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# Dynamic interaction between adjacent buildings through nonlinear soil during earthquakes

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## ABSTRACT

This paper evaluates the effect of Structure-Soil-Structure Interaction (SSSI) between two buildings given different parameters of the buildings, inter-building spacing, and soil type. A two-dimensional simple discrete nonlinear model is proposed that is described by a set of nonlinear differential equations of motion. A nonlinear phenomenological Bouc-Wen model, for the soil directly underneath the foundations, linear rotational interaction spring between buildings and linear behaviour of buildings are assumed. The seismic ground motion employed is spectrally matched with EC8 elastic spectra. The results showed that there are both unfavourable and beneficial configurations of the two buildings that produce important differences between nonlinear SSSI and nonlinear SSI (the uncoupled building case). Importantly it is demonstrated that the adverse effects of SSSI can be more pronounced when the nonlinear soil behaviour is assumed.

## 1. Introduction

Conventionally, buildings in urban areas are designed by considering the response of structures in isolation. However, the high density of buildings in cities inevitably results in the possibility of seismic interaction of adjacent buildings through the underlying soil. This phenomenon is widely known as structure-soil-structure interaction (SSSI) and has been reported in the pioneering works of Luco and Contesse [1], Kobori et al. [2], Lee and Wesley [3], Mattiesen and MacCalden [4], Wong and Trifunac [5], Lysmer et al. [6] and Roesset and Gonzales [7].

The importance of including the beneficial/adverse structural effects of the dynamic interaction between several structures has received sustained attention in recent years. Kitada et al. [8], Yano et al. [9], Hans et al. [10], Li et al. [11] are experimental in situ studies. Aldaikh et al. [12] performed a series of scale model shaking table test to study the effect of SSSI on the response of building with two or three adjacent buildings. Numerical studies based on finite element method (FEM), boundary elements method (BEM) or a combination of these two FEM/BEM procedures with Bard et al. [13], Yahyai et al. [14], Padron et al. [15], Bolisetti and Whittaker [16], Alexander et al. [17], Aldaikh et al. [18], Chouw and Schmid [47] and Ogut and Fukuwa [48].

These studies have highlighted the importance of considering the dynamic coupling between several structures, including the identification of key factors that may control the seismic behaviour and the amount of structural interactions 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 between height to width of buildings and (v) the general soil class.

The interchange of energy between the soil and the structure during nonlinear dynamical responses is an important issue in earthquake engineering. Although the equivalent linear type of analysis is the most popular, they have some well-known limitations for the case of large magnitude earthquake excitation. Several researchers [19–22] have extensively investigated soil-structure interaction (SSI) by explicitly considering the soil-foundation model through a nonlinear macro-element. However, this analysis does not consider the interaction of adjacent buildings via the underlying soil during an earthquake.

Experimental tests of specific building/foundation configurations, Trombetta et al. [50–52] and Mason et al. [53], model the nonlinear behaviour of soil and structure. These represent important validation points for numerical models. However, these experiments are technically challenging. This is because of the problem of scaling soil strains and inertial forces accurately. Additionally, they represent statistically, a small sample and hence provide only a limited parametric exploration of the problem. Some researcher's advocate using advanced computational models (FEA). Ghandil et al. [54] evaluate the SSSI in three different buildings, considering elasto-plastic frame hinges in the structure and two soils profile with a reduction of the soil shear modulus in areas close to the foundation. Bolisetti and Whittaker [55] study the SSSI in a nonlinear model developed in the time-domain code LS-DYNA. Specific cases can be modelled using this method. However,

