward movement and k_d for downward movement with an internal hinge in the middle span equipped with a linear rotational spring of stiffness k_{fj} and axially compressed by constant force P, illustrated in Figure 1.

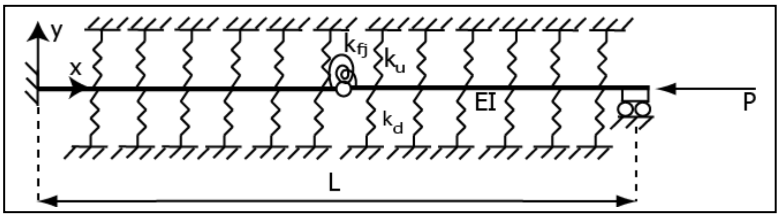

Figure 1: Fixed-fixed beam with flexible joint resting in deformable foundation under compressive load.

Numerical treatment of the problem is carried out using commercial FEM software ADINA [1]. For this purpose the beam illustrated in Figure 1 is considered, featuring an external diameter of 0.9144m (36in), a wall thickness of 0.0119m (0.469in), and a total length of L=1000m. The beam steel is of API5L-X65 type and is considered as bilinear with yield stress 448.50MPa, failure strain 20%, elastic Young's modulus 210GPa and plastic modulus 0.70GPa. Referring to burial conditions, it is assumed that the beam is buried under 1.30m of medium-density sand with friction angle equal to $\varphi=36^o$ and unit weight $\gamma=18kN/m^3$.

The beam is modeled using beam-type finite elements with longitudinal mesh discretization equal to 0.05m, after a mesh density sensitivity analysis was carried out by the authors to investigate the optimum mesh density. Additionally, the soil is introduced through elastic-perfectly plastic unidirectional springs, whose properties are estimated according to ASCE-ALA [2] provisions. So, upward springs' yield force is 45.40kN and yield displacement is 18mm, while for downward springs the values are 1487.46kN and 114mm respectively. Finally, the flexible joint is introduced through an elastic rotational spring with stiffness assumed to be a percentage of the beam's flexural rigidity. Recalling that the aim of introducing a flexible joint is to concentrate strains in the joint that should thus be characterized by very low rigidity, in the present study it is assumed that k_{fj}=0.10%EI=72.15kNm.

3. Linear buckling analysis and imperfection shapes

Linear buckling analysis is primarily carried out in order to obtain eigenmode shapes presented in the left chart of Figure 2, which will then be adopted as imperfection shapes. However, considering that LBA is a linearized analysis which cannot consider soil nonlinearity, stiffnesses of upward and downward soil springs are added. So, LBA's results are not reliable regarding buckling loads.

Furthermore, in structures the presence of imperfections is generally inevitable and they have to be taken into account during design as they may affect significantly the response of buckling sensitive structures. In the present study linear combinations of the first four eigenmodes listed in Table 1 are adopted as imperfection shapes and incorporated in nonlinear analyses (GMNIAs). Imperfections are normalized so that their amplitude equals L/500, which is compatible with common engineering practice for steel members. The resulting imperfection shapes are illustrated in the right chart of Figure 2, where the horizontal axis refers to location along the beam and the vertical one to transverse imperfection magnitude y_{max}, both normalized with respect to beam length L.

imperfection type	linear combination
I	Eig1+Eig2+Eig3+Eig4
II	Eig1+Eig2-Eig3+Eig4
III	Eig1+Eig2+Eig3-Eig4
IV	Eig1+Eig2-Eig3-Eig4

