Doctoral School on Engineering Sciences
Università Politecnica delle Marche

Extended summary

Seismic Response of Extended Pile Shafts Considering Nonlinear Soil-Pile Interaction

Curriculum: Structure and Infrastructure Engineering

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Date: 30-01-2013

Abstract. Single column bents on extended pile shafts are widely used in bridges for their economical and technical advantages. Nevertheless, this system is strongly affected by Dynamic Soil-Pile-Structure Interaction. In addition to the lengthening of the fundamental period of the structure, the compliance of the foundation induces a rocking component of the seismic motion experienced by the overall system that cannot be considered by following the procedures of a common seismic design practice. Although advanced models have been developed in order to account for Soil-Pile-Structure Interaction both in the linear and nonlinear range, Winkler-type approach represents one of the most feasible approaches. In this work, a Beam on Nonlinear Winkler Foundation model is used to investigate the importance of features typical in soil nonlinear behaviour such as yielding, gapping, soil cave-in and cyclic hardening/degradation effects on the performance of extended pile shafts. A procedure to estimate the model parameters from geotechnical soil characterization is presented. Incremental Dynamic Analyses are performed to evaluate the effects of Ground Motion Duration and soil nonlinearity on the performance of extended pile shafts in various homogeneous and two-layered soil profiles, including saturated clay and sand in either fully dry or saturated state with different levels of compaction. A procedure to perform Incremental Dynamic Analysis, including effects on both site response analysis and on the structural performance, is established. Nonlinear kinematic and inertial interaction effects are analyzed by means of an exhaustive parametric investigation. The significant effects of the rocking component and the Ground Motion Duration on the seismic response of extended pile shafts are demonstrated. Comparisons with results obtained with a linear model are also presented. Finally, some considerations are drawn pointing out grey areas of the common design practice.

Keywords. Seismic Soil-Pile-Structure Interaction, Extended Pile Shafts, Incremental Dynamic Analysis, Soil nonlinearities, Ground Motion Duration.

1 Problem statement and objectives

1.1 Statement of research

Single column bents supported on extended pile shafts are a typology of bridges or viaduct structures characterized by a single circular pier column obtained by the extension of the pile-shaft foundation above the ground surface with approximately the same diameter and reinforcement. Therefore, the so-called extended pile-shaft assumes the role of both bridge column and foundation (Fig. 1.1). This system assures several benefits when compared to the pile group foundations with smaller piles connecting to the concrete cap; indeed, the absence of a cumbersome squared pier cap improves the hydrodynamics shape reducing the scour effect around the base of the pier (in the case of pier sited on a river bed) and guarantees significant cost savings as well. Because of this interest, the extended pile shaft is broadly employed for the support of highway and railway structures. Nevertheless, such systems exhibit an important flexibility due to the foundation compliance that must be taken into account. In the past, several damages and collapses in extended pile-shaft have been observed after being struck by earthquake [1],[2].Accordingly, the design or the retrofit of single column bents requires a detail analysis because of the perception that they were more vulnerable than multicolumn bridges due to the lack of redundancy. A Fixed Base model cannot simulate the significant effects induced by the foundation compliance and so such kind of approach should not be applied to assess the seismic demand of an extended pile shaft. Therefore, despite the apparent simplicity of the bridge model, this typology of bridge presents issues that engineers must recognize and overcome. The aim of this work is to analyze the effects of the nonlinearities for the soil on the seismic behaviour of such system and to provide methodologies and indications to deal with this problem.

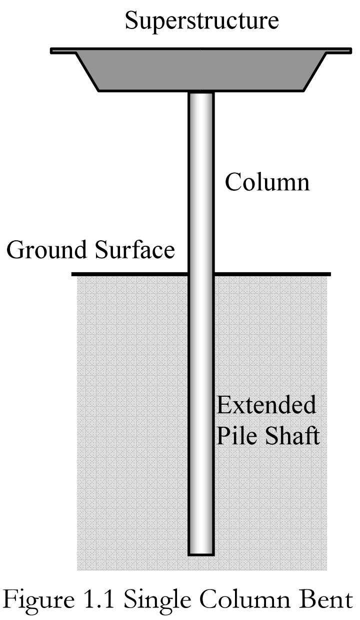


Figure 1.1 Single Column Bent supported on Extended Pile Shaft.

1.2 Research Objectives

The seismic response of Extended Pile Shafts must take into account Soil-Pile Interaction due to the high flexibility of its foundation. Although many advanced models may be used, the Winkler-type model represents one of the most feasible approaches to predict the Soil-Pile Interaction effects, both in the linear and nonlinear range. In this work, a dynamic Beam on Nonlinear Winkler Foundation model [3] is used to investigate the importance of features typical in soil nonlinear behaviour such as yielding, gapping, soil cave-in and cyclic hardening/degradation effects on the performance of extended pile shafts. A thorough investigation of the soil is necessary to estimate the model parameters and to predict accurately the seismic performance of both pile foundation and structure since each soil can differently affect the overall seismic behaviour of extended pile shafts. Therefore, various homogeneous and bi-layer deposits have been taken into account as representative of soil of saturated clay and sand in either fully dry or saturated state, with different levels of compaction. An Incremental Dynamic Analysis (IDA) has been performed to analyze the increasing impact of the nonlinearities of the soil on the overall system. Furthermore, different ground motion accelerograms have been selected relating the Ground Motion Duration (GMD), to analyze the effect of the duration on both the hysteretic behaviour and the cyclic soil degradation/hardening. A parametric investigation is performed by considering different structural fundamental periods. An Analysis Methodology conceived by the author to perform an Incremental Dynamic Analysis for both the site response analysis and the structural analysis is presented. The results are compared with those obtained by means of a linear model.

2 Research planning and activities

2.1 Beam on Nonlinear Winkler Foundation model

The dynamic BNWF model (Fig. 2.1) comprises the pile itself 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. The spring element [3] used in this work, is a degrading polygonal hysteretic model encompassing multilinear backbone curve with defined rules for loading, reloading and unloading. This model is able to capture the dynamic nonlinear behaviour of soil through the following features: (i) it accounts for cyclic soil degradation through simulating unloading - reloading behaviour considering a set of rules such as those proposed by Pyke [4]; (ii) it can simulate gap formation and closing along the soil-pile interface for cohesive soils and reloading in the slack zone (by means of a strain-hardening curve) for cohesionless soils; (iii) the model can handle cyclic soil degradation/hardening as well as reduced radiation damping due to increased soil non-linearity; (iv) the initial confining pressure at zero pile displacement is modeled as a prestraining effect applied to the compression-only elements attached to both sides of the pile. To run this model, several parameters must be calibrated and provided as input, to define the phenomenological model and the mechanical behaviour of the soil.

