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Impact of ground motion duration and soil non-linearity on the seismic performance of single piles

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ABSTRACT

Pile foundations strongly influence the performance of supported structures and bridges during an earthquake. In case of strong earthquake ground motion, soft soils may be subjected to large deformation manifesting aspects typical of the non-linear behaviour such as material yielding, gapping and cyclic degradation. Therefore, nonlinear soil-pile interaction models should be able to capture these effects and improve the prediction of the actual seismic loading transferred from the foundation to the superstructure. In this paper, a beam on nonlinear Winkler foundation (BNWF) model is used, which can simulate cyclic soil degradation/hardening, soil and structural yielding, slack zone development and radiation damping. Incremental Dynamic Analyses (IDAs) are performed to evaluate the effects of Ground Motion Duration (GMD) and soil non-linearity on the performance of single fixed-head floating piles. Various homogeneous and bilayer soil profiles are considered, including saturated clay and sand in either fully dry or saturated state and with different levels of compaction. In order to evaluate the effect of nonlinearity on the response, the results of the nonlinear analyses are compared with those obtained from linear soil-pile analysis in terms of bending moment envelope. Results show the relevance of considering the GMD on the performance of the single pile especially when founded on saturated soils. For low intensities and dry sandy soils, the linear soil-pile interaction model can be used for obtaining reliable results.

1. Introduction

The prediction of the performance of pile foundations during earthquakes is a fundamental task for the seismic design of structures and bridges. Most modern seismic codes (e.g. ASCE 41-06, ASCE 7–10, Eurocode 8, Italian technical code NTC, 2008, Mexico City Building Code) recommend accounting for soil–structure interaction effects in the seismic design of both foundations and superstructures. The mechanism of soil-pile-structure interaction has been extensively investigated by numerous researchers and methods for assessment of the seismic performance of soil-structure systems have improved significantly; a comprehensive review of the problem can be found in Kausel [1]. It is worth mentioning that most of the cited studies on soil-structure interaction are restricted to linearly elastic system by assuming that the relative displacement between foundation and soil remains small in the case of medium dense or firm ground when subjected to moderate earthquake motions. Therefore, when the soil behaves as a linear or equivalent-linear material, the entire soil-foundation-structure system can be subdivided into two separate sub domains, i.e. the superstructure and the soil-foundation, in order to apply the subdomain method [2,3] by separating the effects of inertial and kinematic interactions. On the other hand, when the ground is loose or soft or when the ground undergoes strong earthquake motions, those relative displacements become large and soil non-linearity becomes predominant, hence modifying considerably the dynamic response of the entire system. Converse to the solution based on elastic theory, nonlinear soil response entails gap formation, foundation uplifting, soil yielding as well as softening and hardening constitutive behaviours. Effects of the soil nonlinearity on structures with embedded and deep foundations were observed by Trombetta et al. [4] and Boulanger et al. [5] by means of centrifuge testing, while Pitilakis et al. [6], Massimino and Maugeri [7], Biondi et al. [8], and Abate and Massimino [9], investigated effects of soil nonlinearity in reduced-scale shaking table tests. On the other hand, as observed by Meymand [10], the vast majority of centrifuge and shaking table tests of structures supported by pile foundations were conducted for investigating the soil-pile seismic response in cohesionless soils with liquefaction potential whilst many cases of piles are founded on soil manifesting potential for cyclic strength degradation. Shaking table tests on pile foundations with different pile head conditions are conducted by Chidichimo et al. [11]

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Nomenclature

c_u	undrained shear strength
C_u	coefficient of uniformity
d	pile diameter
D	current cumulative damage
D_r	relative density
D_{50}	diameter of the soil particle for which 50% of the particles are finer
e	void ratio
e_0	initial void ratio
e_{max}	maximum void ratio
e_{min}	minimum void ratio
E_p	elastic modulus of the pile
E_s	elastic modulus of the soil
I_A	Arias Intensity
I_D	damage factor
y	horizontal coordinate
L_p	pile length
p	lateral dynamic load
p_f	ultimate lateral force
p_u	ultimate bearing capacity
p_{ur}	force at the onset of unloading or reloading
p_{us}	shallow ultimate bearing capacity
p_{ud}	deep ultimate bearing capacity
κ	Pike's scale factor
k	lateral nonlinear soil-pile reaction modulus
K_0	backbone curve initial stiffness
K_H	coefficient of lateral earth pressure
t	time
t_D	total duration of the recorded signal
t_E	duration of the strong shaking phase
V_s	shear wave velocity
z	vertical coordinate
β	Rankine's active shear plane failure angle
γ	effective soil unit weight
$\delta_{m\kappa}$, δ_{ms}	stiffness and strength hardening/degradation factors, respectively
δ_k, δ_s	stiffness and strength degradation parameters, respectively
ξ	damping ratio
θ_k, θ_s	stiffness and strength curve shape parameters, respectively
κ	Pike's scale factor
μ_p	mass per unit length of the pile
φ	frictional angle

