Lecture Notes in Civil Engineering

Erick I. Saavedra Flores
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Recent Advances on the Mechanical Behaviour of Materials

Computational Modelling, Theory, and Experiments

Springer

Lecture Notes in Civil Engineering

Volume 462

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ISSN 2366-2557 ISSN 2366-2565 (electronic)
Lecture Notes in Civil Engineering
ISBN 978-3-031-53374-7 ISBN 978-3-031-53375-4 (eBook)
https://doi.org/10.1007/978-3-031-53375-4

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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Preface

Since the establishment of the essential foundations of the mechanics of solid materials during the nineteenth century, significant progress has been achieved in order to describe successfully the complex mechanical response of materials. These remarkable advances have been possible thanks to the efforts coming not only from theoretical research studies but also from extensive experimental campaigns. Furthermore, with the advent of modern computational technologies over the last few decades, the subject of mechanics of materials has become a mature field of investigation, bringing continuous progress and socio-economic development to our societies.

In view of the increasing interest in mechanics of materials, several conferences and symposia have been organised in the past. One of the most renowned scientific gatherings about this subject is the International Conference on the Mechanical Behaviour of Materials (ICM), an international scientific event held every four years to bring together talented researchers from different fields of engineering, science and industry. The objectives of the ICM conferences are to foster research on the mechanical behaviour of materials, to promote related international cooperation among scientists and engineers and to provide means for the public dissemination of the results from these efforts. The ICM conferences are intended to cover progress on all aspects of the mechanical behaviour of materials from both the macroscopic and microscopic viewpoints.

Following a long standing tradition since August 1971, when the 1st ICM conference was held in Kyoto, Japan, the 14th version of ICM (ICM-14) took place for the first time in Latin America, in the city of Santiago, capital of Chile, on 12–14 July 2023. In this opportunity, the ICM-14 conference was organised by the Department of Civil Engineering from the University of Santiago, Chile.

Previous to the conference, potential authors were invited to submit their full length papers for possible publication in the book of the ICM-14 conference proceedings titled *Recent Advances on the Mechanical Behaviour of Materials—Computational Modelling, Theory, and Experiments*. After a critical appraisal and careful selection of articles, the book was completed, representing in many regards the current state of the art on mechanics of materials. The present book is divided into two parts as follows.

– *Computational Modelling and Theoretical Aspects.*

In the first part of the book, research papers dealing with numerical simulations and mathematical modelling are presented. Particular emphasis is given to the description of real-world engineering problems that consider the investigation of complex materials and structures. This collection presents recent findings with the aid of a wide range of analytical and numerical methods, from advanced mathematical procedures to modern computational prediction techniques.

– *Experimental Testing Procedures.*

The second part of the book is focused on contributions that investigate classical and modern materials by means of advanced experimental mechanics and novel structural testing procedures. Special attention is devoted to experimental studies that report data coming from macroscopic and microscopic length scales.

This book is intended to meet the needs of a diverse range of researchers and postgraduate students interested in particular problems related to the mechanical behaviour of materials. Engineers, applied mathematicians and physicists, among others, will find in this collection of papers practical guidelines for performing computational simulations and a valuable source of experimental data.

I would like to express my gratitude to the Civil Engineering Department and the Faculty of Engineering from the University of Santiago, Chile, to all my colleagues, staff members and students, who participated in the organisation of this event, and to Prof. Raj Das from RMIT University, Australia, president of ICM-14, for his continuous advice and support. All of them helped to make this conference successful. Without this support, this scientific gathering would not have been possible. Finally, I would like to give thanks for the efforts made by all of the researchers and scholars who attended and presented at the ICM-14 conference, and particularly those authors who submitted their full length papers for possible publication in this book.

October 2023

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Computational Modelling and Theoretical Aspects

Seismic Structure-Soil-Structure Interaction Between a Pair of Cross-Laminated Timber Buildings Under Seismic Loads

Felipe Vicencio, Sebastián Torres-Olivares, and Erick I. Saavedra Flores

Abstract Frequently, buildings in urban areas are designed by considering the response of structures as stand-alone i.e., a single structure, with no neighbouring structures. Nevertheless, the existence of a high density of buildings in large metropolitan areas inevitably results in the likelihood of seismic interaction of adjacent buildings through the underlying soil. This problem is better known as Structure-Soil-Structure Interaction (SSSI), and this interaction can either increase or decrease the seismic response of a structure, and its relevance was highlighted in early studies (Lee and Wesley in Nucl Eng Des 24:374–387, [1]; Kobori et al. Dynamical cross-interaction between two foundation, [2]; Wong and Luco in Soil Dyn Earthq Eng 5:149–158, [3]; Triantafyllidis and Prange in Soil Dyn Earthq Eng 7:40–52, [4]). In this research, we explore the influence of Structure-Soil-Structure Interaction (SSSI) between a pair of cross-laminated timber (CLT) buildings under seismic excitation. A complete 3-dimensional high-order model of the soil and buildings is performed. The finite element method is used for the numerical simulations in ANSYS. The interaction effects are investigated for different heights of the buildings and soil properties. Results suggest that the SSSI can affect displacement, inter-story drift and accelerations. The impact of the SSSI effects is more relevant for loose soil.

Keywords Structure-soil-structure interaction · Cross-laminated timber buildings · Time history seismic analysis

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E. I. Saavedra Flores et al. (eds.), *Recent Advances on the Mechanical Behaviour of Materials*, Lecture Notes in Civil Engineering 462,
https://doi.org/10.1007/978-3-031-53375-4_1

1 Introduction

The importance of including the adverse structural effects of the structure-soil-structure interaction has received attention in the last decades. Due to the complexity of the multi-structural interaction problem, one of the most used methods are (i) the Boundary Element Method (BEM) [5, 6], (ii) two or three-dimensional Finite Element Modelling (FEM) [7–9], and (iii) a combination of these two FEM/BEM techniques [10–12]. These studies have characterized the important factors that may control the intensity of coupled effects between buildings, such as (i) the separation of building distance, (ii) the relative height and dynamic characteristics of the adjacent buildings, and (iii) the soil class. These approaches, which use commercial design software, allow for the possibility of modelling both complex geometries and, in some cases, nonlinearities for specific structural forms. However, these results almost inevitably end in a very large number of degrees of freedom, producing computationally costly and time-consuming analyses.

Discrete soil/foundation-spring models have been successfully applied in the evaluation of SSSI problems [13–17]. In these mechanical models, a small number of lumped masses, dashpots, and springs are employed. The coupled effects between buildings through the soil were incorporated into the solution using different springs [18–20]. All these previous studies give a theoretical framework for the analysis of SSSI with an efficient and straightforward mathematical formulation. However, a significant gap remains in state-of-the-art knowledge of SSSI when multiple interactions between buildings in a 3D arrangement (allowing different footprints for the building's base), linear or nonlinear behaviour (both in the soil and structures), and multi-directional ground motions are considered.

