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# REPRESENTATIVE SHEAR MODULUS FOR SHALLOW FOUNDATION SEISMIC SOIL-STRUCTURE INTERACTION

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## ABSTRACT

This paper discusses two aspects of the earthquake response of a deposit of clay: firstly the effect of soil nonlinearity on shallow foundation soil-structure interaction is investigated, and secondly the free field response of the ground surface is compared with the response of a shallow foundation on the same soil profile. Differing intensities of earthquake ground motion are generated by varying the peak ground acceleration. Comparisons of response are made by examining acceleration response spectra. It is shown how the properties of an equivalent homogeneous elastic layer, corresponding to a representative 'average' soil shear strain, may be estimated so that the foundation response closely matches that obtained with strain dependent (nonlinear) modelling of the soil mass. This has particular relevance to the design of shallow foundations. Representative shear modulus ratios, expressed as a function of peak ground acceleration, were determined for the C1 and C5 clays. These were compared with the recommendations proposed in the draft EC8 code. It is suggested that the EC8 recommendations need to take account of the fact that the G - $\gamma$ curves for clay depend on the plasticity index. The free field response of the ground surface and the foundation response were found to be very similar, indicating that, for the structure investigated, little of the nonlinear behaviour was due to the foundation rocking and translating on the soil.

## KEYWORDS

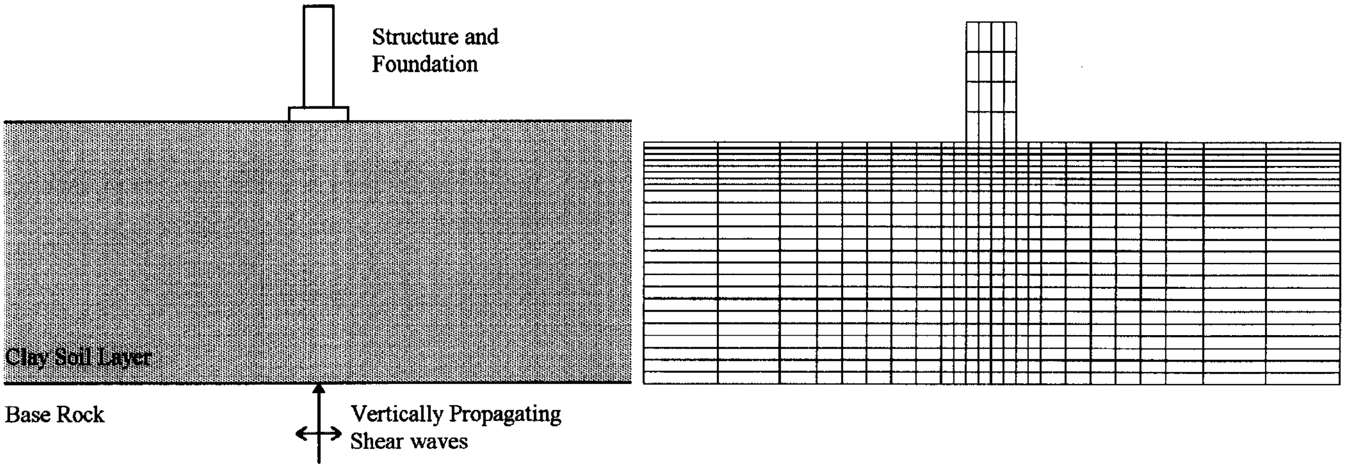
Soil-structure interaction, shallow foundation, clay shear modulus, damping, site response, response spectra.

## INTRODUCTION

The situation being investigated is shown conceptually in Figure 1. The source of the dynamic excitation is an earthquake time history composed of shear waves propagating vertically from the underlaying base rock

The input earthquake motion was recorded at Santa Cruz in the Loma Prieta earthquake of 17th October 1989. In this analysis the record was truncated to the first 20 seconds within which the major excitation was contained. For simplicity vertical accelerations were not included in the analyses.

