

## Soil-foundation-structure interaction in shallow foundation spring-bed modelling

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### ABSTRACT

There is increasing awareness in earthquake engineering of the need to consider the structure, foundation, and underlying soil in an integrated fashion. The traditional design scenario, where the geotechnical and structural considerations are dealt with separately, results in inefficient and sometimes less effective foundation systems. Integrated numerical models provide a means to more appropriately capture the earthquake response of buildings; however, this does not necessarily require the development of evermore complex models. Spring-bed models used to capture the interaction between the foundation and the soil provide a balance between ease of implementation and theoretically rigorous solutions. By incorporating nonlinear interaction effects associated with soil-foundation-structure interaction (SFSI) into a spring-bed model, the earthquake response of buildings can be appropriately captured.

A structure-foundation model on a bed of nonlinear springs has been developed for a multi-storey building on a shallow raft foundation in Christchurch, New Zealand. A widely-used structural design software package (SAP2000) was employed to model this integrated system and existing features of the program were used to capture the nonlinear effects of foundation uplift and soil yielding in the springs. Time history data from the 22 February 2011 Christchurch Earthquake was used to investigate the earthquake response of the building. The results of analysis of this integrated SFSI numerical modelling showed that the earthquake response was very different when loss of contact was allowed between part of the foundation and the underlying soil.

### 1 INTRODUCTION

The investigation of the earthquake performance of buildings 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. Integrated numerical models that include the soil, foundation and structure 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

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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. To achieve this, the nonlinear interaction effects associated with soil-foundation-structure interaction (SFSI) should be incorporated into spring-bed modelling.

SFSI incorporates nonlinear geometrical effects and nonlinear soil deformation effects into integrated numerical analysis of structure-foundation systems (Orense et al., 2010). This is in contrast to traditional soil-structure interaction (SSI), where the interaction between the soil and the foundation is assumed to be 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.

A structure-foundation model on a bed of nonlinear springs has been developed for a multi-storey building on a shallow raft foundation in Christchurch, New Zealand. The widely-used structural design software package SAP2000 (CSI, 2011) was employed to model this integrated system. The building was modelled as a single degree of freedom (SDOF) structure and existing features of SAP2000 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. Time history data from the 22 February 2011 Christchurch Earthquake was used to investigate the earthquake response of the building and interesting insights were gained into the implementation of spring-bed models and the influence of SFSI in the earthquake response of buildings on shallow foundations.

## **2 BACKGROUND - BUILDING MODELLED AND THE CHRISTCHURCH EARTHQUAKE**

An 11 storey building in the central business district (CBD) of Christchurch, New Zealand has been used as the basis to undertake the SFSI analysis in this paper. The building comprises of a 9 storey steel framed tower on top of a 2 storey reinforced concrete podium, with one level of basement resting on a raft foundation about 4 meters below ground level. A cross section of the building in the east-west direction with representative dimensions is presented in Figure 1. The building is one example of many multi-storey buildings on shallow foundations in Christchurch where performance appears to have been satisfactory during the  $M_w$  6.2 Christchurch Earthquake on 22 February 2011.

In the CBD of Christchurch there are a number of multi-storey buildings on shallow foundations where performance appears to have been satisfactory despite the strong levels of ground shaking during the Christchurch Earthquake. This is predominantly the case in areas where liquefaction has not been significantly manifested at the ground surface. Valuable information can be gathered from investigation of these buildings that have performed well, 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. SFSI analysis has been undertaken by creating a simple single degree of freedom (SDOF) model for the superstructure and developing a nonlinear spring-bed model to represent the interaction between the raft foundation and the underlying soil.

