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Sensitivity of seismic structural response to interpretation of soils data

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ABSTRACT

This paper investigates the sensitivity of the predicted seismic response of buildings in a PWR nuclear power station to the potential changes in the techniques and methods of interpreting soil data that have occurred over the last decade. The investigation is based on the Soil Structure Interaction (SSI) response of a typical PWR Reactor Building on a soft site during a seismic event. The current techniques and methods of interpretation of soils data tend to lead to a stiffer site with lower soil material damping than the earlier techniques. This leads to an increase in the SSI natural frequencies of typical buildings and an increase in its seismic response. This increase in the seismic response could put into question any seismic design based on seismic loads derived using the previously accepted generic soil data. The paper concludes with a recommendation for further consideration of the proposed departure from the previously accepted soil data.

INTRODUCTION

The seismic analysis and design of buildings and equipment in a typical nuclear power station are strongly dependent on the dynamic soil properties of the soil on which the power station is founded. The dynamic soil properties for a site are determined from a series of geotechnical investigations, which include in-situ measurements and laboratory tests. Techniques used for the geotechnical investigations and the subsequent interpretation of the data have improved at a considerable rate over the recent years [1]. These improvements have led to the questioning of previously widely held consensus views on generic soil data, in particular the non-linear behaviour of soil under earthquake loading [2, 3]. This paper investigates the sensitivity of the predicted seismic response of a typical PWR Reactor Building on a soft site to the potential changes in the techniques and methods of interpreting soil data that have occurred over the last decade.

DYNAMIC SOIL PROPERTIES FOR SSI ANALYSES

The soil properties required for a seismic Soil Structure Interaction (SSI) response analysis of a building are as follows:

(a) bulk density,
(b) shear modulus,
(c) Poisson's ratio, and
(d) material damping.

The shear modulus, Poisson's ratio and material damping are defined by small strain values (strain levels corresponding to 10^{-4} %) together with their variation with strain.

The bulk density of the soil strata are derived from laboratory or in-situ testing using well established techniques. The low strain shear modulus and Poisson's ratios are established normally using measurements of shear wave velocities and compression wave velocities from cross-hole, down-hole and surface refraction testing on the site. These low strain parameters are calculated as follows:

$$G = \rho V_s^2$$

and

$$\upsilon = (0.5*(V_p/V_s)^2-1)((V_p/V_s)^2-1)$$

where,

ρ = bulk density
G = low strain shear modulus,
V_s = low strain shear wave velocity,
V_p = low strain compression wave velocity, and
υ = Poisson's ratio.

The material damping together with the variation in shear modulus, material damping and Poisson's ratio with strain for a particular site are commonly obtained from an interpretation of literature on similar soil conditions and expert engineering judgement.

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This study is concerned primarily with the interpretation of the literature and the expert engineering judgement used in establishing the variation in soil shear modulus and material damping with strain for a particular site.

VARIATION OF SHEAR MODULUS AND DAMPING WITH STRAIN

The variation of shear modulus and material damping with strain is an important characteristic of the soil strata as it describes its non-linear behaviour under dynamic loading. This characteristic has a great influence on seismic SSI response of buildings and indicates whether the seismic motion will be amplified by the soil strata or attenuated. The variation is normally provided in the form of soil curves which give the degradation of shear modulus and the increase in material damping with increasing strain level.

Traditionally, generic curves produced by Seed and Idriss [4] from field and laboratory tests have been used in the SSI analyses of buildings. These curves are reproduced in Figures 1 and 2. The Seed and Idriss shear modulus curves indicate that soil typically becomes non-linear at strain levels of around 2 to 3 X 10^{-4} % and that the shear modulus degrades to less than 10% of the low strain value at a strain level of 1%. The damping curves indicate a low strain material damping of 0.5% and 2.5% of critical damping for sand and clay respectively rising to a level of damping of over 20% of critical for strain levels greater than 1%.

These generic curves have been used as the basis for defining the non-linear behaviour of soils in SSI response analyses world wide over the last decade. Minor modifications to the curves have been made in some cases to limit the maximum shear modulus degradation and material damping at the higher strains. Typically, the degraded shear modulus may be limited to 40% of the low strain value and the damping may be limited to a maximum of 2% and 15% of critical for the low strain damping and high strain damping respectively.