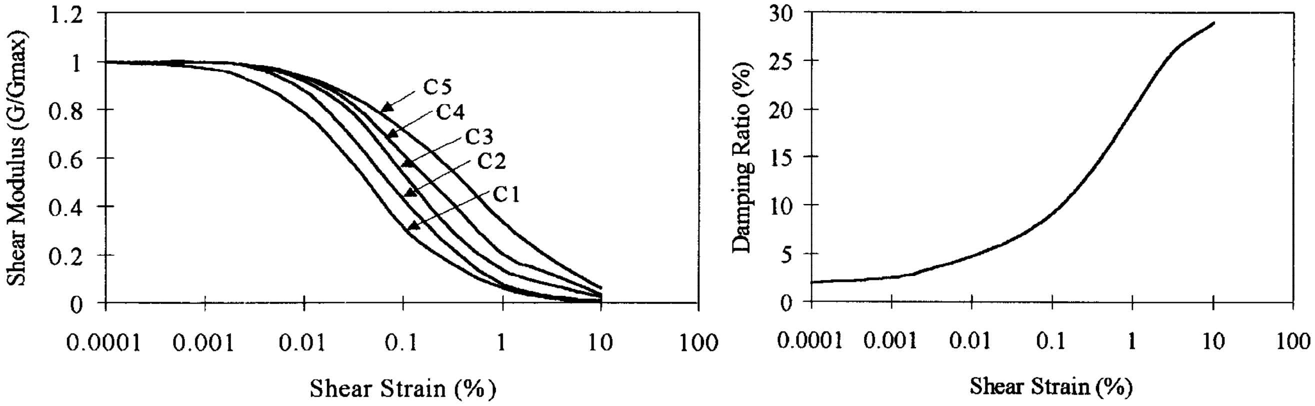
Dynamic soil properties are expressed in terms of the well known relationships for the apparent shear modulus, G, and equivalent viscous damping ratio, $\xi$, as functions of shear strain amplitude, $\gamma$. For clay soils the shear modulus curves have been found to be functions of the plasticity index (PI). Examples of these



(a)

(b)

Figure 1: (a) Idealised Soil and Structure System and (b) Finite Element Mesh.



(a)

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Figure 2: (a) Shear Modulus Ratio and (b) Damping Ratio Curves for Clay Soils (after Sun *et al.* (1988)).

curves, developed by Sun et al (1988), are shown in Fig. 2a. The C1 curve describes low plasticity clays ( PI ≈ 0-10) and the C5 curve describes high plasticity clays (PI>80).

This paper aims at the investigation of two aspects of dynamic soil-structure interaction (SSI) using a plane strain finite element program to model the soil deposit and a structure supported on a shallow foundation. The first considers the use of the equivalent linear method of analysis which handles the strain dependent behaviour of soil, especially adjacent to a foundation, throughout the duration of an earthquake. This method approximates a true nonlinear solution by running successive linear models, changing the dynamic properties in each element between iterations to make the current shear strain compatible with the shear modulus and damping ratio curve for the clay. The surface acceleration time history under the foundation was computed as well as the free field response of the site. For ease of comparison the acceleration time histories of the surface motions are presented as response spectra with 5% damping.

Table 1: Draft EC8 suggested Shear Modulus values for different Earthquake PGA.

| PGA (g) | $V_s/V_{s\,(max)}$ | $G/G_{max}$ |
|---|---|---|
| 0.10 | 0.90 (±0.07) | 0.80 ±(0.10) |
| 0.20 | 0.70 (±0.15) | 0.50 (±0.20) |
| 0.30 | 0.60 (±....) | 0.35 (±0....) |

where: $V_{s\,(max)}$ and $G_{max}$ are the small strain shear wave velocity and shear modulus respectively,
and $V_s$ and G are the shear wave velocity and shear modulus at larger strains.

The model was then re-run with the same input excitation, but with the dynamic soil properties fixed throughout the soil mass. The estimation of these soil properties was based on a representative shear strain. A magnitude of shear strain was initially estimated, and the corresponding shear modulus and damping ratio found from interpolation on the appropriate curves in Fig. 2. The foundation response spectra for the linear model was then compared with the equivalent linear model and the process iterated until the best match found.