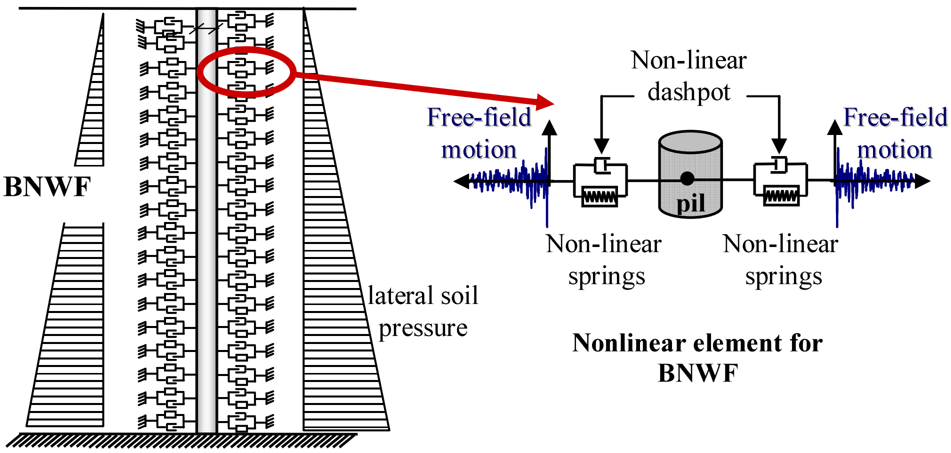


Figure 2.1 Beam on Nonlinear Winkler Foundation model.

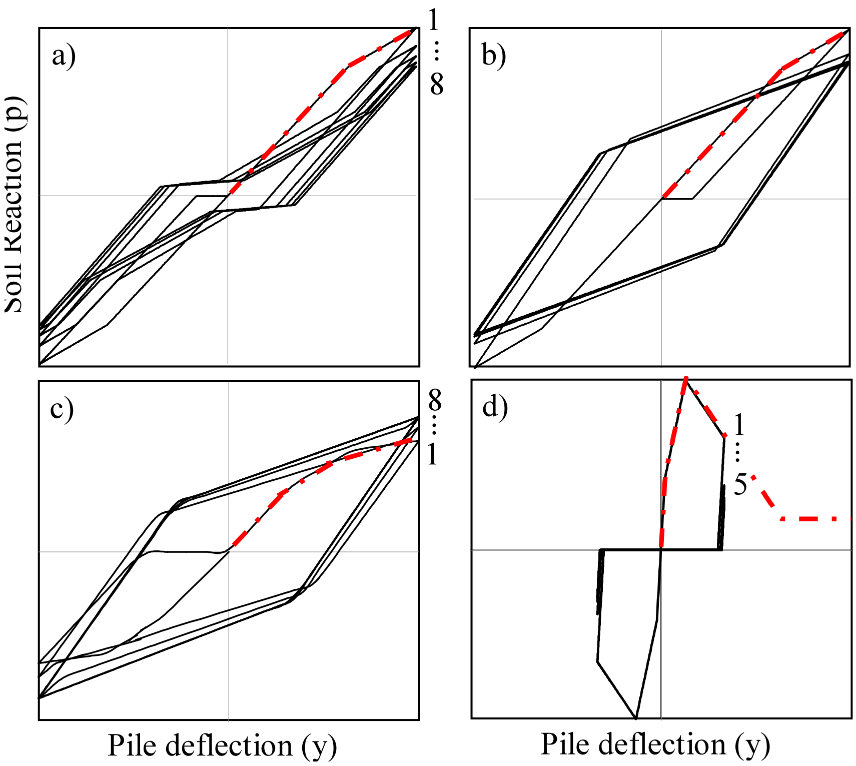


Figure 2.2 a) S-shaped hysteresis curve; b) oval-shape hysteresis curve, c) hardening response, d) post-peak behaviour.

2.2 Model parameters estimation procedure

2.2.1 Types of Soil

Three types of soil, saturated clay and sand in either fully dry or saturated state are investigated. These types of soil are defined in order to point out some typical features of the cyclic behaviour that affect the global response of soil-pile-structure interaction. For saturated soils (sand or soft clay), the cyclic response of the soil along the upper portion of pile is generally considered unconfined and is characterized by an inverted S-shaped hysteresis curve due to slack zone development (Fig. 2.2a). Moreover, in stiff clays, the upper portion of the pile is characterized by the formation of a full gap region On the other hand, the cyclic response of soil along the lower segment of pile is considered confined and characterized by an oval-shape hysteresis curve (Fig. 2.2b). In the case of dry soils (loose sand in particular), soil cave-in is expected to occur, hence the soil cyclic response is characterized by an oval-shape hysteresis curve along the upper portion of the pile as well. Undergoing cyclic loading, soils may exhibit both stiffness and strength degradation depending on the maximum amplitude and on the number of cycles experienced. For saturated soft clay, stiffness degradation is usually more significant than strength degradation, while for dry sands a typical hardening response is expected (Fig. 2.2c). Furthermore, in stiff clay the backbone curve exhibits a brittle behaviour showing an unstable post-peak behaviour (Fig. 2.2d).

2.2.2 General Procedure

In order to characterize exhaustively the soil-pile behaviour, the response to the (i) static monotonic, (ii) cyclic and (iii) dynamic loads should be analyzed. From each of these situations, the parameters for the nonlinear model can be estimated.

(i) *Estimation of the parameters required for obtaining static monotonic behaviour*
The static monotonic behaviour is described by the backbone curve also called p-y curve. The first parameter to estimate is the initial stiffness K_0. This is obtained by approximating the Vesic relationship [5]. Other parameters are evaluated by curve-fitting techniques in order to obtain the four segment multi-linear curve as depicted in Figure 2.3.

