The Collective Dynamics of the Christchurch Hospital Campus subject to Earthquake Signals.

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ABSTRACT: Following the recent events of major earthquakes in Christchurch, a motivation to study the interactions between neighbouring buildings subject to earthquake excitation has risen. This work considers investigations of the dynamic behaviour of the Christchurch Women's Hospital and the Christchurch's General Hospital (Parkside). A linear shear wall model approach is used to describe the behaviour of the superstructures, mapping natural frequencies. The hysteretic nature of the soil, as well as that of the base isolation system, present only in the Christchurch Women's Hospital, are modelled by Wen hysteresis and Park-Wen-Ang hysteresis models, respectively. The coupled system, of one building being on isolators and the other not, is analysed under free and forced excitations (harmonic as well as earthquake inputs). The analysis includes a parameter study of various combinations of soft and stiff soil conditions. Parameters for the Christchurch Women's Hospital and its base isolators have been chosen according to real design data, while the soil parameters and parameters for Christchurch's General Hospital are varied in reference to these quantities. First findings show that the base isolation in the Christchurch Women's Hospital effectively decouples the system from the ground motion as well as from the adjacent Christchurch General Hospital building for low frequencies (and given design parameters).

1. INTRODUCTION

While the interactions of structures through the soil have been the focus among specialists for more than 30 years, a detailed and comprehensive understanding of the interactions between buildings on a microscopic scale is missing. Soil-Structure-Soil Interactions (SSSI) provide insights into the building interactions through the soil, primarily focusing on the dynamics of the soil behaviour [1]. Following this, numerous attempts have been made over the years to model the behaviour of an array of structures in the soil [2, 3]. However, most works done to date use a macroscopic approach to the problem seeing the behaviour of the array of structures as a whole rather than focusing on the individual performance of each building.

Recent works by Sridhar et al. [4, 5] have attempted to model a general configuration of structures (arbitrarily extendable) subject to one dimensional harmonic and seismic input signals. The group has subsequently revealed that a collection of structures connected through the soil produces a coupled behaviour depending on the soil stiffness properties as well as magnitude of excitation. However, a more systematic analysis and quantitative understanding require a model-based investigation of a real-life system.

Seeing Christchurch's hospital campus as a suitable candidate, this paper aims to continue the works done by Sridhar et al. [5]. Recently the group investigated in the real life dynamical behaviour of the Christchurch Women's Hospital (CWH) as a stand-alone structure and focused their analyses on the performance of the base isolator (BI) system. This work aims to extent their work by analysing the dynamic interactions between buildings, the CWH and its adjacent structure, Christchurch's General Hospital, henceforth referred to as CGH.

2. MATHEMETICAL MODEL OF SUPERSTRUCTUREs, SOIL, AND BI SYSTEM

The mathematical model of the system subjected to one directional motion excitation consists of the three parts: 1) a linear shear wall model for the super structures (CWH, CGH), 2) a hysteretic model to represent soil interactions and 3) a hysteretic model to describe the behaviour of the BI system in the CWH, see Fig. 1.

2.1. CLUSTER MODEL OF THE CHRISTCHURCH HOSPITAL CAMPUS

Linear shear wall models of multiple degrees of freedom (DOFs) are derived to model the assembly of the CWH and the CGH. According to the design of the buildings, the CWH is represented by 3DOF, which are the foundation (below the BI system), the combined floors of base and floors 1-3 (above the BI system, K-bracing structure) and the upper floors 4-6 (no K-bracing). The CGH is described by a 2DOF system, where one DOF is referring to the foundation and the other to the top floor of the building. Figure 1 depicts a sketch of the mathematical model. The masses of the foundations of each building also include an estimated soil mass. Applied parameters of the CWH are chosen from the design code [6] and those of the CGH are estimated with respect to the CWH building; all parameter values are listed in the Appendix.

The soil-foundation connections at each building are modelled by a hysteretic element to represent the soil-structure interactions. Both buildings are also coupled via the soil and thus also modelled by a hysteretic model, see Fig. 1. The applied parameters of mass, stiffness and damping coefficients are chosen according to previous works by Gavin & Wilkinson [7] and included in the Appendix.

