SFSI in shallow foundation earthquake response

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ABSTRACT: Soil-foundation-structure interaction (SFSI) incorporates nonlinear geometrical effects and nonlinear soil deformation effects into earthquake analysis of structure-foundation systems. For shallow foundations, this involves uplift of the foundation from the supporting soil and yielding of the foundation soil during large earthquake shaking. These effects can have a significant influence on the earthquake response of buildings on shallow foundations.

Investigation of structure-foundation models on beds of nonlinear springs has provided interesting insights into the earthquake response of shallow foundations. A widely-used structural design software package (SAP2000) was employed to model these integrated systems. The springs were allowed to detach from the foundation to model separation of part of the foundation from the supporting soil and allowed to yield when the compressive loads would indicate bearing failure of the soil beneath. Time history data from the 22 February 2011 Christchurch Earthquake was used to investigate the earthquake response of models of a typical multi-storey building on a shallow foundation.

The effects of foundation uplift and yielding of the foundation soil on the earthquake response of buildings on shallow foundations were demonstrated through this analysis. Integrated structure-foundation numerical modelling showed that the earthquake response of a 10-storey building was very different when loss of contact was allowed between part of the foundation and the underlying soil.

1 INTRODUCTION

The investigation of the performance of buildings during earthquakes has led to an increasing awareness of the need to appropriately model the interaction between the foundation and the underlying soil. Geotechnical and structural considerations are typically dealt with separately in a traditional design scenario, where the axial, shear, and moment loading assuming a fixed base structure is provided to the geotechnical engineer to undertake foundation design. This fragmented approach results in inefficient and sometimes less effective foundation systems, particularly when dynamic loading is considered. Integrated numerical models that include the soil, foundation and structure provide a means to more appropriately capture the earthquake response of buildings.

Soil-foundation-structure interaction (SFSI) incorporates nonlinear geometrical effects and nonlinear soil deformation effects into integrated numerical analysis of structure-foundation systems. This is in contrast to traditional soil-structure interaction (SSI), which is based on the fiction that the interaction between the soil and the foundation is linear elastic. For shallow foundations, SFSI may involve uplift of the foundation from the supporting soil as well as yielding of the foundation soil during large earthquake shaking. Uplift and soil yielding can have a significant influence on the earthquake response of buildings on shallow foundations.

Numerical time history analysis has been utilised to investigate the role of SFSI in the earthquake response of a multi-storey building on a shallow foundation. The widely-used structural design software package SAP2000 (CSI, 2011) was used to model a 10-storey building on a shallow raft foundation, similar to buildings found in the central business district (CBD) of Christchurch, New Zealand. The building was modelled as a single degree of freedom (SDOF) structure on a bed of springs, where the springs were able to detach from the foundation to model separation of part of the foundation from the supporting soil and were able to yield when the compressive loads would indicate bearing failure of the soil beneath. Spring-bed models capture interaction between the foundation and the underlying soil in a relatively straightforward manner and set out to balance ease of use in general engineering practice with more rigorous theoretical solutions for which there may be uncertainties in the input parameters (Harden & Hutchinson, 2009). Time history data from the 22 February 2011 Christchurch Earthquake was utilised to investigate the earthquake response of the structure-foundation system and interesting insights were gained into the influence of SFSI using a range of foundation scenarios.

The influence of SFSI on the earthquake response of the 10-storey building on a shallow foundation was ascertained through numerical analyses comparing uplifting and yielding foundation response with that of a fixed base structure and a non-detaching SSI foundation. Two spring-bed modelling procedures were used in the analyses so that the influence of these different procedures could also be determined. The effects of foundation uplift and the potential effects of yielding of the foundation soil on the earthquake response of buildings on shallow foundations could be demonstrated through this analysis.

