Nonlinear spring-bed modelling for earthquake analysis of multi-storey buildings on shallow foundations

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ABSTRACT: It is important to consider the interaction between the foundation and the underlying soil in the earthquake analysis of multi-storey buildings on shallow foundations. Often this interaction is neglected in current analysis and design practice, and the foundation is assumed to be fixed to the ground. However, nonlinear geometric effects, associated with shallow foundation uplift, and nonlinear soil deformation effects have been shown to have a significant influence on the earthquake response of multi-storey buildings. Therefore, these nonlinear effects should be incorporated into earthquake analysis and design of multi-storey buildings.

This paper presents an approach to including nonlinear soil-foundation-structure interaction (SFSI) effects into spring-bed models of buildings on shallow foundations. Spring-bed models provide a balance between ease of implementation and theoretically rigorous solutions, as well as capacity to include foundation uplift and soil deformation into earthquake analysis of multi-storey buildings on shallow foundations. Existing features of a widely used structural design software package were employed to capture these nonlinear effects and SDOF models of multi-storey buildings on shallow foundations were analysed. These buildings were similar to a number of buildings that appear to have performed satisfactorily during the Christchurch Earthquake and time history analysis suggests that SFSI provides a possible explanation for the good performance of these buildings.

1 INTRODUCTION

The interaction between the soil, foundation and structure during an earthquake has the potential to significantly influence the earthquake performance of multi-story buildings on shallow foundations. Typically, this interaction is neglected in current analysis and design practice, and the foundation is assumed to be fixed to the ground. However, during large earthquake shaking there is often not enough vertical load to preclude uplift of a shallow foundation and this can lead to plastic deformation of the underlying soil (Kelly, 2009; Martin & Lam, 2000). Analytical and experimental studies over recent years have indicated that this nonlinear interaction has a considerable effect on the overall response of multi-story buildings, potentially being beneficial for overall structural performance (for example Anastasopoulos et al., 2010; Gajan et al., 2010). The term soil-foundation-structure interaction (SFSI) has been coined to describe these nonlinear geometrical and soil deformation effects at the soil-foundation interface, differentiating the process from classical linear elastic soil-structure interaction (SSI) (Orense et al., 2010). Integrated numerical models that incorporate SFSI provide a means to more appropriately capture the earthquake response of buildings.

Ideally, integrated numerical models of the structure, foundation and soil should capture all observed physical mechanisms and accurately represent the real system. However, the uncertainty in the input parameters, particularly in earthquake engineering, combined with the time required to develop such models often outweighs the benefits. Spring-bed models, where the interaction between the foundation and the underlying soil is accounted for using discrete, closely spaced springs, provide a balance between ease of implementation and theoretically rigorous solutions (Harden et al., 2005). In addition, most existing structural design software packages have capacity to implement fairly sophisticated spring-bed models. The importance lies in determining the parameters and characteristics of the springs so that the interaction between the foundation and the soil is captured appropriately.

An approach to including nonlinear SFSI effects into spring-bed models of buildings on shallow foundations is presented in this paper. Structure-foundation models of generic 5, 10 and 15 story buildings on beds of nonlinear springs have been developed to investigate the performance of multi-story buildings on shallow foundations in Christchurch during the Christchurch Earthquake. These models were developed to represent a range of buildings in the central business district (CBD) of Christchurch that have performed satisfactorily despite the strong levels of ground shaking experienced. The widely-used structural design software package SAP2000 (CSI, 2011) was employed and the buildings were modelled as single degree of freedom (SDOF) structures. Existing features of the software were used to allow the springs to detach from the foundation, to model uplift, and yield as the compressive loads increased toward bearing failure of the soil beneath. Relevant time history data from the 22 February 2011 Christchurch Earthquake was used to investigate the earthquake response of the models. Comparisons are drawn between the fixed base, traditional SSI and the SFSI responses to ascertain the influence of nonlinear soil-structure interaction in the performance of these buildings.

