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Nonlinear soil and pile behaviour on kinematic bending response of flexible piles

Michele Mucciacciaro, Stefania Sica*

Department of Engineering, University of Sannio, Piazza Roma 21, 82100 Benevento, Italy

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ABSTRACT

In recent years kinematic interaction of piled foundations under seismic loading has been extensively researched from both an experimental and a numerical viewpoint. With regard to numerical aspects, most literature studies implement simplified constitutive models to describe soil and pile behaviour despite current availability of sophisticated constitutive models for both materials. The use of advanced constitutive models is limited in practice due to the difficulty in calibrating several constitutive parameters and the high computation demand which is generally required, particularly if a 3D continuum approach is selected for the analysis. To overcome some of the difficulties above and achieve a better understanding on kinematic response of piles under strong earthquakes, the capability of an advanced but still user-friendly kinematic hardening constitutive soil model has been investigated. The model derives from the classical Von Mises failure criterion with the addition of isotropic and kinematic hardening components to better represent soil response under cyclic loading.

Dynamic 3D finite element (f.e.) analyses were performed in the time domain through a simple scheme of a single pile embedded in a soil deposit made of two cohesive layers. The parametric study elucidates the role of soil nonlinearity (stiffness degradation, hysteresis, soil plasticization) on pile kinematic bending response in respect of the adopted input signal, mobilized transient and permanent shear strain developed in the soil layers. For some accelerometric inputs the diffuse plasticization of the soil around the pile leads to compute high kinematic bending moments especially in soil deposits with the upper layer made of low-plasticity index soft clay. Finally, pile nonlinearity has also been considered by implementing bending moment-pile curvature relationships typical of reinforced-concrete piles.

1. Introduction

Soil-Structure Interaction (SSI) under dynamic loading is a complex boundary value problem to be solved in its globality, especially if the structure is founded on piles. In this case, a fully coupled interaction analysis becomes very cumbersome, even considering the recent advances in computer technology. Until a few years ago, the sub-structuring technique [22] had been the most popular and widespread approach to analyze SSI problems. According to it, the interplay occurring among the soil, the pile and the superstructure is decoupled into two distinct phenomena, namely a kinematic and inertial interaction, which are solved separately and later combined to provide a final solution [31]. Under the assumption of material viscoelastic behaviour, the kinematic and inertial decomposition is rigorous and the two modular problems possess a well-defined physical interpretation. The substructure method definitely was and still is a very useful design approach to get the overall stress state in piles placed in seismic areas.

The paper focuses on the kinematic aspect of SSI of piles under seismic loading. In more recent years, as a result of some remarkable research, many predictive equations have been proposed to predict the kinematic pile bending moment at pile head or at the interface between two soil layers characterized by markedly different shear stiffness. Most of these predictive formulas have been obtained from extensive parameter studies carried out by means of the so-called Beam on Dynamic Winkler Foundation (BDWF) approach [30,32,36,7] or continuum approaches [25,39,8].

The main shortcoming of all the above solutions lies in the constitutive model adopted for modelling soil response under cyclic loading since linear-elastic or linear visco-elastic soil behaviour has often been assumed. As is widely known, the response of the soil is strain-dependent: soil can be considered to behave elastically only under very low strain levels ($\gamma < 10^{-5} \div 10^{-4}$). At higher strains such as those mobilized by medium-strong earthquakes which are able to induce appreciable kinematic effects on piles, soil behaves nonlinearly and manifests complex phenomena such as hysteresis, cyclic degradation, volumetric and distortional coupling. In such conditions, more

* Corresponding author.
E-mail address: stefsica@unisannio.it (S. Sica).

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advanced constitutive models are required to reproduce the complexity of soil response. In routine engineering applications, this complexity is generally avoided and kinematic interaction arising in piles is modeled in the hypothesis of linear visco elastic behaviour of the soil by adopting strain compatible parameters (stiffness and damping) which are determined from equivalent linear site response analyses.

It is worth emphasizing that with reference to laterally loaded piles, soil nonlinearity has however been taken into account since the late Seventies when Matlock et al. [28] first introduced the concept of Beam on Nonlinear Winkler Foundation (BNWF) where the lateral soil-pile interaction is modeled through empirical nonlinear *p-y* curves [27], which define soil resistance *p* as a function of the lateral pile deflection *y*. The same approach was later refined to describe soil-pile interaction under cyclic lateral loading accounting for hysteresis and cyclic degradation of the soil and gap formation at the pile-soil interface [1,12,13]. The main shortcomings of BNWF is an idealization of the continuum soil with uncoupled soil springs. Gerolymos and Gazetas [14,15] developed a dynamic nonlinear Winkler spring model, where material inelasticity was described by means of the Bouc-Wen-Gerolymos-Gazetas (BWGG) constitutive model, a modification of the phenomenological hysteretic Bouc-Wen model developed in the Seventies [38,5]. The BWGG model is able to describe soil stiffness decay with strain amplitude, loss of strength due to pore-water pressure build-up and dependence of soil response on loading direction. The overall procedure was validated by means of in situ monotonic and cyclic pile load tests and by 3D finite element simulations [16,18].

