Approaches to design of shallow foundations for low-rise framed structures

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ABSTRACT: We compare two approaches to the design of the foundations for low-rise reinforced concrete framed structures founded on discrete shallow footings. The underlying soil is stiff clay. The first approach considers the foundations separately from the structure, uses the equivalent static method to estimate foundation actions, and then proportions the foundations to have adequate bearing strength under these actions. The second considers an integrated model of the structure-foundation system. Computer modelling was undertaken using RUAUMOKO (Carr 2004), a nonlinear dynamic structural analysis program. The framed structures on shallow foundations, connected with tie beams (not considered to be part of the foundation), were analysed and the effects of structural yielding, nonlinear soil behaviour and foundation uplift were determined. Yielding and uplift characteristics of the foundations have been modelled by adapting available structural models in the software. The main conclusion from the paper is that the sophistication of the integrated computer model gives an enhanced understanding of the behaviour of the system that may lead to more economical foundation design.

1 INTRODUCTION

In this paper we compare two approaches to the earthquake resistant design of shallow foundations for a three-storey framed structure. Firstly, the equivalent static approach using the NZ Loadings Standard is followed. Secondly, the response of a numerical model of the building/foundation system subject to an earthquake time-history is calculated. In developing this numerical model our aim was to achieve comparable levels of sophistication in representing the structure and foundation.

In recent years there has been a rising demand for superior performance under earthquake loading of both existing and new infrastructure. Assessing accurately the existing state of foundation systems is particularly demanding. By considering the structure and foundation as an integrated system, new opportunities may arise for achieving superior performance; the purpose of this paper is to demonstrate an extension of our initial work in this area (Wotherspoon et al 2004a, 2004b). It is envisaged that integrated design of structure/foundation systems will lead to improvements in an environment where performance-based criteria are the norm, and also assist in making more accurate assessment of the available capacity of existing structures and foundations when retrofit is being considered.

Herein, we explore the application of software for the dynamic analysis of structures and adapt some of the structural models to represent shallow foundations. Both yielding of the foundations and uplift are modelled. Yielding of beams and columns in the structure is included. Our intention in using a software package such as RUAUMOKO (Carr 2004), which is intended for structural analysis, is to investigate what can be achieved with existing facilities, and also to develop an environment to enhance communication between structural and geotechnical specialists.

Various foundation and structural characteristics were investigated to demonstrate effects on the behaviour of the whole system. Herein, discussion is confined to low-rise framed structures on shallow foundations where foundation uplift is the main challenge for the numerical model.

One approach is to follow the equivalent static method. Documents in use in New Zealand imply that the maximum bearing capacity demand during earthquake loading should not exceed more than about half the available ultimate capacity. However, this considers each foundation separately and does not give a view of the behaviour of the total structure/foundation system. The use of RUAUMOKO to examine the performance of the whole system during earthquake excitation overcomes this limitation. To date, our approach has been to make use of different structural elements in RUAUMOKO and consider how they can be adapted to model foundation behaviour. In our earlier papers we illustrated how various structural elements, particularly yielding springs, can represent aspects of foundation behaviour. Herein, we explore this further and overcome one of the limitations of our earlier work. Existing RUAUMOKO elements allowed us to model uplift when the vertical load on the foundation becomes zero, but did not allow us to detach the shear and moment springs at the instant of uplift, so that at this time moment and horizontal equilibrium were not fully satisfied for the structure. We have now developed a detaching foundation element that uplifts when the vertical load on the foundation is zero and also detaches shear and moment springs. As the interaction between the applied actions - vertical load, horizontal shear, moment - and the bearing capacity and stiffness of a shallow foundation is complex, we are still some way from having a satisfactory foundation element.

2 STRUCTURE DESCRIPTION

The design of a three-storey framed structure with shallow foundations is considered; the details are given in Figure 1. As can be seen, the structure is five bays long and three bays wide. Each bay is 7.5 m by 9.0 m and the storey heights are 3.65 m, with the exception of the first storey which is 4.5 m.