2 BUILDINGS MODELLED

To investigate the potential influence of SFSI in the earthquake performance of multi-story buildings on shallow foundations during the Christchurch Earthquake, generic 5, 10 and 15 story buildings were modelled. A number of assumptions were made about the size of the buildings, floor loading, and other properties to represent buildings typical to that found in the Christchurch CBD where shallow foundation performance appears to have been satisfactory following the earthquake. Equivalent SDOF models of these buildings were developed and are shown in Figure 1. The procedures outlined by Priestley et al. (2007) were used, where a characteristic displacement defined an equivalent mass to be lumped at an equivalent height above the foundation. The stiffness of the column supporting the mass in the SDOF model was calculated using an assumed fixed base natural period (T_s) of the structure and this enabled an equivalent column size to be determined. For all the buildings, a 16 metre wide by 32 metre long raft foundation at the ground surface was modelled and a bed of 17 vertical springs captured the interaction between the foundation and the underlying soil for two dimensional analyses in the width direction.

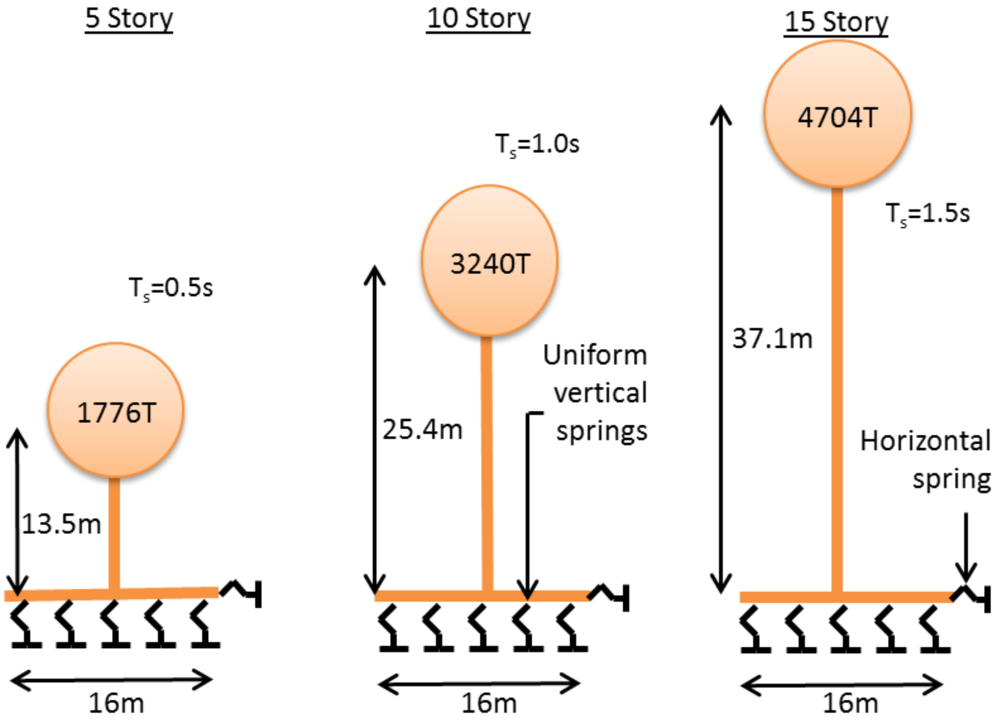

Figure 1. Details of the SDOF models of the multi-story buildings analysed.