Results from these analyses were then compared with those put forward in the September 1993 draft of EC8 in which representative shear modulus values were proposed for different earthquake PGA (refer to Table 1).

A number of analyses were done for earthquake peak ground accelerations from 0.1g to 0.4g and using both the C1 and C5 clay models. This was intended to span the level of earthquake excitation and ground conditions of interest in aseismic foundation design.

The second aim of this work is the comparison of the responses of the foundation and free field during seismic excitation. This was investigated in parallel with the first aim by calculating the response of a surface node some distance from the structure. These responses were again compared by the using response spectra.

## MODEL OF SOIL AND STRUCTURE

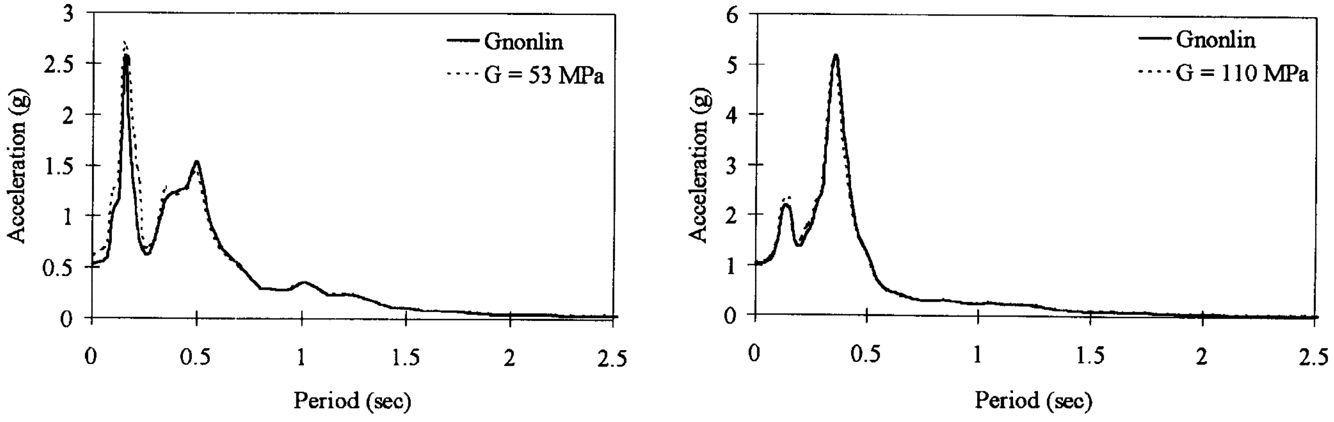
The soil and structure were modelled using the finite element package QUAD4M (Hudson *et al.* (1994)) which allows dynamic two dimensional analysis in the time domain using an equivalent linear solution method. The equivalent linear method runs successive linear analyses, adjusting the properties of each element according to the shear strains induced within the element in the previous iteration. This method converges rapidly to the final solution (typically 4 iterations ensures all elements within 1% of final result). Included in the model is a transmitting base allowing radiation of energy out of the system. As the side boundaries do not have this property the mesh was made wide enough to eliminate any effect of non-transmitting side boundaries. The soil and rock properties are presented in Table 2.

The finite element mesh consisted of four noded quadrilateral elements as shown in Fig. 1b. The soil layer had 576 elements and the structure 16. The soil layer was 20 m deep, the mesh was 56 m wide. The building and foundation was 4 m wide.

The structure was modelled with elements that remained linear elastic during the earthquake excitation. The material properties of these elements were chosen to give the correct mass density (Fenwick *et al.* (1989)) and period (Clough and Penzien (1975)). For the 10 m high structure the period was chosen at 0.3 sec, typical of a three storey structure. The mass density was 235.8 kg $m^{-3}$, and the shear and compression wave velocities were 326.3 m $s^{-1}$ and 565.2 m $s^{-1}$ respectively.