The shallow foundations are located in a layer of stiff clay with an undrained shear strength of 100 kPa. This value is typical of Auckland residual clay which has vane shear strengths in the range of about 70 to 120 kPa plus. For earthquake loading the undrained shear strength will be greater because of the rate of loading. An increase of about 40% in the undrained shear strength of this soil when tested at rates of loading comparable to those during a seismic event has been observed for these soils (Ahmed-Zeki et al 1995). Thus, the value of 100 kPa used herein for earthquake loading is equivalent to the lower end of the range of values found in normal site investigations.

The structure was such that all members contributed to the seismic resistance, and each frame parallel to the direction of earthquake propagation had identical member configuration. The floor loads were a dead load of 7.5 kPa and a live load of 2.5 kPa (to which live load reduction factors were applied – 0.7 for static loads and 0.4 for earthquake). A 7.0 kPa dead load was applied to the roof. The live loads were as required by the New Zealand loading standard, NZS 4203 (1992). The dead load resulted from reinforced concrete frames supporting precast prestressed concrete floor slabs with 65 mm site-poured concrete topping. The footing loads were developed from the roof load and loads from the three above-ground floors.

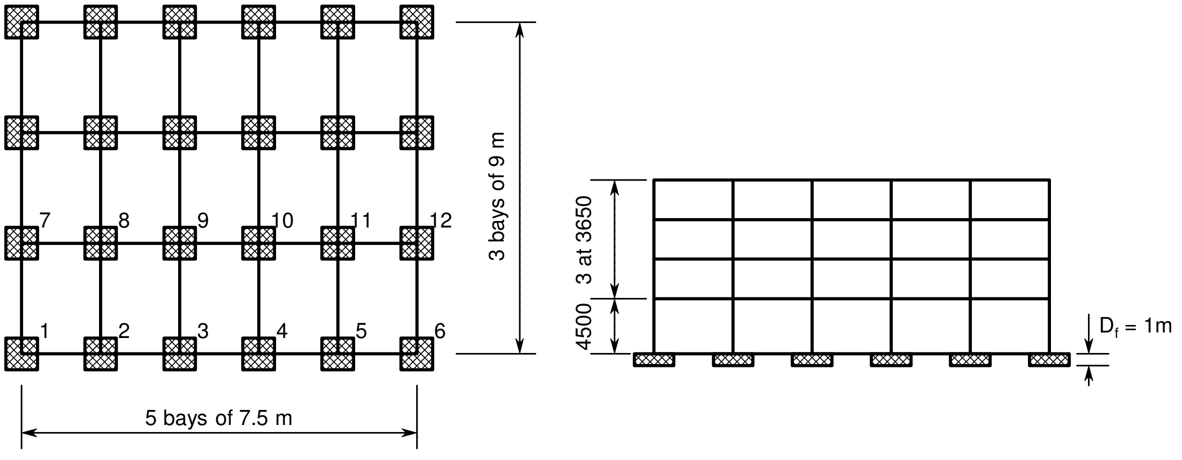


Figure 1 Three-storey structure: elevation, plan and footing numbering.

All the footings were connected with tie-beams. These were assumed to act under axial load but provide no moment-restraint where connected to the footings.

3 EQUIVALENT STATIC MODELLING

The fixed-base first mode period of the structure detailed in Figure 1was close to 0.9 seconds. The draft Australia New Zealand Loading Standard (DR 1170.4/PPC3, 2002) gives for the elastic site hazard spectrum for horizontal seismic loading a coefficient of 0.52 (fraction of g) for a 500-year return period earthquake in the central part of NZ (shallow soil condition, $C_h(T) = 1.29$, $Z = 0.4$, $R = 1$, near-fault factor = 1). The gravity loads, along with earthquake loads generated from a horizontal earthquake acceleration of 5.1 m/s^2, were the basis for the foundation loads used in the equivalent static approach. Appropriate load factors were applied. All the results discussed in this paper are for an earthquake acting parallel to the length of the building.