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## Nomenclature

| | |
|---|---|
| $\alpha_1$, $\alpha_2$ | ratio of foundation/soil to building masses of buildings 1 and 2 respectively [] |
| $\beta$ | ratio of soil/foundation radii of gyration for buildings 1 and 2 respectively [] |
| $\varsigma_1$, $\varsigma_2$ | parameter describing shape and amplitude of hysteresis buildings 1 and 2 respectively [] |
| $\psi_1$, $\psi_2$ | parameter describing shape and amplitude of hysteresis buildings 1 and 2 respectively [] |
| $\gamma_y$ | strain at initiation of nonlinear soil behaviour [] |
| $\delta_\eta$ | Stiffness degradation factor [] |
| $\delta_\nu$ | Strength degradation factor [] |
| $\varepsilon$ | height ratio of buildings 2 to 1 [] |
| $\eta_1$, $\eta_2$ | height to radius of gyration ratios for buildings 1 and 2 respectively [] |
| $\eta(E)$ | damping correction factor of the elastic spectrum [] |
| $\eta_s$ | damping correction factor of the elastic spectrum [] |
| $\theta_1$, $\theta_2$ | rotation at base of buildings 1 and 2 respectively [] |
| $\kappa$ | rotational interaction spring between buildings 1 and 2 [$\mathrm{ML^2\,T^{-2}}$] |
| $\lambda$ | ratio of mass polar moments of inertia of soil-foundation of buildings 1 and 2 respectively [] |
| $\mu$ | Poison's ratio of soil [] |
| $\nu(E)$ | ratio of critical damping of soil beneath buildings [] |
| $\xi_n$ | ratio of critical damping of soil beneath buildings [] |
| $\rho_b$, $\rho_s$ | densities (average) of building and soil respectively [$\mathrm{ML^{-3}}$] |
| $\tau$ | scaled time [] |
| $\boldsymbol{\phi}_n$ | modal eigenvector of the linear system [] |
| $\chi_{ii}$ | percentage change in total displacement power when moving from uncoupled to coupled state for building i |
| $\ddot{\chi}_{ii}$ | percentage change in total acceleration power, moving from uncoupled to coupled state for building i [%] |
| $\omega_1$, $\omega_3$ | modal circular frequency on rock of buildings 1 and 2 respectively [rad $\mathrm{T^{-1}}$] |
| $\omega_2$, $\omega_4$ | circular frequency of soil/foundation of buildings 1 and 2 respectively [rad $\mathrm{T^{-1}}$] |
| $\omega$ | Fourier frequency [rad $\mathrm{T^{-1}}$] |
| $\omega_n$ | natural frequencies of the linear systems [rad $\mathrm{T^{-1}}$] |
| $\varpi$ | interaction circular frequency ratio parameter [rad $\mathrm{T^{-1}}$] |
| $\Omega_0$ | ratio of interaction to building 1 (on rock) circular frequencies [] |
| $\Omega_2$ | ratio of building 1 (soil/foundation) to building 1 (on rock) circular frequencies [] |
| $\Omega_3$ | ratio of building 2 (on rock) to building 1 (on rock) circular frequencies [] |
| $\Omega_4$ | ratio of building 2 (soil/foundation) to building 1 (on rock) circular frequencies [] |
| $A_1$, $A_2$ | total non-dimensional acceleration of building 1 and 2 respectively [] |
| $a_g$ | peak ground acceleration of the elastic response spectrum [$\mathrm{MT^{-2}}$] |
| $a_{gr}$ | peak ground acceleration of the ground motion [$\mathrm{MT^{-2}}$] |
| $\mathrm{B}_1$, $\mathrm{B}_2$ | ratio of linear to nonlinear response of buildings 1 and 2 respectively [] |
| $b$ | foundation width [] |
| $\boldsymbol{C}$ | non-dimensional damping matrix [] |
| $c_1$ | density ratio (soil/buildings) parametric constant [] |
| $c_2$ | frequency ratio parametric constant [] |
| $D_1$, $D_2$ | parameter describing shape and amplitude of hysteresis buildings 1 and 2 respectively [] |
| $E(\tau)$ | dissipated hysteretic energy [] |
| $E_s$ | total power spectral density [] |
| $\mathbf{f}$ | non-dimensional force vector [] |
| $G_s$ | initial tangent shear modulus of the soil [$\mathrm{M\,L^{-1}\,T^{-2}}$] |
| $h_1$, $h_2$ | heights of building 1 and 2 respectively [L] |
| $\boldsymbol{K}$ | non-dimensional stiffness matrix [] |
| $k_{b1}$, $k_{b2}$ | lateral modal stiffnesses of building 1 and 2 respectively [$\mathrm{MT^{-2}}$] |
| $k_{s1}$, $k_{s2}$ | rotational soil stiffnesses of soil beneath building 1 and 2 respectively [$\mathrm{ML^2\,T^{-2}}$] |
| $\boldsymbol{M}$ | non-dimensional mass matrix [] |
| $M_1$, $M_2$ | nonlinear moment due to the rotation and hysteretic rotation of buildings 1 and 2 respectively [$\mathrm{ML^2\,T^{-2}}$] |
| $M_s$ | surface wave magnitude scale |
| $M_w$ | moment magnitude scale |
| $m_{b1}$, $m_{b2}$ | modal masses of building 1 and 2 respectively [M] |
| $m_{s1}$, $m_{s2}$ | soil/foundation masses underneath building 1 and 2 respectively [M] |
| $n_1$, $n_2$ | parameter describing shape and amplitude of hysteresis buildings 1 and 2 respectively [] |
| $Q_{ii}(\omega)$ | power spectral density of total displacement of building i [] |
| $\ddot{Q}_{ii}(\omega)$ | power spectral density of total acceleration of building i [] |
| $q_1$, $q_2$ | non-dimensional nonlinear function of soil [] |
| $\boldsymbol{q}$ | non-dimensional nonlinear moment/rotation vector [] |
| $r_1$, $r_2$ | soil/foundation masses radius of gyration of building 1 and 2 respectively [L] |
| $S_a$ | horizontal elastic response spectra [$\mathrm{MT^{-2}}$] |
| $s$ | aspect ratio – height to width of building 1 [] |
| $T_E$ | system kinematic energy [$\mathrm{ML^2\,T^{-2}}$] |
| $T_B$, $T_c$, $T_D$ | parameters that depends of the soil type, according to the elastic response spectra [] |
| $t$ | time [T] |
| $U_1$, $U_2$ | total non-dimensional relative displacement to ground of building 1 and 2 respectively [] |
| $U_E$ | system potential energy [$\mathrm{ML^2\,T^{-2}}$] |
| $u_1$, $u_2$ | non-dimensional relative displacement to ground of building 1 and 2 respectively [] |
| $u_g$ | non-dimensional horizontal ground displacement time series [] |
| $\boldsymbol{u}$ | non-dimensional degree of freedoms vector [] |
| $V_s$ | shear wave velocity of soil [$\mathrm{LT^{-1}}$] |
| $\overline{V}_s$ | Normalised non-dimensional shear wave velocity of soil [] |
| $x_1$, $x_2$ | relative displacement to ground (in a rotating coordi-nate frame) of building 1 and 2 respectively [L] |
| $x_g$ | horizontal ground displacement time series [L] |
| $y_1$, $y_2$ | internal hysteretic rotations of buildings 1 and 2 respectively [] |
| $z$ | non-dimensional inter-building distance [] |

modelling a whole class of building configurations, in a large-scale parametric study, is very difficult in general. Thus, a large-scale parametric exploration of this problem requires a different method. The alternative is to use system models, with a relatively limited number of degrees of freedom, for a parametric study. These low-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. This parametric studies should be viewed an initial exploration of the problem. They are not meant to replace advanced computational models and experimental work of specific cases.