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Dynamic analysis of beam-soil interaction systems with material and geometrical nonlinearities

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ABSTRACT

In this paper a Hybrid Domain Boundary Element Method is developed for the geometrically nonlinear dynamic analysis of inelastic Euler-Bernoulli beams of arbitrary doubly symmetric simply or multiply connected constant cross-section, resting on viscous inelastic Winkler foundation. The beam is subjected to the combined action of arbitrarily distributed or concentrated transverse dynamic loading and bending moments in both directions as well as to axial loading, while its edges are subjected to the most general boundary conditions. A displacement based formulation is developed and inelastic redistribution is modelled through a distributed plasticity (fibre) approach. A uniaxial hysteretic law is considered for the evolution of the plastic part of the normal stress following the phenomenological hysteresis model, while hysteretic force-displacement model is also employed in order to describe the inelastic behaviour of the Winkler springs. Numerical integration over the beam cross sections is performed in order to resolve the hysteric parts of the stress resultants. Application of the boundary element technique yields a system of nonlinear Differential-Algebraic Equations, which are written in state-space form and solved by an incremental–iterative solution strategy. Numerical examples are worked out confirming the accuracy and the computational efficiency of the proposed beam formulation, as well as the significant influence of material and geometrical nonlinearities in the response of beam-soil interaction systems.

1. Introduction

The dynamic analysis of beam-soil interaction systems is an area of extensive research activity in both structural and geotechnical engineering. The dynamic analysis of such systems is often mandatory in design of significant civil engineering structures such as bridges, offshore piles and wind-turbine foundations. Currently, the design procedure is based on a set of simplifying assumptions while the nonlinear static pushover analysis is preferred over the dynamic time domain procedures. This is attributed to the intricate dynamic methodologies as well as to the increased computational cost. Nevertheless, modern design codes are based on concepts such as the displacement based and performance based design for the estimation of structural integrity [1]. That implies that in order to evaluate the necessary design quantities, a vast amount of nonlinear dynamic analyses are required. Thus, an efficient computational tool capable of performing nonlinear dynamic analysis is essential, conferring several advantages over the pushover procedure [2] and providing insight into complicated phenomena attributed to the inertia and the dynamic motion of the structure.

In order to fully comprehend the beam-soil mechanism, as well as to accurately estimate the response of the structure, all possible causes of nonlinearities should be taken into account. The nonlinearities with the most profound influence on the response of a structure originate from the inherent nonlinear stress-strain behaviour of the materials (material nonlinearity) as well as from the significant variations of the geometrical configuration during dynamic loading (geometrical nonlinearity). On the contrary, in engineering practice the foundation elements are designed to behave elastically for every type of loading. Modern design codes and the existing regulations indicate that the beam-soil interaction systems, such as piles and deep embedded foundations, are designed in order to prohibit the occurrence of any kind of nonlinearity, neither of material nor of geometrical nature. More specifically, Eurocode-8, Part 2, § 5.8 [3] explicitly states that "…*foundations shall not be intentionally used as sources of hysteretic energy dissipation and therefore shall, as far as practicable, be designed to remain undamaged under the design seismic action.*" This restriction, however, is most likely to be extremely conservative leading to financially or even physically

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unfeasible structures. In recent years, significant research efforts [4–6] have investigated the beneficial character of permitting nonlinearities and inelasticity to occur at the beam-soil interaction system.

Furthermore, in order to conduct precise analysis and design cost-effective structures the realistic estimation of the structural member transient response is essential. Towards that direction, the material nonlinearity is incorporated in the analysis either by a refined distributed plasticity (fibre) formulation or by the simplified concentrated plasticity (plastic-hinge) approach. Although time efficient, the cross-sectional stress resultant approaches [7] or lumped plasticity idealizations [8,9] come at the cost of accuracy. On the contrary, the fibre models are proved capable of accurately capturing the inelastic response [10,11], while their main drawback is the increased computational cost due to the numerical integrations at the cross-sectional level. Various beam element models accounting for the nonlinear stress-strain behaviour of the materials, have been proposed following either the displacement-based [12] or forced/mixed-based formulations [13–15]. Moreover, dissipation phenomena have to be explicitly taken into account in the dynamic analysis of nonlinear systems. To this end, several hysteretic modes have been proposed [16] with the most commonly used the Bouc-Wen family of hysteric models [13,17–19]. The hysteric Bouc-Wen model has been successfully introduced into the inelastic analysis of structural members [20–23]. On the contrary, little has been done in case of soil-structure interaction systems [24,25].