Table 2: Soil and Rock Properties

| | Clay | Rock |
|---|---|---|
| Density, $\rho$ | 2000 kg m$^{-3}$ | 2600 kg m$^{-3}$ |
| Poisons ratio, $\nu$ | 0.45 | 0.35 |
| Maximum shear modulus, $G_{max}$ | 150 MPa | 5850 MPa |
| Maximum shear wave velocity, $V_{s\ (max)}$ | 274 m s$^{-1}$ | 1500 m s$^{-1}$ |
| Small strain P-wave velocity, $V_p$ | 909 m s$^{-1}$ | 3122 m s$^{-1}$ |



(a)

(b)

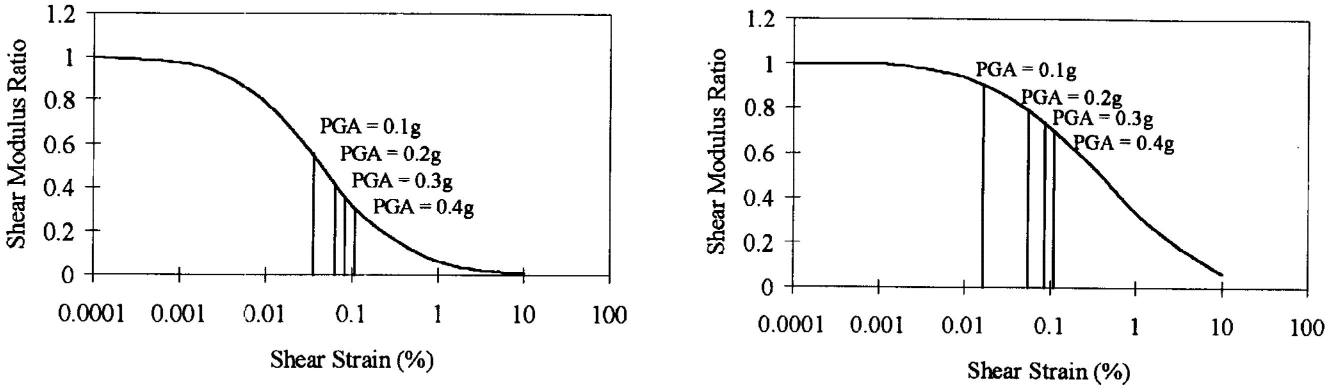
Figure 3: Comparison of Nonlinear and Linear Response Spectra for
(a) C1 clay and (b) C5 clay.

## LINEAR FITTING OF NONLINEAR RESPONSE SPECTRA

The representative linear soil parameters were evaluated using the acceleration response spectrum beneath the centre of the foundation. In general it was possible to find a constant soil stiffness value that gave a foundation response very similar to that from the nonlinear method. Over the range of peak response the linear and nonlinear results matched well both in amplitude and period. For periods in excess of 0.5 seconds the match between linear and non-linear models is very close. The comparison between nonlinear and linear models for an earthquake PGA of 0.3g for the C1 and C5 clay soils is shown in Fig. 3. The response spectrum for the input motion at the soil - rock interface is labelled in Fig. 9 as node 337.

The spectrum for the input motion has two peaks, most clearly seen in Fig. 9b. The major peak occurs at a period of about 0.13 seconds and the second at 0.33 seconds (close to the natural period of the structure). Figures 3a and 3b demonstrate just how different is the response of the two clay models. The C1 model has the greatest amplification for the 0.13 second peak in the input motion whilst the C5 model gives the greatest amplification to the 0.33 second peak. In addition the peak acceleration response at the building foundation for the C5 clay is about double that of the C1 clay. In comparing the nonlinear results with the linear approximation it is seen that for both clay models the match between the two is good, any discrepancy being greatest for the C1 clay as the shape of the G - $\gamma$ curve for this is such that there is a greater range of modulus in the soil profile.