3 SPRING-BED MODELLING

3.1 Elastic spring parameters

A bed of nonlinear vertical springs was used to capture interaction between the foundation and the underlying soil during earthquake loading. In order to determine the appropriate parameters of the springs the overall vertical foundation static elastic stiffness was first calculated. This was done using procedures set out by Gazetas et al. (1985), which use the small strain shear modulus of the foundation soil as defined in Equation 1:

$$G_0 = \rho V_s^{\,2} \tag{1}$$

where ρ is the density and V_s is the shear wave velocity of the soil. These parameters were ascertained assuming a gravel foundation soil immediately beneath the shallow raft foundation. The majority of the multi-story buildings on shallow foundations in the Christchurch CBD appear to be founded on gravel. Available borehole, CPT and multi-channel analysis of surface waves (MASW) investigation data from the CBD was utilised to determine an appropriate small strain shear modulus for this soil. This shear modulus could then be used to calculate the overall vertical stiffness of the foundation.

In the Gazetas et al. (1985) procedure, a basic stiffness parameter is calculated and then modified to account for the shape, depth and sidewall contact of the foundation (Equation 2):

$$K_{embedded} = K_{basic} I_{shape} I_{depth} I_{sidewall} \tag{2}$$

where K_{basic} is the stiffness of an infinite strip footing at the ground surface and the I factors are correction factors that account for stiffness contributions of the foundation shape, the depth of embedment, and the vertical sides of the foundation. Since the foundation in this study was located at the ground surface, only the shape factor was required. Dynamic excitation such as earthquake loading has the potential to modify the static stiffness parameters and further work by Gazetas (1991) develops equations and charts for determining a dynamic stiffness coefficient used to modify the static stiffness value. This work uses a parameter a_o, which is proportional to the frequency of excitation ω as shown in Equation 3:

$$a_o = \frac{\omega B}{2V_s} \tag{3}$$

where B is the width of the foundation. The assumed fixed based natural periods of the buildings were used to determine the excitation frequency and associated a_o parameter. Thus the dynamic coefficients for each model were calculated. The dynamic coefficients were then applied to the static stiffness values to determine the final dynamic vertical stiffness of the foundation in each model.

The total dynamic vertical stiffness of each raft foundation was then uniformly distributed to the vertical springs based the tributary area of that spring. A uniform spring distribution was used because previous work by the authors has suggested it gives a close match to theoretical moment-rotation response derived from field testing (Pender et al., 2013).

Horizontal stiffness of the foundation was assigned to a single horizontal spring, as shown in Figure 1. The stiffness of this spring was calculated in a similar method to that for the vertical springs but follows the formulas developed by Gazetas and Tassoulas (1987). The horizontal dynamic factor from Gazetas (1991) was used to determine the dynamic elastic horizontal stiffness values used for the individual springs in each model, and these spring were defined as linear elastic.

3.2 Nonlinear spring-bed modelling

The dynamic vertical spring stiffness values calculated in the above procedure represent elastic parameters that would be used in traditional SSI analysis. In order to appropriately capture the nonlinear interaction between the foundation and soil associated with SFSI, the effects of uplift and plastic soil deformation needed to be incorporated into the definitions of the vertical foundation springs in SAP2000. In this way the interaction during earthquake loading could be captured appropriately. To achieve this the springs were modelled as multi-linear plastic elements with Takeda hysteresis.

To represent uplift, zero force was set for all displacements in the positive tensile range. When a spring was compressed towards the ultimate vertical load, the force-displacement behaviour followed a tri-linear relationship. This relationship was developed using procedures that have been implemented in OpenSees for shallow foundation spring-bed modelling (Harden, et al., 2005), which use a formulation described in Boulanger et al. (1999). The equation describing the nonlinear/plastic portion of this formulation is shown in Equation 4:

$$q = q_{ult} - (q_{ult} - q_0)\left[\frac{c * z_{50}}{c * z_{50} + |z_p - z_0|}\right]^n \tag{4}$$

where q is the instantaneous load, q_{ult} is the ultimate load, q_0 is the load at the initial yield point, z_{50} is the displacement at which 50% of the ultimate load is mobilized, z_0 is the displacement at the initial yield point, z_p is the instantaneous displacement, and c and n are constant parameters. The initial yield point and the constant parameters were determined based on available information for sands (Harden, et al., 2005). A plot of the tri-linear force versus displacement relationship implemented in SAP2000 for a spring from the 10 story structure is presented in Figure 2 along with comparison with the full nonlinear relationship using Equation 4.