A different approach is physical experimental modelling, which has been implemented in the last decades for the SSSI phenomenon. These studies represent a significant frame of reference for numerical models and provide preliminary estimates of the effects of complex interaction problems. Kitada et al. [21] and Yano et al. [22] studied the SSSI problem for nuclear power plants in field tests and laboratory tests (forced vibration and shaking table tests). Centrifuge tests have been used to evaluate nonlinear behaviour in the materials [23–26]. The results showed that SSSI could be beneficial (reducing the seismic response) or detrimental (increasing the seismic response), depending on the seismic excitation and the dynamic structural parameters. Shaking table tests have also been used to evaluate the SSSI, providing valuable insight into understanding the dynamic behaviour of multiple adjacent structures [27, 28]. The disadvantages of the experimental methods are that they are technically challenging to undertake and produce several difficulties in achieving appropriate scaling of the soil strains and inertial forces. Nevertheless, experimental tests (including shake table and centrifuge tests) still represent a critical dataset of results to benchmark various computational and theoretical models.

Recordings from instrumented buildings constitute an important dataset for benchmarking various numerical models of seismically excited buildings. For example, Celebi [29, 30] studied the seismic response of two adjacent seven-storey buildings in Norwak, California. The results showed that building 1 increases its seismic response by receiving the seismic energy of building 2, highlighting the SSSI effects. The works of Hans et al. [31], Laurenzano et al. [32], and Gueguen and Colombi [33] presented results that showed clear evidence of SSSI between adjacent buildings.

Cross-laminated timber (CLT) has been gaining popularity in residential applications, especially in Europe and North America, due to (i) its good seismic performance, (ii) its ability to self-protect against fire, (iii) its lessened environmental impact, and (iv) its renewable material source [34]. The CLT is a building system based on structural panels made of several layers of boards stacked crosswise and glued together on their faces. These panels are lightweight structural elements with high stiffness and strength for bending, compression, and shear. Therefore, they are an economically competitive building system, and are a suitable candidate compared to traditional options [35].

This study evaluated the SSSI between two cross-laminated timber (CLT) buildings under seismic excitation. The objectives of this research are to answer the following questions:

- Is there evidence that the Structure-Soil-Structure Interaction can significantly increase the seismic response of cross-laminated timber buildings?
- What are the most important parameters that govern this complex problem?

2 Computational Finite Element Model of SSSI for CLT Buildings

Past studies have shown that finite element analyses, in special the commercial finite element software ANSYS [36], can be applied successfully to the problem of SSSI [7–9, 37–39]. Therefore, in this research, a series of full 3D time-history seismic analyses are performed in ANSYS. It is considered the direct approach (i.e., the soil and structure are included within the same finite-element model as a complete system), which enables the solving of the systems into a single step, in contrast with the substructure approach, which is a multiple-step configuration.

2.1 Building Model and Properties

Four different CLT buildings are considered for the purpose of this study. The structure has a square footprint (7 m wide) with an interior wall. The walls and roof are CLT panels (85- and 150-mm thickness for the walls and roof, respectively), modelled with a four-node and six degrees of freedom at each node SHELL181 element. The selection of a maximum mesh size of 150 mm is based on the spacing between panel screws. This size has been observed to correspond to the screw spacing, and it has been demonstrated that the structural elements behave correctly at this mesh size. The panels are connected by screws. The walls are attached to the foundations using angle brackets and hold-down metallic connectors (refer to Fig. 1). These connectors are modelled as COMBIN40 linear springs, with stiffness values obtained from experimental. The shear, axial, and out-of-plane responses are represented using three spring elements connecting 2 coincident nodes.

The reinforced concrete (RC) foundations are modelled using BEAM188, which is a two-node element with six degrees of freedom per node. The transverse section of the foundation measures 45 cm in height and 30 cm in width (refer to Fig. 2). The foundation is connected to the soil by ensuring equal degrees of freedom conditions between neighbouring nodes. It is assumed that the foundation remains stable without lifting under dynamic loads, a hypothesis supported by the absence of vertical reactions during analysis. The foundation mesh aligns with the CLT panels' mesh (150 mm elements) to ensure coincident nodes between both elements.

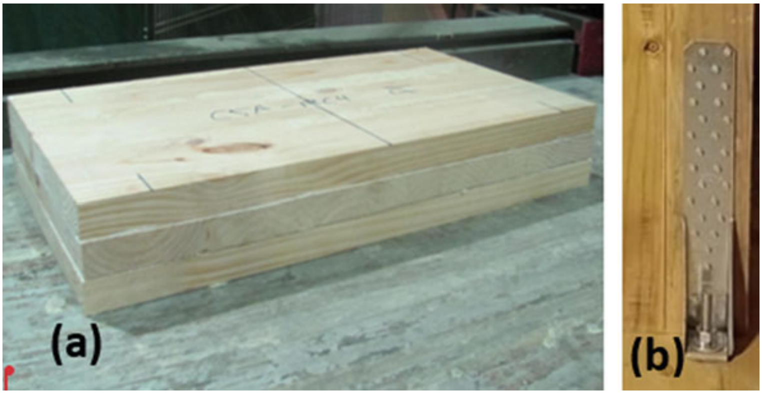

Fig. 1 **a** Cross-laminated timber section, **b** Hold-down connector used in CLT elements

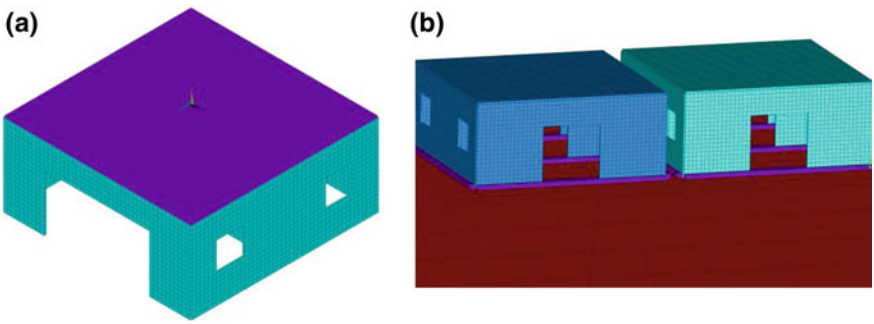

Fig. 2 **a** Structural model of a one-story cross-laminated timber building, **b** Structure-Soil-Structure interaction (SSSI) model

Table 1 Structure material properties

Property	Units	Value
CLT Young modulus	MPa	11,000
CLT Poisson ratio	–	0.35
CLT density	kg/m^3	500
RC Young modulus	MPa	25,650
RC Poisson ratio	–	0.2
RC density	kg/m^3	2500

The structural elements are idealized as linear elastic isotropic materials, and their properties are summarized in Table 1. To incorporate the capacity of energy dissipation into de modelling, the Rayleigh damping is employed with a damping ratio of $\xi = 0.02$. Consequently, the damping matrix C can be calculated as follows,

$$\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K} \tag{1}$$

where **M** is the mass matrix and **K** is the stiffness matrix of the system. The α and β parameters can be calculated by using the first two natural frequencies (ω) of the system.

$$\alpha = 2\xi\frac{\omega_1\omega_2}{\omega_1 + \omega_2}, \beta = \frac{2\xi}{\omega_1 + \omega_2} \tag{2}$$

2.2 *Soil Model and Properties*

The soil was modelled using a symmetric hexahedral mesh in all its dimensions by using the SOLID185 element (an eight-node 3-dimensional element with three degrees of freedom per node). It has been recommended that Finite Element mesh for shallow foundations of width B on isotropic homogeneous soil usually includes an area extending from about $5B$ laterally and $8B$ vertically. The purpose of this is to have all the soil volume where most of the stress variations are expected to occur. To reduce the computational cost of the modelling, a refined mesh of 1-m elements is employed in the soil volume near the influence zone of the foundation of the structures (see Fig. 3), so a mesh with finite elements of different sizes is considered.