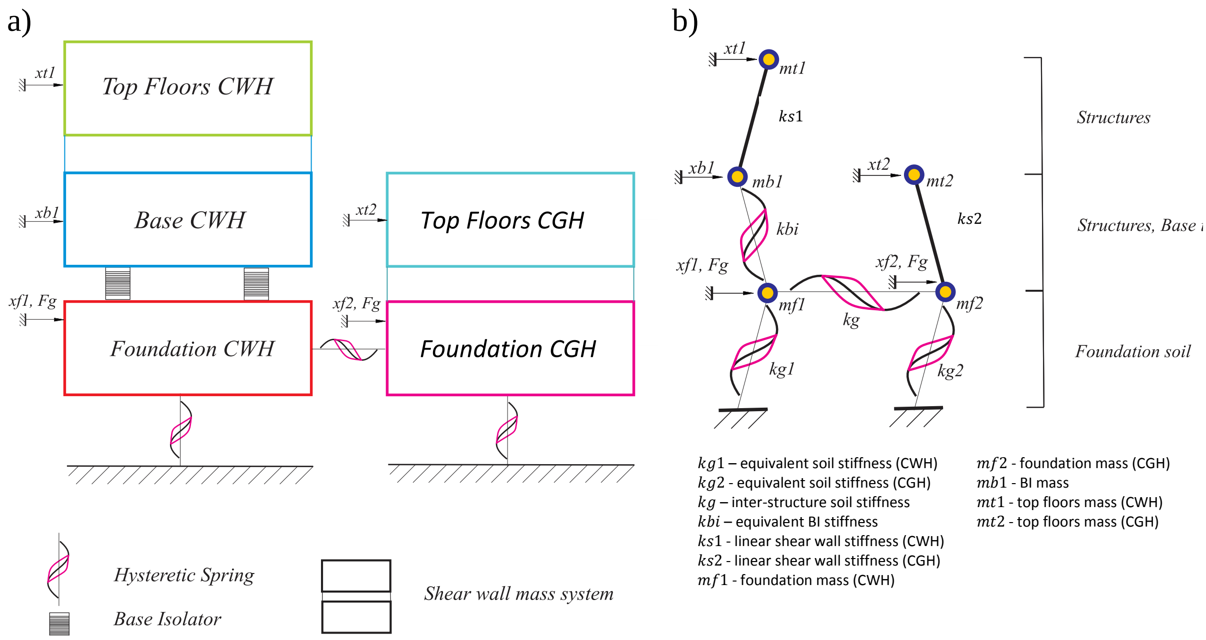


Figure 1. Sketch of the assembly of neighbouring structures in a) showing the DOF. The popsicle model in b) shows the important features of the model.

The floors are assumed to be rigid blocks and columns have a transversal flexibility. These assumptions are classical assumptions related to any shear wall model.

2.2. LINEAR MODEL FOR THE CLUSTER OF STRUCTURES

We first derive the linear governing equations of the assembly as the solution of the linear eigenvalue problem is considered in Section 3.1. The derivations of the equations of motion are performed by applying Newton's 2$^{\text{nd}}$ Law [8], which take on the classical form

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{D}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = -\boldsymbol{M}\ddot{x}_g\,[1\;1\;1\;1\;1]^T. \tag{1}$$

The mass and stiffness matrices in (1) are $\boldsymbol{M} = \mathrm{diag}(m_{f1}\;\; m_{b1}\;\; m_{t1}\;\; m_{f2}\;\; m_{t2})$,

$$\boldsymbol{K} = \begin{bmatrix} k_{g1}+k_{bi}+k_g & -k_{bi} & 0 & -k_g & 0 \\ -k_{bi} & k_{bi}+k_{s1} & -k_{s1} & 0 & 0 \\ 0 & -k_{s1} & k_{s1} & 0 & 0 \\ -k_g & 0 & 0 & k_{g2}+k_g+k_{s2} & -k_{s2} \\ 0 & 0 & 0 & -k_{s2} & k_{s2} \end{bmatrix}. \tag{2}$$

For the mass normalized damping matrix, Caughy damping method [9] is applied and estimated at 10% for all modes. The displacement vector is $\boldsymbol{x} = \left[x_{f1}\, x_{b1}\;\; x_{t1}\;\; x_{f2}\, x_{t2}\right]^T$, whereas the individual displacements of the DOFs refer to absolute quantities. Note, that the excitation is generated at the foundations of both buildings, not via the ground. The stiffness coefficients in (2) k_g, k_{g1}, k_{g2}, k_{bi}, k_{s2}, and k_{s1} denote the inter-structure soil stiffness, the equivalent soil stiffness beneath the CWH, the equivalent soil stiffness beneath the CGH, the equivalent linear stiffness of base isolator, and the linear shear wall stiffness's of the CGH and CWH buildings, respectively. $\ddot{x}_g$ in (1) denotes the acceleration input signal at the foundation level.

2.3. NONLINEAR, SOIL HYSTERESIS MODEL

The initial linear soil model in Section 2.1 is replaced by a hysteretic model to produce a more accurate representation of the soil behaviour. The governing equations of the hysteretic characteristic can be described by

$$\boldsymbol{f_x} = \alpha \boldsymbol{K}_h \boldsymbol{u}_x + (1-\alpha)\boldsymbol{K}_h \boldsymbol{Z}_x \text{ [10]}, \tag{3}$$

where $\boldsymbol{f}_x$ partially replaces the "restoring force" $\boldsymbol{Kx}$-term in (1) of the linear model (see Section 2.4 for the governing equation of the coupled nonlinear system). $\boldsymbol{K}_h$ is the stiffness matrix of the initial slope of the hysteretic characteristic and α is the post-yielding stiffness ratio. The relative displacement vector is

$$\boldsymbol{u_x} = \begin{bmatrix} x_{f1} - x_{f2} & x_{f1} & x_{f2} \end{bmatrix}^T \tag{4}$$

and $\boldsymbol{Z}_x$ is governed by

$$\dot{\boldsymbol{Z}}_x = \alpha \dot{\boldsymbol{u}}_x - \beta |\dot{\boldsymbol{u}}_x \boldsymbol{Z}_x| \boldsymbol{Z}_x - \gamma \dot{\boldsymbol{u}}_x \boldsymbol{Z}_x^2 \,. \tag{5}$$

where α, β and γ are hysteretic parameters that control the behaviour. Parameters applied to model the soil hysteresis are included in the Appendix.