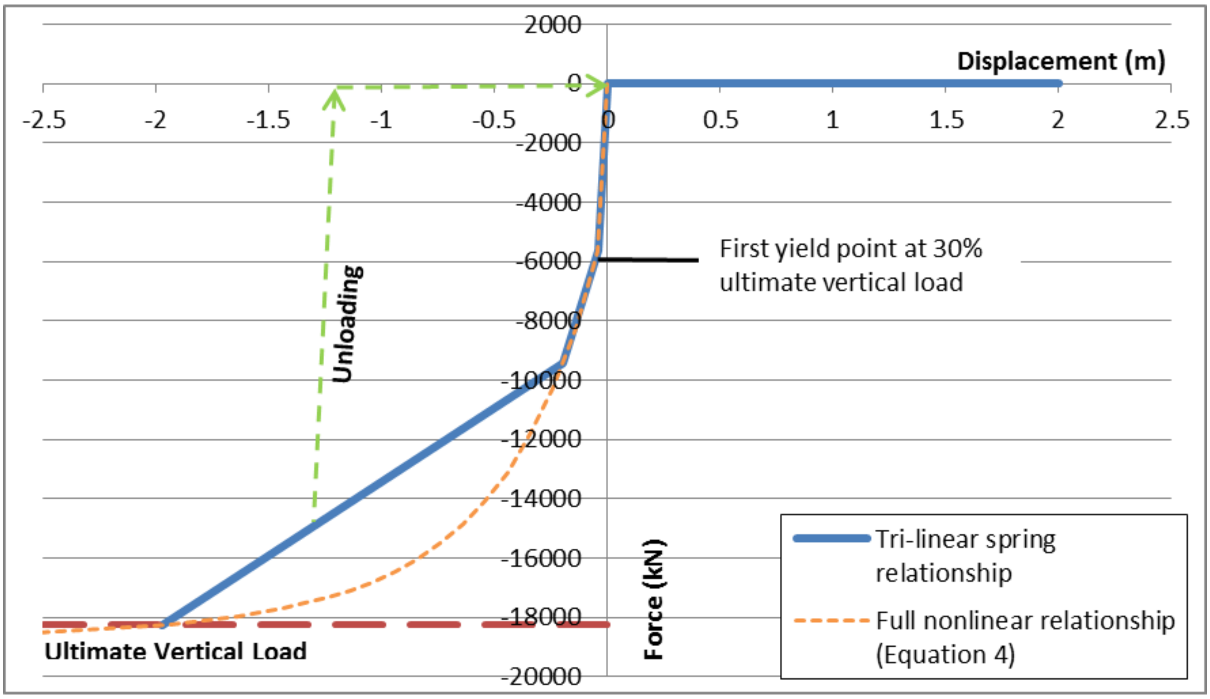

Figure 2. Force-displacement relationship of the vertical springs from the 10 storey building to allow for uplift and plastic soil deformation.

Initially, the elastic stiffness of each spring was used up to 30% of the ultimate vertical load and then two points were chosen to give a reasonable representation of the nonlinear plastic portion. More points could have been specified to give a more accurate approximation of the equation but the tri-linear relationship used was considered appropriate for the scenarios analysed. The ultimate vertical load for the springs was determined by calculating the static bearing capacity of the foundation but allowed for the ultimate moment capacity, which was calculated iteratively so that the bearing capacity matched the vertical load. After plastic deformation occurred, unloading followed the initial stiffness until the horizontal displacement axis was reached, shown by the green dashed arrows in Figure 2, allowing for permanent deformation of a spring and representing the development of a gap beneath the foundation.