2 BACKGROUND – CHRISTCHURCH EARTHQUAKE

Following the 4 September 2010 moment magnitude (M_w) 7.1 Darfield Earthquake, a large series of aftershocks have affected the city of Christchurch, New Zealand. In particular, the M_w 6.2 Christchurch Earthquake on 22 February 2011 has significantly impacted that part of the country. This aftershock is the most costly earthquake to have affected New Zealand, with 181 fatalities and significant damage to lifelines, infrastructure and residential and commercial buildings (Cubrinovski et al., 2011). Despite the tragedy of this earthquake, a wealth of data on the response of the built environment has been and is being gathered, allowing insights into the behaviour of structures, their foundations and the soil they are founded on.

In the CBD of Christchurch there are a number of multi-storey buildings on shallow foundations where foundation performance appears to have been satisfactory despite the strong levels of ground shaking. This is predominantly the case in areas where liquefaction has not been significantly manifested at the ground surface. An area of the CBD, shown by the black square in Figure 1, has been identified as containing many buildings that appear to have performed reasonably well and where the predominant observation following the Christchurch Earthquake was of no observed ejected liquefied material at the ground surface. Valuable information can be gathered from investigation of buildings that have performed well during large earthquakes, not just those that perform unsatisfactorily, and examination of the role of SFSI in the successful performance of buildings in this area of the CBD can provide important insights into the earthquake performance of structures.

3 BUILDING MODELS

A generic 10-storey building on a shallow raft foundation has been used as the basis of this study. A number of assumptions were made about the size of the building, floor loading, and other properties to represent a building typical to that found in the Christchurch CBD where shallow foundation performance appears to have been satisfactory following the Christchurch Earthquake. An equivalent SDOF model of the building was developed using the procedures outlined by Priestley et al. (2007), where a characteristic displacement was used to determine an equivalent mass (3620T) to be lumped at an equivalent height (25.8m) above the foundation. The stiffness of the column supporting the mass in the SDOF model was calculated using an assumed fixed base natural period of the structure and this enabled an equivalent size column to be determined. A 24m square raft foundation was modelled and a bed of 33 vertical springs captured the interaction between the foundation and the underlying soil.

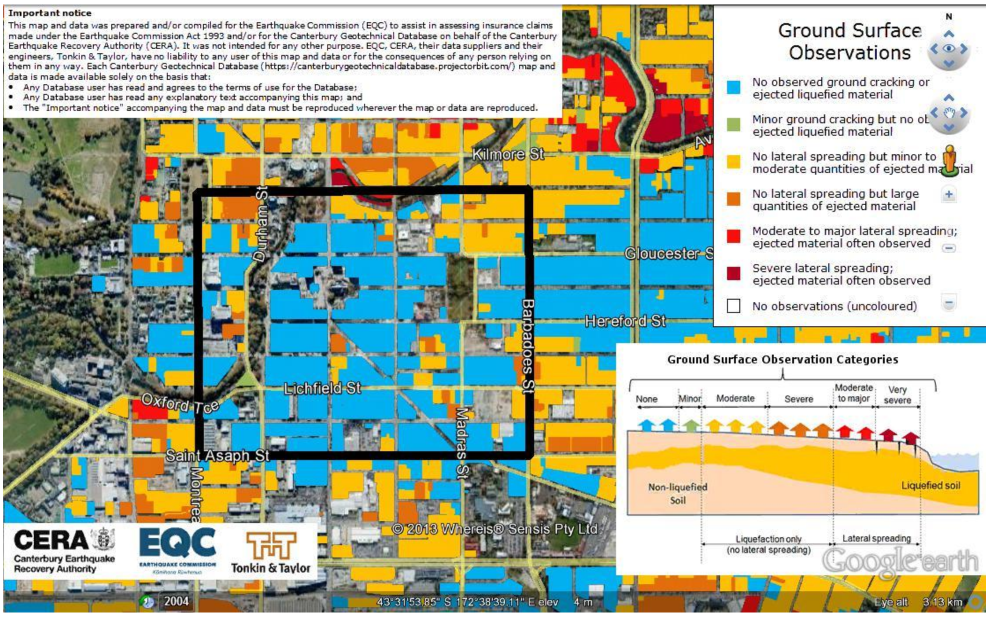

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Figure 1 Area of interest in the Christchurch CBD showing a predominance of no ejected liquefied material following the Christchurch Earthquake (after Canterbury Geotechnical Database, 2012)