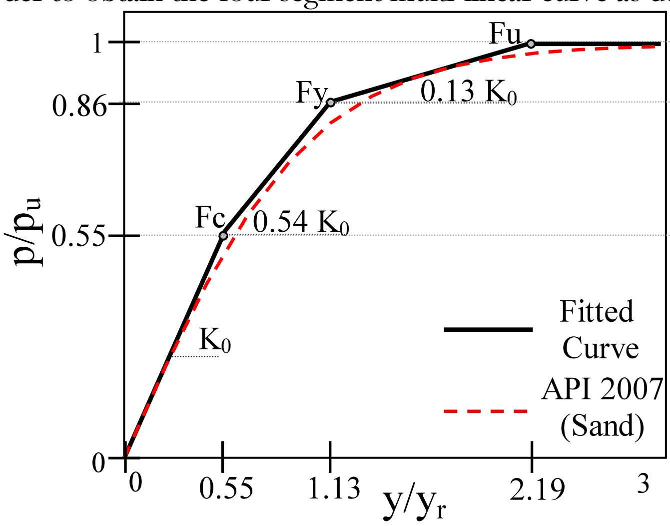


Figure 2.3 P-Y curve for sand and fitted curve used in the model

(ii) Estimation of the parameters required for obtaining the cyclic behaviour

The cyclic behaviour encompasses the definition of the hysteretic curve and the determination of the parameters of cyclic hardening/degradation behaviour. The hysteretic curve is determined by means of the definition of unload and reload curves. The cyclic hardening/degradation behaviour is determined by a cyclic fatigue formulation defining the S-N curve. The S-N curve shows the number of cycles to reach failure ($N=N_f$) when a constant amplitude cyclic stress is applied:

$$S = \frac{\Delta\tau}{\Delta\sigma_c} \tag{1}$$

The stress ratio is normalized in respect to the stress ratio to achieve failure ($S\{N_f=1\}$). It can be obtained by cyclic triaxial tests or cyclic simple shear tests, as reported in the example of the Figure 2.4. From the S-N curve, the stiffness hardening/degradation, the strength hardening/degradation, the slope of the S-N curve, the cyclic stress ratio at N=1 can be obtained. Moreover, the model can predict the damage evolution as a function of the number of current cycle (Fig. 2.5).

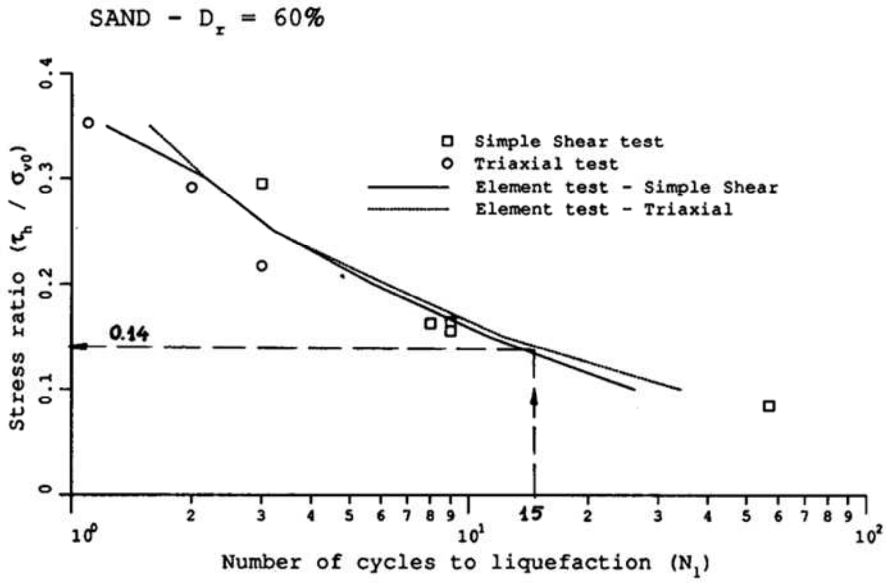


Figure 2.4 Laboratory test results [6] to obtained S-N curve.

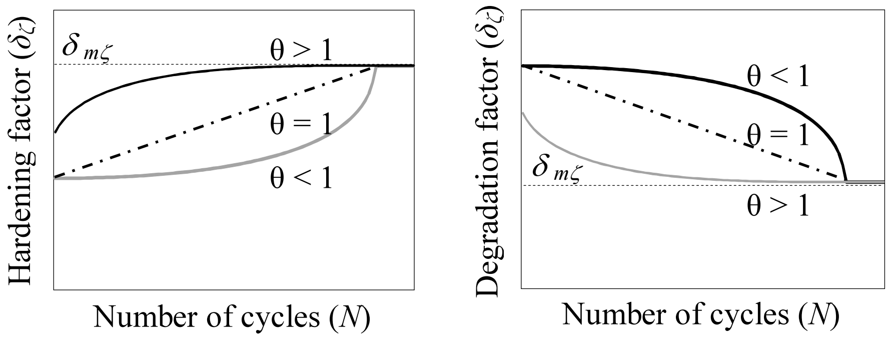


Figure 2.5 Elliptical hardening/degradation curves

(iii) Estimation of the parameters required for obtaining the dynamic behaviour
The dynamic behaviour (dynamic p-y curve) is obtained by modeling a linear dashpot in parallel with the nonlinear spring. The damping parameter is stiffness-proportional decreasing as the hysteretic damping increases. The damping coefficient is calculated by linear fitting of the closed-form formula of radiation damping obtained by Novak [7] in the range of interest of 0-10 Hz

2.3 Incremental Dynamic Analysis considering Soil-Pile-Structure Interaction

The effect of the soil nonlinearities on the dynamic response of extended pile-shafts considering soil-pile-structure interaction is investigated by means of an Incremental Dynamic Analysis (IDA). The aim is to provide useful considerations for the seismic design of extended pile-shafts based on the outcome of these analyses. An uncoupled two-step procedure (i.e. site response analysis and soil-pile-structure interaction analysis) described hereafter is adopted to perform the IDA.

2.3.1 Site response analysis

The 1st step involves the site response analysis to define the free field motion at every depth of the pile to capture the transient earthquake waves. A 1D linear-equivalent site response analysis is performed by means of the elastic parameters and the degrading curves (stiffness and damping). In this step . the definition of the Intensity Measure is required in order to scale the amplitude of the ground motion records selected. The IM is selected as the pseudo-acceleration at the first mode period of vibration
According to the linear-equivalent approach used for the site response analysis, an iterative procedure must be performed. A scaled factor is applied to each ground motion record defined at the bedrock outcropping and the wave propagation analysis is carried out. The scaled factor is adjusted iteratively until the IM converges to the target values. The procedure is illustrated in Figure 2.6.

2.3.2 Soil-Pile-Structure Interaction analysis

The 2nd step consists of the SPSI analysis. The dynamic BNWF requires the direct application of the free field motion to the discrete springs of the model. The approach is a direct method where the global system comprising both structure and soil-pile system must be considered. Nevertheless, this global analysis is performed after a preliminary phase in which kinematic interaction is analyzed. The kinematic interaction is carried out by analyzing the soil-pile system by itself as depicted in Figure 2.7a. The kinematic interaction phenomenon involves the propagation of seismic waves, which causes soil deformations and consequently stresses along the pile. Although the kinematic interaction analysis is intrinsically accounting for by the direct method, the separation of the kinematic and inertial effects can highlight the importance of one upon the other. The global analysis (Figure 2.7b) is performed to obtain the overall behaviour of the extended pile shaft accounting for inertial and kinematic effects. Results are compared in terms of envelopes of bending moments and incremental pseudo-acceleration curves. Furthermore, a comparison between the results obtained by both linear and nonlinear approach is accomplished.