2.4. BASE ISOLATOR HYSTERESIS MODEL

We apply the extended Park-Wen-Ang hysteresis model by Gavin & Wilkinson [7] to represent the behaviour of BI system of the CWH. The governing equation is

$$f_b = C_y g((1-\kappa) Z_b + \kappa \frac{x_b}{D_y} , \tag{6}$$

where f_b is the mass normalized restoring shear force element of the BI, C_y is the yield strength coefficient, κ is the post-yield stiffness ratio and D_y is the isolator yield displacement. The relative displacement is defined as

$$x_b = x_{f1} - x_{b1} \,. \tag{7}$$

The hysteresis component Z_b is governed by the follow differential equation

$$\dot{Z}_b = \frac{\dot{x}_b}{D_y} - (\alpha \operatorname{sign}(Z_b \dot{x}_b) + \beta) \frac{Z_b^2 \dot{x}_b}{D_y} , \tag{8}$$

where α, β are dimensionless quantities that control the hysteresis behaviour. Parameters applied to model the BI system are included in the Appendix.

2.5. **NONLINEAR GOVERNING EQUATIONS OF THE BUILDING CLUSTER**

The mass normalized equations of motion of the coupled nonlinear building cluster can be written in the following form

$$\ddot{\boldsymbol{x}} + 2\sqrt{\frac{\mathrm{C_y g}}{\mathrm{D_y}}}\, \boldsymbol{\zeta} \dot{\boldsymbol{x}} + \boldsymbol{F}_x = \boldsymbol{f}_g \,, \tag{9}$$

where the displacement vector $\boldsymbol{x} = \begin{bmatrix} x_{f1} & x_{b1} & x_{t1} & x_{f2} & x_{t2} \end{bmatrix}^T$ and the excitation force $\boldsymbol{f}_g = \begin{bmatrix} -m_{f1}\ddot{x}_g & 0 & 0 & -m_{f2}\ddot{x}_g & 0 \end{bmatrix}^T$.

The restoring term in (9) becomes

$$\boldsymbol{F}_x = \begin{bmatrix} f_{g1} + f_g + f_{bi} & -f_{bi} & 0 & -fg & 0 \\ -f_{bi} & f_{bi} + k_{s1} & -k_{s1} & 0 & 0 \\ 0 & -k_{s1} & k_{s1} & 0 & 0 \\ -f_g & 0 & 0 & f_{g2} + f_g + k_{s2} & -k_{s2} \\ 0 & 0 & 0 & -k_{s2} & k_{s2} \end{bmatrix}, \quad (10)$$

where, f_g, f_{g1} and f_{g2} are hysteretic restoring force elements of the soil given by (3) and f_{bi} is the hysteretic restoring force element of the BI given by (6).

We solve the state space formulation of (9) to study the behaviour and response of the building cluster for the three cases of free vibration, harmonic and earthquake excited input signals. The assembly is excited by harmonic and earthquake signals at both foundations.

3. RESULTS AND ANALYSIS

3.1. EIGENVALUES AND MODE SHAPES OF THE LINEAR SYSTEM

The modal behaviour of the system is studied to identify any parameter range(s) of coupling between the buildings. Thus, the linear, undamped eigenvalue problem of (1) or (9) is considered. Figure 2 shows a coupled behaviour of the two buildings over the entire frequency range and for the chosen parameter set (CWH=CGH; equal mass and stiffness parameters).

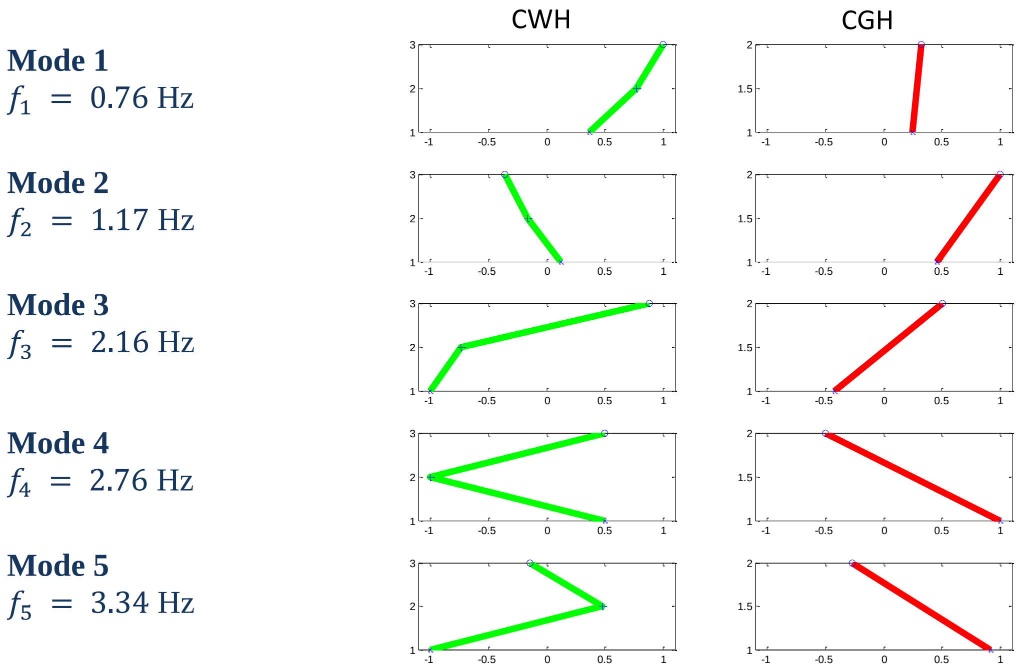


Figure 2. Mode shapes of the linear and the corresponding natural frequencies.

