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Higher mode seismic structure-soil-structure interaction between adjacent building during earthquakes

Felipe Vicencio[a,*], Nicholas A. Alexander[b]

[a] Department of Civil Engineering, University of Bristol, Queen's Building, Bristol, UK
[b] Senior Lecturer in Structural Engineering, Department of Civil Engineering, University of Bristol, Queen's Building, Bristol, UK

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ABSTRACT

This paper evaluates the effect of Structure-Soil-Structure Interaction (SSSI) between two buildings under seismic excitation given different parameters of the buildings, inter-building spacing, and soil type. An extended simplified reduced-order model, that enables higher mode interaction between structures, is proposed. This enables the exploration of the interaction between buildings with a very large difference in height. A database of strong ground motions records with Far-Field, Near-Field Without Pulse and Near-Field Pulse-Like characteristics are employed. Over 3 million system/ground motion cases are analysed in this extensive parametric study. The results suggest that the extended model captures significant interactions, in displacement responses, for the cases of a small building closely flanked by a much taller one.

1. Introduction

During an earthquake, civil structures interact with the surrounding soil beneath their foundations. These structures are typically analysed (dynamically) as singleton structures, i.e. without any consideration of their neighbouring structures. This phenomenon is widely known as Soil-Structure Interaction (SSI), and the importance of including its beneficial or adverse structural effects has been the focus of attention for more than 40 years. Nevertheless, the existence of a high density of buildings in large cities inevitably results in the possibility of seismic interaction of adjacent buildings through the underlying soil. This problem is better known as Structure-Soil-Structure Interaction (SSSI) and has received more attention in recent years. The pioneering works of Luco and Contesse [1], Kobori et al. [2], Lee and Wesley [3], Murakami and Luco [4], Wong and Trifunac [5], Lysmer et al. [6], and Roesset and Gonzales [7] have emphasized the complexity of the problem and have investigated the importance of considering the dynamic coupling between several structures. Some early experimental studies at real or small scaled conducted by Mattiesen and MacCalden [8], and Koroby et al. [9] have also captured the SSSI effects.

More recent investigations have been developed based on numerical two or three-dimensional Finite Element Method (FEM), Boundary Elements Method (BEM) or a combination of these two FEM/BEM procedures. For example, the works of Qian and Beskos [10], Betti [11], Karabalis and Huang [12], Karabalis and Mohammadi [13], Lehmann and Antes [14], Qian et al. [15], Bard et al. [16], Yahyai et al. [17], Padron et al. [18], Bolisetti and Whittaker [19], among others. These studies have identified key factors that control the seismic interaction behaviour such as: (i) the inter-building distance, (ii) the direction of the alignment between foundations, (iii) the relative height and dynamic characteristics of adjacent buildings, (iv) the aspect ratio (the building height to width ratio), and (v) the soil class.

Discrete soil/foundation-spring models have been successfully applied in the evaluation of SSSI problems, where Mulliken and Karabalis [20,21] calculated the interaction between adjacent two and three identical rigid surface foundations supported by a homogeneous half-space soil, and subjected to impulsive, moment, sinusoidal and random loads. Recently, Alexander et al. [22] proposed a set of rotational springs to model the interaction between adjacent closely spaced buildings. These models were validated using finite element analyses. Aldaikh et al. [23,28] and Knappett et al. [29] extended the validation of these proposed interaction-spring models with both physical shake table and centrifuge tests. Additionally, Aldaikh et al. [24] proposed an alternative closed-form analytical expression for these interaction springs based on a Boussinesq approximation of the surficial displacement fields. These alternative formulae where shown to be completely consistent with those initially proposed and validated in [22,23,28]. Vicencio and Alexander [25] extended these previous models further by permitting the soil to exhibit nonlinear hysteretic behaviour. Results indicate that SSSI effects can increase with soil nonlinearity.

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* Corresponding author.
E-mail address: fv16607@bristol.ac.uk (F. Vicencio).