Fixed constraints are applied at the bottom of the soil to simulate the rigid bedrock where the seismic excitation is applied into the ANSYS model. Additionally, in order to simulate an infinite boundary and prevent the reflection of seismic waves, both horizontal and vertical spring-dashpots arrays are utilized [40], as shown in Fig. 4 and obtained by the following equations,

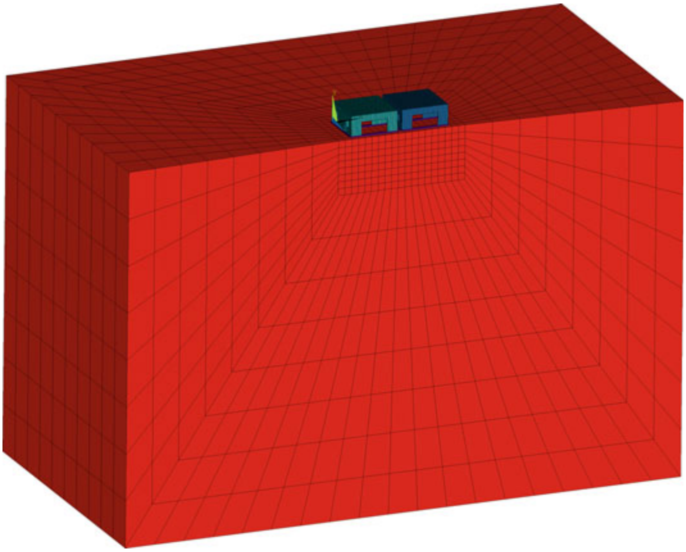

Fig. 3 Lateral view of the 3D FE model of soil and structural model of a one-story cross-laminated timber building

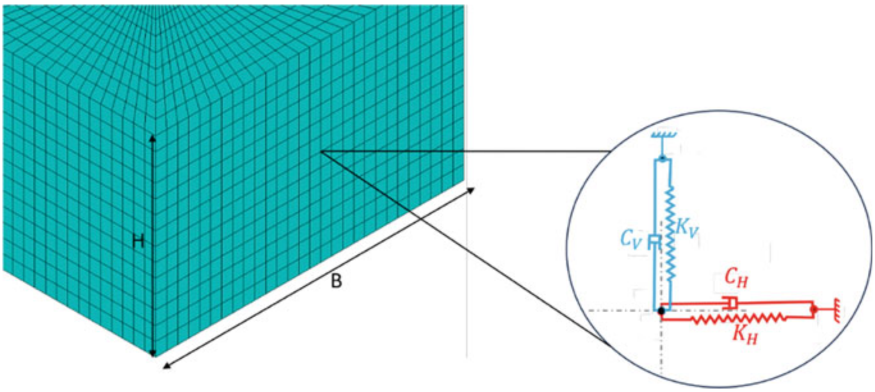

Fig. 4 Boundary conditions of the soil block model

$$K_H = \frac{GA}{B}, C_H = \rho V_s A \tag{3}$$

$$K_V = \frac{GA}{H}, C_V = \rho V_p A \tag{4}$$

Here, G represents the shear modulus of the soil and ρ denotes the soil density. A refers to the element area, H represents the height of the soil block, B represents the

Table 2 Soil shear wave velocities studied

Soil class	Shear wave velocity m/s^2	Shear modulus MPa	Poisson ratio
Soil 1	150	33.75	0.3
Soil 2	200	60.0	0.3
Soil 3	325	158.4	0.35

Table 3 Finite element resume

Finite element	Name	Count
4-node shell	SHELL81	5764
2-node beam	BEAM188	230
8-node solid	SOLID185	10,640
Spring	COMBIN40	2844
Spring/dashpot	COMBIN40	1512

width of the soil, and V_p and V_s denote the compression and shear wave propagation velocities, respectively.

Additionally, to prevent unrealistic soil settlements due to its self-weight, it is necessary to establish initial stresses in the soil before applying the seismic load. This is achieved by performing a static analysis, from which the stresses generated in the soil by its self-weight are extracted. These stresses are then applied in the initial step of the transient analysis, prior to applying the accelerations at the soil base.

In this analysis, we consider three different soil classes, resumed in Table 2.

The base SSI model (Structure and soil) is composed of 20,990 elements and 19,204 nodes, and the finite elements used are resumed in the following Table 3.

2.3 Structure-Soil-Structure Model and Its Properties

It is well known that the proximity of two structures can largely influence the seismic response of the smaller structure. In general, two buildings at a distance shorter than 2.5 times the width of foundations will interact each other and the SSSI effect is relevant. In this work, we have conducted a comprehensive study on the seismic response of adjacent structures, considering four height ratios $\varepsilon = h_2/h_1$ of the adjacent structures. These height ratios are summarized in Table 4.

Table 4 Height ratios cases studied

Parameter	Case 1	Case 2	Case 3	Case 4
Main structure height $\boldsymbol{h}_1$ [m]	3.0	3.0	3.0	3.0
Adjacent structure height $\boldsymbol{h}_2$ [m]	2.4	3.0	3.6	4.5
Height ratio $\boldsymbol{\varepsilon}$	0.8	1.0	1.2	1.5

2.4 Reduced-Order Model for Structure-Soil-Structure Interaction

This model represents a pair of CLT buildings coupled by a rotational ground spring $\kappa_{\theta 12}$, shown in Fig. 5. The buildings are spaced at some arbitrary distance from each other, ζb, where ζ is the non-dimensional interbuilding distance and b is the width of the buildings. Both foundations have a similar square plan area and raft foundation of b^2, the soil/foundation masses are m_s, and the soil/foundation masses radius of gyration are $r = 0.33b$. The system considered here corresponds to the case of two buildings placed very close to each other, i.e., at a spacing distance of $0.1b$ ($\zeta = 0.1$). This interbuilding spacing is large enough to avoid pounding but close enough to maximize the SSSI effects. The effect of the vertical ground motion and P-Delta effects in the structures' response is neglected in this formulation, i.e., small lateral displacements are considered. For more information about this low-order model, please refer to [41, 42]. This model was calibrated and validated using finite element analysis [43], physical experimental test using the University of Bristol's shaking table [44], and University of Dundee's centrifuge [45].