Two commonly used spring-bed models were used in this study. Firstly, a "Uniform Spring" model was developed where the stiffness of the foundation was divided evenly between the foundation springs. Procedures set out by Gazetas et al. (1985) were used to determine foundation vertical stiffness, which was then distributed based on each springs tributary area. Secondly, a "FEMA Spring" model was developed using the procedures outlined in the FEMA-356 (2000) document. In this code the vertical and rotational stiffness of the footing can be made compatible by assigning higher vertical stiffness at the edge of the footing, allowing a more accurate representation of foundation rotational stiffness. In both models, a single spring was used to model the horizontal stiffness of the foundation and the stiffness of that spring was determined using the formulas developed by Gazetas and Tassoulas (1987). The final two structure-foundation models of the 10-storey building implemented in SAP2000 are shown in Figure 2.

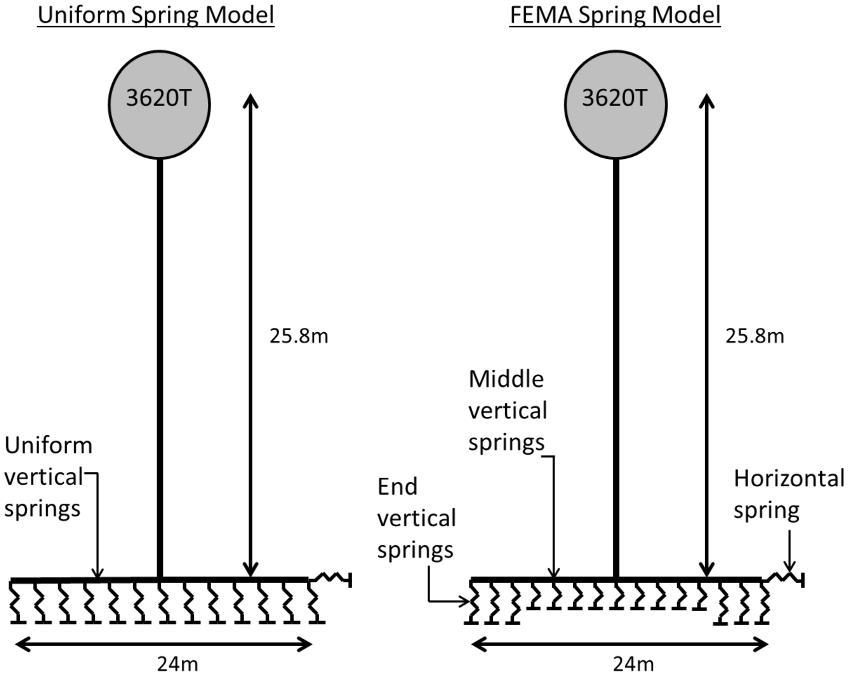

Figure 2 SDOF building and foundation spring models implemented in SAP2000

The properties of the springs were ascertained assuming a gravel foundation soil immediately beneath the shallow raft foundation. The majority of the multi-storey buildings on shallow foundations in the Christchurch CBD appear to be founded on gravel and parameters consistent with findings from geotechnical investigations in the city were used to model this material.

To model uplift, the foundation needed to be able to detach from the springs when the force in a spring reduced to zero. In this way the foundation would not apply tensile forces to the underlying soil. For the analysis of uplift only, this was achieved in SAP2000 by setting the springs as gap elements. These elements can take compression loads only so that when the spring force reaches zero a gap opens up between the foundation beam and the spring.

For analysis of combined uplift and yielding, the springs were modelled using the multi-linear plastic with Takeda hysteresis property available in SAP2000. To represent uplift, zero force was set for all displacements in the positive tensile range. When a spring was compressed, the load deformation behaviour followed a bilinear relationship in that once the load reached 0.8 times the ultimate vertical load, determined using the static bearing capacity for the tributary area of each spring, the spring yielded and the spring stiffness reduced to 10% of the initial value. Once yielding occurred, unloading followed the initial stiffness until the horizontal displacement axis was reached, allowing for permanent deformation of a spring.