3.2. CLUSTER RESPONSE DUE TO HARMONIC EXCITATIONS

The investigations are extended by forced harmonic excitations at both foundations over the same frequency range.

The response spectrum of the linear model, depicted in Fig. 3, shows that coupling occurs throughout the entire range of natural frequencies and thus, confirms the modal pattern found previously. Thus, for the assumption that the natural modal parameters of the CWH and CGH are approximately equal (or similar) the building assembly appears to be coupled over the entire range of frequencies.

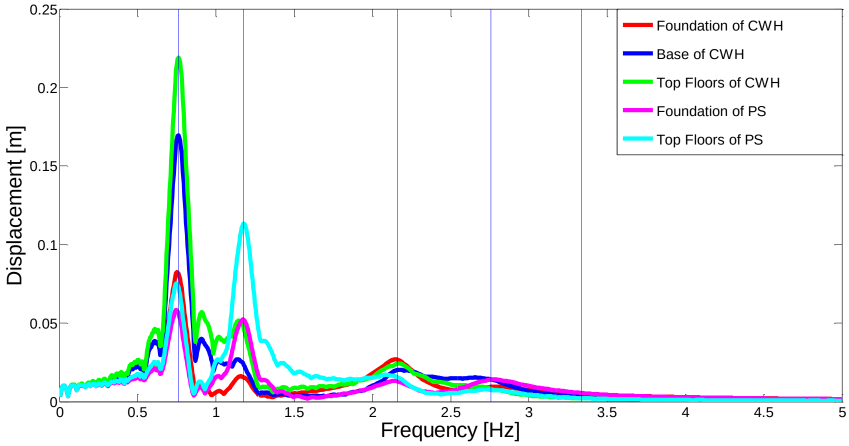


Figure 3. Response spectra of linear model subject to harmonic excitation.[1]

The responses of the nonlinear system, including the hysteretic BI model as well as that of the soil, are depicted in Fig. 4.

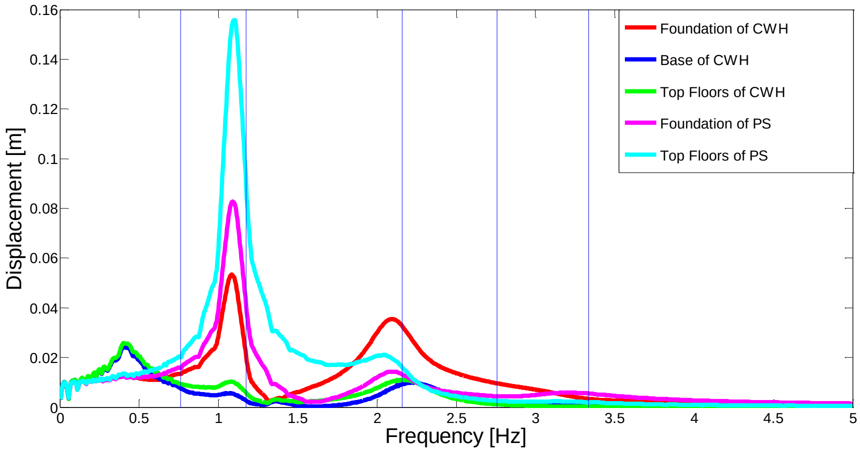


Figure 4. Response spectra of the nonlinear system subject to harmonic excitation.

Figure 4 reveals decoupling between the CWH and CGH building at lower frequencies. This decoupling stems from the installed BI system between the foundation and the base of the CWH building. The blue and green lines are the DOFs above the BI system and clearly show a peak separated from the remaining DOFs. However, at higher frequencies the cluster behaves in a coupled manner.

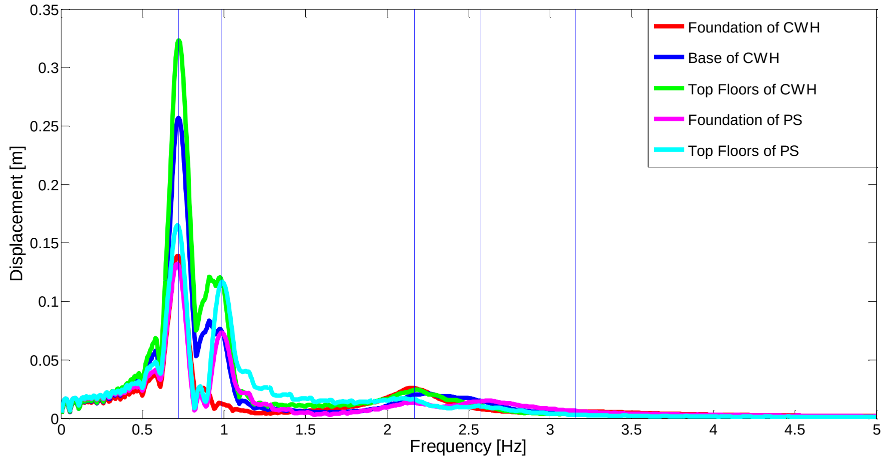
[1] Figures refer to DOFs of the "PS" building, describing the adjacent Parkside building, which is denoted as CGH building in this paper.