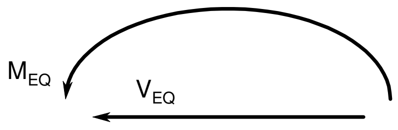
The gravity loads on each footing were estimated using a tributary area assignment. This means that the outer footings carry smaller vertical loads than the internal footings, the corner footings carrying only one-quarter of gravity load of the internal footings. During earthquake loading, the foundations are subject to vertical load, horizontal shear and moment. The assumed distribution of shear and moment between the footings is described in Figure 2.

Footings 3.4 m square, with the underside 1 m beneath the ground surface, were adopted for all 24 column foundations (the reason for this constant footing-size will become apparent later). Using the load factors given in NZS 4302 (1.2 for dead load and 1.6 for live load), bearing capacity calculations reveal that these foundations had adequate bearing strength for the applied static vertical loads. In fact, the side and corner foundations had much greater static bearing strength than the applied loads.

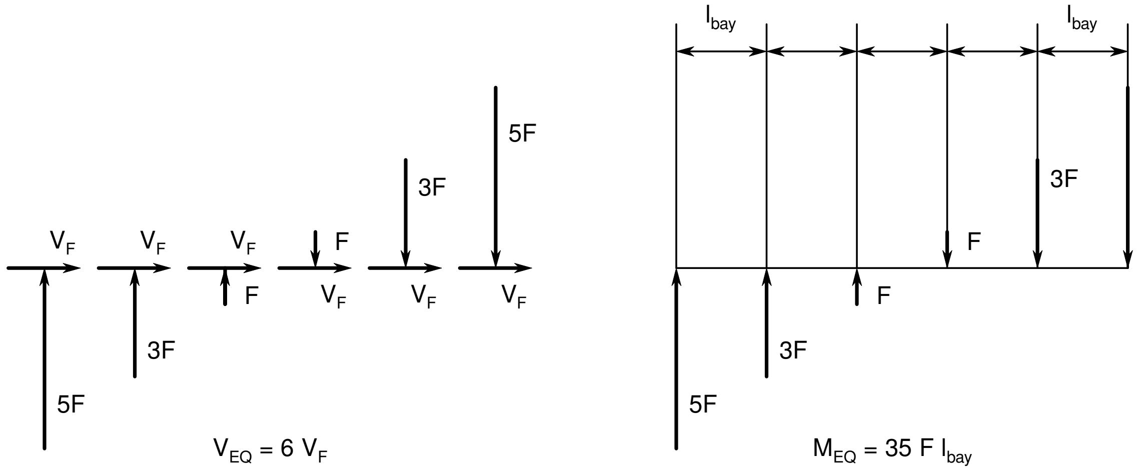
Next, the bearing strengths of the shallow foundations were checked under earthquake loading. In the first instance, this was done with the assumption that the column-footing connections were pinned so that no moment was applied to the foundation during the earthquake. As shown in Figure 2, the earthquake base shear was distributed evenly between the footings, and the global earthquake moment applied to the foundation was equilibrated with cyclic vertical forces at the footings. Using load factors for seismic combinations, all of the 3.4 m square foundations were again found to have adequate bearing strength for these loadings.

The final step was to consider the foundations fixed to the columns so that moment loads are applied to the foundations. The assumption used to estimate these moments was that the columns were fully fixed and the moment was generated by the foundation shears. The column-base moments reduce the cyclic vertical forces needed to equilibrate the overall moment induced by the earthquake. The application of moment to a shallow foundation has a severe effect on the bearing strength. Furthermore, this reduction is dependent on the vertical load on the foundation. Larger vertical loads increase the moment capacity. The way the moment is equilibrated is to offset the reaction on the underside of the foundation which has the penalty that the available bearing area, and hence bearing strength, is reduced. In addition, the application of shear force reduces the bearing strength of the foundation. As above, the bearing strength of the foundations under these actions was evaluated. It was found the end and corner foundations, despite the large reserve of capacity under the static vertical loads, had inadequate bearing strength when the earthquake-induced load increment reduced the vertical load on the foundation.