4 ANALYSIS AND RESULTS

Nonlinear direct integration time history analyses were undertaken on the Uniform Spring and FEMA Spring models of the 10-storey building using SAP2000. Time history data from the 22 February 2011 Christchurch Earthquake was used to investigate the earthquake response of building with a range of foundation scenarios. The earthquake response of a fixed base model was compared with the Uniform Spring and FEMA Spring foundation models for cases where the springs did not detach from the foundation, as in traditional SSI, and where the springs were able to uplift and yield. Varying amounts of uplift and yielding were represented by scaling the earthquake record and this enabled investigation of the influence of SFSI on the earthquake response of the building to be undertaken. In addition, comparisons were made between the two foundation modelling procedures. From these analyses conclusions are drawn about the influence of SFSI on the response of buildings on shallow foundations in the Christchurch CBD.

4.1 Scaled earthquake time history analysis

Direct integration time history analyses were run in SAP2000 using scaled earthquake records from the CHHC recording station (S89W component) located in the Christchurch CBD (see GNS Science, 2012). This record was used because the soil profile at the site of this station is considered to be applicable for sites where multi-storey buildings on shallow foundations are located in Christchurch. The vertical load was applied first so that the foundation springs were initially in a compressed state. This was seen to be the case in reality as the soil is already loaded due to the weight of the building. Then each scaled earthquake time history was applied and the analysis run for about an extra 25% of the total time of the earthquake excitation to capture the free response and subsequent decay of motion of the building after the excitation. Damping was specified as directly proportional to the mass and the stiffness to achieve 5% system damping for a fixed base structure.

Once the analysis was complete the computed absolute horizontal acceleration of the lumped mass was retrieved for each scaled earthquake time history. The 5% damped pseudo-acceleration response spectrum of this data was calculated to make comparisons between the responses of the systems at different levels of acceleration. This was done for a fixed base case as well as a non-detaching SSI case, an uplift only case and an uplift and yielding case for the Uniform Spring model and the FEMA Spring model. The results of these analyses are presented in Figure 3 along with the pseudo-acceleration response spectrum plots of the scaled input acceleration records for reference in the top right corner of the figure. The combined uplift and yielding case is not included in Figure 3 because it was found that yielding did not occur during excitation and so the response was the same as for the uplift case presented.