3.3. INFLUENCE OF PARAMETERS OF THE CGH BUILDING ON THE INTERACTION BETWEEN THE STRUCTURES

INFLUENCE OF MASS

To investigate the influence of the mass of the adjacent CGH building the mass of the CGH building was doubled. Furthermore, the linear stiffness of the CGH building was also doubled, describing the behaviour of the CGH building as a rigid block.

a)



b)

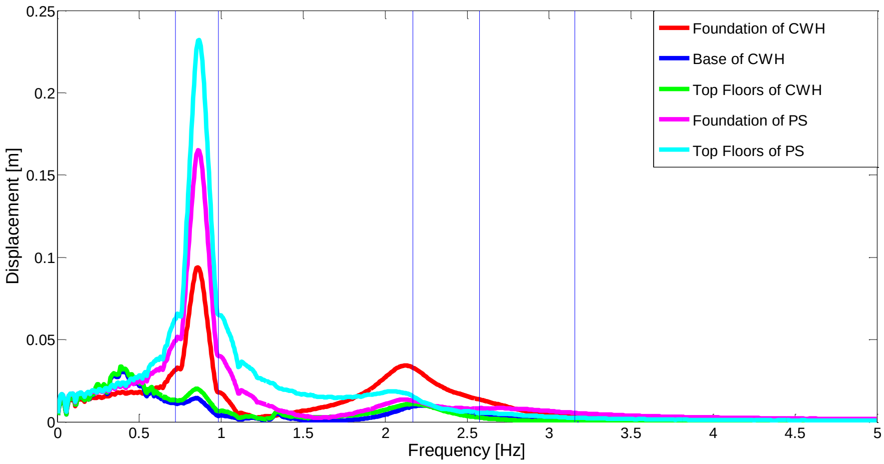


Figure 5. Frequency spectra plotted to investigate the influence of mass of neighboring building for a) linear model and b) hysteretic model.

The effects from doubling the mass of neighboring building can be seen in Fig. 5, wherein a high degree of coupling is evident for both linear and nonlinear models. For the linear system, the two buildings behave co-dependently, reaching resonance peaks collectively. In the nonlinear system decoupling of the top floors of the CWH building from the rest of system DOFs can be observed again at lower frequencies. For frequencies above 1.5 Hz however, the cluster of buildings appear to be behave co-dependently. Note that a shifting of natural frequencies to higher values is evident and that the coupled behaviour occurs over a larger range of frequencies, easily observed in the nonlinear response.

INFLUENCE OF SOIL STIFFNESS's (EQUAL TO BOTH FOUNDATIONS)

To investigate the influence of the soil stiffness on the interaction between the CWH and CGH buildings, the parameters of the soil stiffness's beneath and between the CWH and CGH are varied to extreme cases, whereby the stiffness change is changed by a factor 10.

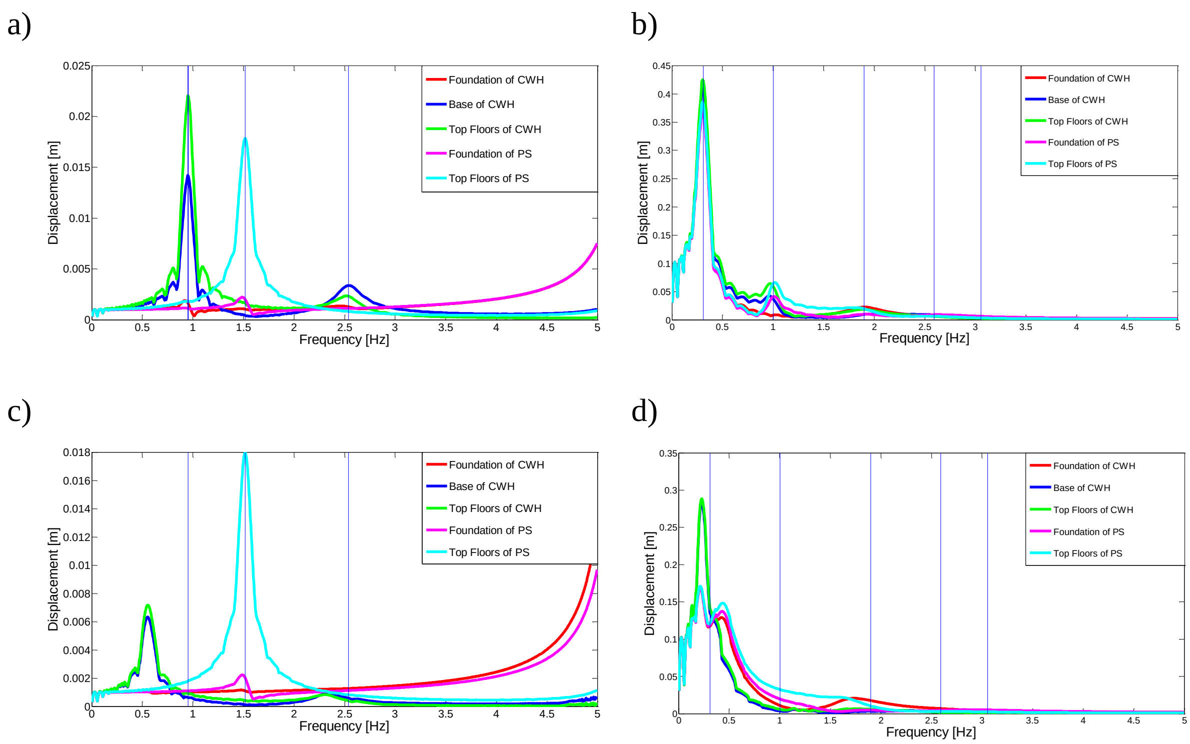


Figure 6. Comparison of frequency responses to different soil stiffness properties; a) and c) stiff soil; b) and d) soft soil; a) and b) linear model; c) and d) nonlinear model.