At this point, we could recommend that for low-rise buildings on shallow foundations the column–footing connections should be pinned. However, we also need to point out that the load distribution in Figure 2, and its extension to the case with foundation moments, is assumed, and ignores the possibility that the structure/foundation system may be able to equilibrate the earthquake actions in other ways.



Global seismic actions applied to foundations



Footing actions which equilibrate the global actions

Figure 2 Earthquake foundation actions for the equivalent-static calculations (pinned column/footing connections).

4 RUAUMOKO MODELLING OF THE STRUCTURE-FOUNDATION SYSTEM

Previous research was completed by the Building Research Association of New Zealand (BRANZ) on a suite of structural models for use in development of the AS/NZS 1170 Draft Loading Standard (SANZ 2002). These were also used as the basis for the modelling undertaken in this paper. The structural model used herein was based on the limited ductile displacement (ductility 3) structural models developed by Compusoft Engineering (Bell, 2003). Seismic analysis and member design of the suite of structures was determined using the ETABS (Wilson and Habibullah, 1995) finite element analysis program. Structural members were designed in accordance with the AS/NZS Draft Loading Standard, NZS 3101 (SANZ, 1995) and NZS 4203 (SANZ, 1992).

Models were designed such that all members contributed to the seismic resistance of the structure and each frame parallel to the direction of earthquake propagation had identical member configuration. Models of -imensional, three-storey reinforced concrete, moment-resisting frame structures could be analysed with both fixed-base and compliant foundations. The configuration of the structural model is given in Figure 1.

Each floor was modelled as a lumped mass and a rigid.

The RUAUMOKO model was developed using the same assumptions as above to undertake detailed nonlinear modelling. The numerical model could be run as an elastic structure or as a ductile one. For ductile behaviour under seismic loading, a sway mechanism develops with column-hinging at foundation level and beam-hinging to within 1.5 beam-depths from the column faces. All but one of the sets of calculations discussed here was for an elastic structure. Columns were modelled using concrete beam-column frame members, and beams were modelled using Giberson-beam frame members. The Giberson frame members consisted of an elastic central section with potential plastic spring hinges located at the ends. The concrete beam-column members were of similar form, but the central section was defined by a beam-column yield surface instead. As with the ETABS design model, column hinges were restricted to ground level in the RUAUMOKO model. Hinge lengths were taken as 2/3rds of the member depth. For the RUAUMOKO modelling, 5% Rayleigh damping was applied.

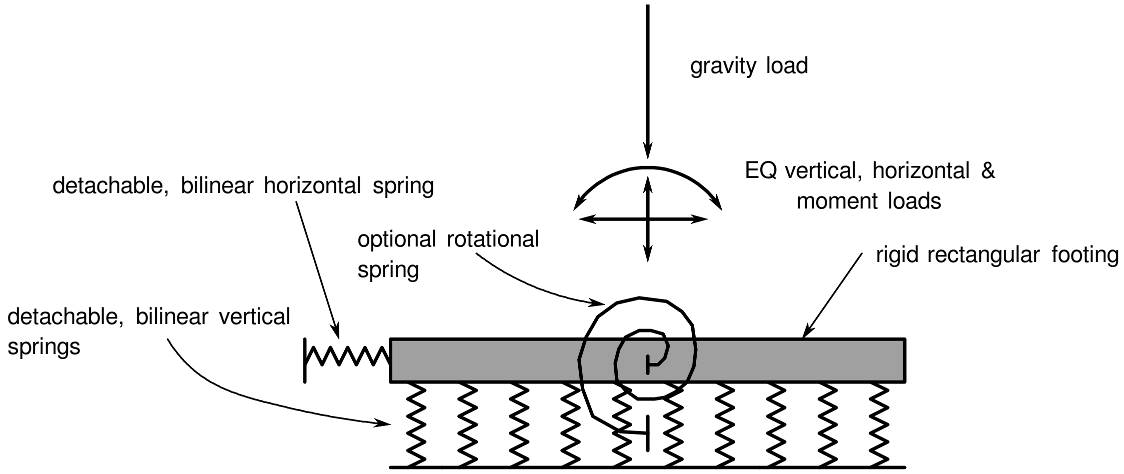


Figure 3 RUAUMOKO multispring footing model.