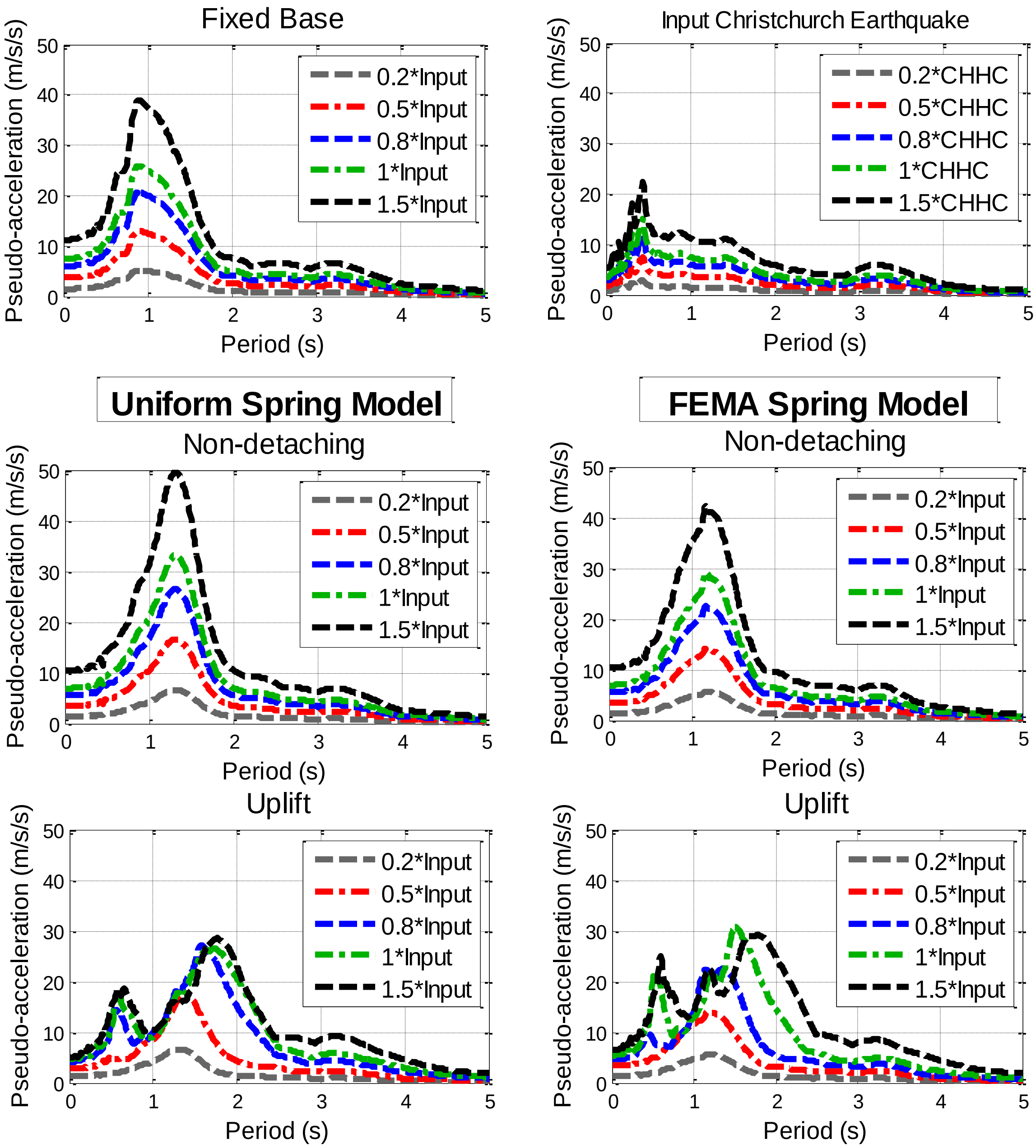

Figure 3 Pseudo-acceleration response spectrum plots of the absolute acceleration of the lumped mass due to the scaled Christchurch Earthquake input excitation (CHHC record - pseudo-acceleration response spectrum shown in the top right) for a fixed base case, and non-detaching and uplifting cases for the Uniform Spring and the FEMA Spring models

4.2 Influence of SFSI on earthquake response

Uplift of the foundation from the supporting soil was found to have a significant influence on the response of the structure. The results in Figure 3 show that the period of maximum response increased from the fixed base case to the non-detaching SSI cases and then increased further when uplift occurred. The period of maximum response in the non-detaching plots occurred at the same value for all levels of excitation. In contrast, once uplift was initiated at excitations greater than 0.5 times the Christchurch Earthquake record, the period of maximum response occurred at higher and higher values as the level of excitation and corresponding uplift increased. This is referred to as a softening system. The shift in period of maximum response to higher values means that the response of the structure moves away from the typically higher acceleration content of an earthquake found at lower period (higher frequency) values and may mean that the forces transmitted to the structure are reduced. By comparing the fixed base and non-detaching plots with the uplift plots for the 1.5 times Christchurch Earthquake record, it can be seen that uplift reduced the response of the structure considerably.

Uplift appears to act as an effective isolation mechanism for the structure. Uplift of the foundation from the supporting soil causes the magnitude of the peak response of the structure to not change significantly as the scale of the time history increases. This can be seen in Figure 3, where the peak response did not change considerably when uplift occurred from 0.8 to 1.5 times the Christchurch Earthquake. In contrast, the peak response almost doubles for the fixed base and non-detaching spring cases from 0.8 to 1.5 times the input record. By accounting for the SFSI effect of an uplifting shallow foundation it appears that the loads transmitted to the structure may be reduced and this has the potential to reduce structural damage.