From the responses of the linear system, Figs. 6a-b, a significant difference in the coupling behaviour can be observed for different soil stiffness's. Responses show a highly decoupled behaviour over a large frequency range. The DOFs belonging to each building show peaks independently of each other. Soft soil conditions, on the other hand, produce responses with a higher degree of coupling, observed by the peaks of the corresponding DOFs of each building to appear together, Fig. 6b. As the stiffness of the soil lessens, the effects of the inter-coupling soil (unchanged in this case) become more dominant and cause a high degree of coupling between the buildings.

Similar results can also be seen in the responses of the nonlinear system, Figs. 6c-d, whereby a high degree of decoupling is observed for stiff soil and a highly coupled behaviour for soft soil conditions. For stiff soil conditions, the nonlinear response shows again the decoupled motion of the above BI DOFs belonging to the CWH building, as expected due to the presence of the BI system. Note that apart from the decoupling of the system, stiff foundation soil conditions also shift the natural frequencies of the system to higher values. In Figs. 6a+c higher natural frequencies are omitted as these values lie beyond the frequency range of interest.

INFLUENCE OF THE INTER-BUILDING SOIL STIFFNESS

Continuing the study on the effects of soil properties on the building interactions, the focus of the study is extended to the effects of the stiffness of the inter-coupling soil between the buildings. As the foundations of each building are modelled to be connected via the soil, the stiffness is varied by a factor of 10 to study the interaction of the two buildings.

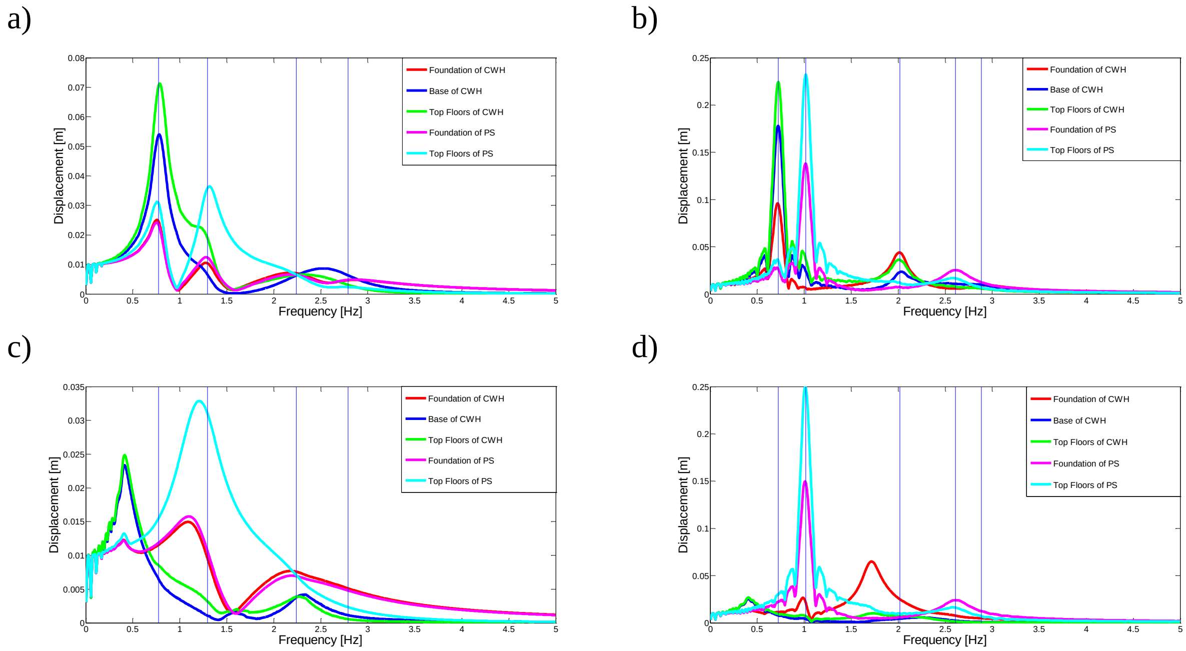


Figure 7. Frequency responses of a) linear model under stiff inter-coupling, b) linear model under soft inter-coupling, c) hysteretic model under stiff inter-coupling and d) hysteretic model under soft inter-coupling.

As observed in Fig. 7a, a stiff inter-foundation soil condition creates a highly coupled system, whereas soft inter-foundation soil conditions reveal a decoupled response of the two buildings, Fig. 7b. As such it could be concluded that a stiffer inter-structure soil condition causes a coupled behaviour as compared to softer inter-foundation soil conditions. The nonlinear, hysteretic responses of the system DOFs show similar results, whereby high interaction between the buildings is observed for stiff inter-foundation soil conditions as compared to the softer counterpart. Initially at lower frequencies, the base isolator effectively isolates the top DOFs of the CWH from the rest of the system. However, at higher frequencies, dominant inter-coupling soil behaviour causes the buildings to behave in an interactive manner. Soft inter-foundation soil conditions, on the other hand, produce a decoupled response, Fig. 7d.