The Euler–Lagrange equations of motion describing the dynamics of the discretized system can be derived in the standard way by variational calculus and are formulated in the matrix equations of motion (5).

$$\widehat{\mathbf{M}}\ddot{\mathbf{x}} + \widehat{\mathbf{C}}\dot{\mathbf{x}} + \widehat{\mathbf{K}}\mathbf{x} = \mathbf{p}\ddot{x}_g \tag{5}$$

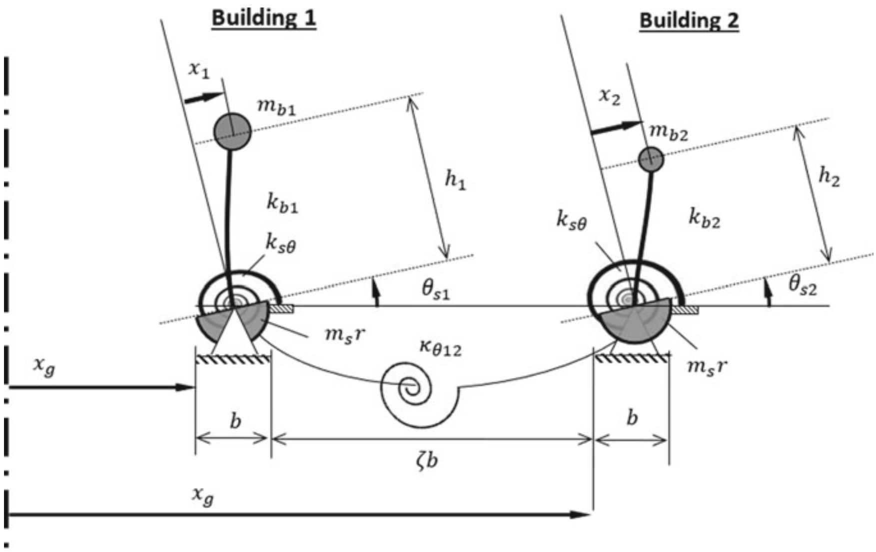

Fig. 5 Structural model of a two-buildings system subjected to horizontal ground motion

where system matrices are defined as follows,

$$\widehat{\mathbf{M}} = \begin{bmatrix} m_{b1} & -m_{b1}h_1 & 0 & 0 \\ -m_{b1}h_1 & m_{b1}h_1^2 + m_s r^2 & 0 & 0 \\ 0 & 0 & m_{b2} & -m_{b2}h_2 \\ 0 & 0 & -m_{b2}h_2 & m_{b2}h_2^2 + m_s r^2 \end{bmatrix} \tag{6}$$

$$\widehat{\mathbf{K}} = \begin{bmatrix} k_{b1} & 0 & 0 & 0 \\ 0 & k_{s\theta} + \kappa_{\theta 12} & 0 & -\kappa_{\theta 12} \\ 0 & 0 & k_{b2} & 0 \\ 0 & -\kappa_{\theta 12} & 0 & k_{s\theta} + \kappa_{\theta 12} \end{bmatrix} \tag{7}$$

$$\mathbf{p} = \begin{bmatrix} -m_{b1} \\ m_{b1}h_1 \\ -m_{b2} \\ m_{b2}h_2 \end{bmatrix}, \mathbf{x} = \begin{bmatrix} x_1 \\ \theta_1 \\ x_2 \\ \theta_2 \end{bmatrix} \tag{8}$$

The system's linear viscous damping matrix **C** defined in Eq. (5) assumes that each natural mode $n \in [1, 4]$ is damped at $\xi_n = 0.05$ of critical damping, $\boldsymbol{\phi}_n$ is the modal eigenvector of the mode n, ω_n are the natural frequencies of the systems. These ω_n were calculated considering the completely elastic system. Thus, the Caughey orthogonal damping matrix **C** can be calculated as [38] by equation.

$$\mathbf{C} = \mathbf{M}\left(\sum_{n=1}^{4} \frac{2\xi_n \omega_n}{\boldsymbol{\phi}_n^T \mathbf{M} \boldsymbol{\phi}_n} \boldsymbol{\phi}_n \boldsymbol{\phi}_n^T\right)\mathbf{M} \tag{9}$$

2.5 Seismic Input

The seismic loading chosen in this study correspond to the event recorded in Kobe, Japan, in 1995 (solid ground near the JMA Kobe station) with a magnitude of $M_w = 6.9$ and a peak ground acceleration (PGA) equal to $a_g = 0.83g$. . This ground motion was obtained from the Pacific Earthquake Engineering Research (PEER) Centre Database [46], supposed as recorded on weak soil with a shear wave velocity of $V_s = 200\text{m/s}$.

Considering the seismic record accelerations as free field surface motion, the bedrock accelerations are estimated by applying a transfer function 'F2' to the frequency domain data to filter the main frequencies amplificated by the soil, as illustrated in Fig. 6. The transfer function proposed by Kramer [47] for low-damping soils is utilized,

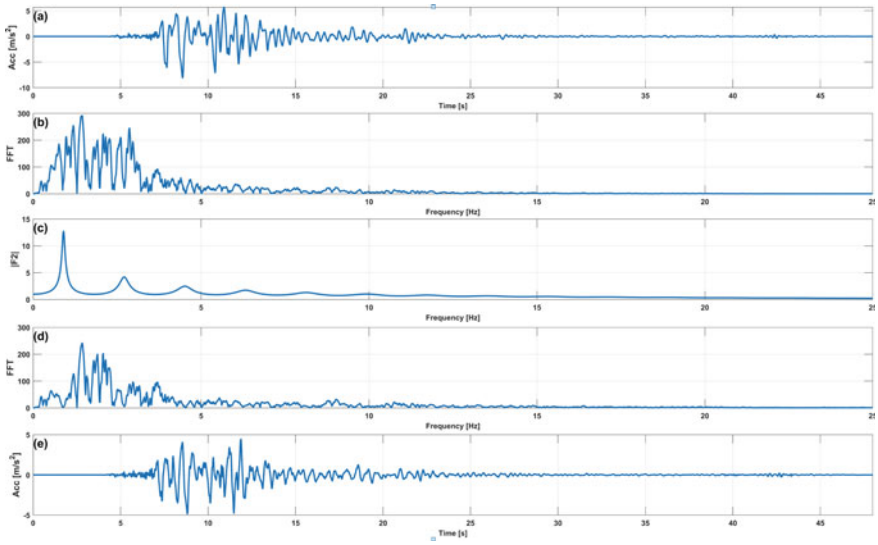

Fig. 6 Original acceleration record and bedrock estimation

$$\mathrm{F}_2(\omega) = \frac{1}{\cos(\omega H/V_s(1+i\xi))} \tag{10}$$

3 Numerical Results and Analysis

The influence of the SSSI on the dynamic response of two cross-laminated timber (CLT) buildings under seismic excitation is addressed in this section. As a measure of change in the response between SSSI and SSI, we will use the maximum displacement X_{b1} and accelerations $\ddot{X}_{b1}$ for the buildings 1. The percentage difference in the response total power $\ddot{\chi}_{bj}$ (for building j), when using the response SSSI (Structure-Soil-Structure Interaction) rather than SSI (Soil-Structure Interaction) is defined in Eq. (11).

