# Classical soil-structure interaction and the New Zealand structural design actions standard NZS 1170.5 (2004)

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**ABSTRACT**

The purpose of this paper is to evaluate the provisions of the New Zealand structural design actions standard (NZS 1170.5 (2004)) with respect to classical elastic soil-structure interaction effects on the earthquake design of shallow foundations supporting multi-storey buildings. Work by earlier researchers had led to the suggestion that for tall buildings the lengthening of the structure-foundation period caused by soil-structure interaction might give reduced foundation design actions. The results of numerical modelling using the modal response spectrum method did not reveal any evidence for such a reduction, in fact generally there was an increase. We suggest that the jumps between the design spectra when moving from a rock site, to a shallow soil site, to a deep soil site are more significant than the subtle soil-structure interaction effects caused by the modest period lengthening of the structure-foundation system.

## 1 INTRODUCTION

The recent New Zealand Design Actions Standard, NZS 1170.5 (2004), specifies actions for the design of structures to resist earthquakes. The purpose of this paper is to consider soil-structure interaction effects on the response of multi-storey buildings on shallow foundations using the spectral modal analysis procedure and the seismic hazard acceleration coefficient curves in the New Zealand standard. The standard provides elastic and ductile seismic hazard spectra for various site conditions ranging from rock to very soft soil.

Early work on soil-structure interaction effects by Merritt and Housner (1954) concluded that for low rise buildings, foundation compliance has little effect on the earthquake base shear, but, for tall buildings, foundation compliance may reduce the base shear, although the effect varies from earthquake to earthquake. Parmalee et al (1968) concluded that when the shear wave velocity of the foundation soil was less than about 300 m/sec soil-structure interaction effects could be significant. More recently Stewart et al (1999) have analysed recorded earthquake response of a number of buildings; they found that for some structures soil-structure interaction effects are significant but in most cases the effect is modest.

The response of a number of structures ranging from 1 to 24 storeys is considered in this paper. The embedded foundations are modelled as rigid blocks supported with a horizontal spring and a rotational spring. The results discussed are derived for shallow foundations consisting of one or more basement levels or, for low rise structures, discrete footings beneath the columns.

The responses of the models on rock, shallow soil and deep soil are compared. Some effort has been made to ensure that the properties for the soil are realistic and also that the foundation actions satisfy the LRFD bearing strength inequality. The majority of the results are for the shallow site condition, with soil properties representative of a stiff cohesive soil.

At this point we need to define soil-structure interaction and site effects. When recorded earthquake motions are available both on a soil profile and an adjacent rock outcrop, one can compare the motion at the soil site with that on the rock. The difference between these two is known as a site effect – that is the way in which the soil motion is different from that on the adjacent rock. If the soil responds in an essentially elastic manner then the motion at the soil site will be amplified with respect to the rock motion; the amount of amplification being dependent on the ratio of the stiffness of the rock to that of the soil. For gentle rock motions the soil motion will be amplified as long as the shear strains in the soil profile are within the elastic range for the soil. From about the time of the 1985 Mexico City earthquake and the 1989 Loma Prieta event it was realised that many soils behaved "elastically" over a greater strain range than had hitherto been realised. This meant some amplification with respect to an adjacent rock site can be expected for most natural soil deposits for all but the highest values of peak ground acceleration. This is the reason that design spectra in loading standards indicate that soil sites will develop larger earthquake motions than an adjacent rock site. The information in the loading standards is, of course, derived empirically by "averaging" a large number of recorded ground motions.

Soil structure interaction is different in that it considers how the response of a given structure will differ when founded on soil from that when it is founded on rock. Clearly, this gets mixed in with the site effect outlined above. However, in principle soil structure interaction is much simpler and can be understood in relation to the response spectrum concept. The response spectrum gives the peak response of a single degree of freedom structure to a given earthquake motion. The first mode period of a structure on rock will be less than that of the same structure on soil as the presence of the soil lengthens the natural period of the structure-foundation system. If the period lengthening is along a part of the response spectrum with a falling curve, then soil-structure interaction effects are expected to reduce the earthquake actions (the arrow marked AC in Fig. 6), and vice versa along a portion of the response spectrum with a rising curve.