The foundation element used in the RUAUMOKO calculations is illustrated in Figure 3. In this the vertical, horizontal and rotational stiffness of the foundation was modelled. In addition, the vertical, horizontal, and moment springs can yield. RUAUMOKO has a gapping element. Initially this was used to model uplift of a footing when the vertical load reached zero. However, because each degree of freedom in RUAUMOKO is independent the shear spring is not detached – so true uplift of the footing does not occur. To handle this problem, a special version of the RUAUMOKO multi-spring model was developed by one of the authors to detach the shear spring when uplift occurs.

The initial stiffness of the springs assumed elastic behaviour of the soil beneath the foundation and gives the settlement under gravity load. To estimate the foundation stiffnesses, we used formulae for the vertical, horizontal and rotational stiffness of rigid, rectangular foundations on an elastic soil (Gazetas, 1991). From Figure 3, the rotational stiffness is linked to the stiffnesses of the independent vertical springs. It was found that the ratio between vertical and rotational stiffness implied was not the same as that given by the Gazetas stiffnesses. This problem was resolved in either of two ways. One was by attaching a separate rotational spring to the foundation as shown in Figure 3. Alternatively, additional vertical springs were attached to the footings on outriggers. It is important to get the ratio between vertical and rotational stiffness of the shallow foundations correct as the rotational stiffness based on the vertical springs in Figure 3 is much smaller than the rotational stiffness from the Gazetas expressions.

A single earthquake record was used in the analysis and was applied parallel to the longest plan dimension of the structure. This record was from the La Union event, N85W Michoacan, Mexico 1985. The original records were scaled, using the method outlined in the AS/NZS Draft Loadings Standard, to the spectrum representing an earthquake in the Wellington region of New Zealand for a 1 in 500-year return period event. The resulting earthquake time history had a peak ground acceleration of 3.46 m/s^2. The response spectrum with 5% damping gives a spectral acceleration at the natural period of the structure similar to that used for the equivalent linear calculations (5.1 m/s^2 for the equivalent linear, and 5.6 m/s^2 for the La Union record).

Three methods were used to size the shallow foundations: all footings with adequate bearing strength from static LFRD ultimate limit state considerations (bearing capacity factor of safety of 3 in older terminology), all footings to have equal static settlement, and all footings to have equal vertical stiffness, with the most heavily-loaded footings having adequate static LRFD bearing strength. However, as the bearing capacity of shallow footings decreases rapidly with the application of moment, this was found to be the critical design consideration. Whether the structure remains elastic or is designed as ductile, moments were generated at the base of the ground-floor columns. These moments were transferred to the foundation. It was found that only the equal stiffness footings were of sufficient size to accommodate these moments. This appears to result in exterior footings which are extravagant in size. However, although these footings carry the smallest gravity loads, they have the largest cyclic vertical loads during the earthquake - as well as cyclic shear and moment. During the unloading part of the cycle, the response becomes critical as it is then that the moment has the most adverse affect on the bearing strength of the footing.