4 ANALYSIS AND RESULTS

Numerical analysis of the earthquake response of the generic 5, 10 and 15 storey buildings was undertaken using SAP2000. Nonlinear direct integration time history analyses were carried out using data from the Christchurch Earthquake. The dominant East-West component of records from the CBGS, CCCC and CHHC recording stations in the Christchurch CBD were used in separate analyses. These stations were selected because they have soil profiles that are considered applicable to the location of multi-story buildings on shallow foundations in Christchurch. For each of the buildings and earthquake records, the fixed base and SSI scenarios were compared with the SFSI scenario to assess the influence of uplift and soil deformation on the response of the buildings.

The peak acceleration of the lumped mass during earthquake shaking gives an indication of the maximum force each generic building is subjected to during the earthquake. Figure 3 compares the peak acceleration of the lumped mass of the fixed base structures with that of the structures where elastic SSI and nonlinear SFSI was included for the Christchurch Earthquake records used in this study. When compared to the fixed base scenario, SFSI significantly reduces the peak acceleration of the structure in all cases. SSI generally reduces the peak acceleration compared to the fixed base but to a lesser degree than SFSI and less consistently across the structures and earthquake records. A reduction in peak acceleration means that the forces transmitted to the structure are reduced and suggests improved structural performance.

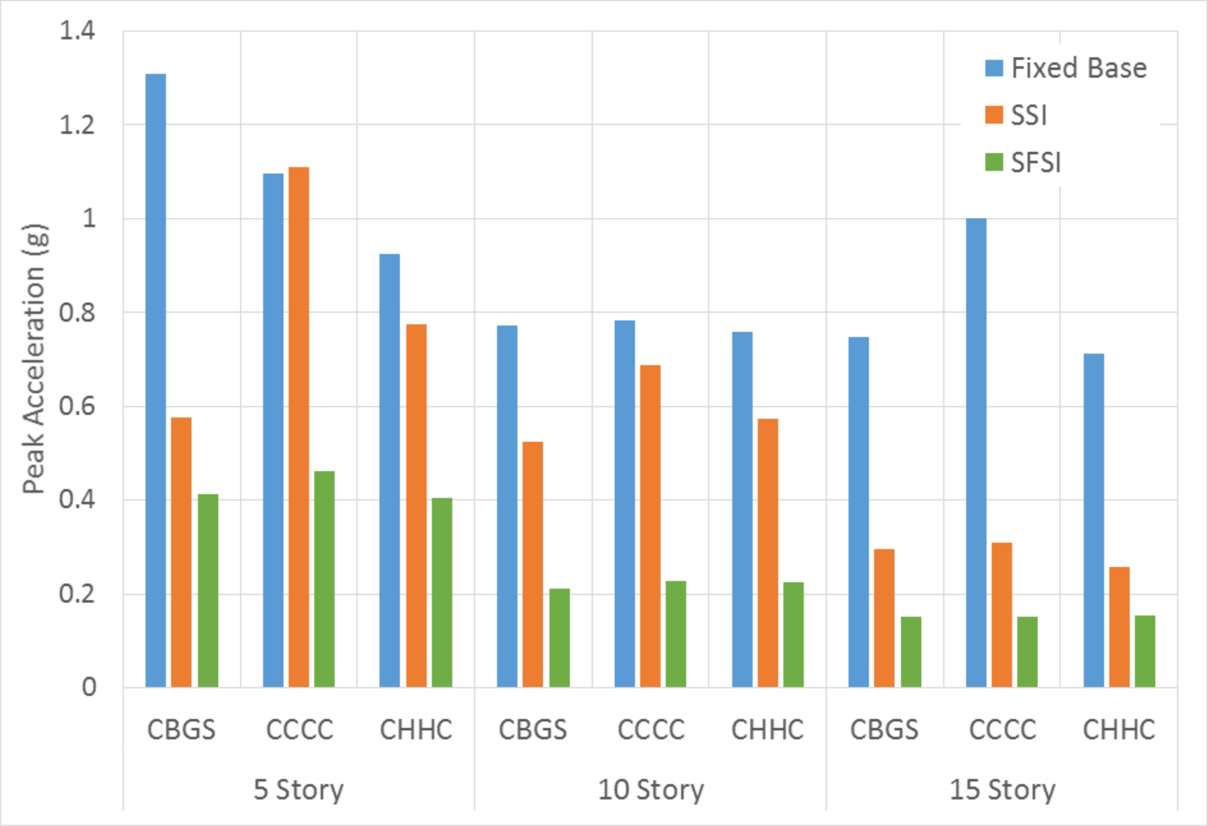

Figure 3. Peak accelerations of the lumped mass of the 5, 10 and 15 story SDOF models with fixed base, SSI and SFSI conditions subjected to 3 Christchurch Earthquake CBD records used in this study (CBGS, CCCC, and CHHC).