The representative constant shear modulus and damping ratio, and corresponding shear strains, which gave the best match to the nonlinear model are presented in Figs. 4 and 5. As the intensity of the earthquake increased the representative level of shear strain increased correspondingly. For both clays the shear strains



(a)

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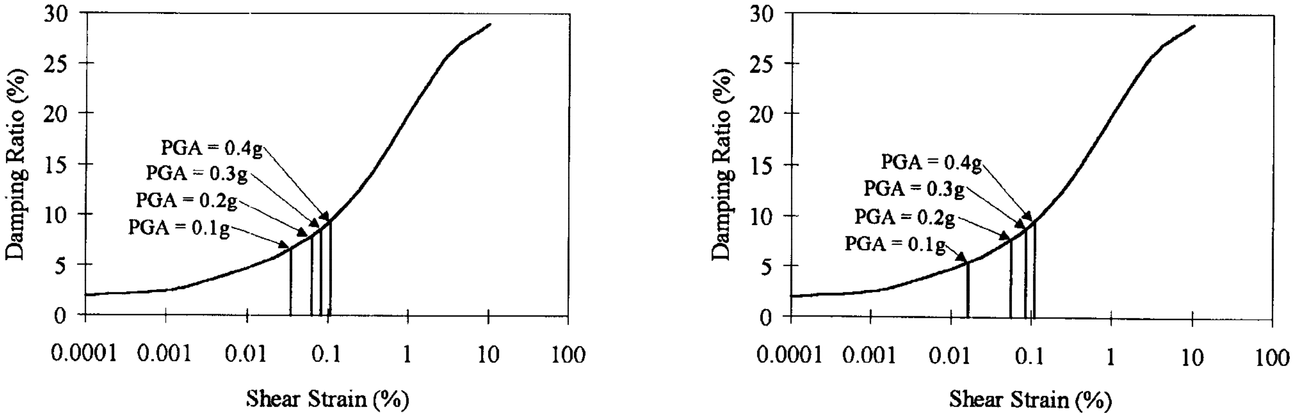
Figure 4: Linear Equivalent Shear Modulus Ratios for (a) C1 Clay and (b) C5 Clay for different Input Earthquake PGA's.



(a)

(b)

Figure 5: Linear Equivalent Damping Ratios for (a) C1 clay and (b) C5 clay for different Earthquake PGA's.

were of similar magnitudes at the various levels of earthquake excitation. For a low level of excitation the soil shear strains were in the order of 0.02 to 0.04 percent, and at high levels of excitation the shear strains are just in excess of 0.1 percent.

The comparison of the shear modulus ratios found in the present study with those in the draft of the EC8 code is presented in Fig. 6. The general trend of each curve is similar, with a drop off of shear modulus ratio with increased PGA, but the representative shear modulus for a given PGA is very dependant on the details of the particular G - $\gamma$ curves.

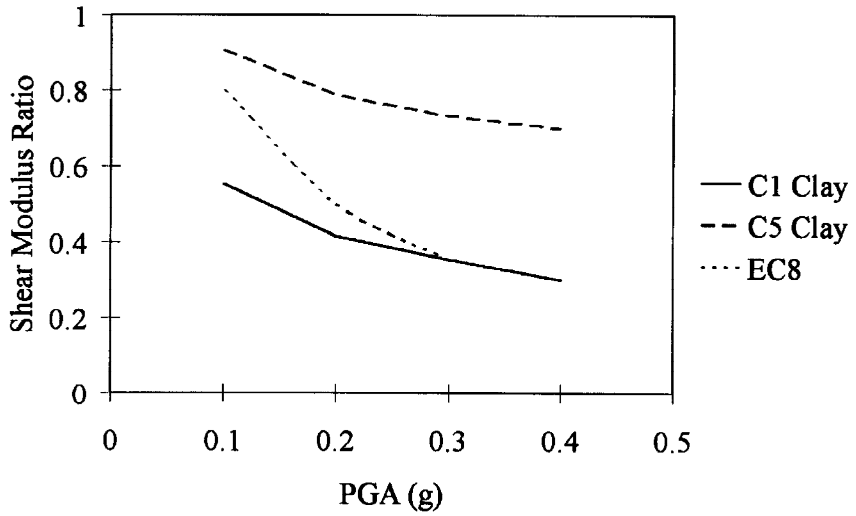


Figure 6: Comparison of Shear Modulus Ratio for C1 clay, C5 clay and draft EC8 suggestions with Earthquake PGA