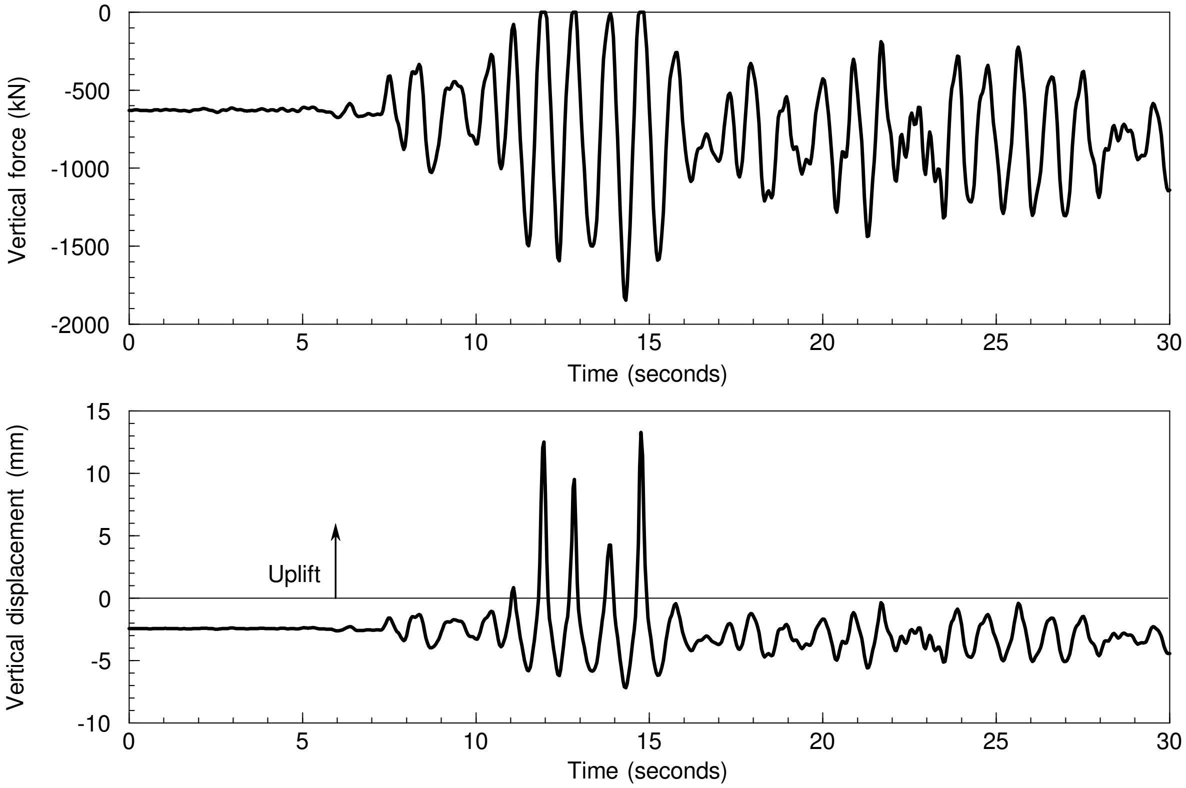


Figure 4 Vertical force and displacement of footing number1.

4.1 Results

Figure 4 shows the time history of vertical load and vertical displacement of the corner footing (footing number 1 in Figure 1) during the earthquake. As the corner footings carry the smallest gravity load, it is these that are most affected by the earthquake. It is seen that there are four brief instances of uplift during the earthquake. These are indicated by zero vertical load on the footing and positive displacement. The upper part of Figure 4 shows that the gravity load on the footing is about 845 kN and, from the lower part, the static settlement is about 2.7 mm (the sign convention being negative for compressive forces and downward displacements). The response of footing number 6 is similar. However, footings 7 and 12 had reductions in vertical force and consequent upward movement of the footing, but no uplift. A most interesting outcome from the RUAUMOKO modelling is the vertical force history at the internal footings. All footings 2 to 5 and 8 to 11 exhibit very nearly constant vertical force during the earthquake motion. The results for footing 10 are displayed in Figure 5. The top part of the figure gives the moment history for the footing. The bottom part of Figure 5 gives the displacement history of the footing. The three traces are the vertical displacement of the centre of the footing and the displacements of the two edges of the footing. The trace for the centre of the footing shows no movement which is consistent with the observation that the vertical force does not change. The vertical displacements of the edges are out of phase with each other, and indicate the rotational response of the footing to the applied moment.

Figure 6 shows the horizontal displacement history of the foundations. The floor slabs have been modelled as rigid diaphragms. Consequently, the lateral displacements are the same for all the footings.

