Soil Dynamics and Earthquake Engineering 67 (2014) 326–344

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Seismic response of reinforced concrete frames on monopile foundations

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ARTICLE INFO

Article history:
Received 27 December 2013
Received in revised form
12 August 2014
Accepted 14 October 2014

Keywords:
Lumped parameter model
Monopile foundations
R.c. frames
Seismic soil–structure interaction
Substructure method

ABSTRACT

The paper focuses on the effects of soil–structure interaction on the seismic response of reinforced concrete frames on monopile foundations connected by tie beams. Such systems are usually designed by considering fixed restraints at the column bases and the effects of the foundation compliance have not yet been investigated. The soil–foundation system is analysed in the frequency domain by means of a numerical model that allows obtaining the dynamic impedance functions of the system and the foundation input motion necessary for the subsequent nonlinear inertial soil–structure interaction analysis which is performed in the time domain. Tie beams with different stiffness and soil deposits characterised by three different profiles of shear wave velocity are considered. Results of incremental dynamic analyses carried out on frames with monopile foundations are compared with those obtained considering double-pile foundations and the fixed base assumption. Soil–structure interaction is found to affect considerably the response of frames on monopile foundations by increasing the structural deformation and modifying the evolution of the dissipative mechanisms. Analyses accounting for the actual soil–foundation system compliance and the foundation input motion may be crucial for a reliable prediction of the actual distribution of stresses in the superstructure and the foundation elements.

1. Introduction

Reinforced concrete frames are commonly designed considering fixed restraints at the base of columns. For foundations constituted by pile groups, this assumption is deemed to be justified by the significant rotational stiffness of the foundation system whereas, in the case of monopile foundations, stiff tie beams are usually designed to limit the foundation rotations. However, conventional fixed-base models developed for the structural design cannot provide information about the effectiveness of tie beams to prevent the column base rotations. In order to obtain a reliable prediction of the structural seismic response, especially when deformable tie beams are adopted, Soil-Structure Interaction (SSI) analyses have to be performed accounting for the soil–foundation frequency dependent compliance and the actual foundation input motion. Given that monopile foundations are increasingly used in reinforced concrete frame structures due to their ease of execution and low cost, these aspects have to be examined in detail to provide practicing engineers with a useful guidance.

With reference to frame structures, this is made possible by the use of comprehensive models able to account for (i) the behaviour of the soil–foundation system of each column and (ii) the real structural configuration, to capture the evolution of the distributed dissipative mechanisms and the actual redistribution of stresses among elements of superstructure and foundations. In the literature, simplified models have been generally used to qualitatively understand SSI effects on the seismic behaviour of structures. Among the others Maragakis et al. [1] developed a model for the rigid body motions of skew bridges to study the impact between the bridge deck and the abutments; Makris et al. [2] presented a simple procedure to analyze the problem of soil–pile–foundation–superstructure interaction by modelling the superstructure with a simple six degree of freedom structural model while Mylonakis and Gazetas [3] investigated the beneficial or detrimental role of SSI on the dynamic response and ductility demand of bridge piers by considering single degree of freedom systems for the structural modelling. Concerning buildings, Medina et al. [4] studied effects of SSI on vibration periods and damping of one-storey shear type frames whereas Lin et al. [5] presented an approximated method for the seismic analysis of elastic buildings by considering multi-storey shear-type systems.

Simplified models are useful for the research, as long as it focuses on the overall behaviour of the system, but are somewhat simplistic to capture the real behaviour of complex structures [2,6–8] where local effects may arise because of particular

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http://dx.doi.org/10.1016/j.soildyn.2014.10.012

structural configurations and specific SSI effects (e.g. rotation of the single foundations may be responsible for an early damage of the structure and for increments of stress resultants along piles). For this purpose, many researchers used refined linear and nonlinear models. For example, Kappos et al. [9] investigated the seismic response of reinforced concrete bridges with irregular configuration by using finite element models which include the bridge foundation system and the surrounding soil; Sextos et al. [7,8] studied the nonlinear seismic response of bridges including the spatial variability of ground motion, site effects and soil–structure interaction phenomena by means of accurate finite element structural models. Furthermore, Elgamal et al. [10] performed three-dimensional nonlinear dynamic finite-element analysis of the Humboldt Bay Middle Channel Bridge by modelling the whole bridge-foundation-ground system; Jeremic et al. [11] presented a numerical investigation of the influence of non-uniform soil conditions on a concrete bridge by developing nonlinear soil–foundation–structure finite element models. As for buildings on deep foundations, the authors studied the linear and nonlinear response of coupled wall-frame structures founded on piles in order to investigate effects of SSI on the dual load path mechanism by adopting superstructure finite element models [12,13]. More recently, Hokmabadi et al. [14] performed a series of shaking table tests for fixed-base and compliance base mid-rise buildings and compared the experimental results with those furnished by a fully nonlinear three dimensional numerical model.