## 2 CLASSICAL SOIL STRUCTURE INTERACTION

Classical soil structure interaction calculations demonstrate the effect of elastic compliance of the soil beneath the foundation in lengthening the natural period of the structure foundation system. The simplest way of considering this is to use an equivalent single of degree of freedom model with the mass lumped in one position as shown in Fig. 1. A standard result obtained from this idealisation is that the natural frequency of the system is given by:

$$\omega_e{}^2 = \frac{\omega_s^2}{1 + \frac{k_s}{k_h} + \frac{k_s h^2}{k_\phi}} \tag{1}$$

where: $\omega_e$ is the natural frequency of the structure foundation system, $\omega_s$ is the natural frequency of the structure alone, $k_s$ is the bending stiffness of the structure, $k_h$ is the horizontal stiffness of the foundation, $k_\phi$ is the rotational stiffness of the foundation, and h is the height above the foundation of the equivalent SDOF mass.

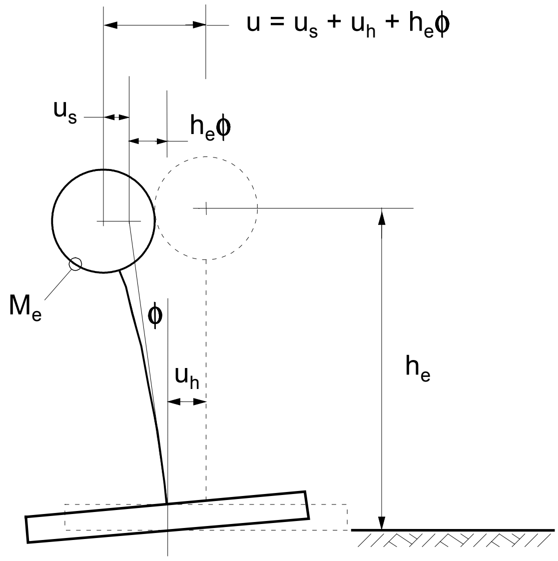


**Figure 1: Single degree of freedom (SDOF) soil structure interaction model.**

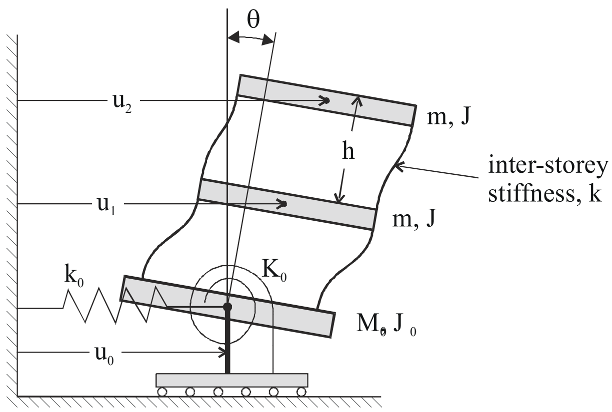


**Figure 2: Structure-foundation model for a two storey building.**

This shows that the natural frequency of the system when foundation compliance is present is always smaller than the natural frequency of the structural element alone.

A potential criticism of the above model is that the mass distribution in a building foundation system is too complex to be represented by a single mass. A more likely model is shown in Fig. 2 in which the foundation mass and rotational inertia are included. The behaviour of this system was investigated using a standard method of structural dynamics: spectral modal analysis with SRSS (square root of the sum of the squares) combination.

## 3 BUILDING AND FOUNDATION MODELS

The shallow foundations modelled are considered as rigid blocks supported by a translational and a rotational spring. These shallow foundations are beneath the ground surface so part of the stiffness is generated from interactions between the sides of the foundation and the surrounding soil. Above ground the structures are represented by four columns and a mass (rigid diaphragm) at each floor. The layout of the structure-foundation systems is shown in Fig. 2 for a structure with 2 storeys. Models for 1, 2, 4, 8, 12, 18 and 24 storey buildings were developed using Mathcad (PTC 2006). Common dimensions adopted were: storey height 3.5m, column spacing 8m, and the depth of each level of basement 4.5m. The building models were assumed to have the same floor masses and column stiffnesses for each storey, and the gravity loading at each floor level, permanent load plus imposed load, was set at 7.2kPa. The column stiffnesses were assigned by ensuring that the first mode period of the structures satisfied the following equation which is applicable to reinforced concrete framed structures constructed in New Zealand:

$$T_1 = 0.11H^{0.75} \tag{2}$$

where: $T_1$ (seconds) is the period of the first mode and H (metres) is the total height of the structure.

