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Buckling and Post-buckling Behavior of Beams With Internal Flexible Joints Resting on Elastic Foundation Modeling Buried Pipelines

Vasileios E. Melissianos *, Charis J. Gantes

Institute of Steel Structures, School of Civil Engineering, National Technical University of Athens, 9 Iroon Polytechneiou str., Zografou Campus, GR-15780, Athens, Greece

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ABSTRACT

The buckling and post-buckling behavior of axially loaded Winkler beams with flexible internal hinges is addressed, aiming to provide a background for the investigation of upheaval buckling of buried pipelines equipped with flexible joints for their protection against activation of reverse seismic faults. In order to acquire qualitative understanding of the interaction between the hinge stiffness and the soil stiffness for different cases, the beams under investigation are considered as either simply-supported or clamped. At first, elastic critical buckling loads and corresponding eigenmodes are numerically obtained using linearized buckling analysis, and eigenmode cross-over is investigated considering soil and hinge rotational stiffness. Geometrically nonlinear analyses with imperfections (GNIA) are then performed, indicating for most cases descending post-buckling paths, thus unstable post-buckling behavior, with the exception of cases of very soft soil. The sensitivity of the response to initial imperfection shape and magnitude is also addressed, to identify their impact on the post-buckling behavior. Beam buckling behavior is moreover examined by considering the beam being surrounded by soil exhibiting different stiffness in the upward and the downward direction. The results are compared to the case of a continuous beam, in order to highlight the impact of internal hinges on the beam overall buckling behavior.

1. Introduction

The so-called Winkler model of a beam resting on elastic foundation is a commonly applied engineering approach in various problems involving interaction between a structural member and the surrounding soil, due to its reliability and computational simplicity and efficiency. Applications of this model can be found in different areas of soil – structure interaction, such as foundation engineering, buried structures and railway tracks. Soil is considered as a single layer that can be represented by a series of closely spaced and mutually independent transverse springs with proportional resistance to deflection. Different aspects regarding the overall buckling behavior of continuous beams resting on elastic foundation can be found in the literature [1–5]. Timoshenko and Gere [6] showed the impact of soil stiffness on the critical eigenmode shape of axially loaded simply-supported Winkler beams, demonstrating that variation of soil stiffness may lead to eigenmode cross-over. Wu and Zhong [7] implemented the energy method to analytically investigate the buckling of elastically supported beams of finite length under compression for different end conditions, identifying eigenmode transition and then carried out post-buckling analysis of perfect beams and used post-buckling curvature to examine beam stability. Rao and Neetha [8] developed a detailed analytical methodology to estimate the elastic foundation stiffness that corresponds to the first transition of the critical eigenmode, using free vibrations. Buckling and post-buckling behavior of beams resting on elastic foundation was also investigated by Kounadis et al. [9], who derived analytical expressions of the post-buckling equilibrium path for a 1-DOF model. Song and Li [10] focused on thermal buckling and post-buckling of pinned – fixed beams on elastic foundation; they introduced a so-called "shooting method" to analytically solve the complex boundary condition problem and also adopted the energy method to describe post-buckling behavior considering buckling temperature. Li and Batra [11] presented equations for buckling and post-buckling behavior of laterally supported simply-supported and clamped beams. The major conclusions of this study included the insignificant impact of the nonlinear foundation parameter on the buckling load temperature and the post-buckling deformation. Aristizabal-Ochoa [12] introduced a methodology to estimate the critical buckling load of axially loaded columns resting on Winkler foundation with generalized end conditions.

The aforementioned studies deal with beams of finite length. However, elongated structures, such as railway tracks and pipelines, are usually modeled as infinite beams. In such case, buckling localization

* Corresponding author.
E-mail addresses: melissia@mail.ntua.gr (V.E. Melissianos), chgantes@central.ntua.gr (C.J. Gantes).

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emerges as an important issue. Localization of the buckling pattern depends among others on the applied axial force and the soil stiffness. Research on this topic is extensive and several researchers have presented rigorous analytical studies, trying to deal with the significant nonlinearity of the problem through advanced mathematical tools, among which prominent is the work by Hunt and Wadee (e.g. [13–16]).

In cases of buried steel pipelines crossing tectonic faults, flexible joints between pipeline parts have been proposed as mitigating measures against the consequences of possible fault activation [17]. Such joints are effective in protecting the pipelines from the two most common failure modes encountered in such cases, namely local buckling due to high compressive strains and girth weld fracture due to high compressive strains, by absorbing deformation through relative rotation of adjacent pipeline parts, which then remain virtually undeformed. However, in case of reverse faults high compressive axial forces may develop along the pipeline, and the reduction of overall stiffness induced by the flexible joints may lead to a third possible failure mode, which is flexural buckling, also known as upheaval buckling, as the pipeline may then deform outside the trench.