The above studies tried to enhance the role of soil nonlinearity for piles subjected to static, quasi-static and cyclic lateral loading. Less attention was paid to pile response under seismic excitation.

Some pioneering works on kinematic pile bending in nonlinear soil deposits are reported in Wu and Finn [40], Kimura and Zhang [23] and Bentley and El Naggar [4].

Maheshwari et al. [24] adopted a hierarchical single surface (HiSS) advanced plasticity model to investigate the effects of soil plasticity and nonlinearity on the kinematic response of single piles and pile groups, also accounting for gapping at the soil–pile interface. This study highlighted that soil nonlinearity may significantly affect the seismic response of pile foundations. In particular, the effect of nonlinearity depends on the frequency of excitation causing an increase in the system response at low frequencies. Martinelli et al. [26] have recently published a study on kinematic interaction of a pile embedded in a saturated coarse-grained deposit where soil behaviour is described according to the kinematic hardening constitutive model of Dafalias and Manzari [6], which is developed within the framework of the critical state theory. The authors pointed out that for some accelerometer signals, excess pore water pressures developing in loose sands could cause an abrupt increase in the maximum kinematic bending moment arising in the pile at the interface between two soil layers having different shear wave velocity.

Due to the difficulty in calibrating several constitutive parameters usually required by more advanced constitutive models and to a high computational demand, no extensive parametric studies have been carried out to date. To overcome some of the above difficulties and achieve a better understanding of the kinematic response of foundation piles under severe earthquakes, the capability of an advanced but still user-friendly kinematic hardening soil constitutive model has been investigated. Dynamic 3D analyses were performed in the time domain using the ABAQUS f.e. code. A single pile embedded in a soil deposit made of two cohesive layers where the upper layer is much softer than the lower one was considered. The parametric study aimed at elucidating the role of soil nonlinearity on pile bending response in respect of the adopted input signal, level of mobilized shear strains and plastic strain which had been accumulating in each soil layer during cyclic loading. As a result, the paper presents: (i) a validation of the developed 3D f.e. model in the hypothesis of linear elastic behaviour of both soil and pile; (ii) the effect of soil nonlinearity and plasticity on the kinematic bending moments generated in a flexible pile under different accelerometric signals; (iii) the effect of pile nonlinearity when bending moment-curvature relationships, which are typically used for reinforced concrete piles, are implemented. Since other important aspects affecting the nonlinear response of piled foundation such as the pile working load, the initial raft-soil contact pressure and the interaction between closely spaced piles, are not taken into account, the obtained findings cannot be extended to different hypotheses other than the simplifying ones adopted for the investigation. Finally, when material nonlinearity is introduced in solving SSI boundary-value problems, the basic idea of the substructure method (i.e., validity of the superposition principle) vanishes. Consequently, the inertial and kinematic contribution cannot be summed and this aspect, which is out of the scope of the paper, represents a crucial issue for the practical design of piles in seismic areas.

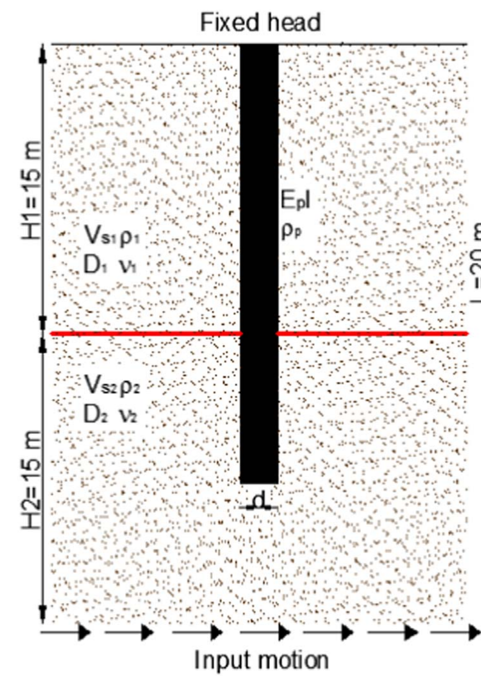

Fig. 1. Soil-pile configuration scheme.

2. Problem statement

The problem under investigation consists of a cylindrical concrete pile, of diameter d = 0.6 m and length L = 20 m, embedded in a stratified soil deposit with two layers of different stiffness (Fig. 1). The upper layer of thickness H_1 = 15 m has a shear wave velocity Vs_1 = 100 m/s and initial damping D_1; the bottom layer of thickness H_2 = 15 m is stiffer, with a Vs_2 = 400 m/s and initial damping D_2. The selected configuration scheme lacks a transition layer between the soft and the stiffer soil in order to represent the worst conditions in terms of kinematic pile bending at the soil layer interface. Actually, the presence of a transition layer (a sort of weathered zone of the stiffer layer) close to the interface could reduce the huge stiffness contrast between the consecutive soil layers considered in this study.

The idealized scheme has been extensively investigated since 2010 within the framework of the Italian research project named ReLUIS (Laboratory University Network of Seismic Engineering).

2.1. Analysis method

The problem was analyzed in 3D by means of the finite element code ABAQUS. The overall 3D domain of analysis was 70 m × 70 m in plan and 30 m high in the vertical direction (Fig. 2). The soil and the