The lateral and rotational stiffnesses of the foundations were evaluated assuming that the foundation soil was elastic. Formulae are given by Gazetas (1991) for estimating the stiffnesses of embedded foundations of arbitrary shape and arbitrary sidewall contact.

## 4 EARTHQUAKE SPECTRA

The elastic site hazard spectrum is expressed in NZS 1170.5 by:

$$C(T) = C_h(T)\, Z\, R\, N(T, D) \tag{3}$$

where: T is the period, $C_h(T)$ is the basic seismic hazard acceleration coefficient given in the loading standard, Z is the hazard factor, R is the return period factor, and N(T,D) is the near fault factor. In Figure 4 curves for the basic seismic hazard acceleration coefficients from NZS 1170.5 are plotted. For all the calculations reported herein Z was set to 0.4 (representative of the central part of New Zealand), R to 1.0 (i.e. a 500 year return period), and N(T,D) to 1.0 (i.e. no nearby fault).

A limitation of all the work in the paper is that no special consideration was given to damping in the model. Because of the analysis method used the only damping consideration was that implied in the 5% damped elastic spectrum on which the hazard spectrum is based.

## 5 SOIL PROFILES

The standard classifies site conditions using a mixture of depth of material and site period. In the rock category the shear wave velocity is greater than 360 m/sec. Herein the rock spectrum is used to model a fixed base structure so the foundation "soil" modulus is set to a very high value. The shallow site condition is specified as having a site period of 0.6 seconds or less. For this case we have assumed clay with an undrained shear strength of 100 kPa and a shear wave velocity of 200 metres per second. The depth corresponding to a period of 0.6 seconds for the