INFLUENCE OF SOIL STIFFNESS's (DIFFERENT TO EACH FOUNDATION)

The soil influences on the interaction between both buildings is studied further by investigating in the responses due to different soil stiffness parameters beneath each foundation. The changes in soil conditions are made in increments of factor 10.

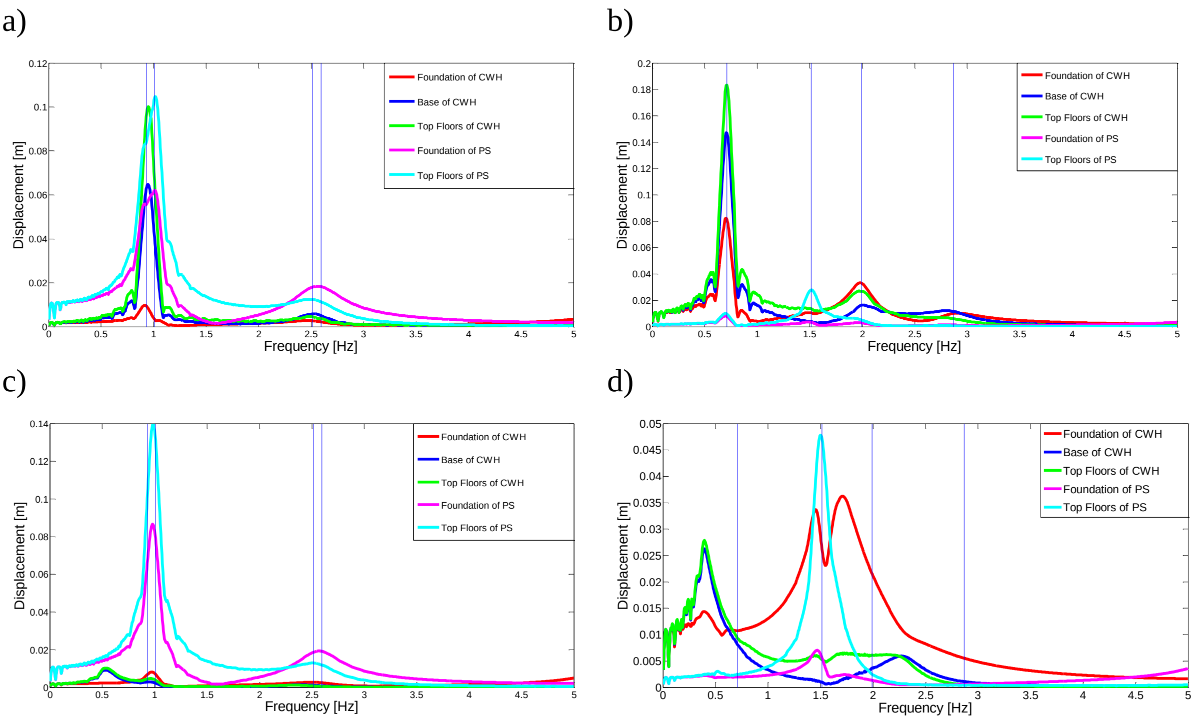


Figure 8. Frequency response of a) the linear system with stiff foundation soil condition beneath CWH and soft foundation soil condition beneath CGH, b) linear system with stiff soil beneath CGH and soft soil beneath CWH, c) nonlinear system with stiff soil beneath CWH and soft soil beneath CGH, and d) nonlinear system with stiff soil beneath CGH and soft soil beneath CWH.

Stiff soil conditions beneath CWH show a coupled response of the cluster at lower frequencies and decoupled response of the system at higher frequencies (as amplitudes of the corresponding CWH DOFs become negligibly small). Stiff soil conditions beneath CGH, on the other hand, show clear decoupling behaviour between the two neighbouring buildings over the frequency range of interest. The nonlinear systems, however, show a different scenario of responses. As expected, the stiff soil beneath the CWH shows a decoupling behaviour of the system over the entire range of frequencies. In contrast, the nonlinear response of the system subjected to stiffer soil conditions beneath the CGH reveals that the BI system decouples the corresponding DOFs of CWH from the rest of the system DOFs and influences of inter-structure soil conditions between the two buildings, Fig 8d. At higher frequencies, the coupling behaviour becomes immediately prominent above the frequency of 1 Hz.

3.4. CLUSTER RESPONSES OF THE NONLINEAR SYSTEM SUBJECT TO EARTHQUAKE EXCITATION

Generous counts of earthquake signals from the Canterbury Quakes 2010/11 have provided abundant amounts of ground acceleration recordings in the hospital campus [4, 5, 11]. Installed at various locations in the CWH and CGH, tri-axial accelerometers have been recording of ground accelerations for numerous incidents of earthquakes since July 2011 [4, 5, 11]. The recordings from 23rd December 2011 of M5.8 Richter are used to excite the nonlinear system.