$$X_{bj} = 100\left\{\frac{[E_s(X_{bj})]_{SSSI}}{[E_s(X_{bj})]_{SSS}} - 1\right\},\ \ddot{\chi}_{bj} = 100\left\{\frac{[E_s(\ddot{X}_{bj})]_{SSSI}}{[E_s(\ddot{X}_{bj})]_{SSI}} - 1\right\} \tag{11}$$

where $E_s(\ddot{X}_{bj})$ are the total power spectral density (which is based on all data points of response time series $\ddot{X}_{bj}$) for the acceleration (referring to building j). The power spectral density (PSD) is defined using Parseval's theorem according to Eq. (12).

$$E_s(\ddot{X}_{bj}) = \int_{-\infty}^{\infty} |\ddot{X}_{bj}(t)|^2 dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} |\ddot{X}_{bj}(\omega)|^2 d\omega \tag{12}$$

where $\ddot{X}_{bj}(\omega)$ is the continuous Fourier transform of $\ddot{U}_{bj}(t)$. Using total power as a comparative metric delivers a statistical estimate of magnitude that is more robust than employing a single peak of the function.

The system analysed in this research corresponds to the case when the two buildings are placed in very close proximity to each other, at a spacing distance equal to $0.1b$. Due to the complexity of the problem, the results for the nonlinear building 1 are divided into the next sections,

- Section 3.1 explores the differences between the SSI and SSSI seismic responses for a set of parameters.
- Section 3.2 explores the influence of different soil classes, on SSSI responses.
- Section 3.3 explores the influence of height ratio ε, on SSSI responses.
- Section 3.4 evaluate the differences between the high-order and reduced-order model.

3.1 Initial Analysis of SSSI for Different Parameter Set

In this section, initial results are presented for SSSI and SSI responses in cross-laminated timber buildings. The rigid base period of building 1 is $T_x = 0.1$ seconds. Figure 7a, b shows the uncoupled SSI (blue line) and coupled SSSI (red line) response for the top of building 1 (relative displacement of the roof level U_{b1} for Fig. 7a and the acceleration of the roof level A_{b1} for Fig. 7b), when it is adjoined by 50% taller building, the building 1 has height to width ratio equal to $s = h_1/b = 0.43$, and soil class 1. Figure 7c shows the corresponding power spectral density (PSD) for the displacement and Fig. 7d shows the PSD for the total acceleration for the building 1 considering the coupled (SSSI) and uncoupled (SSI) case. Comparing the uncoupled and coupled responses, building 1's response appears to be significantly affected by the presence of the taller building in all the time-history. The change in power, defined in Eq. (11), is equal to $\chi_{b1} = 23\%$ for the displacement and $\ddot{\chi}_{b1} = -14\%$ for the acceleration. The peak in the PSD of Fig. 7c, d represents approximately the fundamental frequency of the system, where the frequency does not change very much between the SSI and SSSI systems (small shift of the PSD peaks).

Figure 8a, b shows the uncoupled and coupled responses for the top of building 1, that is displacement and acceleration. Comparing the SSI and SSSI responses, there is a transfer of earthquake energy between building 2 to building 1. Nevertheless, the amplification is more limited compared with the previous graph, suggesting that the worst seismic interaction conditions occur on loose soil class 1.

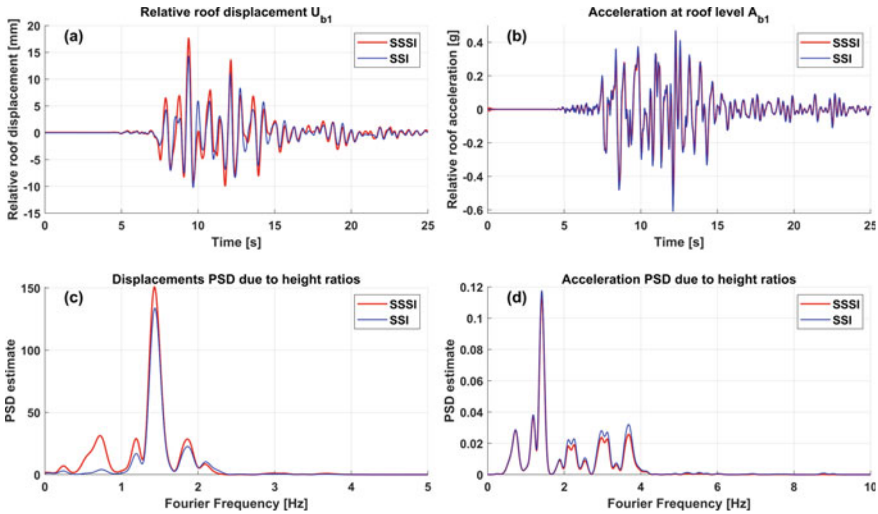

Fig. 7 **a** Displacement and **b** total acceleration responses, **c** Power spectral density of displacement and **d** total acceleration—Seismic response for the parameter set (Soil class 1, shear wave velocity $V_s = 150\text{m/s}$, height ratio $\varepsilon = h_2/h_1 = 1.5$)

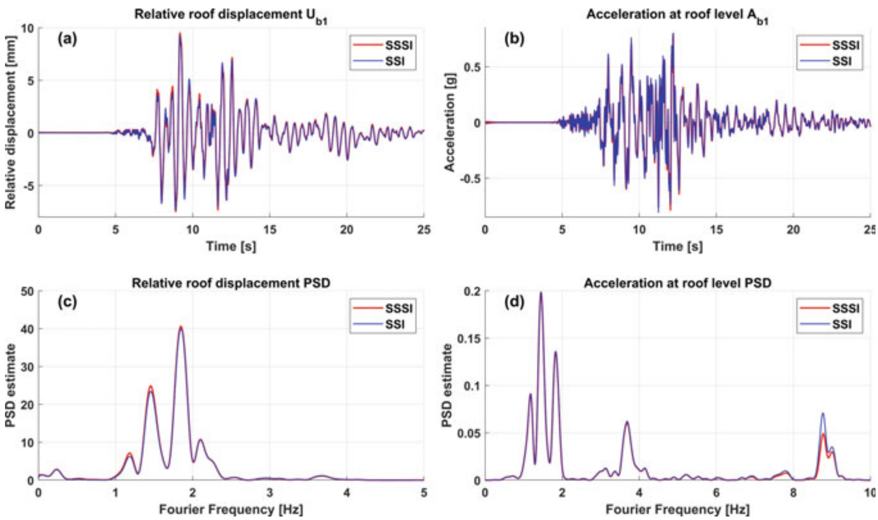

Fig. 8 **a** Displacement and **b** total acceleration responses, **c** Power spectral density of displacement and **d** total acceleration—Seismic response for the parameter set (Soil class 2, shear wave velocity $V_s = 200\text{m/s}$, height ratio $\varepsilon = h_2/h_1 = 1.5$)

3.2 *Time History Analysis and Change in Power Due to the Variation in Soil Properties*

In this section, we delve into the analysis of the response of the previously defined three classes of soil, examining both the time history response and power spectral density (PSD) of the structures. To investigate the soil-structure interaction (SSI), we specifically focus on the height ratio of $\varepsilon = h_2 / h_1 = 1.0$.

