Computers and Structures xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Computers and Structures

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

Analysis of nonlinear soil-structure interaction effects: 3D frame structure and 1-Directional propagation of a 3-Component seismic wave

M.P. Santisi d'Avila [a,*], F. Lopez-Caballero [b]

[a] Laboratoire J.A. Dieudonné, CNRS UMR7351, Côte d'Azur University, France
[b] Laboratoire MSS-Mat., CNRS UMR8579, CentraleSupélec, Paris-Saclay University, France

ARTICLE INFO

Article history:
Accepted 12 February 2018
Available online xxxx

Keywords:
Soil-structure interaction
3-Component seismic load
1-Directional wave propagation
3D frame
Finite Element Method

ABSTRACT

In this paper, a finite element modeling technique, taking into account the effects of soil-structure interaction (SSI) is proposed for structural analysis and design. The one-dimensional model of a nonlinear multilayered soil profile is assembled with a multi-story multi-span frame model and the dynamic equilibrium problem is solved directly. The one-directional propagation of three-component seismic waves (1D-3C) is modeled taking into account the SSI, in the case of rigid shallow foundation and negligible rocking effects.

The 1D-3C wave propagation model provides the three components of motion at the base of the frame structure, allowing the reduction of mesh size and computation time, compared with a fully three-dimensional model, and avoiding modeling difficulties to realize a reliable three-dimensional soil domain, related among others to boundary conditions.

The proposed model allows the analysis of those structural dynamic features, seismic wave and local soil stratigraphy, that produce changes in the ground motion at the surface. The model reproduces well expected phenomena, in the case of layered soil with increasing nonlinearity and for different inertia distribution in the frame structure. SSI combined with seismic site effects is analyzed in a Japanese soil profile, using as seismic loading a 3C record of 2011 Tohoku earthquake.

1. Introduction

The seismic response of structures depends on ground motion features and on mechanical properties of both structure and underlying soil. The stratigraphy of the soil profile and mechanical features of soil influence the propagation of seismic waves during the path from bedrock to the surface and, at the same time, the oscillation of structures at the soil surface modifies the ground motion. This effect is known as soil-structure interaction (SSI) and it depends on dynamic properties of the structure and on the difference in principal frequencies of soil and structure.

Considering SSI, the natural period of the structure should increase because the structure is more flexible compared to the corresponding fixed base structure. In some cases, the effects of the SSI can be detrimental for the structure (Mylonakis and Gazetas [2]) depending on site stratigraphy, nonlinear soil behavior under cyclic loading, dynamic features of the structure and frequency content of seismic waves.

According to Stewart et al. [3], two mechanisms of interaction take place between the structure, its foundation and soil: inertial and kinematic interaction. Inertia developed in the structure due to its own vibrations causes changes in seismic waves at the base of the structure, compared with the free field. Furthermore, the presence of a deep foundation modifies seismic waves in the soil due to the stiffness contrast between soil and foundation. There is not any kinematic interaction in the case of shallow foundations, where the foundation is simply laid on the soil surface, for the model with vertical propagation (Betbeder-Matibet [4]).

There are two basic methods to model the SSI (Wolf [5]): substructure method and the direct solution. The substructure method is based on the decomposition of the complete soil-foundation-structure domain to several subdomains (as described by Saez et al. [1]) under the assumption of geometric and material linearity or using linear equivalent approach (Pitilakis et al. [6]). The response of each subdomain is evaluated separately and superposed to obtain the total system response. In contrast, direct methods are applied to take into account soil nonlinearity. The soil-foundation-structure system is modeled in its integrity, considering a significant part of the soil around the structure, and the incident waves must be imposed at the lateral boundaries

---

* Corresponding author.
E-mail address: msantisi@unice.fr (M.P. Santisi d'Avila).

https://doi.org/10.1016/j.compstruc.2018.02.002
0045-7949/© 2018 Published by Elsevier Ltd.

according to the soil behavior in free-field conditions. If boundaries of the soil domain are close to the structure, the influence of the outgoing waves is important. Then, absorbing boundaries are needed in order to satisfy a radiation condition for the incompatible outgoing waves. Two-dimensional (Gandomzadeh [7], Saez et al. [8]) and three-dimensional spatial discretization of soil (Toki and Fu [9], Iida [10], Jeremic et al. [11], Mazzieri et al. [12], Karapetrou et al. [13]), in SSI models, allow modeling surface waves, the multi-dimensional propagation path and the foundation rotation due to rocking effects. The extensive application of three-dimensional (3D) SSI models in the usual engineering practice is hindered by the lack of geotechnical data that makes more difficult realizing a reliable soil model and, on the other hand, the dimension of soil domain results in a significant modeling and computation time.

The free surface motion applied at the base of a structure as seismic loading (two-step approach) does not take into account the SSI (Saez et al. [1]). This research aims to simulate, using a one-step approach (direct solution), the behavior of a system composed by a multi-story multi-span frame structure over a horizontally layered soil basin, under three-component (3C) seismic loading. The assumption of rigid shallow foundation allows the transmission of the 3C-motion from the soil to the base of frame columns. The rotation of the structure at the foundation level is not permitted.

The one-directional three-component (1D-3C) propagation model proposed by Santisi d'Avila et al. ([14,15]) is adopted. The three components of seismic waves are simultaneously propagated in one direction, from the soil-bedrock interface to the ground surface. The incident direction of the seismic loading at the soil surface, that shakes the structure base, can be detected by modeling the 3C wave propagation.