Although, considerable effort has been made into investigating the soil inelasticity [26,27], as well as the dynamic response of beam-soil interaction systems employing the *Beam-on-Nonlinear-Winkler-Foundation* (BNWF) model [28–31], only few studies have encountered the inelastic behaviour of both the beam and the foundation elements in dynamic analysis. According to this context, the beam stress-strain and the foundation load-displacement relations are assumed to follow nonlinear inelastic constitutive laws. To start with, Budek et al. [32] presented a Winkler beam model formulation to represent the lateral force response of a reinforced concrete pile in cohesionless soil. An inelastic finite-element analysis was performed on the structure, using as the pile constitutive model the section moment-curvature relationship based on confined stress-strain relationships for the concrete. The influence of various parameters, such as the pile head boundary conditions, the height of pile head above grade level and the soil stiffness were investigated. The soil models were assumed linear, bilinear and hyperbolic. The analysis reviled that shear could be significantly underestimated by an elastic analysis, as inelastic behaviour moved the point of maximum moment in the pile shaft closer to the surface, thus reducing the shear span. Hutchinson et al. [33] used nonlinear static and dynamic analyses to evaluate the inelastic seismic response of bridge and viaduct structures supported on extended pile shafts. For the nonlinear dynamic soil–pile interaction analyses the beam on nonlinear Winkler foundation model was employed. Nonlinear fibre beam-column elements were used to model the reinforced concrete sections, and one-dimensional site response analyses for the free-field soil profile response. The results focused on the influence of the ground motion characteristics and the variations in structural configurations on the performance measures which evaluated the inelastic seismic response of the structures examined. Later on, Gerolymos and Gazetas [34] studied the inelastic response of soil-pile interaction systems employing a phenomenological Bouc-Wen model designated as BWGG to account for the nonlinear response of the soil. The separation of the pile from the soil, the radiation damping and the loss of strength due to pore-water pressure where also taken under consideration. The pile inelasticity was treated macroscopically at a cross-sectional level through a plastic-hinge approach utilizing the BWGG mode. An explicit finite differences method was used to solve the system of differential equations while this formulation was applied to piles subjected to laterally monotonic and cyclic loading. The developed model was then applied to conduct a parametric study of pile-column supported bridge structures, in order to investigate the consequences of pile yielding behaviour and soil-structure interaction on structure ductility demand [6]. Allotey and El Naggar [35] developed a generalized dynamic normal force–displacement BNWF model capable of accounting for various soil–structure interaction effects. The backbone curve of the model comprises a four-segment adaptable multi-linear curve that can represent both monotonic and post-peak behaviour. The cyclic degradation was modelled as a modified version of the rainflow-counting technique of Anthes [36]. The proposed model was verified by comparing the results with those from centrifuge tests of piles in weakening and partially weakening soil showing good agreement. Lately, Mullapudi and Ayoub [37] studied the cyclic performance of an inelastic beam resting on a nonlinear soil bed. The material nonlinearity was handled through a fibre beam element model and the discretization of the cross-section was introduced in order to derive the nonlinear terms of the governing equation regarding the uniaxial stress-strain relations. The soil was handled as a semi-infinite element consisting of a single layer Winkler springs in conjunction with a Vlasov's parameter that can provide moment resistance. The tensionless character of the soil was also taken into account, while the foundation parameters were based on a plane strain assumption. This investigation was then extended to the study of the seismic behaviour of the inelastic beam resting on a nonlinear foundation [38]. In both studies the models were implemented in the finite element program FEAP [39].

In this paper a Hybrid Domain Boundary Element Method is developed for the geometrically nonlinear dynamic analysis of inelastic Euler-Bernoulli beams of arbitrary doubly symmetric simply or multiply connected constant cross-section, resting on viscous inelastic Winkler foundation. The beam is subjected to the combined action of arbitrarily distributed or concentrated transverse dynamic loading and bending moments in both directions as well as to axial loading, while its edges are subjected to the most general boundary conditions. A displacement based formulation is developed and inelastic redistribution is modelled through a distributed plasticity (fibre) approach. A uniaxial hysteretic law is considered for the evolution of the plastic part of the normal stress following the Sivaselvan and Reinhorn [13] phenomenological hysteresis model, while a hysteretic Bouc-Wen force-displacement model is employed in order to describe the inelastic behaviour of the Winkler springs. Numerical integration over the beam cross sections is performed in order to resolve the hysteric parts of the stress resultants. Three boundary value problems are formulated with respect to the transverse and axial displacements and solved using the Analog Equation Method [40,41], a BE based method [42]. Application of the boundary element technique yields a system of nonlinear Differential-Algebraic Equations (DAE), which are written in state-space form and together with the hysteretic evolution equations are solved iteratively using the Petzold-Gear backward differentiation formula [43], a linear multistep method for differential equations coupled to algebraic equations. The essential features and novel aspects of the present formulation compared with previous ones are summarized as follows.

i. The dynamic response of beam-foundation systems accounting for both material and geometrical nonlinearities, has not yet been investigated implementing BNWF model.
ii. A distributed plasticity (fibre) approach has been employed, while the formulation is a displacement based one taking into account inelastic redistribution along the beam axis.
iii. A uniaxial hysteretic law is considered for the evolution of the plastic part of the normal stress following the Sivaselvan and Reinhorn [13] model, whereas the inelasticity of the soil medium is taken into account employing a hysteretic Bouc-Wen force-displacement model.
iv. The geometrical nonlinearity is taken into account by retaining the square of the slope in the strain–displacement relations, avoiding in this way the simplifications arising from a linearized second-order