Upon further investigation of the numerical time history analyses, it was discovered that not just the extent of foundation uplift but the number of times a large amount of uplift occurred had a significant influence on the response of the structure-foundation system. A similar total extent of uplift can be observed for 1 times the Christchurch Earthquake record and 1.5 times the input record. However, there was an increase in the period of maximum response for the larger input acceleration due to this extent of uplift occurring more often and for a longer period of time. The influence of SFSI appears to be more significant as the level of earthquake excitation increases and the extent and occurrence of uplift increases.

As mentioned, it was found that yielding of the foundation gravel did not manifest in the structure-foundation model analysed despite a large extent of uplift observed. If it had occurred then it is likely that it would have resulted in further softening of the structure-foundation system and possibly reduced forces transmitted to the structure (Anastasopoulos et al., 2010; Pecker & Chatzigogos, 2010). However, the consequence would be residual foundation settlement and/or rotation. The lack of soil yielding is likely to have had an influence in the successful performance of multi-storey buildings on shallow foundations in Christchurch, which are predominantly founded on gravel. The stiff nature of the gravels and the distribution of loads across a large raft foundation may have meant that a shallow foundation could undergo brief instances of substantial uplift without any soil deformation.

4.3 **Uniform Spring and FEMA Spring models**

The uplift responses of the Uniform Spring model and FEMA Spring model to the scaled Christchurch Earthquake time history appeared to be quite similar in Figure 3. However, at closer inspection, when uplift occurred at excitations greater than 0.5 times the Christchurch Earthquake record, the period of maximum response appeared to be slightly lower for the FEMA Spring model. For the non-detaching cases, the period of maximum response was the same for all acceleration levels but the magnitude of the response was consistently smaller for the FEMA Spring model. These differences in response appear to be due to the way the distribution of vertical springs influences the foundation response.

The FEMA Spring model was developed to more accurately represent foundation rotational stiffness by having stiffer vertical springs on the edges of the foundation. This foundation model resulted in smaller foundation rotation during the earthquake excitation, with maximum values of 0.08° for the non-detaching case and 0.5° for the uplift case, when compared to the Uniform model, which had maximum foundation rotations of 0.2° for the non-detaching case and 0.8° for the uplift case. The smaller rotation may provide the reason for the consistently smaller response of the FEMA model for the non-detaching case. However, when uplift occurred, the FEMA model experienced a larger maximum extent of uplift (more springs detached) than the Uniform model and uplift occurred over a shorter period of time during the excitation. This is evident in Figure 4, which displays the number of springs attached to the foundation during a portion of the 1 times the Christchurch Earthquake time history when uplift is occurring. It appears that even though fewer springs remained attached for the FEMA foundation, suggesting that the maximum extent of uplift was greater, the combination of smaller foundation rotation and the shorter time of uplift occurring caused a reduced shift in the period of maximum response of the structure when compared to the Uniform Spring model. Therefore, more appropriately capturing the rotation stiffness of a foundation appears to affect the overall response of the structure, highlighting the need to capture and appropriately model the interaction between the foundation and the underlying soil in the earthquake response of buildings on shallow foundations.