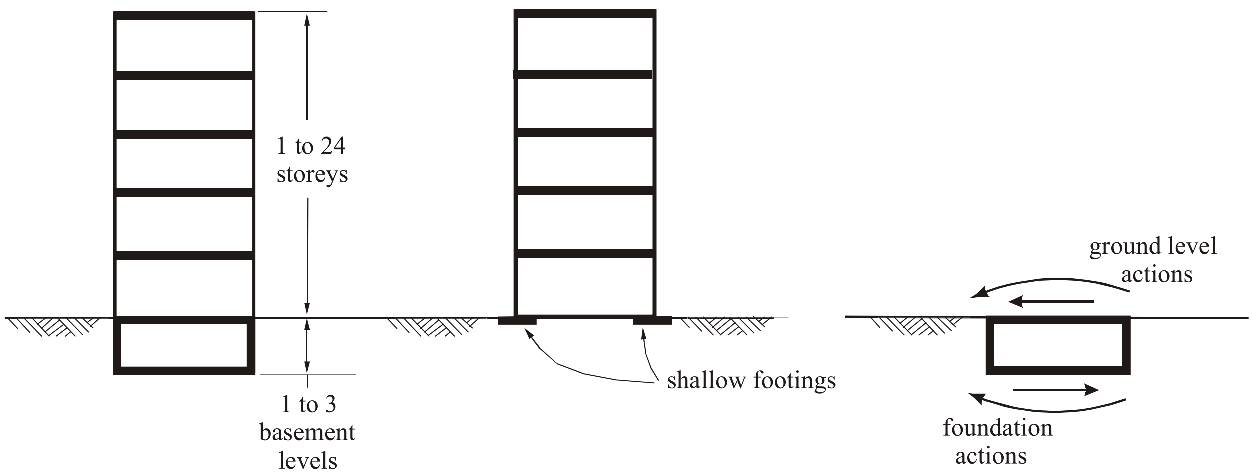


**Figure 3: Building and foundation models.**

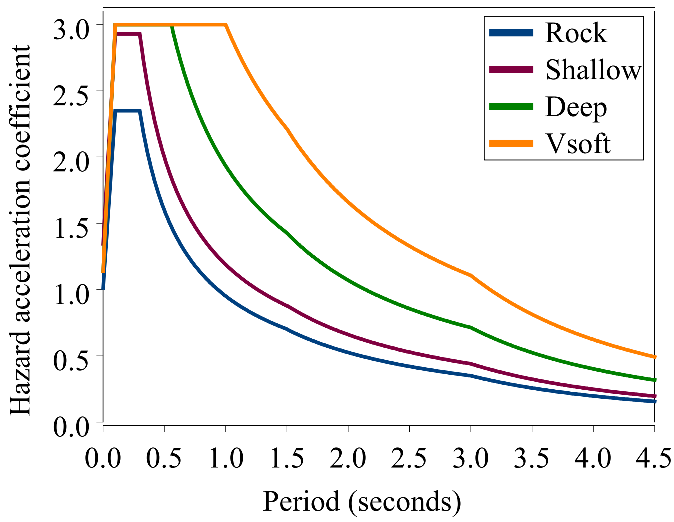


**Figure 4: Basic seismic acceleration coefficients given for New Zealand in NZS 1170.5 (2004) - curves for rock, shallow soil, deep soil and very soft soil site conditions.**

shallow soil profile is 30m – deep enough to justify the use of the formulae mentioned above for the foundation stiffness. For the deep soil profile the soil was assumed to have an undrained shear strength of 40kPa and a shear wave velocity of 126 m/sec. In this case the soil depth corresponding to a period of 0.6 seconds is 18 m. Both these depths are within the ranges given in the standard.

A value of 0.4 for the seismic hazard factor, Z, implies a moderately severe design earthquake for which it is likely that there will be some nonlinear deformation of the soil beneath the foundations. This is handled herein by using a recommendation from Part 5 of Eurocode 8 (CEN 2003) in which it is suggested that if the peak ground acceleration is about 0.3g then the "operational" stiffness of the soil adjacent to a foundation is about one third of the small strain stiffness corresponding to the shear wave velocity.

## 6 RESULTS

The response of the buildings on a foundations consisting of one level of basement in a shallow soil profile was compared to that of fixed base structures at a rock site. This comparison is presented in Figure 5; the normalised foundation shears for the two cases are compared in Figure 5a, and the normalised foundation moments in Figure 5b. The shears are normalised with respect to the total weight of the above ground part of the structure (i.e. the storey weight times the number of storeys) and the moments are normalised with respect to the weight of the building times the building height. The results for elastic site conditions in Fig. 5 show that the foundations in shallow soil pick up larger design actions than the foundations in rock regardless of the natural period of the structure.

The elastic spectra generate large foundation and building actions. We also did ductile response calculations. Space precludes discussion of these results here, but the same general comments can be made about the ductile results as those for the elastic response. Likewise there is not space to discuss the results with multiple level basements.

The elastic spectra generate large foundation actions, consequently the ultimate limit state of the shallow foundations was checked. For seismic excitation the load factor for the combination of permanent load plus imposed load plus seismic load is unity and the strength reduction factor for the bearing strength is 0.5. If the LRFD inequality was not satisfied the size of the foundat-

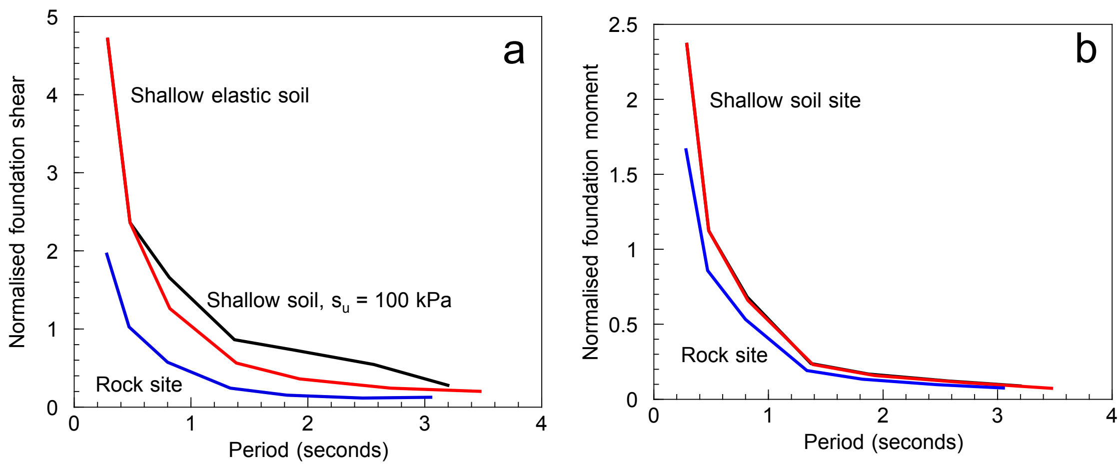


**Figure 5: Foundation actions (single storey basement) for structures on rock and shallow soil using elastic spectra: a normalised foundation shears, b normalised foundation moments.**