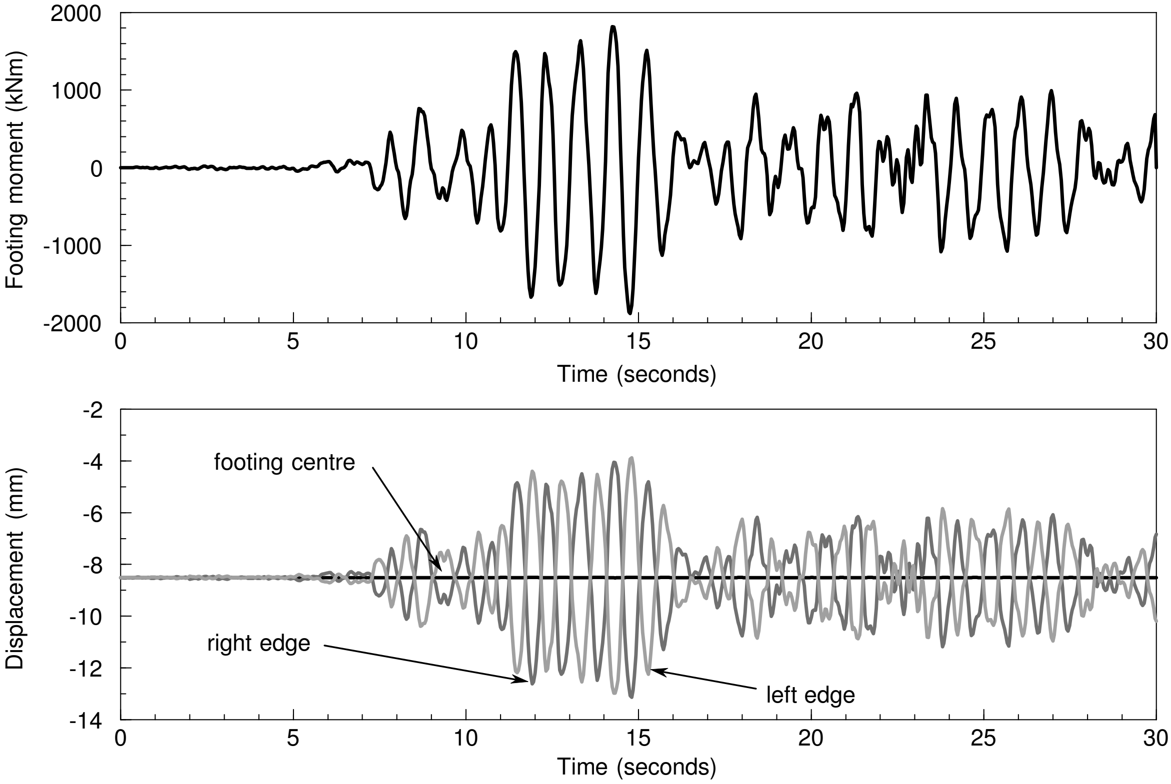


Figure 5 Moments and vertical displacements for footing number10.

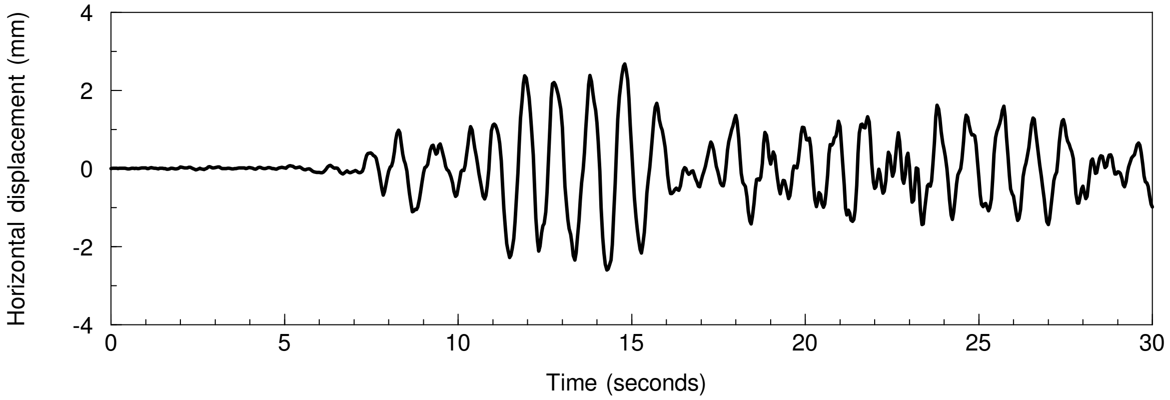


Figure 6 Foundation horizontal displacement history during the earthquake motion.