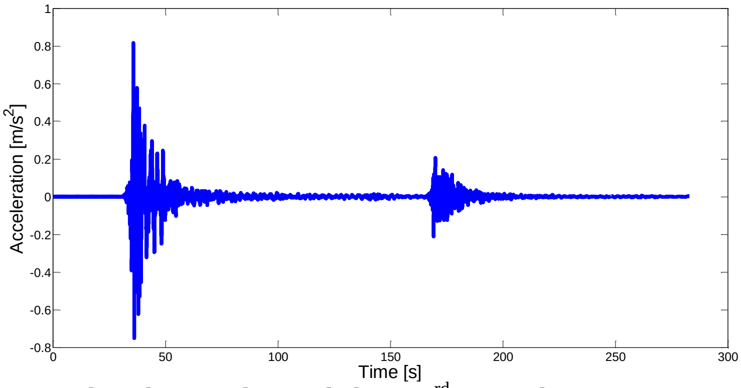


Figure 9. Earthquake signal recorded on 23rd December 2011, M5.8 Richter

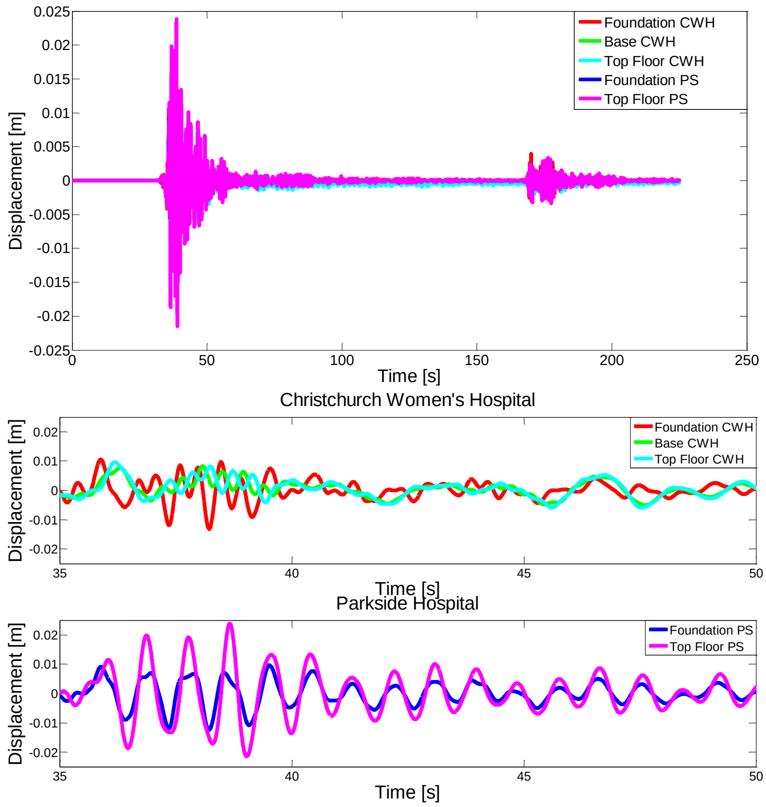


Figure 10. a) Modelled earthquake responses of the nonlinear model to real-life M5.8 earthquake excitation on 23rd December 2011; b) responses of individual building DOFs (zoom in of (a)).

Figure 9 shows the acceleration input signal of the recorded M5.8 earthquake on 23rd December 2011. The measurement location was at the foundation of the CWH building [5]. Figure 10 exhibits the expected behaviour of the BI system. Effective isolation of the CWH shows a smaller amplitude response of the top floors as compared to the foundation of the building. Note the synchronous response of the CWH foundation to the DOFs of the CGH, observed by the in-phase motion. Furthermore, it suggests that the CGH building behaves like a vibrating rigid block.

4. SUMMARY AND FUTURE WORKS

Initial investigations of interaction phenomena due to different soil conditions confirm significant coupling and interactions between buildings that built close to each other. In the presence of BI, effective isolation occurs for the corresponding DOFs above the BI system.

Thus, the foundations remain to have a significant influence on the neighbouring building. Furthermore, investigations revealed that increasing the mass of the adjacent CGH increases the effects of coupling. In addition, the stiffness's of the soil beneath as well as in between foundations determine the degree of interaction present between buildings. The stiffness condition of the inter-coupling soil seems to create a contrasting effect compared to the soil conditions beneath the foundations.

Future investigations will include validations of these findings by analysing the real-life data from the hospital campus.

ACKNOWLEDGEMENTS

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APPENDIX

Model parameters of the hysteresis model (BI system)

parameter	design value	comments
D_y	10 mm	isolator yield displacement
C_y	0.0286	yield strength coefficient
κ	0.157375	post-yield stiffness ratio
α	0.8	
β	0.2	

Model parameters of the CWH and CGH building:

The seismic weight of the CWH building is approximately 169,700 kN [12]. This together with an additional estimated 50% live load is used as the total weight of the superstructure ($m_{total} = 2.6 \cdot 10^7$ kg) and is split across the DOFs as follows:

parameter	value	unit
floor mass, $m_{t1} = m_{t2}$	0.2 m_{total}	kg
floor mass, m_{b1}	0.3 m_{total}	kg
floor mass, $m_{f1} = m_{f2}$	0.5 m_{total}	kg
shear wall stiffness, $k_{s1} = k_{s2}$	$1.66 \cdot 10^9$	N/m