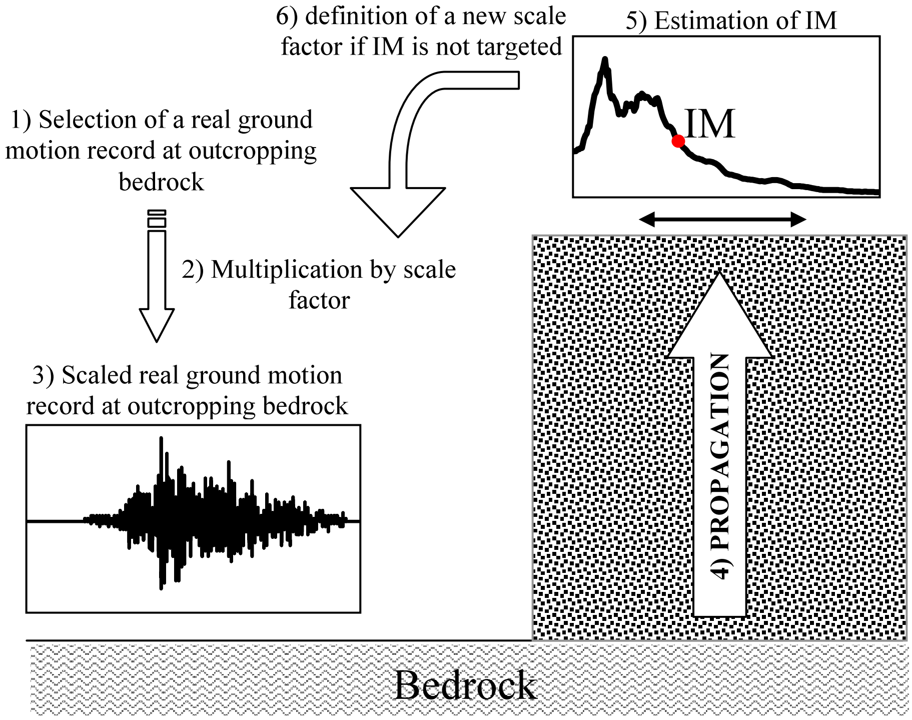


Figure 2.6 Iterative procedure used to perform IDA in the site response analysis.

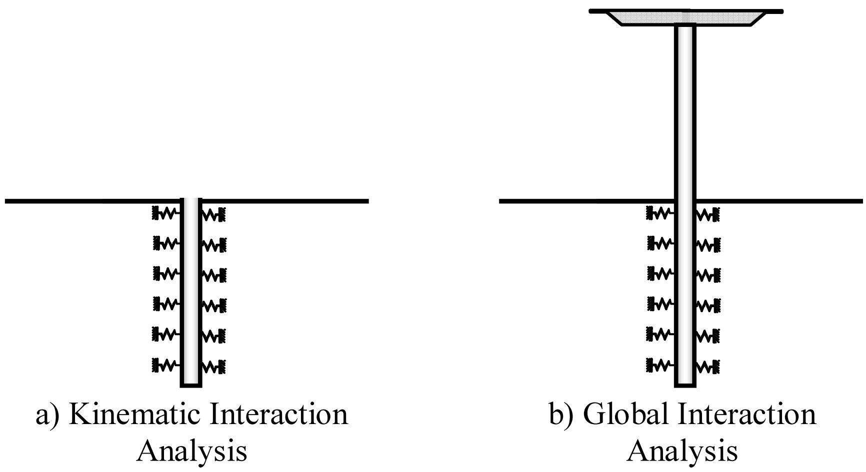


Figure 2.7 a) Kinematic Interaction model and b) Global Interaction model.

2.4 Definition of the ground motion records

Under cyclic or dynamic loads, the soil exhibits hardening/degrading behaviour and can considerably change its strength and stiffness in response to an applied stress. The response of foundation then becomes strongly affected by the duration and the Ground Motion Duration (GMD) could become an important parameter influencing the piles response. In this work, 4 ground motion records are selected to cover different scenarios ranging from "small duration" to "large duration". The ground motion records featuring different durations (I_D) are extracted from the list selected by Iervolino et al. [8]; the 4 real ground motion records defined at the bedrock outcropping are obtained in increasing order of duration from the events of the San Fernando Earthquake (I_D =4.4), the Loma Prieta Earthquake (I_D =6.6), the Chi Chi Earthquake (I_D =14.3) and the Imperial Valley Earthquake (I_D =24.2). Table 2.1 describes the data related to the selected records. Every record is dealt with signal processing techniques such as zero padding and baseline correction to avoid numerical errors.

2.5 Outline of the Incremental Dynamic Analysis

An extensive parametric analysis is carried out varying the soil profiles as well as the superstructure. The soil profiles (Fig. 2.8) investigated are 9: 6 homogeneous (single layered) deposits and 3 two-layered deposits obtained by considering 3 types of soil, saturated clay and sand in either fully dry or saturated state, with different level of compaction to achieve different shear wave velocities. The geotechnical and dynamic parameters are selected to be suitable to laboratory and in situ tests available in literature. The structural system, namely the extended pile-shaft, is calibrated in order to achieve 4 fundamental periods for any soil profiles varying only the height of the pier (Fig. 2.9). This approach permits to examine a broader number of situations such as several kinds of single column bents ranging from short viaducts to bridges or bridges with different slenderness or else any simple structures with different first mode of vibration.

Two different systems have been used in this work, a linear model consisting of a superstructure with a compliance base characterized by a Lumped Parameter Model and a nonlinear model based on a Beam on Nonlinear Winkler Foundation. The comparison of the response of the two models adopted permits to highlight the influence of the nonlinearities of the soil on the behaviour of the superstructure. Soil yielding, formation of gap or slack zone as well as cyclic hardening or degradation are the nonlinearities involved and analyzed in this study. Hence, every kinds of soil exhibit a specific cyclic behaviour.

The Incremental Dynamic Analysis is performed to evaluate the effect of the nonlinearities at 4 levels of intensity varying between 0.1g to 0.6g. 4 accelerograms, related to a Ground Motion Duration parameter are selected in order to determine four scenarios of duration, ranging from small to long duration; the duration affects the soil response because of the cyclic hardening/degradation behaviour of the soil and the hysteretic damping developed during cycling.