SFSI influences the response of multi-story buildings on shallow foundations by affecting the way earthquake acceleration of the ground is transmitted into the structure. To gain an understanding of this influence, the 5% damped pseudo-acceleration response spectrum of the acceleration of the lumped mass during the time history analyses can be plotted and comparisons drawn between fixed base, SSI and SFSI responses. Figure 4 presents the response spectrum plots for the three buildings subjected to the CHHC earthquake record. The reduction in peak spectral response due to SFSI is evident in the plots, however, SSI only reduces the peak spectral response for the 15 storey structure and even increases the response for the 10 storey structure. SSI is based on the assumption that the there is always full contact between the underside of the foundation and the supporting soil and that there is always a significant reserve of bearing strength, so during large earthquake shaking it is not likely to accurately capture the response of the building. Nonlinear SFSI is a more appropriate method for capturing how earthquake shaking may be transmitted to a structure.

In Figure 4, the period of maximum response increases when interaction effects are included. There is generally a slight increase for the SSI cases and a more significant increase for the SFSI cases. This increase means that the response of the structure moves away from the typically higher spectral acceleration content of an earthquake found at lower period (higher frequency) values. Also included in Figure 4 are analysis cases where the springs were only able to uplift (i.e. there is no plastic soil deformation). The similarities between the SFSI and uplift only cases suggest that uplift was the dominant mechanism for the systems analysed.