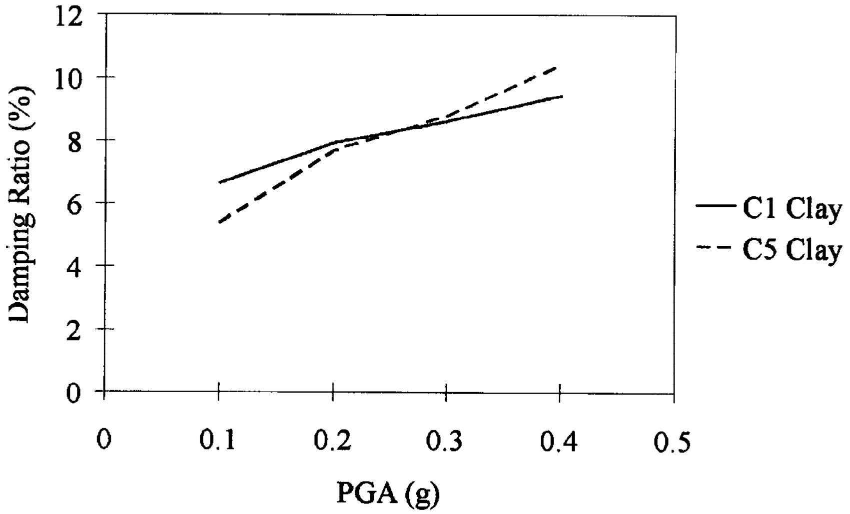


Figure 7: Comparison of Damping Ratio for C1 clay and C5 clay with Earthquake PGA.

The variations with earthquake PGA of damping and shear strain for both the C1 and C5 clays are illustrated Figs. 7 and 8. Of interest is the relative closeness of the shear strain values despite the differences in dynamic properties. Figure 8 indicates that an alternative approach, possibly more satisfactory than that suggested in EC8, to predicting foundation response during earthquake loading is to use a representative shear strain to estimate the modulus and damping. The calculations reported herein suggest that this is independent of the type of clay and increases approximately linearly with the peak ground acceleration. Figure 8 demonstrates an increase in the representative shear strain of about 0.025 to 0.03% for each 0.1g increase in the PGA.

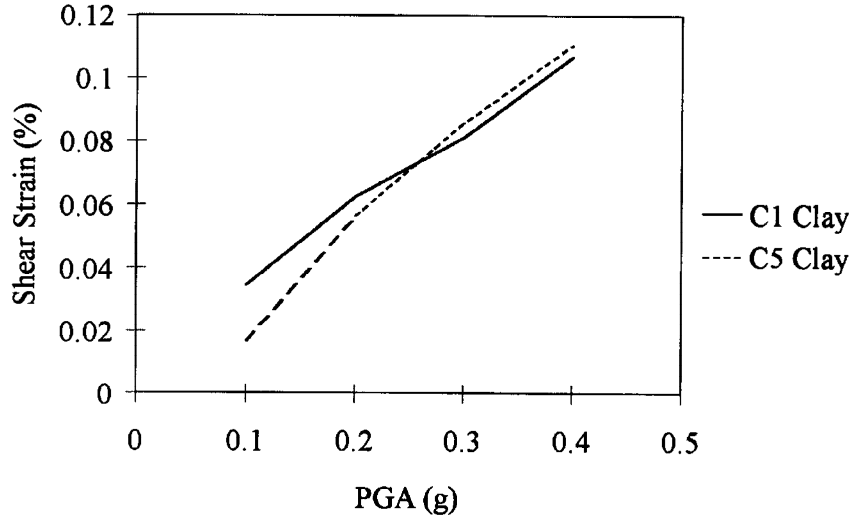


Figure 8: Comparison of Representative Shear Strain for C1 clay and C5 clay with Earthquake PGA.

In the draft of the EC8 code the design shear modulus was given for various levels of earthquake PGA, but the damping in the soil is not taken into consideration, possibly neglecting material damping which has a significant effect on nonlinear soil behaviour. Figure 7 indicates that the overall damping of the soil is expected to increase with increasing PGA. At present data on soil damping are rather scattered so that it is not possible to have different damping curves to complement the different G - $\gamma$ curves. The information in Fig. 7 tends to confirm the use of a common damping curve for all clays.

