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Two dimensional numerical and experimental models for the study of structure–soil–structure interaction involving three buildings

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ABSTRACT

This paper explores the adverse and beneficial effects of structure–soil–structure interaction (SSSI) under seismic excitation on a group of three buildings. A simple discrete formulation of the problem is employed that uses rotational interaction springs between buildings. A physical experimental shake-table test program is used to qualitatively validate the discrete theoretical model. Subsequently, a numerical study is performed which demonstrates that the central building in a three building case can act as a tuned mass damper for its adjacent buildings. Results indicated that this adverse effect can be more pronounced than the case where there are just two buildings interacting.

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1. Introduction

While it is common practice to determine the seismic response of structures in isolation, the existence of a high density of buildings in cities and urban areas inevitably results in the possibility of interaction and dynamic coupling of adjacent buildings via the underlying soil. This phenomena is better known as Structure–Soil–Structure Interaction (SSSI), Luco and Contesse [1] but it can also be referred to as Dynamic Cross Interaction (DCI), Kobori et al. [2] or as Through Soil Coupling (TSC), Lee and Wesley [3]. As with the single soil–structure interaction problem, the main question is in what situations the dynamic SSSI effects could be favourable or detrimental for the individual elements of the system? Should the seismic design of a single building integrate the presence of adjacent buildings? How does a new construction modify the dynamics of the existing neighbouring structures?

Based on a discrete theoretical formulation and a physical small-scale experimental model, this paper explores the SSSI issues for the case of a generic dynamic structural system composed of three buildings.

1.1. Brief review of previous work

The study of the dynamic interaction between several structures with consideration of coupling effects through the underlying or surrounding soil has received sustained attention in recent years, Lou et al. [4]. Pioneering work of Luco and Contesse [1], Kobori et al. [2], Lee and Wesley [3], Wong and Trifunac [5] and more recent investigations of Bard et al. [6], Yahyai et al. [7], Padron et al. [8], Bolisetti and Whittaker [9], Alexander et al. [10] and Aldaikh et al. [11] have emphasized the scale of the problem and its importance for consideration in the dynamic analyses, including the identification of key factors that may control the degree of multi-structural interactions like, for example: relative inertial and dynamic characteristics of adjacent buildings, separation building distances, soil type and the configuration of buildings plan arrangements.

Discrete modelling analyses have been long applied to single static and dynamic soil–structure systems. In these approaches, the dynamic properties of the discrete elements are taken either to be excitation frequency independent, Barkan [12], Lysmer and Richart [13], Gazetas [14], Wolf and Meek [15] and Wolf [16] or frequency dependent as in Wolf and Song [17]. While Mulliken and Karabalis [18,19] showed that the former approach can equally be successfully applied in the evaluation of SSSI problem, recent work of Alexander et al. [10] demonstrated the usefulness of these kind of qualitative approaches in analyses of the influence of key SSSI controlling factors. The analysis of much more realistic dynamic boundary value systems has also been conducted based on analytical methods (Lee and Wesley [3], Triantafyllidis and Prange [20,21]), numerical two or three-dimensional finite element method (FEM), Lysmer et al.[22], Roesset and Gonzalez [23], boundary element method (BEM), Qian and Beskos [24], Betti [25] and Lehmann and Antes [26], or hybrid FEM/BEM procedures,

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Qian et al. [27], Lin et al. [28], Wang and Schmid [29]. Some early experimental studies at real or small scales, as the one conducted by Mattiesen and MacCalden [30] and Kobori et al. [31], have also succeeded in capture the SSSI effects. Shohara et al. [32] calibrated a shaking table model test results (for the dynamic interaction between two identical adjacent foundations) with 2D finite element and 3D boundary element models. While Shimomura et al. [33] conducted forced vibration field tests and Kitada et al. [34], Kitada and Iguchi [35] and Yano et al. [36,37] studied the SSSI problem for nuclear power plants in situ and in laboratory tests. More recent experimental studies by, Trombetta et al. [38,39] and Mason et al. [40], have investigated the SSSI effects through the use of physical models in centrifuge tests. Li et al. [41] conducted shaking table model tests on the interaction of two identical adjacent 12 storey cast-in-place reinforced concrete frames resting on 3 by 3 group piles.

1.2. Aims

In this study, we extend a previous work on the SSSI of two buildings, Alexander et al. [10] to the case of three buildings. Additionally we shall now employ real ground motion rather than a Kanai–Tajimi artificial ground motion. The previous paper highlighted the possibility of a smaller adjacent building acting as a beneficial tuned mass damper for a taller building. In this case there was a reduced seismic risk to the taller building and an increase seismic risk to the smaller one. In this study we explore the case of a central building that is surrounded to the left and to the right by buildings. We parametrically explore what configuration of adjacent buildings produces the lowest and highest seismic risk for the central building. As a validation of the theoretical/numerical model we also investigate a small-scale parametric experimental model of the three building SSSI problem. The small-scale experimental model was subjected to a number of different real ground motions and long duration white noise. The model testing was conducted using the shake-table facility at the Earthquake Engineering Research Centre (EERC) of the University of Bristol, UK.

2. A theoretical model for SSSI

2.1. Assumptions

The proposed theoretical formulation is restricted to the following arguments:

1. Soil and structures are assumed to behave linearly and elastically.
2. Only the horizontal translation of the buildings and foundation/soil mass rotation (rocking about out of plane axis) are considered.
3. Foundation design including embedment is not directly considered. Foundations are considered simple rigid plates on rotational springs.
4. Time-delayed ground excitation as in [19,42,43] and thus wave passage effects and spatially heterogeneous ground displacements, [44,45], are not taken into account.
5. Buildings are separated sufficiently so that inter-building pounding (see [46,47]) is not permitted.