Table 1: Imperfection combinations considered in GMNIA

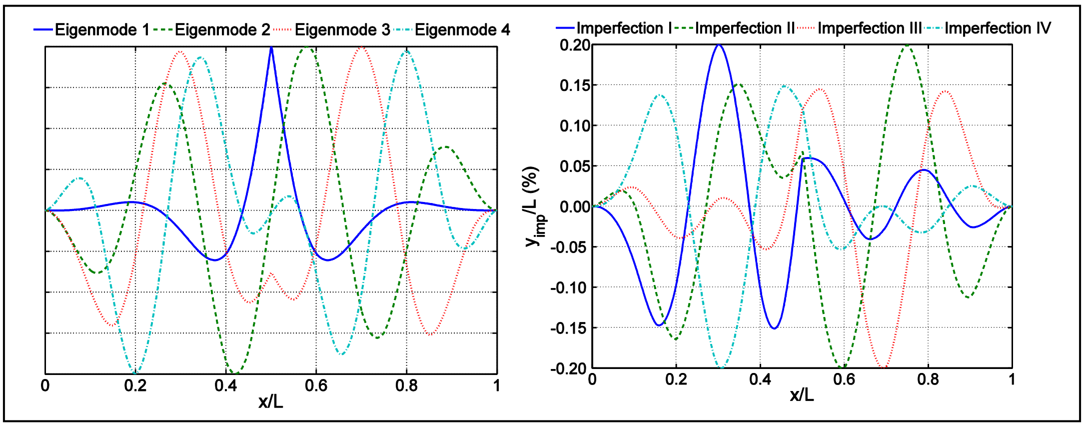

Figure 2: Eigenmode shapes (left) and imperfection shapes (right).

4. Geometrically and materially nonlinear analysis

Buckling is characterized by geometrical nonlinearity where equilibrium equations must be formulated in the deformed configuration of the structure, as it significantly differs from the undeformed one. So, it is deemed appropriate to carry out geometrically and materially nonlinear imperfection analysis (GMNIA) in order to detect inelastic buckling accounting for soil nonlinearity due to different soil stiffness and strength in the upwards and downwards direction, as defined in section 2 and provided by ASCE-ALA [2]. All imperfection types defined in section 3 are investigated, in order to detect all possible imperfection sensitivities. Buckling and post-buckling behavior of the beam is assessed through the equilibrium path of a characteristic node, which is selected as the position along the beam axis with maximum transverse displacement (y_{max}), plotting on the horizontal axis y_{max} normalized with respect to beam length (y_{max}/L) and on the vertical axis the applied axial load P normalized with respect to the maximum ultimate load P_{max} of the cases presented (P/P_{max}). Moreover, the deformed shape of the beam at the end of the analysis is presented and compared to the shapes of the initial imperfections, leading to very interesting conclusions.

GMNIA results are illustrated in Figure 3 where the first observation is that equilibrium paths are descending beyond a limit point, indicating unstable post-buckling behavior for all imperfection types. Additionally, equilibrium paths indicate imperfection sensitivity in terms of ultimate load which reaches about 15%. Imperfection sensitivity appears also in the beam deformed shapes and is located around the flexible joint position.

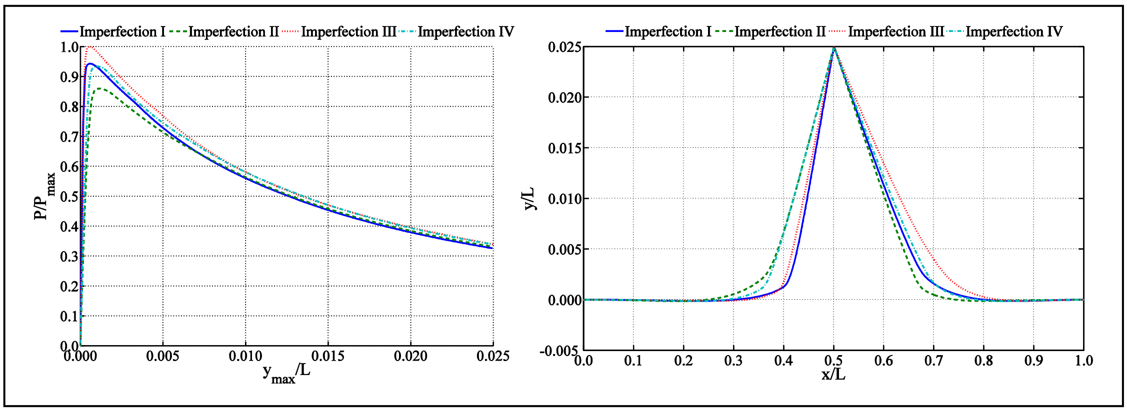

Figure 3: Equilibrium path (left) and deformed shape (right) for all imperfection cases.