5 DISCUSSION

Figure 4 confirms the conclusion from the equivalent static approach that the end footings are the most critically loaded during the earthquake. The equivalent static approach indicated that all the end footings would have inadequate bearing strength despite the fact that these footings were large in relation to the gravity loads carried. The RUAUMOKO analysis results showed uplift for the corner footings, and footings 7 and 12 approaching uplift. Of course, these two mechanisms are different, as uplift and bearing failure are not the same. However, the footings will not be able to sustain moment if the vertical force is zero - so uplift implies zero bearing-strength.

Figure 5 indicates that the manner in which the structure responds to the earthquake loading is quite different from that presented in Figure 2. The vertical force results show that only the outer footings experience cyclic vertical forces and moments during the earthquake, whilst the internal footings are subjected to cyclic moments at constant vertical load.

The RUAUMOKO results suggest that the structure accommodates the earthquake loading more effectively than the simple assumptions presented in Figure 2. This indicates that this integrated modelling approach merits further development. However, we still need to refine the model for the shallow foundation and, in particular, ensure that it does not allow actions which exceed the bearing strength to be applied.

6 CONCLUSIONS

In this paper we have demonstrated the use of an existing dynamic structural analysis package in modelling the earthquake response of framed structures on shallow foundations. The yielding and uplift characteristics of the foundations have been modelled by adapting available structural models in the software.

The main conclusion is that the computed behaviour of the RUAUMOKO model is different from that assumed in the equivalent static approach to the design of the shallow foundations. Whereas equivalent static indicates bearing failure for the end footings, the RUAUMOKO model has uplift of the corner footings. This suggests that the structural system is able to accommodate the earthquake loading in a more effective manner than the assumptions of Figure 2 indicate.

At present, this approach to the integrated design of structure/foundation systems shows promise. The next task is to ensure that the RUAUMOKO model does not allow load combinations that exceed the bearing strength of the shallow foundation.

7 ACKNOWLEDGMENTS

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8 REFERENCES

Ahmed-Zeki, A.S., Pender, M. J. and Fitch, N. R. 1999. Strain-rate effects on the undrained shear strength of Waitemata residual clay, in Proc. 8th *Australia-NZ Conference on Geomechan*ics, Hobart, 2: 791-796.

Bell, D. 2003. Compusoft Engineering, private communication.

Carr, A. J. 2004. RUAUMOKO: inelastic dynamic analysis program, University of Canterbury - Department of Civil Engineering, Christchurch, New Zealand.

Gazetas, G. 1991. Foundation Vibrations. In *Foundation Engineering Handbook*, H. Y. Fang, Ed. Van Nostrand, 553-593.

Standards New Zealand. 2002. General Design Requirements and Loading on Structures, Draft AS/NZS1170:2002.

Standards New Zealand. 1992. General structural design and design loadings for buildings, NZS 4203:1992.

Standards New Zealand. 1995. The Design of Concrete Structures, NZS 3101:1995.

Wilson, E. L. and Habibullah, A. 1995. ETABS – Three dimensional analysis of Building Systems, Computers & Structures Inc, Berkeley, USA.

Wotherspoon, L. M., Pender, M. J. & Ingham, J. M. 2004a. Effects of Foundation Model on the Earthquake Response of Building Systems. In Proc. *3rd ICEGE and 11th ICSDEE*, Berkeley, USA: Vol 2: 766-773.

Wotherspon, L. M., Pender, M. J. & Ingham, J. M. 2004b.Combined modelling of structural and foundation systems, Proc. *13th World Conference on EQ Engineering*, Vancouver, 1 - 6 August, Paper 411, 15 pages.