Figure 9 provides a comprehensive visualization of the relative roof displacements and their corresponding PSD for structure 1 across the three different soils studied. By comparing the curves for both the SSSI and SSI cases, we can discern the disparities in terms of magnitude and distribution of signal frequency components. This enables us to observe and analyse the variations in the structural response due to the presence of an equally dimensioned adjacent CLT structure.

Similarly, Fig. 10 showcases the total acceleration obtained at the roof level and its PSD for structure 1 within the three distinct soils studied. By contrasting the curves for the SSSI and SSI cases, we can gain insights into the differences in amplitude and spectral characteristics of the acceleration response. This aids in understanding how the structure-soil-structure interaction affects the overall dynamic behaviour of the structure.

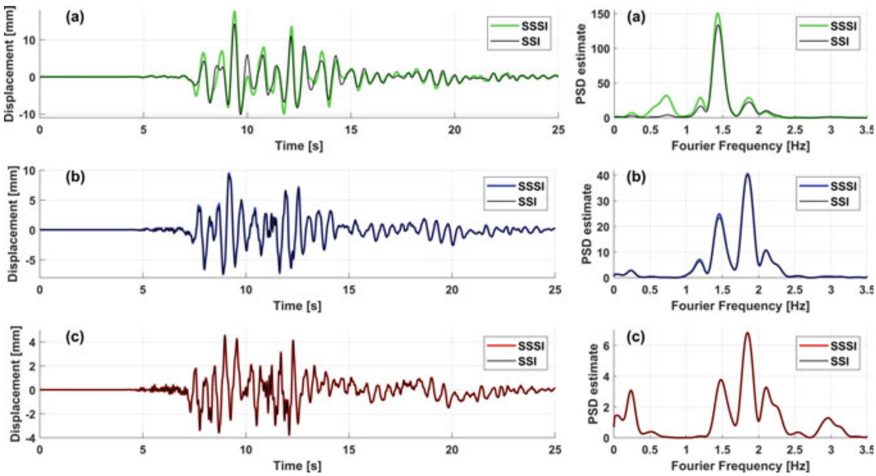

Fig. 9 **a** Relative roof displacement and PSD for soil class 1 **b** Relative roof displacement and PSD for soil class 2, **c** Relative roof displacement and PSD for soil class 3—Seismic response for the height ratio $\varepsilon = h_2/h_1 = 1.0$

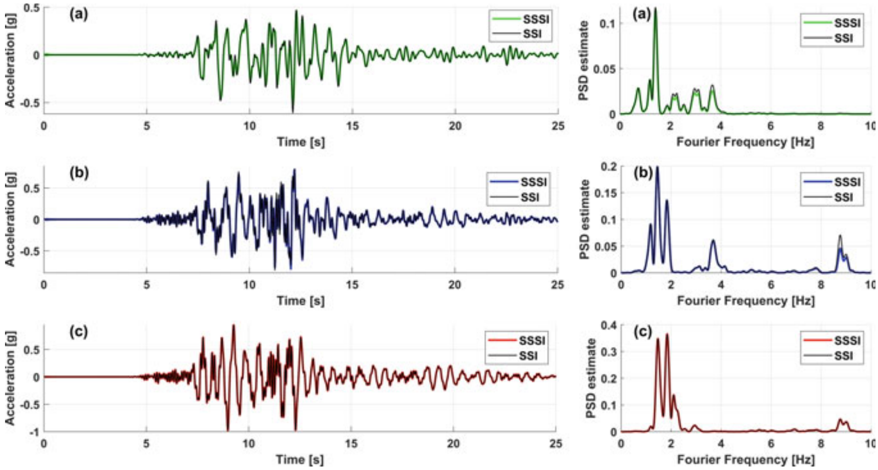

Fig. 10 **a** Roof acceleration and PSD for soil class 1 **b** Roof acceleration and PSD for soil class 2, **c** Roof acceleration and PSD for soil class 3—Seismic response for the height ratio $\varepsilon = h_2/h_1 = 1.0$

3.3 Change in Power Due to the Variation in Height Ratios $\boldsymbol{\varepsilon = h_2/h_1}$

In this section, results are presented (χ_{b1} and $\ddot{\chi}_{b1}$) for buildings with height ratios of $\varepsilon = h_2/h_1 = 0.8$, 1.0, 1.2 and 1.5 at every soil class.

Figure 11 presents the changes in the response of structure 1 when varying the height of the adjacent structure. It showcases the changes in power and variations of peak values, providing two approaches for evaluating the response modifications. These values are obtained for total roof acceleration and relative displacement in each studied soil class.

It can be observed that the changes are nearly consistent across all the height ratio cases, regardless of whether there is a significant variation from the SSI case or not. This suggests that, for the studied height ratios, there are no substantial differences, even in soils where SSSI is observed.

3.4 Comparison of the Dynamic Response Between the High-Order and Reduced-Order Models

In order to evaluate the formulation presented here, a qualitative comparison has been carried out between the high order model develop here and an analogue reduced-order model. The validation/comparison is carried out for different parameter set. Nevertheless, in this paper, as an example of the good match, we present presented in Fig. 12, the results for a selected combination of parameters (shear wave velocity

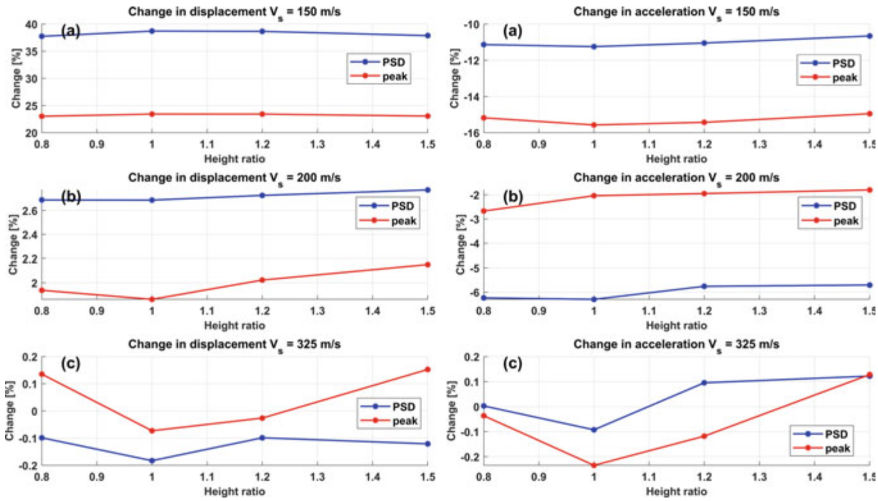

Fig. 11 Change in displacement and acceleration for **a** Soil class 1, **b** Soil class 2 and **c** Soil class 3 **d** from PSD and peak values

$V_s = 150\text{m/s}$, height ratio $\varepsilon = h_2/h_1 = 1.2$). Figure 12 shows the reduced-order model (red line) and the high-order Finite Element Model (blue line) response for the roof acceleration of building 1. Comparing the responses, we can observe that the response agree well for all time-history and the low-order model provides a good match in terms of peaks estimates, despite the simplicity of the reduced-order model.

