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Research Paper

Dynamic soil-structure interaction: A three-dimensional numerical approach and its application to the Lotung case study

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ABSTRACT

This paper presents a three-dimensional non-linear finite element (FE) approach to analyse the dynamic soil-structure interaction (SSI) phenomena observed at the Lotung Large-Scale Seismic Test (LSST) site. The numerical study is carried out in the time domain by a commercial FE code, taking into account the non-linear behaviour of soil and the multi-directional nature of real seismic events. The soil response is simulated by an isotropic hardening elasto-plastic hysteretic model (HSsmall) implemented in the material model library of the code. This model allows to describe the non-linear cyclic response ranging from small to large strain amplitudes and to account for the variation of the initial stiffness with depth.

In the paper, the FE numerical approach is first validated through a series of parametric analyses simulating simplified cases (i.e. linear visco-elastic structures founded on a homogeneous linear visco-elastic soil deposit) for which analytical solutions exist. Then, it is adopted to back-analyse the behaviour of the 1/4-scale nuclear power plant containment structure constructed at the Lotung LSST site which was shook by several earthquakes of different intensities and frequency contents. The FE results are thus compared to the recorded in-situ free-field and structural motions, highlighting the satisfactory performance of the numerical model in replicating the observed response. The overall outcome of this research proves that nowadays complex dynamic SSI phenomena can be tackled by direct approach, overpassing the strong simplifications of the well-established substructure approaches.

1. Introduction

Most of the famous and devastating earthquakes, such as those occurred in Mexico (Mexico City, 1985), USA (Loma Prieta, 1989; Northridge, 1994) and Japan (Kobe, 1995), highlighted the important role played by soil-structure interaction phenomena on the dynamic response of surface structures [1]. It is thus well-recognised that the transient and permanent seismic-induced motion of structures is generally affected by the compliance of the soil-foundation system and it typically differs from that experienced by the same structure when supported by a rigid base (e.g. rock). The occurrence of a vibrating structure influencing the response of the soil and, at the same time, the ground motion affecting the response of the structure is referred to as dynamic Soil-Structure Interaction (SSI) [2,3].

The main consequence of SSI is the deviation of the motion at the base of the structure from that experienced by the soil at the same level under free-field conditions (i.e. in absence of structures). This difference is attributed to the simultaneous occurrence of two mechanisms dominating the SSI: the kinematic and the inertial interaction. The kinematic interaction, which is particularly relevant for embedded and piled foundations, arises because of the inability of a stiff foundation to follow the deformations that would occur in the soil, thus producing a deviation (usually a reduction) of the foundation motion from that of the ground under free-field conditions. The kinematic interaction induces an amplitude reduction of the translational component of motion at high frequencies and gives rise to rotational components [4–6]. The inertial interaction results from the development of inertial forces in the vibrating structure, associated to additional shear and bending excitation at the foundation level together with supplementary relative displacements between the foundation and the soil. This kind of interaction produces a variation of the dynamic properties of the structure-foundation system in terms of natural frequencies and associated damping ratio. In fact, the fundamental frequency of

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the system can be significantly decreased, depending on the relative stiffness of the structure and the soil, and the damping ratio is typically increased as a consequence of both wave radiation emanating from the foundation and soil dissipative capacity [6–12].

The role of SSI in the seismic response of structures founded on soft soil has traditionally been considered beneficial from a structural point of view, though in some cases it has been demonstrated to be detrimental, depending on the characteristics of seismic events [13,14].

In standard engineering practice, the evaluation of SSI effects is commonly performed adopting the so-called *substructure approach*, consisting in separately analysing the inertial and kinematic interaction mechanisms, often referring to analytical solutions available in the literature [4–9,11,15–20]. In this case the SSI analyses are typically carried out in the frequency domain, assuming a linear behaviour for both the structure and the soil.

In presence of strong earthquakes soil non-linearity should not be disregarded: at this scope, it is worth adopting a non-linear numerical approach in the time domain, by using the so-called *direct method*. This latter consists in modelling the entire soil-structure system in a single analysis [2]. Although a lot of scientific effort has been put in the development of sophisticated methodologies to account for seismic SSI phenomena, the numerical analyses are frequently conducted under two dimensional plane strain conditions, assuming an equivalent-linear approach to account for the dynamic non-linear soil behaviour [21–25]. Nevertheless, more accurate and realistic solutions would ideally require the use of a three-dimensional numerical model combined to truly non-linear constitutive laws [26–29].