Although a significant number of works dealing with the SSI effects on the seismic response of structures on pile foundations are available, only few of them refer to frame structures [12–14] and there is a specific lack of knowledge about the effects of the foundation compliance on the seismic response of reinforced concrete frames founded on monopiles connected by tie beams. In this paper such systems, which are expected to be sensitive to SSI effects, are numerically investigated by applying the substructure approach, which consists in studying separately the soil–foundation system and the superstructure on compliant-base subjected to the foundation input motion. The paper aims to investigate the effects of the soil–foundation compliance on the seismic response of the system taking into account the nonlinear behaviour of the superstructure. The effects of tie beam stiffness on the behaviour of both the superstructure and piles are investigated considering different soil deposits. The SSI analyses are performed taking advantage of the procedures developed by the authors for the frequency-domain analysis of the soil–foundation system [15] and the assemblage of suitable Lumped Parameter Models (LPMs) to reproduce the soil–foundation dynamic behaviour for the nonlinear analysis of the superstructure [13]. 6-storey 3-bay reinforced concrete frames founded on 3 different soil deposits, falling within types B, C and D defined in EN1998-1 [16], are considered in the analyses. Both superstructures and foundations of case studies are designed starting from results of fixed base analyses. In particular, foundations are designed in order to obtain two structural behaviours characterised by stiff and deformable tie beams, respectively. SSI effects are evaluated for earthquakes with increasing intensity by means of Incremental Dynamic Analyses (IDAs). The results, concerning both the superstructures and foundations, are compared with those achieved under the fixed base assumption and also considering double-pile foundations chosen to represent systems characterized by resisting mechanisms in which overturning moments are resisted mainly by compression/traction axial forces in the piles.

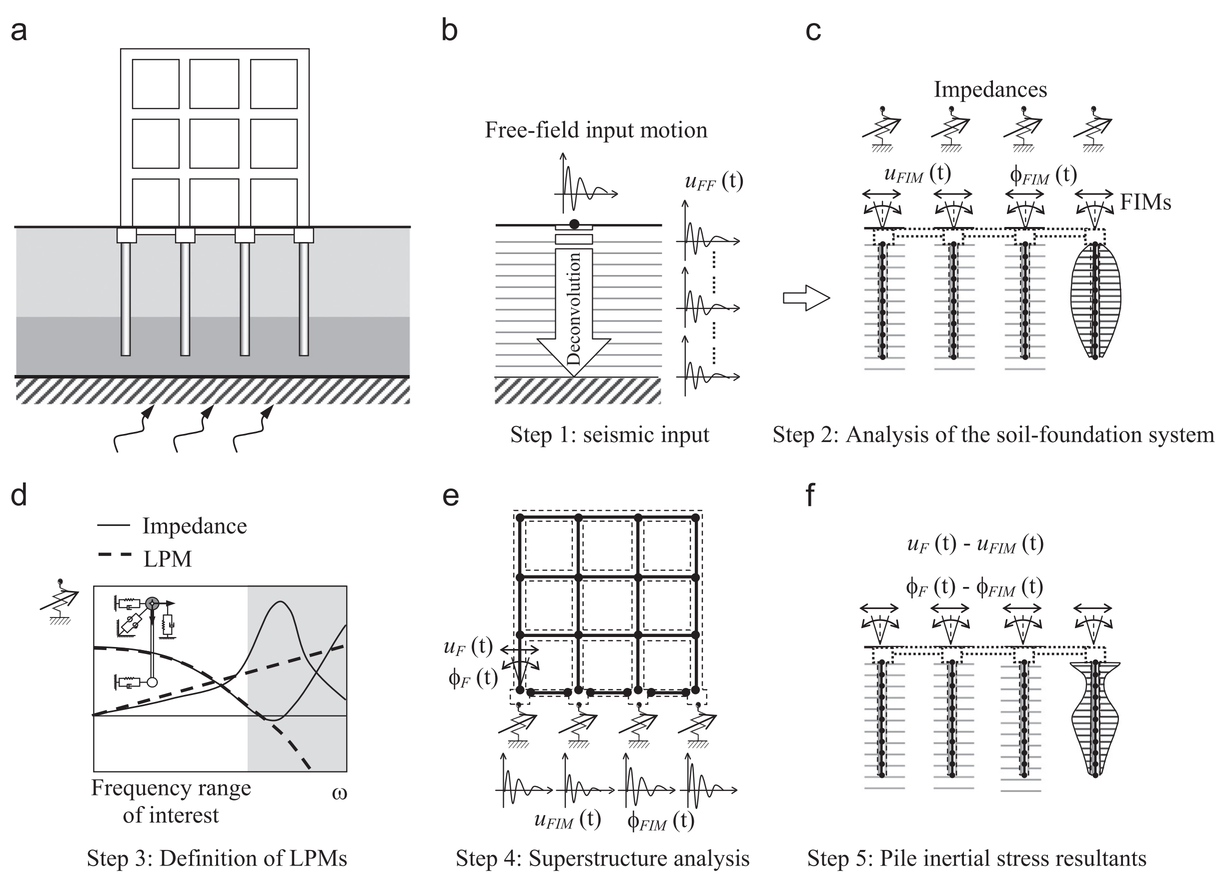

Fig. 1. Analysis methodology: (a) complete soil–foundation–superstructure system; (b) definition of seismic input and site analysis; (c) analysis of the soil–foundation system; (d) definition of LPMs; (e) superstructure analysis; and (f) evaluation of the inertial stress resultants along piles.