2.2. Derivation of the equations of motion for discrete system

Dimensions of all symbols used are stated in unit mass {M}, length {L}, time {T} and dimensionless {}. A three buildings system is shown in Fig. 1, buildings are coupled with a rotational interaction spring. Each building-soil system is a two degree of freedom system with one rotational degree of freedom at the foundation level (θ_1, θ_2 and θ_3 {}) and one translational degree of freedom (x_1, x_2 and x_3 {L}). The translational dofs are relative to the ground translation x_g {L}. All dofs are non-dimensionalised follows: $x_1 = u_1 r_1, x_2 = u_3 r_2, x_3 = u_5 r_3, x_g = u_g r_1$ and $\theta_1 = u_2,\ \theta_2 = u_4$ and $\theta_3 = u_6$. The soil/foundation mass radii of gyration r_i {L} are used to non-dimensionalise the translation degrees of freedom x_i; thus $\forall u_i$ are dimensionless. Employing Lagrangian energy mechanics [48], the equation of motion describing the dynamics of the discretised system is formulated. The kinetic energy T {ML^2 T^{-2}} and potential energy U {ML^2 T^{-2}} of this system are written as (1) and (2) respectively. The total kinetic energy can be stated as the sum of two terms (i) the translational kinetic energy (due to sway and foundation rotation) of each building's mass and (ii) the rotational kinetic energies of each foundation/soil mass. The potential energy is the sum of three terms, (i) the internal work due to building deformations, (ii) the work done due to rotation of the foundation springs underneath the buildings, and (iii) the work done due to the differential rotation between buildings.

$$T = \frac{1}{2}\sum_{j=1}^{3}\left\{ m_{2j-1}\left(r_j\dot{u}_{2j-1} + r_j\dot{u}_g - h_j\dot{u}_{2j}\right)^2 + m_{2j}\left(r_j\dot{u}_{2j}\right)^2\right\} \tag{1}$$

$$U = \frac{1}{2}\sum_{j=1}^{3}\left\{ k_{2j-1}\left(r_j u_{2j-1}\right)^2 + k_{2j}\left(u_{2j}\right)^2\right\} + \frac{1}{2}\sum_{j=1}^{2}\kappa\left(u_{2j} - u_{2j+2}\right)^2 \tag{2}$$

where m_j {M} is the modal masses of building j, h_j {L} is the effective height of building j, k_{2j-1} {M T^{-2}} is the modal stiffness of building j, k_{2j} {ML^2 T^{-2}} is the rotational spring stiffness of the soil beneath building j and κ {ML^2 T^{-2}} is the rotational interaction spring between buildings 1–2 and 2–3. The dynamic behaviour of these buildings (on a rigid base) are more accurately characterised by some MDOF system. In this paper we approximated the buildings by a single generalised coordinate that can be viewed as a modal amplitude of this MDOF system. Thus, the terms 'modal mass' and 'modal stiffness' used in this paper refer to a mode (typically the fundamental mode) of this characteristic MDOF system. $m_2 r_1^2, m_4 r_2^2$ and $m_6 r_3^2$ are foundation/soil modal mass polar moments of inertia underneath each building. We introduce the following non-dimensional parameters,

$$\eta_1 = \frac{h_1}{r_1}, \quad \eta_2 = \frac{h_2}{r_2}, \quad \eta_3 = \frac{h_3}{r_3}, \quad \lambda_1 = \frac{m_1 r_1^2}{m_3 r_2^2},$$
$$\lambda_2 = \frac{m_5 r_3^2}{m_3 r_2^2}, \quad \beta_1 = \frac{r_1}{r_2}, \quad \beta_2 = \frac{r_2}{r_3} \tag{3}$$

where η_j {} are the ratios of height to soil/foundation radius of gyration of building j, $\lambda_1,\ \lambda_2$ {} are the ratios of mass polar moments of inertia of soil/foundation 1–2 and 3–2 respectively. β_1, β_2 {} are the ratios of soil/foundation radii of gyration for building 1–2 and 3–2 respectively. So, we have chosen to use the central building characteristics to non-dimensionalise some of the system parameters. Mass ratios α_j {} are the building to foundation/soil mass ratios for building j, hence,

$$\alpha_1 = \frac{m_2}{m_1}, \quad \alpha_2 = \frac{m_4}{m_3}, \quad \alpha_3 = \frac{m_6}{m_5} \tag{4}$$

Frequency parameters (where ω_{2j-1} {T^{-1}} is the circular natural frequency of building j on a rigid foundation, ω_{2j} {T^{-1}} is the circular natural frequency of foundation/soil system without the building's presence, and ω_θ {T^{-1}} is the interaction modal frequency parameter hence,

$$\omega_1^2 = \frac{k_1}{m_1}, \quad \omega_2^2 = \frac{k_2}{m_2 r_1^2}, \quad \omega_3^2 = \frac{k_3}{m_3}, \quad \omega_4^2 = \frac{k_4}{m_4 r_2^2},$$
$$\omega_5^2 = \frac{k_5}{m_5}, \quad \omega_6^2 = \frac{k_6}{m_6 r_3^2}, \quad \omega_\theta^2 = \frac{\kappa}{m_3 r_2^2} \tag{5}$$

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