The contribution of this paper goes along this latter direction: a 3D Finite Element (FE) approach is adopted to investigate the seismic ground response and the dynamic soil-structure interaction problem in a unique analysis, accounting for the non-linearity and possible heterogeneity of a realistic soil deposit. The numerical model is set up by adopting the FE code PLAXIS 3D [30]. The non-linear soil behaviour under wave propagation processes is accounted for by an isotropic hardening elasto-plastic hysteretic model for the soil, named Hardening soil model with small strain stiffness (HSsmall). This constitutive model accounts for the non-linear behaviour of soil in the small strain range, which is particularly relevant in the seismic wave propagation problems, by means of a para-elastic hysteretic scheme based on a modified version of the Masing's rules, which is coupled to a distortional isotropic hardening plasticity model. In detail, it allows to take into account the variation of the initial stiffness with depth and the soil non-linearity, to mimic the shear modulus and damping ratio reduction curves [31–33]. The predictive capability of the HSsmall constitutive model in geotechnical earthquake engineering applications has recently been investigated [34–37]. In [37] the para-elastic response of the model has been examined in detail and validated at the single element level for both standard and multi-directional simple shear conditions. Furthermore, the back-prediction of the free-field seismic ground response as observed in a well-documented case history has been carried out, under both single-directional and multi-directional loading conditions, demonstrating the capability of the constitutive model in simulating wave propagation processes. The proposed 3D numerical approach has then been adopted to perform some preliminary investigations on its predictive capability with reference to proper SSI cases (i.e. in presence of a surface structure), limiting the analyses solely to single-directional conditions, i.e. only applying a single horizontal component of the selected input motion [38].

The present paper is aimed at extending this research programme, in order to tackle realistic 3D multi-directional SSI problems. As a first step, a preliminary parametric study of SSI phenomena is conducted by modelling simple linear visco-elastic structures, represented by single-degree-of-freedom (SDOF) structural models, founded on a linear visco-elastic soil medium. This is aimed at verifying the effectiveness of the approach in reproducing well established analytical results proposed in the literature for such simplified conditions. In particular, the analytical solutions proposed by Veletsos and co-workers [9,10] for surface foundations are adopted to assess the capability of the numerical model in replicating SSI effects and to explore in detail the impact of the inertial interaction phenomenon.

In the following sections, a more complex 3D non-linear FE model is developed to back-analyse the behaviour of the 1/4-scale model of a nuclear power plant containment structure set up at the Large-Scale Seismic Test site (LSST) in Lotung. This site experienced many seismic events, providing high quality accelerometric data at different depths in the ground and on the model structure. In the following, reference will be made to the three earthquakes that shook the site in 1986, denoted as LSST7, LSST11 and LSST19.

A number of studies were conducted to investigate the free-field seismic ground response at Lotung site, highlighting the role of soil non-linearity and demonstrating the predictive capabilities of constitutive models and numerical codes [39–46]. Most of the soil-structure interaction analyses for that site were focused on the response of the structure as modelled by the substructure method, thus assuming an equivalent-linear approach to account for strain-dependent soil non-linearity [47–49]. With reference to the direct method approach, a 3D finite element approach was developed by Borja et al. [50] to study the effects of SSI on the ground motion recorded in the proximity of the containment structure, assuming for the soil behaviour an elasto-plastic constitutive model, but this did not include the structure itself in the numerical model.

In the present study the focus is on the dynamic response of both the structure and the soil deposit, as predicted by a unique model incorporating the containment structure and the soil. On site, the structural motion was monitored by accelerometers installed at the top and the bottom of the structure, while the free-field ground motion was recorded by a downhole array located sufficiently far away from the containment structure. The elasto-plastic hysteretic model HSsmall is here adopted to simulate the non-linear behaviour of soil, while a linear visco-elastic hypothesis is assumed for the structural model. The 3D numerical analyses are performed by simultaneously applying both horizontal components of each selected earthquake event as recorded by the accelerometer located at the larger depth along the instrumented downhole array.

2. Preliminary parametric SSI study

2.1. Analytical solution for inertial interaction

The inertial interaction mechanism is typically investigated by assimilating the structure to a simplified Single-Degree-Of-Freedom (SDOF) oscillator of height h and mass m_{str} supported by a rigid circular foundation resting on a homogeneous linearly elastic medium. In the analytical solutions proposed by Veletsos and co-workers [9,10] the soil compliance is represented by couples of springs and dashpots attached to the foundation element accounting for each mode of vibration (translational or rotational). Springs and dashpots are characterised by frequency-dependent dynamic impedance functions, expressed in the form:

$$k_j^* = k_j(a_0, \nu) + i\omega c_j(a_0, \nu) = K_j(\alpha_j + ia_0\beta_j) \quad (1)$$

where j denotes each mode of vibration, ω is the angular frequency of the input signal, a_0 is a dimensionless frequency parameter