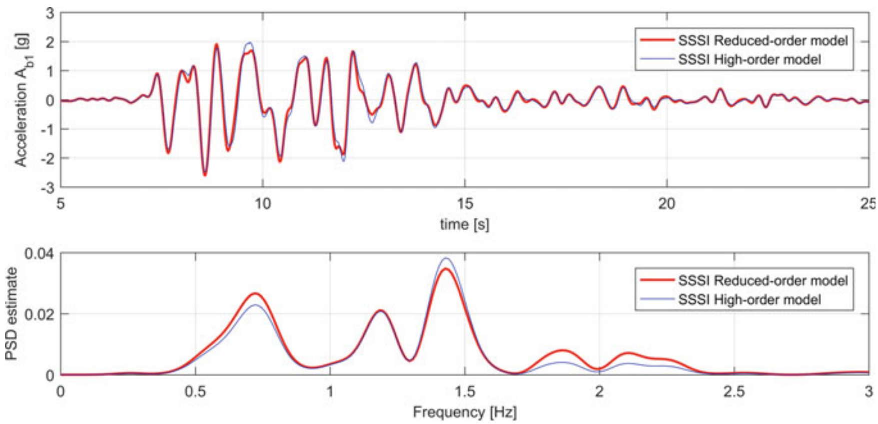

Fig. 12 **a** Total acceleration responses and **b** Power spectral density of total acceleration—Reduced-order and high-order models comparison for the parameter set (Soil class 2, shear wave velocity $V_s = 150\text{m/s}$, height ratio $\varepsilon = h_2/h_1 = 1.2$)

4 Conclusion

In this paper, we present a high-order 3-dimensional formulation for Structure-Soil-Structure Interaction between two cross-laminated timber (CLT) buildings under seismic excitation. The finite element method is used for the numerical simulations in the software ANSYS. The interaction effects are investigated for different heights of the buildings and soil properties. This research has led to the following principal conclusions:

- Comparing the uncoupled and coupled responses, building 1's response appears to be significantly affected by the presence of the adjacent building in all the time-history.
- The worst seismic interaction conditions occur on loose soil class 1, suggesting that both adverse and beneficial effects diminish the soil stiffness increases.
- It can be observed that the change in power is not affected by the height ratio, regardless of whether there is a significant variation from the SSI case or not.

Acknowledgements The first author is grateful to the Ministry of Science, Technology, Knowledge and Innovation and the National Agency of Research and Development (ANID), for the financial support through FONDECYT Grant N° 11230400. Sebastián Torres Olivares acknowledges the financial support from the Chilean National Agency for Research and Development (ANID), Subdirección de capital humano, Magíster nacional 2022, Folio 22221341. E.I. Saavedra Flores acknowledges financial support from the Chilean National Agency for Research and Development (ANID), Fondecyt Regular project 1211767.

References

1. Lee TH, Wesley DA (1973) Soil-structure interaction of nuclear reactor structures considering through-soil coupling between adjacent structures. Nucl Eng Des 24:374–387. https://doi.org/10.1016/0029-5493(73)90007-1
2. Kobori T, Minai R, Kusakabe K (1977) Dynamical cross-interaction between two foundation. Proceedings of the 6th world conference on earthquake engineering
3. Wong HL, Luco JE (1986) Dynamic interaction between rigid foundations in a layered half-space. Soil Dyn Earthq Eng 5:149–158. https://doi.org/10.1016/0267-7261(86)90018-7
4. Triantafyllidis T, Prange B (1988) Rigid circular foundation: dynamic effects of coupling to the half-space. Soil Dyn Earthq Eng 7:40–52
5. Liang J, Han B, Todorovska MI, Trifunac MD (2017) 2D dynamic structure-soil-structure interaction for twin buildings in layered half-space I: incident SH-waves. Soil Dyn Earthq Eng 102:172–194. https://doi.org/10.1016/j.soildyn.2017.08.017
6. Han B, Chen S, Liang J (2020) 2D dynamic structure-soil-structure interaction: a case study of Millikan Library Building. Eng Anal Bound Elem 113:346–358. https://doi.org/10.1016/j.enganabound.2020.01.012
7. Yahyai M, Mirtaheri M, Mahoutian M, Daryan AS, Assareh MA (2008) Soil Structure Interaction between two adjacent buildings under earthquake load. Am J Eng Appl Sci 1:121–125. https://doi.org/10.3844/ajeassp.2008.121.125

8. Gan J, Li P, Liu Q (2019) Study on dynamic structure-soil-structure interaction of three adjacent tall buildings subjected to seismic loading. Sustainability 12:336. https://doi.org/10.3390/su12010336
9. De Borbon F, Domizio M, Ambrosini D, Curadelli O (2020) Influence of various parameters in the seismic soil-structure interaction response of a nuclear power plant. Eng Struct, 217. https://doi.org/10.1016/j.engstruct.2020.110820
10. Padrón LA, Aznárez JJ, Maeso O (2011) 3-D boundary element–finite element method for the dynamic analysis of piled buildings. Eng Anal Bound Elem 35:465–477. https://doi.org/10.1016/j.enganabound.2010.09.006
11. Clouteau D, Broc D, Devésa G, Guyonvarh V, Massin P (2012) Calculation methods of Structure-Soil-Structure Interaction (3SI) for embedded buildings: application to NUPEC tests. Soil Dyn Earthq Eng 32:129–142. https://doi.org/10.1016/j.soildyn.2011.08.005
12. Aji HDB, Wuttke F, Dineva P (2022) 3D structure-soil-structure interaction in an arbitrary layered half-space. Soil Dyn Earthq Eng 159:107352. https://doi.org/10.1016/j.soildyn.2022.107352
13. Mulliken JS, Karabalis DL (1998) Discrete model for dynamic through-the-soil coupling of 3-D foundations and structures, 27. https://doi.org/10.1002/(SICI)1096-9845(199807)27:7<687::AID-EQE752>3.0.CO;2-O.
14. Vicencio F, Alexander NA, Saavedra Flores EI (2023) A State-of-the-art review on Structure-Soil-Structure interaction (SSSI) and Site-City interactions (SCI). Structures 56:105002. https://doi.org/10.1016/j.istruc.2023.105002
15. Vicencio F, Alexander NA (2019) Numerical analysis of structure-soil-structure interaction for two different buildings during earthquakes. COMPDYN Proceedings, vol 3, Athens: Institute of Structural Analysis and Antiseismic Research School of Civil Engineering National Technical University of Athens (NTUA) Greece, pp 5597–609. https://doi.org/10.7712/120119.7330.18590
16. Vicencio F, Alexander NA (2018) Dynamic interaction between adjacent buildings through nonlinear soil during earthquakes. Soil Dyn Earthq Eng 108:130–141. https://doi.org/10.1016/j.soildyn.2017.11.031
17. Vicencio F, Alexander NA (2018) Higher mode seismic structure-soil-structure interaction between adjacent building during earthquakes. Eng Struct 174:322–337. https://doi.org/10.1016/j.engstruct.2018.07.049
18. Alexander NA, Ibraim E, Aldaikh H (2013) A simple discrete model for interaction of adjacent buildings during earthquakes. Comput Struct 124:1–10. https://doi.org/10.1016/j.compstruc.2012.11.012
19. Aldaikh H, Alexander NA, Ibraim E, Knappett JA (2018) Evaluation of rocking and coupling rotational linear stiffness coefficients of adjacent foundations. Int J Geomech 18:04017131. https://doi.org/10.1061/(asce)gm.1943-5622.0001041
20. Vicencio F, Alexander NA (2022) Seismic structure-soil-structure Interaction between a pair of buildings with consideration of rotational ground motions effects. Soil Dyn Earthq Eng 163:107494. https://doi.org/10.1016/j.soildyn.2022.107494
21. Kitada Y, Hirotani T, Iguchi M (1999) Models test on dynamic structure–structure interaction of nuclear power plant buildings. Nucl Eng Des 192:205–216. https://doi.org/10.1016/S0029-5493(99)00109-0
22. Yano T, Naito Y, Iwamoto K, Kitada Y, Iguchi M (2003) Model test on dynamic cross interaction of adjacent building in nuclear power plants—overall evaluation on field test, k06–2. Transactions of the 17th international conference on structure mechanical in reactor technology
23. Trombetta NW, Mason HB, Hutchinson TC, Zupan JD, Bray JD, Kutter BL (2014) Nonlinear soil–foundation–structure and structure–soil–structure interaction: centrifuge test observations. J Geotechn Geoenviron Eng 140:04013057. https://doi.org/10.1061/(asce)gt.1943-5606.0001074
24. Mason HB, Trombetta NW, Chen Z, Bray JD, Hutchinson TC, Kutter BL (2013) Seismic soil-foundation-structure interaction observed in geotechnical centrifuge experiments. Soil Dyn Earthq Eng 48:162–174. https://doi.org/10.1016/j.soildyn.2013.01.014