In the present study, a large number of cases are investigated: 16 records (4 records by 4 intensities) imposed to 36 systems (consisting in 9 profiles by 4 fundamental periods) summing a total of 576 analysis cases for each models. Furthermore, both total and kinematic interaction analyses are performed reaching a total number of 2304 analyses.

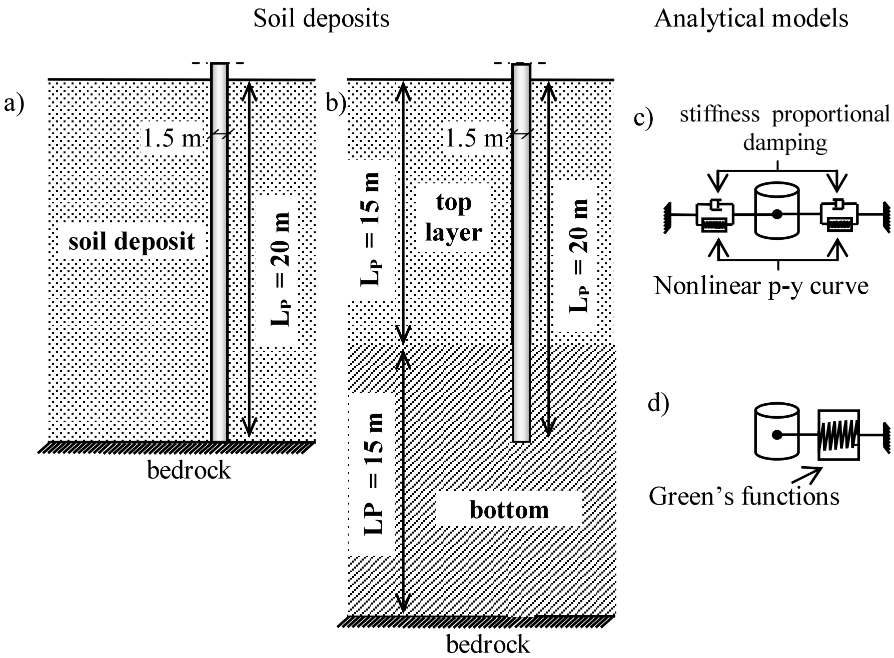
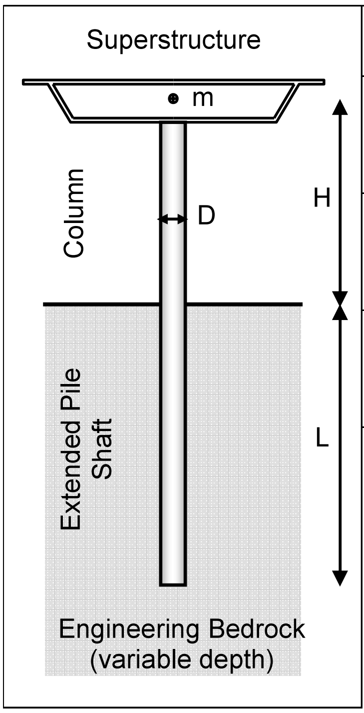


Figure 2.8 Frameworks of a) and b) soil deposits and c) Allotey and El Naggar [3] and d) Dezi et al. [9] analytical models.



	T_{SSI} = 0.4s	T_{SSI} = 0.8s	T_{SSI} = 1.2s	T_{SSI} = 1.6s
Vs = 100 m/s	H = 3m	H = 8m	H = 12m	H = 15m
Vs = 100 – 300 m/s	H = 3m	H = 8m	H = 12m	H = 15m
Vs = 200 m/s	H = 5m	H = 10m	H = 14.5m	H = 17m

Constant parameters:
D = 1.5 m
L = 20 m
Ep = 2.25×10^7 kPa
m = 115 Mg
ρ = 2.5 Mg/m^3

Figure 2.9 Structural Parameters used in the work.

Table 2.1 Earthquakes data of the ground motion records adopted in the work.

Event	Data	Station	Record	T [sec]	I_D
San Fernando	*09/02/1971 14:00*	994 Gormon-Oso Pump Plant	SFERN/OPP270	9.22	**4.4**
Loma Prieta	*18/10/1989 00:05*	57066 Agnews State Hospital	LOMPA/AGW000	39.95	**6.6**
Chi Chi	*20/09/1999*	CHYO50	CHICHI/CHY050-N	89.95	**14.3**
Imperial Valley	*15/10/1979 23:16*	6605 Delta	IMPVALL/H-DLT262	99.92	**24.2**

3 Analysis and discussion of main results

3.1 Kinematic Interaction in Extended Pile-Shafts

Results are presented in terms of kinematic bending moment envelopes within the pile and with reference to the analysis cases characterized by a homogeneous soil profile with an average shear wave velocity of 100 m/s. Figure 3.1 shows the envelopes of the kinematic bending moments for the analysis cases considering the three types of soil, i.e. Dry Sand, Saturated Sand and Saturated Clay, with the spectral acceleration value defined at T_0 = 0.4s. Both San Fernando and Imperial Valley Earthquakes, representing the scenarios of small and large duration, respectively, are considered. For low levels of intensity, the kinematic bending moments obtained for a specific ground motion are rather similar, independently from the soil type, proving that the soil behaves linearly. At higher levels of intensity, the three types of soil exhibit a different behaviour. As previously observed, kinematic bending moments in clayey soil are lower than those obtained from the other two cases, because of the site response analysis. By observing the kinematic bending moment obtained for sands, it is evident how the cyclic behaviour affects the seismic response. Indeed, in the small duration scenario defined by the San Fernando Earthquake, the pile response is similar for both the sand states, due to the same shear modulus attenuation curve used in the site response analysis. On the other hand, in the large duration scenario defined by the Imperial Valley Earthquake, the behaviour of these two soils progressively diverges by increasing the seismic intensity. Therefore, the duration parameter causes different trends as it affects the cyclic response of the soil. It is worth remembering that fully dry sand is a hardening soil whereas saturated sand exhibits a cyclic degradation under undrained shearing. Moreover, the more is the intensity of the shear stress applied to the soil, the less is the number of cycles required to achieve the shakedown or the failure of soil. The effect of degradation of the soil determines a decrease of the maximum kinematic bending moment along the pile