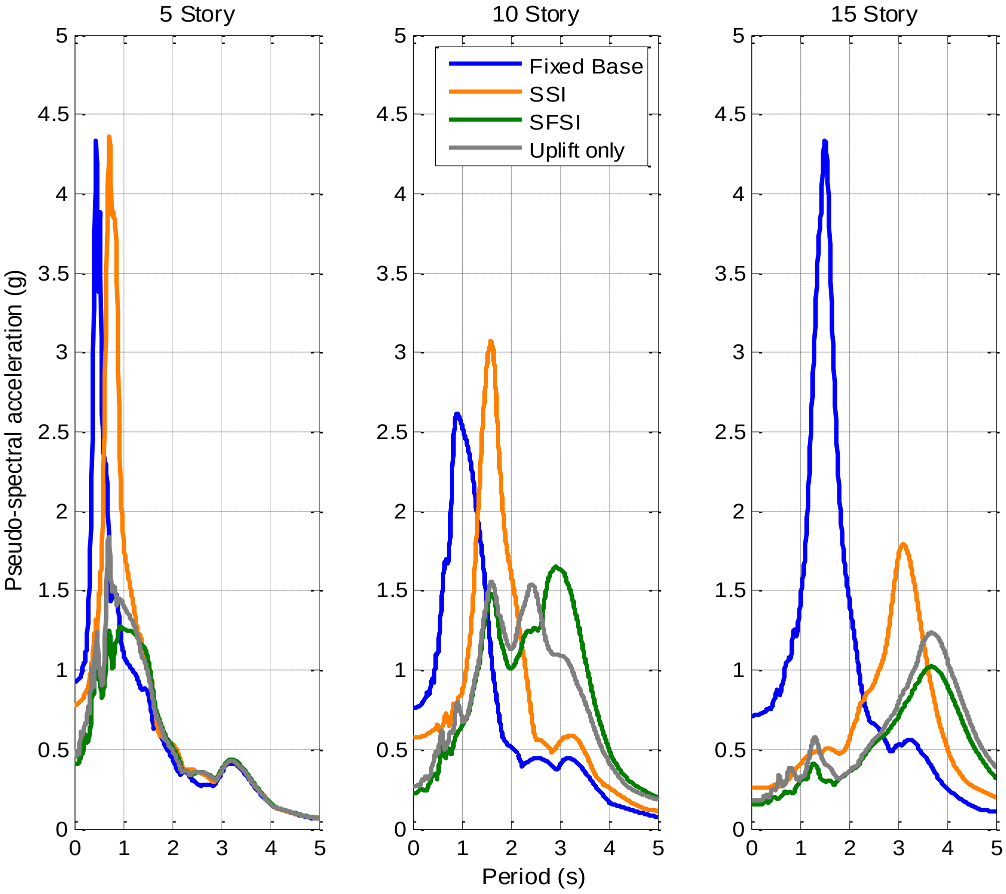

Figure 4. Pseudo-spectral acceleration response spectrum plots of the acceleration of the lumped mass of each building subjected to the CHHC record for fixed base, SSI, SFSI and uplift only conditions.

Uplift of the foundation from the supporting soil appears to have a significant influence on the response of the multi-story buildings. However, the extent of foundation rotation required to cause this uplift is not significant. Figure 5 (a) gives an example of the time history of foundation rotation for the 10 story building subjected to the CHHC record. The maximum rotation is only 0.017rad (about 1°) yet the effect on the overall response of the structure has been shown to be significant. In Figure 5 (b), the time history of an uplift parameter *U*, defined as the instantaneous number of springs attached to the foundation divided by the total number of springs, gives an indication of the foundation contact area during the earthquake. Together the plots in Figure 5 show that even though the foundation rotation is small, a large percentage of the foundation loses contact during excitation and this causes a reduction in the response of the structure as shown in Figures 3 and 4.

Plastic deformation of the soil does not appear to have had as significant an influence as uplift on the response of the buildings. Figure 6 (b) shows that plastic deformation occurs for the 10 story building subject to the CHHC record, and at the end of the excitation the springs on the end of the foundation were found to have permanently detached. This was the case for all the buildings scenarios analysed. However, the bearing capacity static factors of safety for the 3 buildings are large, ranging from 380 for the 5 story building to 144 for the 15 story building. This means there was a large reserve of bearing capacity even when a large portion of the foundation uplifted. Thus, the buildings on shallow raft foundations in Christchurch that predominantly rest on stiff gravel were able to uplift during the Christchurch Earthquake without having a detrimental effect on bearing capacity, even when plastic deformation of the soil occurred at the peripheries. A small extent of uplift has resulted in plastic soil deformation but uplift has been the main mechanism in causing a significant reduction in the response of multi-story buildings on shallow foundations in Christchurch.