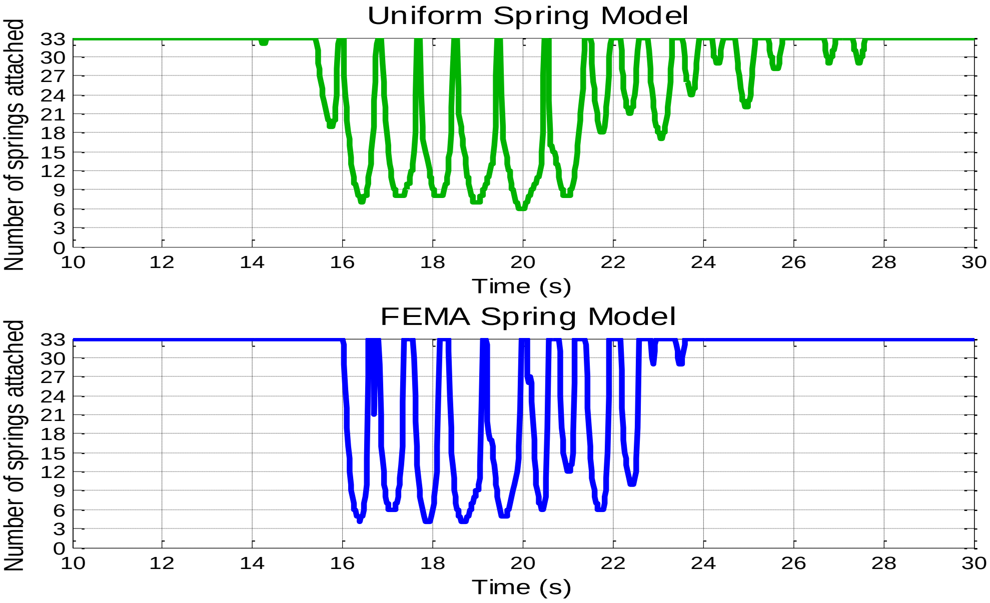

Figure 4 A portion of the time history of the number of springs attached to the foundation during the 1 times Christchurch Earthquake record for the Uniform Spring and FEMA Spring models

It can also be generally concluded that small foundation rotations result in a large extent of foundation uplift and overall this has a significant influence on the response of the structure. It may be considered conservative to design to prevent uplift and soil yielding occurring during earthquake loading but it is suggested that during strong shaking these phenomena cannot be avoided. A small rotation of the foundation resulted in substantial uplift and influenced the overall response of the structure in the analysis. Furthermore, uplift and soil yielding appeared to be beneficial for building performance. Therefore, rather than neglecting the nonlinear interaction between the foundation and the soil, it is suggested that SFSI should be incorporated into earthquake design of buildings on shallow foundations.

5 FURTHER WORK

The results presented in this paper provide important understanding of the role that SFSI may have in the earthquake response of buildings on shallow foundations and further work is planned to follow up these findings. The existing features available in SAP2000 have been used in the analyses described and incorporation of SFSI was relatively straightforward. Therefore, having a more detailed structural model can be easily developed and models of actual buildings in Christchurch, with allowance for SFSI effects, will be able to be easily implemented into the existing SAP2000 framework. Comparisons can then be made between different SFSI models and actual building response during the Christchurch Earthquake to ascertain what procedure may be more appropriate. Also, damping can be more appropriately assigned to the foundation springs and the structure separately to get a more realistic representation of foundation energy dissipation during earthquake loading. This work will allow the performance of buildings on shallow foundations to be more accurately determined and may aid future earthquake design.

6 CONCLUSIONS

This paper has shown the role SFSI may have in influencing the earthquake response of buildings on shallow foundations. There are a number of multi-storey buildings on shallow foundations in the

Christchurch CBD that have performed reasonably well following the Christchurch Earthquake in 2011, particularly in areas where liquefied material has not been manifested at the ground surface. Integrated numerical modelling of a generic 10-storey building on a shallow raft foundation similar to buildings in the Christchurch CBD has shown that SFSI may have been influential in the successful performance of these buildings.

It was found that uplift of the foundation from the supporting soil may have acted as an effective isolation mechanism and potentially reduced damage to the structure during the earthquake. The fundamental period of the structural response was shifted to higher values, away from the typically damaging energy content of an earthquake, reducing the forces transmitted from ground shaking to the structure. In addition, the stiff nature of the gravel soil that generally underlies these buildings on shallow foundations was found to not yield during the large extent of uplift experienced, and this is likely to have also had an influence on the successful performance of these buildings. By comparing traditional fixed base and non-detaching SSI models with models that allow for the nonlinearities of foundation uplift and soil yielding, it was shown that SFSI may provide improved understanding of the observed successful earthquake performance of multi-storey buildings on shallow foundations.

Two commonly used spring-bed models, a Uniform Spring model and a FEMA Spring model, were used to represent the interaction between the foundation and the underlying soil. Both models showed the significant influence of SFSI on the earthquake response of buildings on shallow foundations. A small foundation rotation was found to cause a substantial extent of foundation uplift and significantly influence to the overall response of the structure. It is suggested that SFSI should not be neglected, may be beneficial to structural performance, and should be incorporated into assessment of the performance of buildings during large earthquakes to aid future earthquake resistant design.

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