5. Effects of soil plastification

In the analyses of section 4 the upward and downward soil springs were assumed as nonlinear with an elastic – perfectly plastic law in compression and zero resistance in tension. In order to investigate the effects of soil plastification an additional case is considered in the present section, where soil springs are assumed as linear tensionless, i.e. soil springs are elastic with infinite deformation in compression but without stiffness in tension. Comparison between models with fully nonlinear and elastic tensionless soil springs is carried out through GMNIAs for imperfection type I. The results are presented in Figure 4, where equilibrium paths indicate unstable post-behavior for both cases, while the beam resting in linear tensionless soil reaches a slightly larger ultimate load.

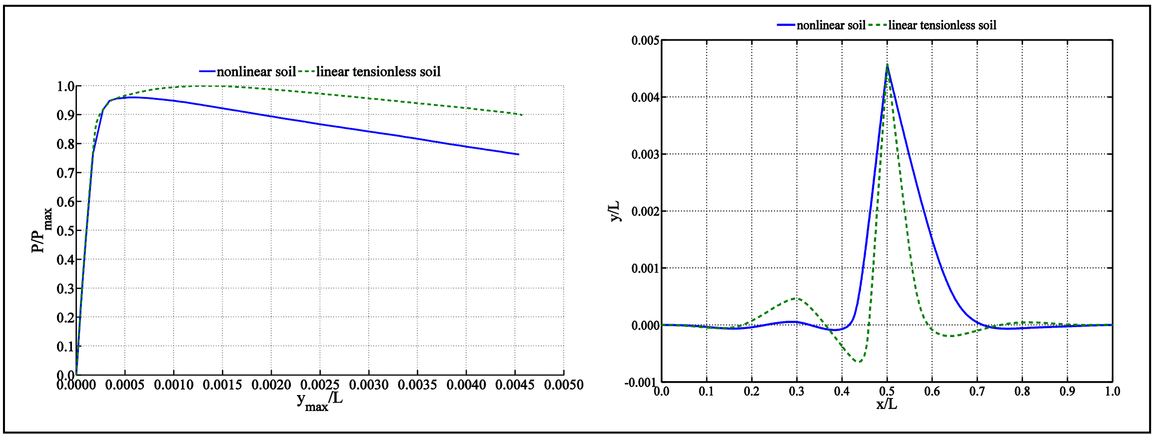

Figure 4: Equilibrium path (left) and deformed shape (right) for comparison of nonlinear vs. elastic tensionless soil cases.

These findings are then confirmed by Figure 5, where soil spring forces are illustrated for upward springs in the left chart and downward springs in the right chart. On the horizontal axis the distance along the beam axis is presented normalized with respect to beam length L, while on the vertical axis the soil spring force is presented normalized with yield force F_y. Figure 5 indicates that the elastic tensionless upward springs exhibit their maximum force at the flexible joint position, unlike nonlinear upward springs that exhibit yielding over a significant part of the beam's length. On the other hand, elastic tensionless downward springs exhibit their maximum just before the location of the flexible joint, unlike nonlinear downward springs that develop forces much lower than their yield limit. As expected, in both cases of soil properties, upward springs are compressed in beam areas in which downward springs are not compressed and vice versa.

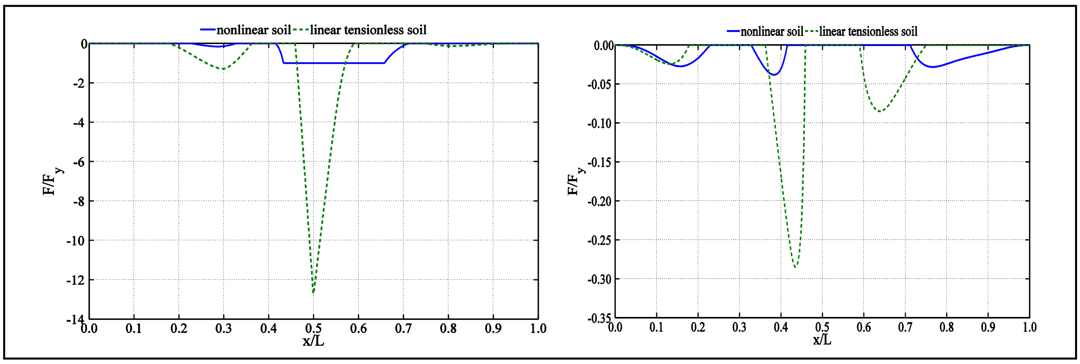

Figure 5: Upward (left) and downward (right) soil spring force for nonlinear vs. elastic tensionless soil.