25. Kirkwood P, Dashti S (2018) A centrifuge study of seismic structure-soil-structure interaction on liquefiable ground and implications for design in dense urban areas. Earthq Spectra 34:1113–1134. https://doi.org/10.1193/052417EQS095M
26. Qi S, Knappett JA (2020) Influence of foundation type on seismic response of low-rise structures in liquefiable soil. Soil Dyn Earthq Eng 128:105786. https://doi.org/10.1016/j.soildyn.2019.105786
27. Schwan L, Boutin C, Padrón LA, Dietz MS, Bard PY, Taylor C (2016) Site-city interaction: theoretical, numerical and experimental crossed-analysis. Geophys J Int 205:1006–1031. https://doi.org/10.1093/gji/ggw049
28. Li P, Liu S, Lu Z, Yang J (2017) Numerical analysis of a shaking table test on dynamic structure-soil-structure interaction under earthquake excitations. Structural design of tall and special buildings, 26. https://doi.org/10.1002/tal.1382
29. Celebi M (1993) Seismic responses of two adjacent buildings. I: Data and analyses. J Struct Eng 119:2461–76. https://doi.org/10.1061/(ASCE)0733-9445(1993)119:8(2461)
30. Celebi M (1993) Seismic responses of two adjacent buildings. II: Interaction. J Struct Eng 119:2477–92. https://doi.org/10.1061/(ASCE)0733-9445(1993)119:8(2477).
31. Hans S, Boutin C, Ibraim E, Roussillon P (2005) In situ experiments and seismic analysis of existing buildings. Part I: Experimental investigations. Earthq Eng Struct Dyn 34:1513–29. https://doi.org/10.1002/eqe.502
32. Laurenzano G, Priolo E, Gallipoli MR, Mucciarelli M, Ponzo FC (2010) Effect of vibrating buildings on free-field motion and on adjacent structures: The Bonefro (Italy) case history. Bull Seismol Soc Am 100:802–818. https://doi.org/10.1785/0120080312
33. Guéguen P, Colombi A (2016) Experimental and numerical evidence of the clustering effect of structures on their response during an earthquake: a case study of three identical towers in the City of Grenoble, France. Bull Seismol Soc Am 106:2855–2864. https://doi.org/10.1785/0120160057
34. Schmidt J, Griffin CT (2013) Barriers to the design and use of cross-laminated timber structures in high-rise multi-family housing in the United States. Cruz PJS, editor. Structures and architecture. New concepts, applications and challenges
35. Mohammad M, Gagnon S, Douglas BK (2012) Podesto L. Introduction to cross laminated timber. Wood Des Focus, 22
36. Ansys, User Manual, Version 13.0 2010
37. Ada M, Ayvaz Y (2019) The Structure-soil-structure interaction effects on the response of the neighbouring frame structures. Latin Amer J Solids Struct 16:1–3. https://doi.org/10.1590/1679-78255762
38. Wang H, Lou M, Chen X, Zhai Y (2013) Structure–soil–structure interaction between underground structure and ground structure. Soil Dyn Earthq Eng 54:31–38. https://doi.org/10.1016/j.soildyn.2013.07.015
39. Nateghi-A F, Rezaei-Tabrizi A (2013) Nonlinear dynamic response of tall buildings considering structure-soil-structure effects. Struct Des Tall Special Build 22:1075–1082. https://doi.org/10.1002/tal.753
40. Wolf J (1985) Dynamic soil-structure interaction. Englewood Cliffs, N.J.: Prentice-Hall
41. Vicencio F, Alexander NA (2021) Method to evaluate the dynamic structure-soil-structure interaction of 3-D buildings arrangement due to seismic excitation. Soil Dyn Earthq Eng 141:106494. https://doi.org/10.1016/j.soildyn.2020.106494
42. Vicencio F (2021) Linear and nonlinear structure-soil-structure interaction during Earthquakes. PhD Thesis, University of Bristol
43. Aldaikh H, Alexander NA, Ibraim E, Oddbjornsson O (2015) Two dimensional numerical and experimental models for the study of structure-soil-structure interaction involving three buildings. Comput Struct 150:79–91. https://doi.org/10.1016/j.compstruc.2015.01.003
44. Aldaikh H, Alexander NA, Ibraim E, Knappett J (2016) Shake table testing of the dynamic interaction between two and three adjacent buildings (SSSI). Soil Dyn Earthq Eng 89:219–232. https://doi.org/10.1016/j.soildyn.2016.08.012

45. Knappett JA, Madden P, Caucis K (2015) Seismic structure–soil–structure interaction between pairs of adjacent building structures. Géotechnique 65:429–441. https://doi.org/10.1680/geot.SIP.14.P.059
46. Stewart JP, Shyh-Jeng Chiou, Graves RW, Somerville PG, Abrahamson N (2001) Ground motion evaluation procedures for performance-based design—PEER report 2001/09. Pacific Earthquake Engineering Research Center, University of California, Berkeley
47. Kramer SL (1996) Geotechnical earthquake engineering. 1st ed. Essex: Pearson