## COMPARISON OF FOUNDATION AND FREE FIELD RESPONSE

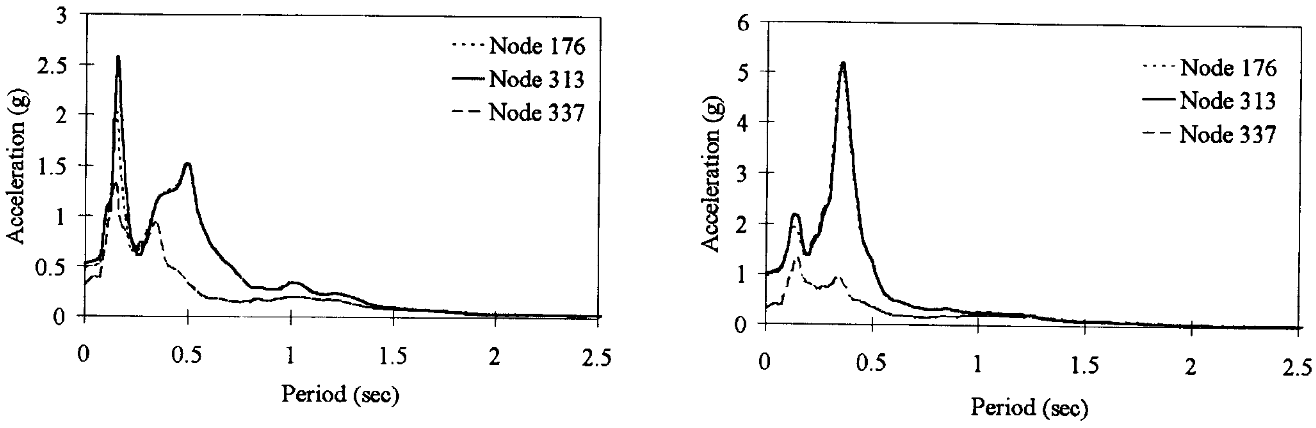
Of interest in this investigation was the influence of the structure on the surface response of a soil mass. In situations where a large horizontal translation and rotation response of the foundation occurs an additional soil strain may be induced in the near field. This can be termed secondary non-linearity in contrast to primary nonlinearity generated by the earthquake waves propagating up through the soil mass.

The comparison between the free-field response and that beneath the foundation showed little difference between the two. An example for an earthquake PGA of 0.3g, Fig. 9, shows the response at node 176 (free field) and node 313 (centre of foundation) to be very similar.

For this study, the influence of the structure on the response of the surface of the soil layer appears to be negligible. This may be due to the small mass of the structure relative to that of the soil adjacent to the narrow foundation. Before any general conclusions can be drawn a range of possibilities incorporating different soil, structure and earthquake parameters must be investigated.

## CONCLUSIONS

In this paper a comparison is made between the results of two methods for calculating the seismic response of shallow foundations in clay. The two approaches are the equivalent linear method of handling the nonlinear soil response and a linear elastic calculation based on a representative shear modulus. The following conclusions have been obtained from the results of the calculations reported:



(a) (b)

Figure 9: Comparison of surface Response Spectra of Free-field (176) and Foundation (313) with Base Input Excitation (337) for (a) C1 clay and (b) C5 clay, PGA = 0.3g

(a) The existence of a representative shear modulus which is a function of the intensity of earthquake excitation (represented herein with the PGA), broadly in line with the suggestions made in the 1993 draft of EC8, has been confirmed. This is shown in Fig. 6. However, the representative shear modulus depends on the shape of the G - $\gamma$ curve for the clay.

(b) A representative shear strain, independent of the G - $\gamma$ curve, seems to be a simpler approach to estimating seismic soil-structure interaction. The evidence for this conclusion is presented in Fig. 8.

(c) For the particular structure modelled it was found that the free field motion at the ground surface was very close to that at the centre of the foundation, Fig. 9.

(d) Differences in the clay models give large differences in response of the soil profile, and hence of the structure, as is evident from comparison of Figs. 3a and 3b and Figs. 9a and 9b.

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