while Durante et al. [12] investigated the soil-pile-structure interaction of a single degree of freedom supported by single and group pile foundation. It is worth mentioning that in both works nonlinear soil effects are elicited by comparison the actual response with the expected pile response in linear elastic material. Direct effects of the soil nonlinear constitutive behaviour of pile foundations were observed by Meymand [10], through large scale shaking table tests.

A fully nonlinear analysis should be performed to properly evaluate the response of soil-pile system during strong ground motion events, rather than equivalent linear procedures that provide soil stiffness and damping ratio corresponding to the earthquake induced level of shear strain. Full 3D nonlinear soil–pile–structure interaction analyses are generally carried out through the finite element approach [13–17]. However, this approach is generally unattractive when used for solving large nonlinear models.

An alternative approach consists of using the beam on nonlinear Winkler foundation (BNWF) model where the soil-pile interaction is simulated through nonlinear springs. The dynamic BNWF approach is a two-step method that uncouples the nonlinear behaviour of the near-field from the assumed linear or equivalent linear behaviour of the far-field in order to apply the principle of superposition of both effects. A few examples of different implementations can be found in [5,18–27].

The dynamic soil-pile interaction effect is also referred to as kinematic interaction phenomenon, which is commonly incorporated in the framework of substructure technique. Nevertheless, kinematic interaction entails the stresses that are generated within the pile due to the propagation of the seismic waves through the soil excluding the inertial loading of the superstructure. In this context, the analysis of the kinematic interaction in nonlinear soil is an important task for the reliable assessment of the actual performance of foundation, as already investigated by Bentley and El Naggar [28]. Furthermore, the role of ground motion duration as an important factor influencing the nonlinear structural response is still topic of some debate as evident from the different conclusions in [29,30].

In this paper, Incremental Dynamic Analyses (IDAs) are carried out in order to investigate the effects of the nonlinearity on the kinematic interaction of single piles. Although it is commonly used as tool to assess the capacity of structures [31], in this work, IDA is here performed to evaluate the performance of single piles by proposing a novel procedure to derive the scaled earthquake ground motions by means of an iterative site response analysis. A structural Intensity Measure (IM), namely the spectral acceleration, is used to scale the earthquake ground motions to multiple levels of intensity. This aims to generate results that might be easily extended to the structural counterpart so to create a link between geotechnical and structural engineering. The analysis combines the Allotey and El Naggar's BNWF model [23] with the new proposed framework for the equivalent linear site response analysis. Finally, the impact of the Ground Motion Duration (GMD) is evaluated by considering earthquake event with different duration scenarios.

2. Methodology and scope of work

This paper aims to evaluate the effects of Ground Motion Duration and soil non-linearity on the performance of single fixed-head floating piles. Incremental Dynamic Analyses are performed by considering various homogeneous and bilayer soil profiles including: saturated clay and sand in either fully dry or saturated state, with different levels of compaction.

The non-linear kinematic interaction analysis proposed in this paper encompasses two steps. Firstly, the free-field displacements within the deposit along the pile are defined by means of a linear-equivalent site response analysis starting from real accelerograms opportunely defined at the outcropping bedrock. Secondly, the soil-pile interaction is evaluated using a BNWF model, which approximates the soil-pile interaction using non-linear (p-y) springs in parallel with stiffness proportional dampers. This allows estimating the relative displacements between soil and pile due to the free-field motion. In the BNWF model the pile itself is modelled as a series of beam-column elements, each with discrete springs connecting the pile to the soil, and the free-field motion obtained within the deposit is applied to the p-y springs as excitation to the system.

In this paper, the BNWF model proposed by Allotey and El Naggar [23] is employed for investigating the effect of soil nonlinearity on the seismic performance of a single pile. This BNWF model is able to simulate generalized dynamic normal force-displacement relationships, accounting for cyclic soil degradation/hardening, soil and structural yielding, slack zone development and radiation damping. In addition, this BNWF model was revised [32] to account for the build-up of pore pressure due to cyclic loading and the different compaction levels of the