6. Comparison of pipeline with flexible joint vs. continuous pipeline

The introduction of flexible joints, as stated in section 1, aims at relieving steel pipeline parts from strain concentrations. However, this may render pipelines more susceptible to upheaval buckling, thus it seems necessary to investigate the consequences of flexible joint on pipeline's global behavior through equilibrium paths. For that purpose a continuous beam (CP) is considered, adopting the same geometrical, pipeline steel and soil characteristics as the one with flexible joint (PFJ) defined in section 2.1. Moreover, for comparison reasons several cases of rotational joint stiffness, all lower than 0.1%EI, are considered, including the case that the internal hinge is not equipped with a rotational spring. All beam cases under examination rest in nonlinear elastic-plastic soil, as defined in section 2, and are investigated through GMNIAs adopting imperfection type I. Comparison of equilibrium paths is illustrated in Figure 6, where interesting results can be obtained. Firstly, in all cases the post-buckling behavior is clearly unstable, while the CP reaches an ultimate load about 4% greater than any PFJ case. Secondly, for all PFJ cases, the reduction of rotational stiffness does not alter buckling and post-buckling behavior even for the case of pure hinge (k_{fj}=0%EI). It is thus deduced that the lateral restraint provided by the soil is sufficient to prevent severe adverse effects of the flexible joint on global pipeline stability in this case. Parametric studies to establish the range of soil stiffness for which this is indeed the case are needed.

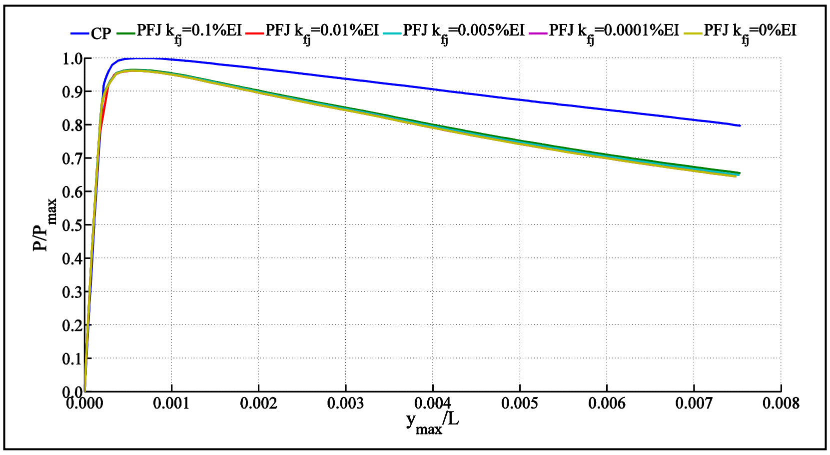

Figure 6: Comparison of equilibrium paths of continuous pipeline and pipelines with flexible joint.

7. Conclusions

Flexural buckling of a long fixed-fixed beam resting on nonlinear foundation having in its middle an internal hinge equipped with an elastic rotational spring is investigated numerically in the present study, as a decisive step towards modeling earthquake induced upheaval buckling of buried transmission pipelines with flexible joints. Beam's buckling and post-buckling behavior is assessed through geometrically and materially nonlinear analyses accounting for initial imperfections, considering also the soil's nonlinear properties. Results indicate unstable post-buckling behavior that has to be taken into account during the design of pipelines against upheaval buckling. Moreover, equilibrium paths and beam deformed shapes denote imperfection sensitivity. Additionally, comparison between models accounting for elastic tensionless and nonlinear soil was carried out indicating that unrestrained soil deformation leads to larger ultimate load and alters the beam deformed shape. Finally, equilibrium paths of a continuous beam and beams with varying rotational stiffness have been compared indicating a small reduction of the ultimate load due to the presence of the flexible joint for the considered level of soil stiffness, corresponding to a relatively stiff soil. It is noted that axial and transverse stiffness of the flexible joint have been considered as infinite in the present work. Their potentially detrimental effect to the pipeline's global stability should be addressed in future research.

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