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Nomenclature

$\alpha_1,\ \alpha_2$	ratio of foundation/soil to building masses of buildings 1 and 2 respectively []
β	ratio of soil/foundation radii of gyration for buildings 1 and 2 []
ε	height ratio of buildings 2 to 1 []
$\eta_1,\ \eta_2$	height to radius of gyration ratios for buildings 1 and 2 respectively []
$\theta_1,\ \theta_2$	rotation at base of buildings 1 and 2 respectively []
κ	interaction spring between buildings 1 and 2 [$\mathrm{ML^2\,T^{-2}}$]
λ	ratio of mass polar moments of inertia of soil-foundation of buildings 2 to 1 []
μ	Poison's ratio of soil []
ξ_n	critical damping of the system []
$\rho_b,\ \rho_s$	average densities of building and soil respectively [$\mathrm{M\,L^{-3}}$]
τ	scaled time []
ϕ_n	modal eigenvector of the system []
χ_{ii}	percentage change in total displacement power when moving from uncoupled to coupled state [%]
$\ddot{\chi}_{ii}$	percentage change in total acceleration power, moving from uncoupled to coupled state [%]
ω_{rb1}	modal circular frequency on rock of building 1 [$\mathrm{rad\,T^{-1}}$]
ω_{b1}	frequency parameter of building 1 [$\mathrm{rad\,T^{-1}}$]
ω_{b2}	frequency parameter of building 2 [$\mathrm{rad\,T^{-1}}$]
ω_{s1}	freq. parameter of soil/foundation building 1 [$\mathrm{rad\,T^{-1}}$]
ω_{s2}	freq. parameter of soil/foundation building 2 [$\mathrm{rad\,T^{-1}}$]
ω	Fourier frequency [$\mathrm{rad\,T^{-1}}$]
ω_n	natural frequencies of the systems [$\mathrm{rad\,T^{-1}}$]
ϖ	interaction frequency ratio parameter [$\mathrm{rad\,T^{-1}}$]
Ω_0	ratio of interaction to building 1 frequency parameter []
Ω_2	ratio of building 1 (soil/foundation) to building 1 frequency parameter []
Ω_3	ratio of building 2 to building 1 circular frequencies []
Ω_4	ratio of building 2 (soil/foundation) to building 1 circular frequencies []
$A_1,\ A_2$	total non-dimensional acceleration of building 1 []
$A_3,\ A_4$	total non-dimensional acceleration of building 2 []
b	foundation width []
$\mathbf{C}$	non-dimensional damping matrix []
$\hat{\mathbf{C}}$	dimensional damping matrix [$\mathrm{MT^{-1}}$]
c_1	density ratio (soil/buildings) parametric constant []
c_2	frequency ratio parametric constant []
E_s	total power spectral density []
$h_1,\ h_2$	total heights of building 1 and 2 respectively [L]
$\mathbf{K}$	non-dimensional stiffness matrix []
$\hat{\mathbf{K}}$	dimensional stiffness matrix [$\mathrm{MT^{-2}}$]
k_s	soil/foundation rotational spring in absence of building interaction [$\mathrm{ML^2\,T^{-2}}$]
$k_{b1},\ k_{b2}$	lateral stiffnesses of building 1 and 2 resp. [$\mathrm{MT^{-2}}$]
$k_{s1},\ k_{s2}$	rotational soil stiffnesses of soil beneath building 1 and 2 respectively [$\mathrm{ML^2\,T^{-2}}$]
$\mathbf{M}$	non-dimensional mass matrix []
$\hat{\mathbf{M}}$	dimensional mass matrix [M]
M_w	moment magnitude scale
$m_{b1},\ m_{b2}$	total masses of building 1 and 2 respectively [M]
$m_{s1},\ m_{s2}$	soil/foundation masses underneath building 1 and 2 respectively [M]
	non-dimensional force vector []
$\hat{\mathbf{p}}$	dimensional force vector [$\mathrm{ML\,T^{-2}}$]
$r_1,\ r_2$	soil/foundation masses radius of gyration of building 1 and 2 respectively [L]
s	aspect ratio of building 1 []
T_E	system kinematic energy [$\mathrm{ML^2T^{-2}}$]
t	time [T]
$U_1,\ U_2$	total non-dimensional relative displacement to ground of building 1 []
$U_3,\ U_4$	total non-dimensional relative displacement to ground of building 2 []
U_E	system potential energy [$\mathrm{ML^2\,T^{-2}}$]
$U_i(\omega)$	Fourier transform of $U_i(\tau)$
$u_1,\ u_2$	non-dimensional relative displacement to ground of building 1 []
$u_3,\ u_4$	non-dimensional relative displacement to ground of building 2 []
u_g	non-dimensional horizontal ground displacement time series []
$\ddot{u}_g$	non-dimensional acceleration ground motion []
$\mathbf{u}$	non-dimensional degree of freedoms vector []
V_s	shear wave velocity of soil [$\mathrm{L\,T^{-1}}$]
$\overline{V}_s$	normalised non-dimensional shear wave velocity of soil []
$\mathbf{v}_{b1}(\omega)$	displacement transfer function for building 1
$\mathbf{v}_{b2}(\omega)$	displacement transfer function for building 2
$\ddot{\mathbf{v}}_{b1}(\omega)$	acceleration transfer function for building 1
$\ddot{\mathbf{v}}_{b2}(\omega)$	acceleration transfer function for building 2
$x_1,\ x_2$	relative displacement to ground (in a rotating coordi-nate frame) of building 1 [L]
$x_3,\ x_4$	relative displacement to ground (in a rotating coordi-nate frame) of building 2 [L]
x_g	horizontal ground displacement time series [L]
$\ddot{x}_g$	horizontal acceleration ground motion [$\mathrm{L\,T^{-2}}$]
$\mathbf{x}$	dimensional degree of freedoms vector []
z	non-dimensional inter-building distance []

Hans et al. [26] and Li et al. [27] have conducted some experimental in situ investigation, at real or small scales, which used a series of shaking table test to study the effects of SSSI on the response of buildings. Trombetta et al. [30,31] and Mason et al. [32] have investigated the SSSI effects using physical models in centrifuge tests. Kitada et al. [33] and Yano et al. [34] studied the SSSI problem for nuclear plants in the field and developed laboratory tests.

Experimental tests of specific cases are essential as validation points. However, we should be under no illusions; these experiments are challenging to undertake. This is because of the problems of scaling. Results represent a statistically small sample, and inevitably they provide only a limited parametric exploration of the generalised problem. Some would advocate that advanced computational models (FEA) that are the obvious choice for exploring these problems. However, it is very difficult to characterise both structures and soil in a general and generic sense for a whole class of building configurations. Thus, large-scale parametric exploration of this problem is difficult to achieve with these approaches. In some sense, the burden of information required (in terms of ground motion, building geometry and material parameters) for the specification of advanced computational models can obscure insights into the problem as there are too many system parameters to explore. Therefore, an alternative approach are parametric studies using reduced order models with a relatively limited number of degrees of freedom. These reduced-order models (i) capture the most significant dynamic behaviour (ii) have a relatively small number of system parameters and (iii) are computationally simple enough for exploring a huge number of generic cases. These parametric studies should be viewed as an initial exploration of the problem. They are not meant to replace advanced computational models and experimental work of specific cases.

In this paper, over 3.1 million of different time-histories cases are explored using the BlueCrystal, the High-Performance Computing (HPC) machine belonging to the Advance computing research centre at the University of Bristol.