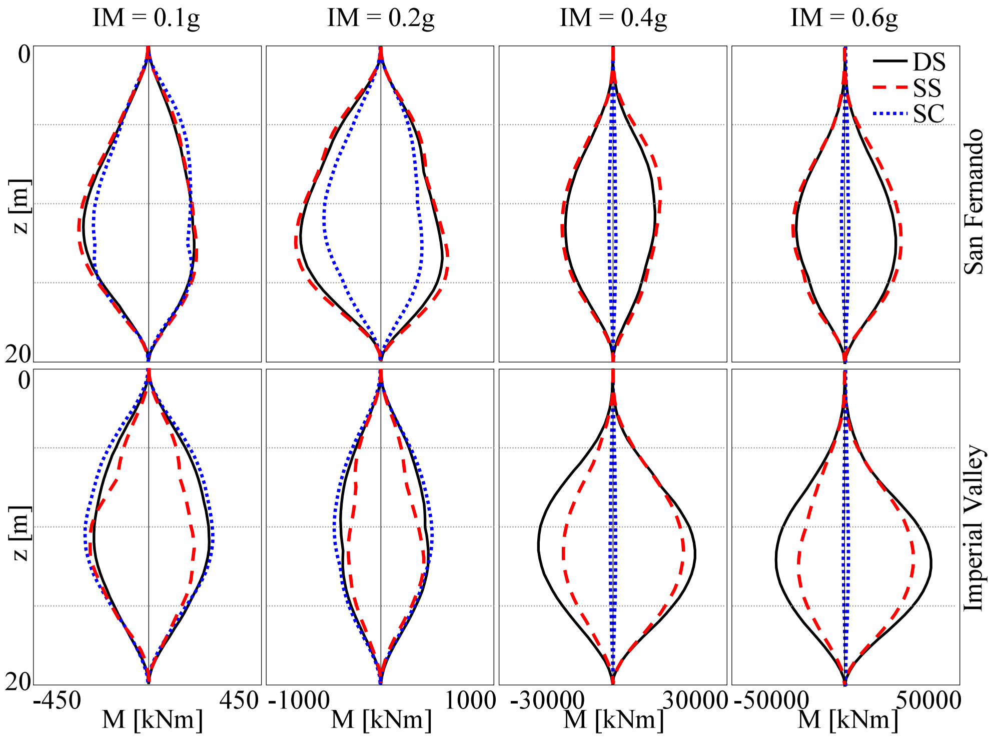


Figure 3.1 Comparison of the nonlinear kinematic moments for short and large scenarios.

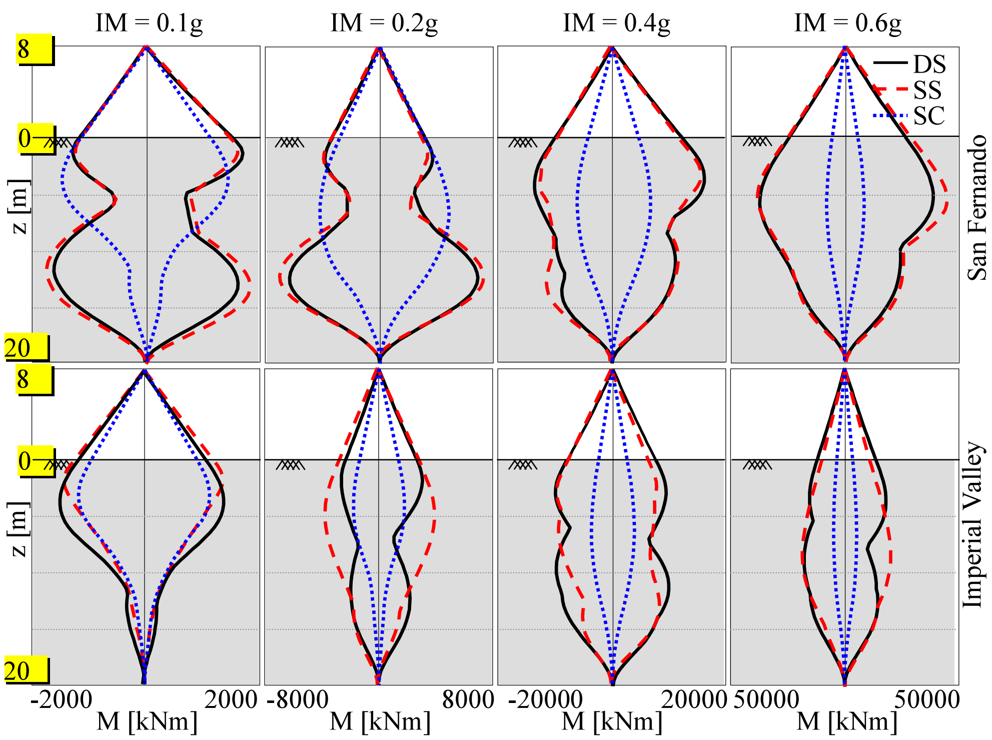


Figure 3.2 Comparison of the nonlinear global moments for short and large scenarios

3.2 Soil-Pile-Structure Interaction in Extended Pile-Shafts

Results in terms of global (kinematic and inertial) bending moment are presented for the analysis cases characterized by a homogeneous soil profile with average shear wave velocity of 100 m/s. Figure 3.2 shows the envelopes of the kinematic bending moments for the analysis cases considering the three types of soil, i.e. Dry Sand, Saturated Sand and Saturated Clay, with the spectral acceleration value defined at T_0 = 0.8s. Both San Fernando and Imperial Valley Earthquakes, representing the scenarios of small and large duration, respectively, are considered. It is expected that the cyclic hardening/degradation behaviour (in dry soil and saturated soil, respectively) affects the soil-pile response according to the duration of the scenario. For short scenario, although the soil-pile response in soft clay is rather different from that relative to sandy deposits because of the nonlinearities developed in the site response analysis, the envelopes of the global bending moment for sandy deposits are similar. Conversely, for long scenario, it can be seen a marked difference between soil-pile response in dry and saturated sand even for low level of intensity. It is worth remembering that the same considerations were drawn for nonlinear kinematic bending moments even if a higher intensity has been requested to involve the cyclic behaviour.
Moreover, results of the Incremental Dynamic Analyses are illustrated in form of pseudo-acceleration curves. Pseudo-acceleration is determined as the ratio between the shear stress at the base of the column and the mass at the top of the column.