In order to describe the nonlinear soil behavior under dynamic loading, a 3D constitutive relationship of the Masing-Prandtl-Ishlinskii-Iwan type (Iwan [16] and Joyner 1975 [17]) is used. Modeling the 3D constitutive behavior of soils, compared with the case when only one stress component is considered, permits to consider the consequent reduction of shear strength. The mechanical coupling of multiaxial stresses also increases the nonlinear effects.

The one-directional wave propagation modeling using one-dimensional (1D) spatial discretization of the soil profile reduces modeling difficulties and computation time, guarantying a reliable geotechnical model, easy to characterize with limited geotechnical investigations.

The proposed 1D-3C propagation model that considers SSI effects allows estimating mutual influence of soil and structure on their response to seismic loading. The seismic response of soil profiles can be significantly different in the cases of free surface and presence of a structure. Preliminary results are shown in Santisi d'Avila and Lopez Caballero [18], using the 6 April 2009 Mw 6.3 L'Aquila earthquake as seismic loading.

In this research, the effects of SSI for different combinations of soil features, dynamic properties of structures and earthquake frequency content are investigated, using typical soil profiles and a synthetic signal. The three components of seismic motion are evaluated at the base of the 3D frame structure, taking into account soil nonlinearity, impedance contrast in a multilayered soil and soil-structure interaction.

A case study is developed in this paper, using geotechnical data of the Japanese K-Net database and records of the 11 March 2011 Mw 9 Tohoku earthquake. Ground motion time histories at the surface, profiles with depth of stress, strain and motion components, and stress-strain hysteresis loops at a fixed depth are estimated for the soil stratification. Principal frequencies of the frame structure are evaluated, as well as deformation during the time history.

2. 1-Directional 3-Component wave propagation model

The propagation of a 3C seismic wave into a multilayered soil column is modeled by using a finite element scheme and a nonlinear constitutive relation for soils. Along the horizontal direction, at a given depth, the soil is assumed to be a continuous, homogeneous and infinite medium. Shear and pressure waves propagate vertically (z-direction in Fig. 1). Soil stratification is discretized into a system of horizontal layers (parallel to the xy plane) using quadratic line elements with three nodes. The assumption of horizontal infinitely extended soil implies zero lateral strain and null strain variation in horizontal directions.

The horizontally layered soil profile is spatially discretized into n_e quadratic line elements in a finite element scheme and consequently into $n_g = 2n_e + 1$ nodes (Fig. 1). Each node has the three displacements in directions x, y and z as degrees of freedom. The cross-sectional area and soil properties are assumed constant in each element e.

The nonlinear mechanical behavior of soil demands time discretization of the process and linearization of the constitutive behavior within each time step. Accordingly, the incremental equilibrium equation in dynamic analysis, including compatibility conditions, 3D constitutive relation and boundary conditions, is expressed in the matrix form as

$$\mathbf{M}_g\,\Delta\ddot{\mathbf{D}}_g + \mathbf{C}_g\,\Delta\dot{\mathbf{D}}_g + \mathbf{K}_g\,\Delta\mathbf{D}_g = \Delta\mathbf{F}_g \tag{1}$$

where $\mathbf{D}_g$ is the assembled $3n_g$-dimensional vector of nodal displacements in the ground domain, $\dot{\mathbf{D}}_g$ and $\ddot{\mathbf{D}}_g$ are the velocity and acceleration vectors, respectively, i.e. the first and second time derivatives of the displacement vector. $\mathbf{M}_g$ and $\mathbf{K}_g$ are the assembled $(3n_g \times 3n_g)$-dimensional mass and stiffness matrix, respectively. The Finite Element Method, as applied in the present research, is completely described in the works of Batoz and Dhatt [19], Cook et al. [20] and Reddy [21]. The propagation model of 3C seismic waves is detailed in Santisi d'Avila et al. [14]. $\mathbf{C}_g$ and $\mathbf{F}_g$ in Eq. (1) are the assembled $(3n_g \times 3n_g)$-dimensional damping matrix and the $3n_g$-dimensional load vector, respectively, derived from the

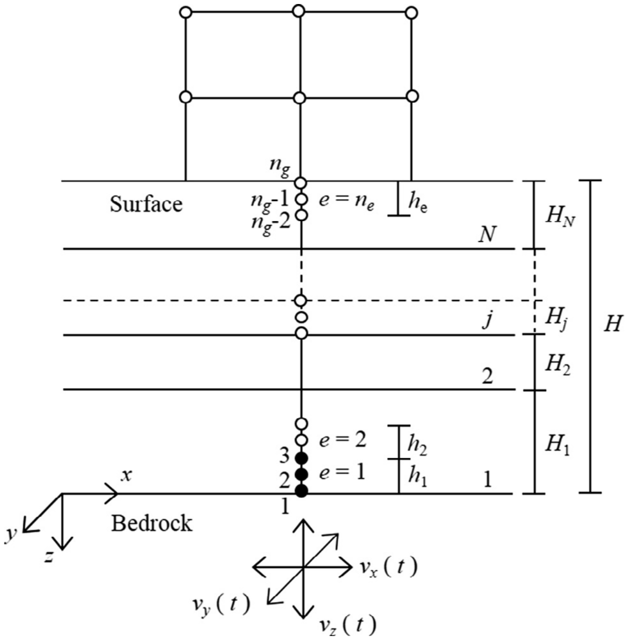

Fig. 1. Spatial discretization of a horizontally layered soil with a frame structure at the top and loaded by a three-component earthquake in terms of incident velocity.

Please cite this article in press as: Santisi d'Avila MP, Lopez-Caballero F. Analysis of nonlinear soil-structure interaction effects: 3D frame structure and 1-Directional propagation of a 3-Component seismic wave. Comput Struct (2018), https://doi.org/10.1016/j.compstruc.2018.02.002