A Winkler beam with internal hinges constitutes an appropriate model to investigate the potential of upheaval buckling when the pipeline is subjected to combined bending and compression due to reverse faulting [18,19]. An internal hinge modifies the beam global stiffness and consequently affects the corresponding buckling and post-buckling behavior. The extent of this effect depends on the relative pipeline – joint – soil stiffness and must be taken into account in case such mitigating measures are proposed. The buckling behavior of an axially loaded, clamped beam without lateral support and with two internal hinges was presented by Wang [20]. The author applied an analytical approach to maximize the critical buckling load through the optimization of hinges' location. Later, Wang [21] extended the formerly developed model by introducing a single elastic support to strengthen the hinge location. The critical buckling load of an elastic beam with various end conditions was maximized by optimizing the hinge location considering the elastic restraint stiffness. Later, Wang [22] presented a more detailed model of a beam resting on elastic foundation to address the optimum hinge location for maximizing the critical buckling load and recently he presented an analytical study on the buckling of an infinite beam resting on elastic foundation with one or more internal hinges subjected to compressive force [23].

The topics of buckling behavior and eigenmode cross-over of continuous beams that rest on elastic Winkler foundation have been discussed in depth by previous researchers, as summarized above. However, the pertinent work regarding internally hinged beams is limited. Aiming at addressing this issue, in the present study the effect of hinge rotational stiffness on eigenmode cross-over with respect to soil stiffness is first quantified by means of numerical linearized buckling analysis. Furthermore, the beam post-buckling behavior is not adequately addressed in the existing literature. Hence, this study then focuses on the numerical investigation of the beam post-buckling behavior through geometrically nonlinear imperfection analysis. Simply-supported and clamped boundary conditions are considered, with the second being representative of the deformed shape assumed by buried pipelines that are subjected to fault activation. Two cases of internal hinges are analyzed: an internal hinge located in the beam middle and two internal hinges equally spaced along the beam. The internal hinges are assumed to be equipped with elastic rotational springs, while relative translations of the two beam parts at each hinge are restrained, to represent a hinged flexible joint.

As mentioned above, the beam buckling behavior is first studied through linearized buckling analysis [24], and the results are directly compared to the corresponding ones in cases of continuous beams [25]. Parametric studies highlight the effect of soil stiffness, hinge rotational stiffness and beam boundary conditions on critical buckling loads and eigenmode shapes. Geometrically nonlinear analyses are then carried out, providing useful conclusions regarding the post-buckling behavior, imperfection sensitivity and the effect of soil restraint on ultimate loads. Additionally, the effect on beam response of different upward and downward springs with different stiffness is investigated compared to elastic soil in terms of ultimate loads. Research results can be significant for hazardous structures such as pipelines, as well as other major facilities such as railway tracks, as the design assumptions and safety factors to be considered are highly affected.

2. Analysis model

In order to investigate the overall buckling response of an Euler-Bernoulli beam with internal hinges resting on elastic or nonlinear foundation, an appropriate numerical approach has been adopted. This approach is considered as suitable for dealing with this problem from a structural design rather than engineering mechanics point of view, as it can in future be readily extended to issues that are commonly encountered in practice, such as non-straight pipeline route, inhomogeneous soil conditions, and varying axial force distribution along the pipeline accompanied by bending moments.

In case of buried pipelines subjected to fault rupture, the source of the applied action on the structure, namely the fault location, is well defined. If the fault is activated, the pipeline is forced to follow the ground motion and to deform on the two sides of the fault in an s-shaped pattern extending to two so-called anchor points, one on each fault side, beyond which the developing stress-state is nearly negligible. If the fault is reverse, significant axial compression develops in the pipeline, with a maximum value at the fault and gradually diminishing towards the anchor points due to soil friction. Aiming at addressing this problem in a simplified, conservative manner, the adopted numerical model is that of an elastic Winkler beam of length L, defined by the anchor points, and flexural rigidity EI, subjected to axial compressive force P. It is also noted that the adopted model of a finite beam for the simplified pipeline modeling is sufficient regarding also the issue of buckling localization, taking into account that the location of the source of the applied action is well defined, while the anchor points represent the assumed boundary conditions. To that effect, either hinged or clamped boundary conditions are considered at the two ends, even though for long struts actual boundary conditions are less significant as the deflections and their derivatives all tend to zero near the boundaries. Furthermore, the problem is treated as static, given that the dynamic effects of fault movement are considered by pertinent codes as negligible [26,27].

The beam longitudinal displacement is denoted by x and the transverse displacement by $y(x)$. Beams rest on Winkler foundation that exhibits stiffness k_s, which is normalized via the expression:

$$K_S = k_S L^4 / EI \tag{1}$$

and ranges from a minimum value $K_s = 180$ to a maximum value $K_s = 20{,}000$. Three characteristic soil stiffness values are selected, namely $K_s = 180$, $K_s = 10{,}000$ and $K_s = 20{,}000$, which correspond to the critical eigenmode shape of the continuous beam being the first symmetric, the first antisymmetric and the second symmetric, respectively. These soil stiffness values are selected based on the fact that soil stiffness increase leads to eigenmode cross-over for the continuous beam among the three above mentioned types of modes [25]. Furthermore, the selected soil stiffness values are reasonable assumptions for the soil stiffness of upward soil springs in buried pipeline analysis. For example, the value $K_s = 10{,}000$ corresponds to a small diameter, shallowly buried pipe in dense backfill sand, while $K_s = 180$ to a large diameter, deeply buried pipe backfilled with loose sand. Estimation of soil springs' stiffness for buried pipelines is carried out using the suggestions of pertinent codes and provisions (e.g. ALA [26], EC8 [27], ASCE [28]) or expressions found in the literature [29] depending on the backfill material properties. According to these sources, the soil material laws are nonlinear,