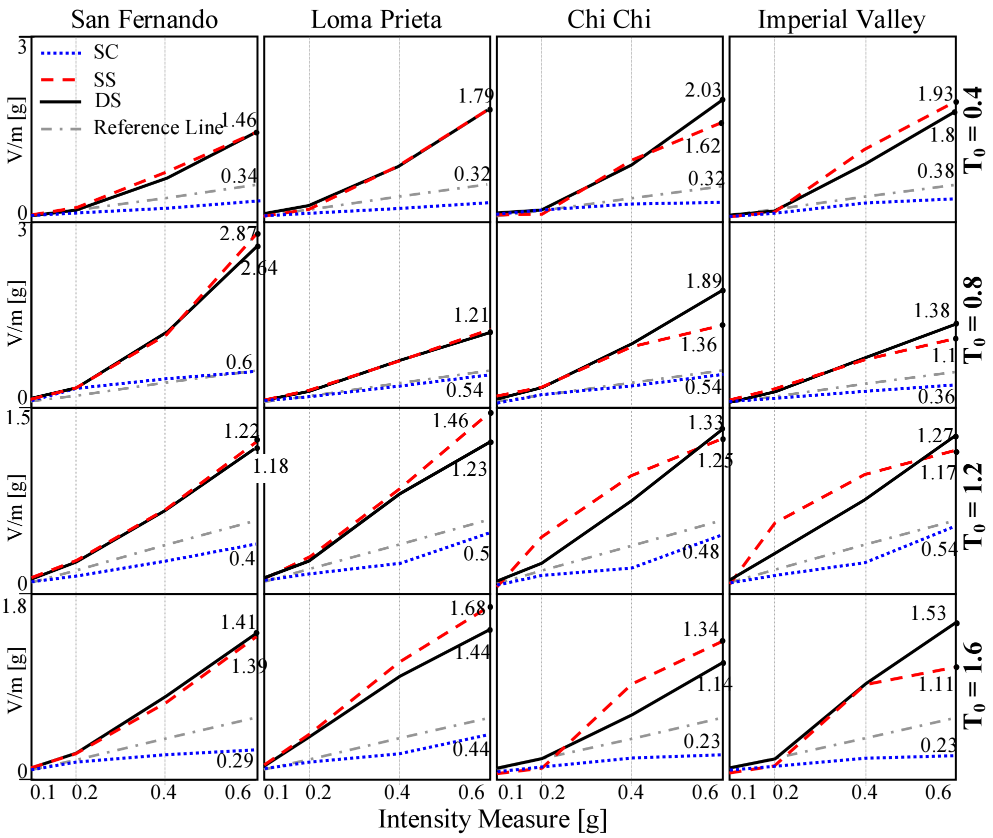


Figure 3.3 Pseudo-acceleration curves related to the profiles characterized by Vs = 100 m/s

Figure 3.3 shows the pseudo-acceleration curves for all cases related to the homogeneous soil deposits with shear wave velocity of 100 m/s. The grey dash-dot line, namely the reference line, is the diagonal straight line that correlates the IM with the expected pseudo-acceleration of a FB models (e.g. IM=0.6g with V/m = 0.6g). As previously analyzed for the bending moments, the results of the case analyses related the clayey deposits are lower than related to the sandy deposits. Moreover, the pseudo-acceleration curves are tracked below the reference line; thus this is evidence of a beneficial influence of the nonlinear soil-pile-structure interaction. Conversely, the pseudo-acceleration curves regarding sandy deposits exhibit values higher than related to the reference line. Therefore, the nonlinear soil-pile-structure interaction determines detrimental effects on the structure. Values of pseudo-accelerations more than twice as high as that expected in FB models, are recorded. This is caused by the amplification of the input applied to the structure related to the foundation input motion in place of the free field motion.. The overall response of stiffer structures is more affected by the foundation input motion even despite the lower height of the column. With the increasing of the level of intensity, the pseudo-acceleration curves related to the case of dry sand increase more than proportionally. Conversely, the pseudo-acceleration curves related to the case of saturated sand increase less than proportionally as IM rises. This is especially true for cases where the nonlinear effects induced by the soil degradation are marked. In fact, the influence of the GMD is evident in the investigated cases. Regarding the short scenarios represented by the events of San Fernando Earthquake and Loma Prieta Earthquake, the curves of both saturated and dry sand cases are nearly overlapping. On the other hand, longer scenarios as those determined from the events of Chi Chi Earthquake and Imperial Valley Earthquake cause a relevant impact on the cyclic soil degradation affecting the overall structural response. The pseudo-acceleration curves of saturated sandy cases diverge from that related to dry sandy cases approaching lower values. In particular, these effects are marked in structures with higher columns where higher inertial bending moments at the base are expected.

3.3 Importance of the rocking component of the Foundation Input Motion

In order to investigate the linear effects of the Soil-Structure Interaction on the seismic response of Extended Pile Shafts, an elastic response spectrum accounting for the lengthening of the fundamental period, the increase of the damping, as well as the foundation input motion, is presented. Hereafter, the system fully restrained at base is referred to as the Fixed Base (FB) model; the system with the compliant base is referred to as the Compliant Base model and it is here labeled as CB-FFM or CB-FIM when the input applied at the base is the free field motion or the foundation input motion obtained by a kinematic interaction analysis, respectively. The small difference between elastic spectra for FB and CB-FFM models is only due to the increase of the damping owing to the radiation damping and the influence of the frequency-dependent response of the foundation. On the other hand, a marked difference is observed between the spectra for CB-FFM and CB-FIM models. Figure 3.4 shows a comparison among the elastic pseudo-acceleration vs the equivalent periods of FB, CB-FFM and CB-FIM model for the case relative to the saturated sand. The difference in this comparison is due to the input applied to the system. In particular, the rocking component of the foundation input motion greatly affects the dynamic response of the system and cannot be neglected in the seismic design of the extended pile-shafts.

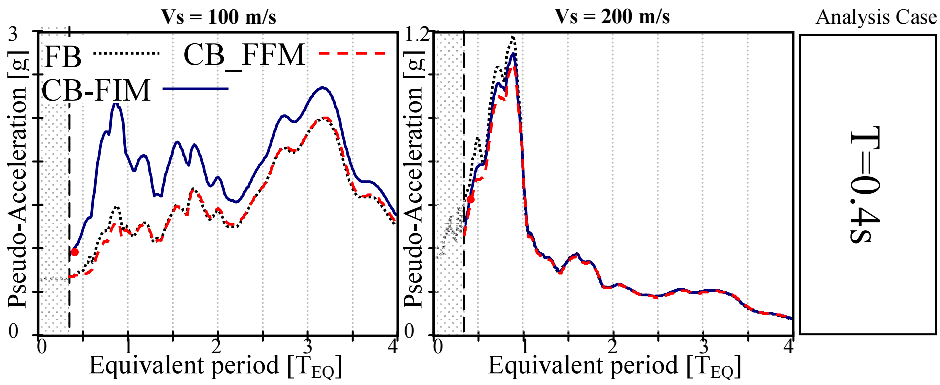


Figure 3.4 Elastic response spectra for CB systems for Imperial Valley Earthquake (0.6g).