ion was increased, for the shallow soil site the required foundation size had to be increased for 4 storey structures and above, for the 24 storey building a foundation 14 metres square was required for the 8 metre square above ground structure. The inclusion of bearing strength considerations is a distinctive feature of this paper. Thus in Figure 5a there are two curves for the shallow soil profile, one considering bearing strength and the other keeping the foundation size the same for all structures. As would be expected the larger foundations, required to satisfy the LFRD requirements, generate larger shear forces. It so happens that there is negligible difference between the normalised moment curves for the two shallow soil conditions, Figure 5b.

## 7 SOIL STRUCTURE INTERACTION AND SITE EFFECTS

In the introduction two approaches to gauging the effect of foundation-structure interaction were described briefly. Parmalee et al suggest that when the shear wave velocity of foundation material is greater than about 300 m/sec soil-structure interaction effects will not be significant. All the calculations herein are for shear wave velocities of 200 m/sec or less, and many are for effective velocities of 115 m/sec. (a consequence of following the EC8 method of soil stiffness reduction). This implies that significant differences should be apparent when the results for the rock foundation condition are compared with those for the shallow soil or deep soil site. This is certainly apparent from Figures 5a and 5b where an increase in foundation actions appears as the site condition moves from rock to shallow soil to deep soil.

Contrary to the information given above in Figure 5, Merritt and Housner concluded that for tall structures foundation compliance tends to reduce the base shear. They computed the response of building models to earthquake time histories and found that for a given building configuration the reduction in base shears varied from one earthquake motion to another, and for some cases there was a negligible reduction. Their conclusion, from the point of view of building design, was that the maximum design base shear in a typical building was essentially unaffected by any degree of foundation compliance that can be expected in practice.

From the results presented herein we find little evidence of reduced foundation or ground level actions because of foundation compliance. The results presented seem to be dominated more by the respective shapes of the hazard spectra. In Figs. 5a and 5b the foundation actions for the for the deep soil site are greater than those for the shallow soil and rock sites simply because

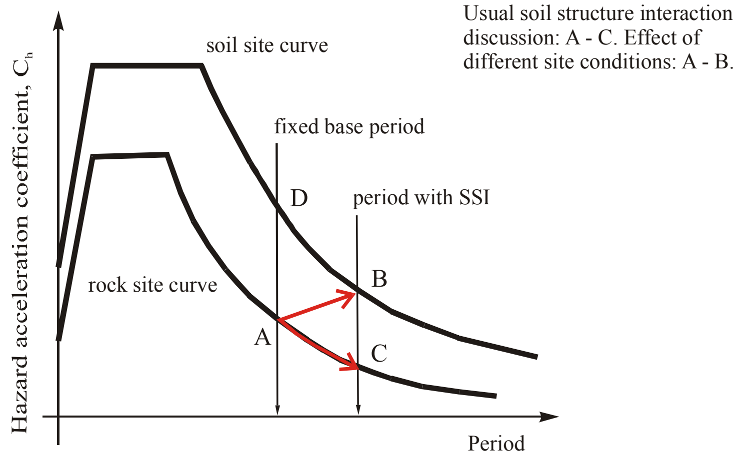


**Figure 6: Soil-structure interaction and seismic hazard curves.**

that is what the spectra impose. In other words the major requirement of the hazard spectra is to represent the "average" of the free-field responses of many earthquakes for a given site condition.

The overall conclusion we reach after these comparisons is that the jumps between the various hazard curves in the draft standard are the source of the increased actions as the site conditions move from rock to deep soil in Figure 4. This point is further clarified in Figure 6 where site hazard coefficient curves are sketched for rock site and soil site conditions. At the rock site the period of the structure-foundation system will be very close to that of the fixed base period of the structure, whereas at the soil site the period will be lengthened because of the compliance of the foundation. Point A on the rock spectrum will give the design actions for that site condition and point B on the spectrum for the soil site will give the design actions for that site condition. The usual qualitative discussion of soil-structure interaction effects considers a fixed spectral curve, and so is represented by the AC arrow in Figure 6. On the other hand the results of the calculations in this paper follow the AB arrow in Figure 6. Does this mean that soil-structure interaction effects do not occur when the curves of the draft standard are applied? No, because without the period lengthening due to foundation compliance the design actions for the soil site would be taken from point D on the soil site curve rather than point B.