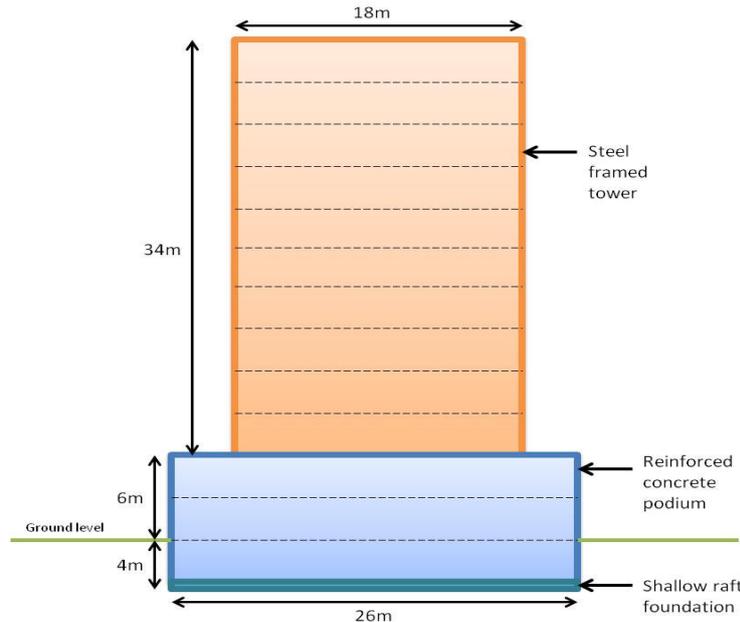


Figure 1: Cross section of the 11 storey building analysed in this paper (east-west)

### 3 BUILDING MODEL DEVELOPMENT

A model of the 11 storey building on a shallow raft foundation analysed for this paper was developed in SAP2000 by making a number of assumptions. The 9 storey steel tower was modelled as an equivalent SDOF “lollipop” type structure (see Figure 2), where an equivalent mass of the entire building (including the mass of the podium) was lumped at the top of the tower. To determine the building mass, assumptions were made about the floor loading to determine appropriate values for steel and reinforced concrete portions of the building. The procedures outlined by Priestley et al. (2007) were used to develop the SDOF model of the structure, where a characteristic displacement was used to determine an equivalent mass (4128T) to be lumped at an equivalent height (27.4m) 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 tower and this enabled an equivalent size column to be determined. The podium was modelled as a rigid, massless box as it was much stiffer than the steel tower. Finally, the 42 meter by 26 meter raft foundation was modelled and a bed of 11 vertical springs captured the interaction between the foundation and the underlying soil for analysis in the east-west direction (analysis in the north-south direction was not included in this paper).

#### 3.1 Spring-bed modelling

A bed of nonlinear vertical springs was used to capture SFSI effects on the response of the building to 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:

$$G_0 = \rho V_s^2 \quad (1)$$

where  $\rho$  is the density and  $V_s$  is the shear wave velocity of the soil. The raft foundation of the building analysed in this study rests on gravel, as do the majority of multi-storey buildings on shallow foundations in Christchurch that have performed well during the earthquake. Available borehole, CPT and MASW investigation data in the vicinity of the building was utilised to determine the small strain shear modulus of 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):

$$K_{embedded} = K_{basic} I_{shape} I_{depth} I_{sidewall} \quad (2)$$

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. 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  $\omega$  as shown in Equation 3:

$$a_o = \frac{\omega B}{2V_s} \quad (3)$$

where  $B$  is the width of the foundation. The assumed fixed based natural period of the building was used to determine the excitation frequency and associated  $a_o$  parameter. Thus the dynamic coefficient for the raft foundation in this study was calculated. The dynamic coefficient was then applied to the static stiffness value to determine the final dynamic vertical stiffness of the foundation.

The total dynamic vertical stiffness of the raft foundation was then distributed to the vertical springs using two procedures. The first procedure involved distributing the stiffness uniformly to the springs based on each springs tributary area to create a "Uniform Spring" model. The second procedure used the FEMA-356 (2000) document to distribute the foundation stiffness to the springs. 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. From this a "FEMA Spring" model was developed. The final two structure-foundation models of the 11-storey building implemented in SAP2000 are shown in Figure 2.