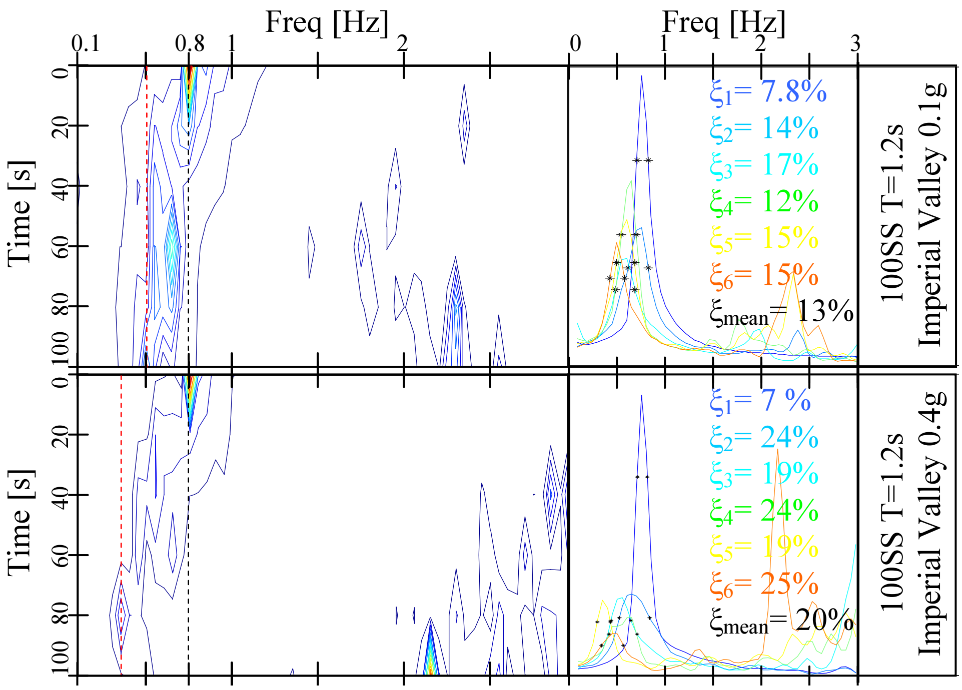


Figure 3.5 Spectrogram and estimation of equivalent damping of the 100SS case, T = 1.2s, Imperial Valley scaled at 0.4g

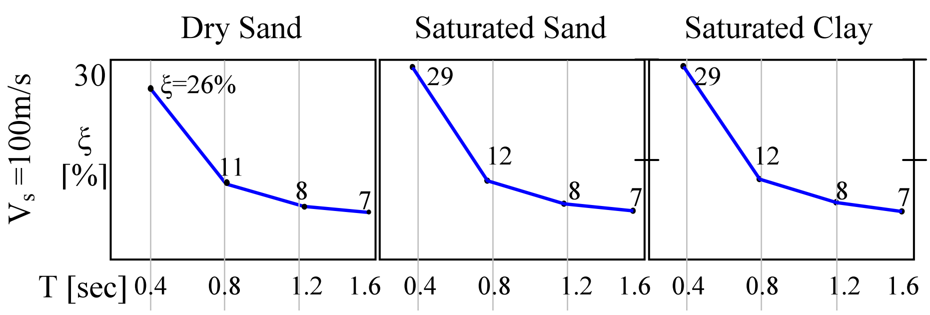


Figure 3.6 Equivalent Damping Curves

3.4 Evolution of the fundamental period and estimation of the damping

To track the alteration of the dynamic properties of the nonlinear system, a procedure accounting for Short Time Fourier Transform [10] is used. Figure 3.5 shows the outcome of the procedure applied to the case characterized by fully saturated sand for two levels of intensity. It can be seen that a degradation of the stiffness of the system occurs caused by the soil nonlinearities such as yielding, gap formation as well as cyclic degradation acting together. At the first part of the signal, the system responds elastically. With the progress of time, the system becomes softer and moves towards higher periods. The entity of this shifting is related to the level of intensity. The second column of the same figure shows the transfer functions for each of the windows in which the signal is divided. It is possible to assess, as previously done, the average equivalent damping ratio of the system. The equivalent damping increases according to the level of intensity. To estimate the equivalent damping, the half-bandwidth method is applied to the transfer function of the system. In linear system, the equivalent damping decreases as the fundamental period increases (Fig 3.6) because of the viscous contribution of the radiation damping.

4 Conclusions

An extensive investigation on the seismic response of single column bent bridges supported on extended pile shafts, accounting for nonlinear soil-pile-structure interaction, has been presented. Several soil profiles are considered combining homogeneous and two-layered soil deposits with different types of soil; in particular, saturated clay and sand in either fully dry or saturated state with different level of compaction (in order to achieve different shear wave velocities) are investigated. Incremental Dynamic Analyses are performed to evaluate the effects of the soil nonlinearities and of the Ground Motion Duration on the seismic response of extended pile shafts. Four levels of intensity are considered. By selecting four real ground motions, characterized by increasing GMD values, different scenarios, representative of small and large duration, are investigated. The parametric studies are carried out by means of two models, the first linear model was developed by Dezi et al. (2009) and the latter is a Beam on Non-linear Winkler Foundation (BNWF) model (Allotey and El Naggar, 2008), which accounts for cyclic soil degradation/hardening, soil, gapping , slack-zone development and radiation damping. A two-step uncoupled procedure is used in the analysis: firstly, the free field motion is evaluated considering an equivalent linear site response analysis; secondly, soil-pile-structure interaction analyses were performed. The IDA involves both site response analysis and SPSI analysis. Differences between expected and obtained results prove the relevance of the SSI effects.
A summary of the main conclusions are:

- single column bents supported on extended pile shafts are sensibly affected by SSI because of high compliance of the soil-pile system;
- the rocking component of the foundation input motion sensibly affects the dynamic behaviour of extended pile shafts
- the selection of input motions for performing dynamic analyses has to account for the main characteristics of the wave motion such as amplitude, frequency content and duration;
- although the SPSI causes a detrimental effect on the overall structure, the effect of the soil yielding can result in an opposite beneficial effect as already reported in litera-

ture [11], [12], [13]. By increasing the intensity level, the pile bending moment reduces with respect to that obtained by a linear model; this consideration applies for free-head piles.

- the equivalent damping decreases with the increase of the fundamental period of the global system. At low fundamental periods, the radiation damping is high while it decreases until reaching the structural damping value at high fundamental periods;
- the soil yielding increases the hysteretic damping and decreases the radiation damping. Thus, the average equivalent damping can be higher or lower than that obtained by a linear model.

The future research aims to extend investigations on such type of structures by including the nonlinear behaviour of the structure also in presence of liquefiable soils.

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