Another factor that is thought to influence foundation behaviour during earthquake excitation is nonlinear soil behaviour. This is not explicitly addressed in NZS 1170.5 but has been considered herein by following the recommendation of Part 5 of Eurocode 8 (CEN 2003) which advises reducing the soil modulus to a third of the small strain maximum value when the earthquake peak ground acceleration is 0.3g or greater (assumed to be a consequence of a Z value of 0.4). A comparison was made between the results with this reduced soil stiffness and those with the small strain shear modulus, the maximum value possible, for building models with one basement level on the shallow soil condition. This is equivalent to decreasing the shear wave velocity of the foundation soil from 200 m/sec to 115m/sec. From the results of calculations with these reduced stiffness values it was apparent that there is little difference between the two sets of results. This is probably a consequence of the modest period lengthening caused by soil structure interaction for the soil properties used in the models. For the 24 storey building the fixed base period was 3.05 seconds, 3.19 seconds using the small strain stiffness of the foundation clay and 3.45 seconds using the stiffness reduced as recommend in EC8.

## 8 CONCLUSIONS

The purpose of this paper was to look at the provisions of the New Zealand loading standard with respect to the effect of soil-structure interaction on the earthquake design actions for shallow foundations supporting multi-storey structures. The standard gives a suite of seismic hazard acceleration coefficients for site conditions ranging from rock to very soft soil. Investigations by earlier researchers had led to the suggestion that, for tall buildings, the lengthening of the structure-foundation period, induced by soil-structure interaction, would give reduced foundation design actions.

We investigated this in the light of the standard by setting up a series of simple models of multi-storey buildings on a foundations having lateral and rotational compliance. Care was taken to assign realistic soil stiffnesses and also to ensure that the shallow foundations satisfied the ultimate limit state in bearing during the earthquake loading.

The results of the numerical modelling undertaken did not reveal a reduction in foundation actions due to soil-structure interaction, in fact generally there was an increase rather than a decrease. We suggest two reasons why the foundations on soil profiles have larger design actions than the same foundation on rock:

- the jumps between the design spectra when moving from a rock site, to a shallow soil site, to a deep soil site, disguise soil-structure interaction effects,
- the shallow foundations must satisfy the LRFD bearing strength inequality, so foundations in soil for tall structures will be larger than foundations for the same structure on rock, this means additional mass and additional stiffness in the system, consequently the design actions are larger.

Nevertheless soil-structure interaction induced period lengthening does have a beneficial effect along the falling part of the design spectrum. This, as illustrated in Fig. 6, is because the seismic hazard acceleration coefficient will be smaller than that at the fixed base period of the building, in other words the design action comes from point B on the soil site curve in Fig. 6 rather than point D.

## 9 REFERENCES

CEN (2003) *Comité Européen de Normalisation*, EC8 Drafting Committee Eurocode 8, *Design for structures for earthquake resistance. Part 5: Foundations, retaining structures and geotechnical aspects*. Brussels.

Gazetas, G. 1991. Foundation Vibrations. In Hsai-Yang Fang (ed), Foundation Engineering Handbook, 2nd edition, Chapter 15, pp. 553-593.

Merritt, R. G. and Housner, G. W. 1954. Effect of Foundation compliance on earthquake stresses in multi-storey buildings. Bulletin Seismological Society of America 44(4) 551-569.

Parmelee, R. A., Perelman, D. S, Lee, S. L. and Keer, L. M. 1968. Seismic response of structure-foundation systems Proc ASCE Jnl. Engineering Mechanics, 94 (EM6) 1295-1315.

PTC (Parametric Technology Corporation) (2006) *Mathcad 14.* Masachussetts.

NZS 1170.5: 2004 “Structural Design Actions Part 5: Earthquake Actions – New Zealand” Standards New Zealand, Wellington.

Stewart, J. P., Fenves, G. and Seed, R. B. (1999) Seismic soil-structure interaction in buildings. II: Empirical findings. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 125, No. 1, pp. 38 – 48.