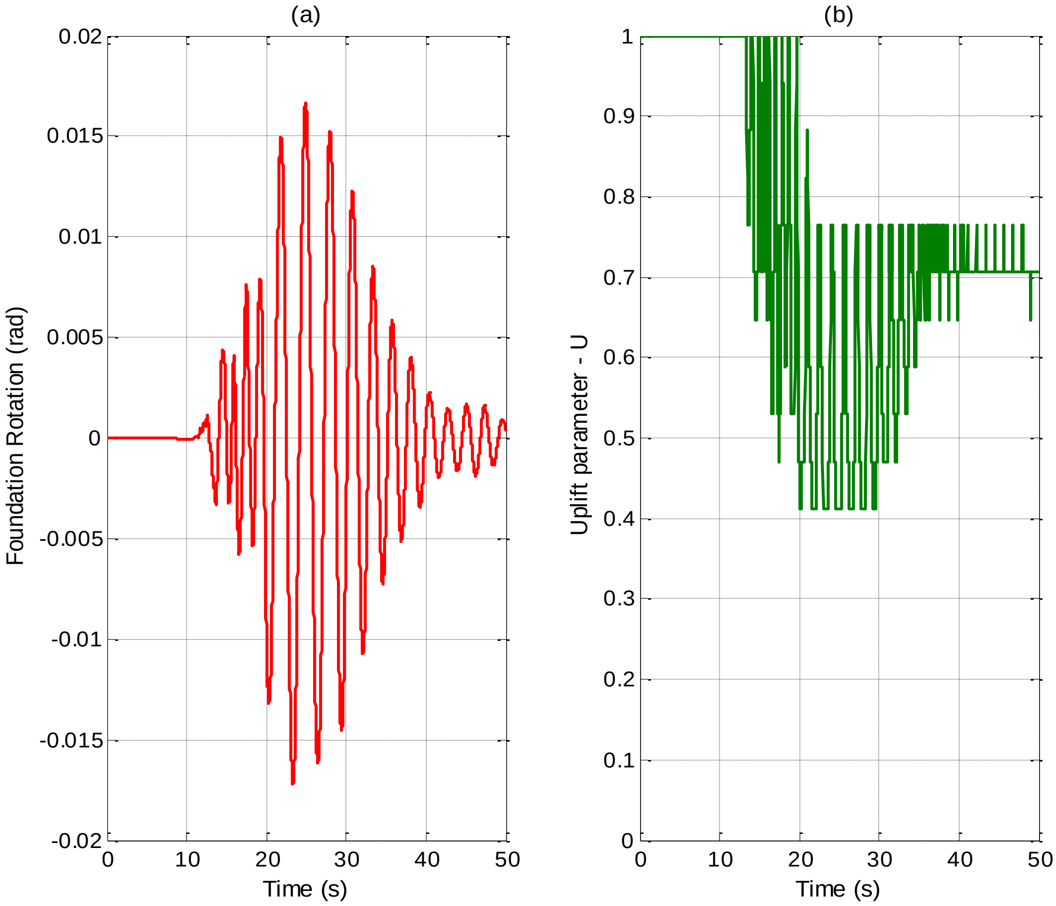

Figure 5. 10 story building earthquake time history response (CHHC record) of (a) foundation rotation and (b) uplift parameter *U* (springs attached / number of springs).

5 CONCLUSIONS

A straightforward approach for including the nonlinear effects of SFSI in spring-bed modelling of buildings on shallow foundations subject to earthquake excitation has been presented. Existing features of the widely used structural design software package, SAP2000, were utilised to undertake nonlinear spring-bed modelling, highlighting the capability of existing software and the ease with which SFSI can be incorporated into the earthquake analysis of structures. More sophisticated modelling techniques and software are available and may more accurately represent the nonlinear geometric and soil deformation behaviour but it is also important that structural and geotechnical disciplines work effectively together to appropriately analyse and design for SFSI. From analysis of SDOF 5, 10 and 15 storey buildings on shallow foundations, similar to those found in the CBD of Christchurch, it was found that SFSI may have been influential in the successful performance of these buildings during the Christchurch Earthquake.

The importance of integrated numerical modelling and the consideration of appropriate interaction between the foundation and the underlying soil has been highlighted in this paper with specific reference to building performance during the Christchurch Earthquake. Shallow foundations of multi-story buildings in the Christchurch CBD are likely to have uplifted, causing plastic deformation of the underlying soil, which together have significantly reduced the peak acceleration of the structure during the earthquake. However, uplift is likely to have been the dominant mechanism due to the large reserve of bearing capacity available from the large raft foundations resting on stiff gravel soils. Importantly, it was also found that only small foundation rotations and extents of uplift were required to have a large effect on structural response. Overall, SFSI may provide improved understanding of the observed earthquake performance of multi-storey buildings on shallow foundations.

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