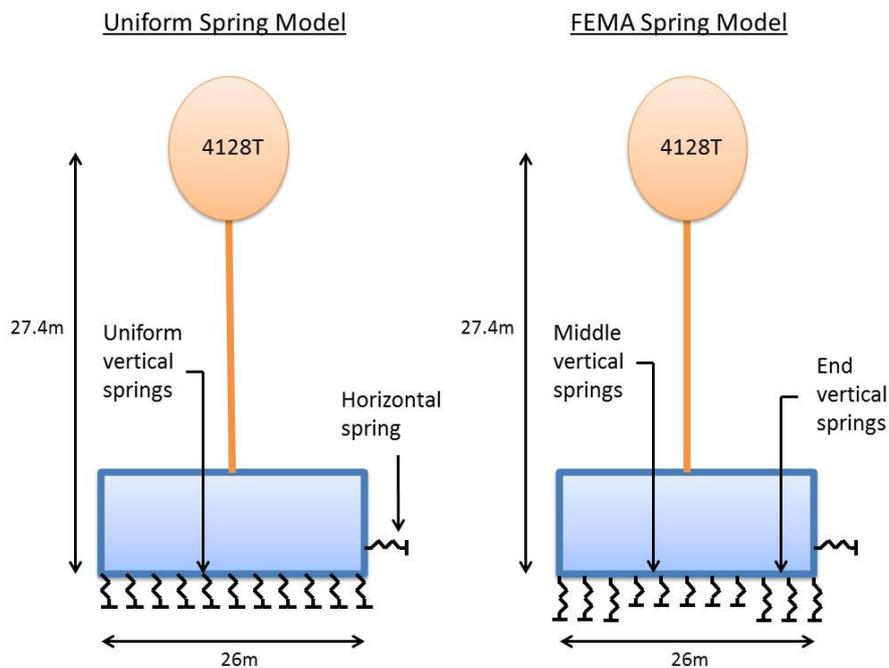


Figure 2: SDOF building and foundation spring models implemented in SAP2000

In both models the horizontal stiffness of the foundation was assigned to a single elastic horizontal spring shown in Figure 2. The stiffness of this spring was calculated in a similar method to that explained above for the vertical stiffness but follows the formulas developed by Gazetas and Tassoulas (1987), with the dynamic factor applied from Gazetas (1991).

### 3.2 SFSI in spring-bed modelling

Once the elastic spring stiffness values were ascertained, the nonlinear SFSI effects of uplift and soil yielding needed to be incorporated into the definitions of the foundation springs in SAP2000. In this way the interaction between the foundation and the soil 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. The ultimate vertical load was determined by calculating the static bearing capacity for the tributary area of each spring but allowed for the ultimate moment capacity of the foundation, which was calculated iteratively so that the bearing capacity matched the vertical load. The force versus displacement relationship for a spring on the edge of the Uniform Spring model is presented in Figure 3.

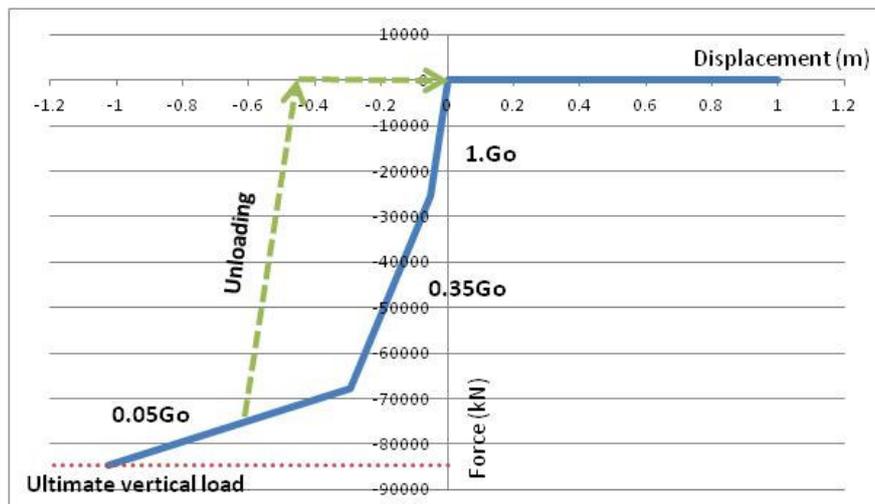


Figure 3: Force-displacement relationship of vertical springs to allow uplift and yielding

In the yielding, compressive portion of the spring force-displacement relationship, the stiffness using the full  $G_o$  value was used for low loads up to 30% of the ultimate. After this point the spring yielded and a factor of 0.35 was applied to  $G_o$  at intermediate loads between 30% and 80% of the ultimate. The 0.35 factor was derived from Eurocode 8-Part 5 (2003), which suggests an "operational" value for the small strain stiffness to account for the level of strain anticipated in earthquake loading. After the load reached 80% of ultimate, the spring yielded further and the stiffness reduced to 5% of the initial value. Once yielding occurred, unloading followed the initial stiffness until the horizontal displacement axis was reached, shown by the green dashed arrows in Figure 3, allowing for permanent deformation of a spring.

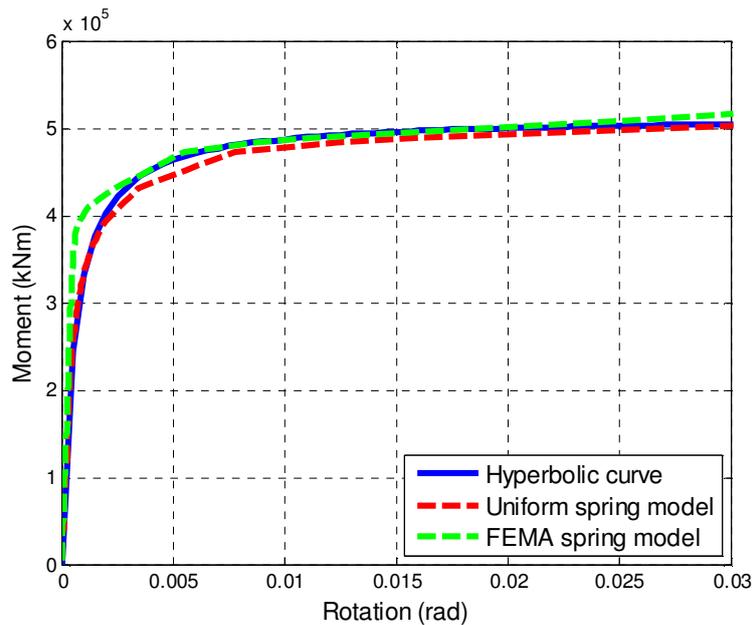
## 4 ANALYSIS AND RESULTS

Numerical analysis on the earthquake response of the 11 storey building was undertaken using SAP2000. Firstly, static push-over analysis was carried out to investigate the effects of SFSI on the response of the structure and compare the Uniform Spring and FEMA Spring models. Then nonlinear direct integration time history analyses were undertaken using time history data from the Christchurch earthquake to investigate the earthquake response of the building with different

foundation scenarios. 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, as in SFSI.

#### 4.1 Static pushover analysis

The first part of the numerical modelling involved investigation of the static push-over characteristics of the two spring-bed models. The vertical load was applied first and then a horizontal load was applied as an acceleration of the lumped mass in a step-wise manner until the critical moment was reached. The results of these analyses are presented in Figure 4 and established the moment-rotation characteristics of the Uniform Spring and FEMA Spring models.



**Figure 4: Moment-rotation curves for pushover analysis of the spring-bed models and comparison with a theoretical hyperbolic curve**

Figure 4 was developed following the work done by Pender et al. (2013), where the moment-rotation curves for the two spring-bed models were compared with a theoretical hyperbolic curve developed by Algie (2011). This hyperbolic curve was established through correlating field experimental data from the rocking response of a shallow foundation with finite element modelling. It uses the initial rotational stiffness of the foundation (calculated using the "operational" shear modulus mentioned previously) and the moment capacity of the foundation to give an accurate representation of the theoretical moment-rotation response of a shallow foundation.

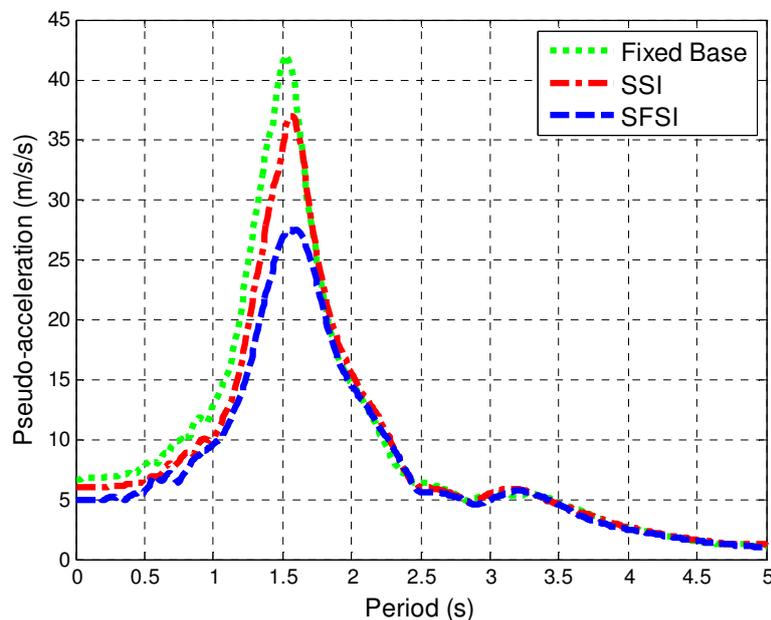
Firstly, the pushover analysis results for the Uniform Spring and FEMA Spring models show how the response of the foundation becomes increasingly nonlinear with inclusion of the effects of SFSI. This could have a significant influence on the response of a structure. Secondly, the Uniform model matches the hyperbolic relationship fairly closely whereas the FEMA model over-predicts the foundation moment for small rotation values. These small rotation values are important for the evaluation of SFSI effects on shallow foundation design.

#### 4.2 Christchurch time history analysis

Direct integration time history analyses were run in SAP2000 using the earthquake record 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 the site of the 11 storey building analysed in this paper. 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 the earthquake time history was applied and the analysis run for about an extra 20% 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. The 5% damped pseudo-acceleration response spectrum of this data was calculated to make comparisons of the response of a fixed base case with that for a non-detaching SSI case, and an uplift and yielding SFSI case. The results for the Uniform Spring model are presented in Figure 5, and the results for the FEMA Spring model were similar.



**Figure 5: Pseudo-acceleration response spectrum plot of the absolute acceleration of the lumped mass due to the scaled Christchurch Earthquake input excitation (CHHC record) for a fixed base case, a non-detaching SSI case and an uplift and yielding SFSI case for the Uniform Spring model**

SFSI was found to have a significant influence on the response of the structure. The results in Figure 5 show that the maximum response of the structure reduces considerably from the fixed base case when SFSI is considered. Also, the period of maximum response increased from the fixed base case to the non-detaching SSI case and SFSI case. 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. The SFSI effects of uplift and soil yielding appear to reduce the forces transmitted to the structure from earthquake ground shaking.

On closer inspection of the time history of the foundation spring force-displacement results, it was found that the first yield point (at 30% of the ultimate vertical load) was never reached in any of the springs. This suggests that yielding of the foundation gravel did not occur during the loading despite a fairly large extent of uplift occurring. It appears that the combination of uplift of the foundation from the supporting soil and lack of yielding of that soil may have had an influence in the successful performance of this multi-storey building on a shallow foundation in Christchurch.

## 5 CONCLUSIONS

This paper has shown the importance of integrated numerical modelling and the consideration of appropriate interaction between the foundation and the underlying soil. It has also shown the role SFSI may have in the earthquake performance of buildings on shallow foundations.

A widely used structural design software package, SAP2000, was used to model nonlinear interaction effects associated with SFSI through spring-bed modelling. Through pushover analysis, the spring-bed models have been shown to appropriately capture the moment-rotation characteristics of a shallow foundation, particularly for the case where the vertical foundation stiffness was distributed uniformly to the springs. Spring-bed models provide a balance between ease of implementation and theoretically rigorous solutions, and by assigning appropriate parameters and characteristics to the springs, can appropriately capture the earthquake response of multi-storey buildings on shallow foundations.

It was found that uplift of the foundation from the supporting soil may have potentially reduced damage to an 11 storey structure on a shallow raft foundation in the Christchurch CBD during the Christchurch Earthquake. The maximum response of the structure was reduced when SFSI was considered, and the fundamental period of the structural response was shifted to higher values, away from the typically damaging energy content of an earthquake. This meant that forces transmitted from ground shaking to the structure were reduced. In addition, the analyses suggest that the gravels underlying this building did not yield during the large extent of uplift experienced, and this is likely to have also had an influence on the successful performance of this building. 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. 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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