However, recent site response studies during real earthquakes have been published which suggest that the non-linear behaviour of soils may not be as pronounced as that indicated by the Seed and Idriss curves, even with the modifications outlined above [1,2]. Also there appears to be evidence that the onset of non-linear behaviour is at a higher strain level than that indicated by the Seed and Idriss curves. This has placed some doubt on the applicability of the generic Seed and Idriss curves for describing the non-linear behaviour of soil insitu under seismic events. Although the evidence in literature on this topic may not be considered to be entirely conclusive, it has led to re-interpretations of site investigation reports and studies of recently available literature. These re-interpretations result in stiffer and less damped sites.

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Due to the importance of the non-linear behaviour of the soil on the SSI response of buildings and the fact that the Seed and Idriss curves have been used extensively in the past, a sensitivity study on a typical PWR Reactor Building has been carried out. The SSI response of the Reactor Building on a typical soft site has been re-calculated using a soil model arising from a re-interpretation of site investigation reports for that site and recently available literature for similar soil conditions.

SSI RESPONSE ANALYSIS OF TYPICAL REACTOR BUILDING

The SSI response analysis of the Reactor building was carried out following a procedure developed by NNC Ltd for the seismic SSI analysis of PWR buildings. The procedure is based on the impedance (sub-structure) approach. The procedure typically involves the determination of soil properties consistent with the strain levels expected during a seismic event using SHAKE and the calculation of soil impedances using CLASSI. The soil impedances are attached to a finite element model of the building and a time history response analysis is carried out using UAI/NASTRAN. An outline of the procedure, which has been validated against measured results is given in [5].

Soil Impedances

The soil is modelled in the analysis by soil impedances which comprise a set of six frequency independent elastic springs and dampers representing each of the six rigid body degrees of freedom. These springs and dampers represent the dynamic stiffness of the soil underlying the building and that surrounding the embedded portion of the building.

A soil model was calculated using typical curves established following the review of recent literature on the non-linear behaviour of soils and re-interpretation of site investigation reports, see Figures 3 and 4. A seismic event with a maximum horizontal peak ground acceleration of 0.25g and with a frequency content typical of that expected in a UK soft site was used in the derivation of strain compatible soil properties, see Figure 5.

The resulting soil model is compared with the soil model previously derived using the Seed and Idriss curves in Table 1. Table 1(a) shows that, as expected, the re-interpretation of the soil properties leads to a much stiffer representation of the site. The stiffness terms in the new soil model are around twice the stiffness terms in the soil model based on the Seed and Idriss curves. On the other hand, the comparison of damping terms given in Table 1(b) does not show a consistent trend. The damping in the translational degrees of freedom is increased by the re-interpretation of the soils data but the damping in the rocking and torsional degrees of freedom is reduced. Although the reduction is small (approximately 5%), the latter is of particular importance to the SSI response analysis as the predominant mode of vibration of the

Reactor Building is a rocking mode.

Table 1
Comparison of Soil Impedances for the Reactor Building

Direction	Seed & Idriss	New Curves
Translational (N/m)	1.64E+10	3.87E+10
Vertical (N/m)	4.44E+10	9.27E+10
Rotational (Nm/rad)	1.38E+13	2.64E+13
Torsional (Nm/rad)	7.84E+12	1.78E+13

(a) Stiffness Terms

Direction	Seed & Idriss	New Curves
Translational (Ns/m)	7.47E+08	1.02E+09
Vertical (Ns/m)	2.58E+09	3.39E+09
Rotational (Nms/rad)	3.11E+11	2.95E+11
Torsional (Nms/rad)	1.45E+11	1.25E+11

(b) Damping Terms

The apparent inconsistency in the trend exhibited by the damping values can be attributed to the fact that the damping terms in Table 1 include contributions from both the internal soil material damping and the radiation damping. The radiation damping is expected to increase with the increased stiffness of the site but the internal soil material damping is expected to reduce due the lower damping curve which resulted from the re-interpretation of the soil properties. The differences observed in Table 1(b) represents the nett effect of these two damping terms.

SSI Response

The increase in the stiffness terms comprising the soil impedances increases the predicted SSI natural frequencies of the Reactor Building. The fundamental SSI frequency which corresponds to a rocking mode of vibration increases by about 40% from 1.5Hz to 2.1Hz. A similar increase in observed for the first vertical mode of vibration which increases from 3.4Hz to 4.9Hz.

An examination of the frequency content of the type of earthquakes expected in UK soft sites (see Figure 5) indicates that the frequencies of the fundamental SSI rocking mode lie in the constant velocity, ie increasing

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acceleration, part of the spectrum. Thus the predicted increase in the fundamental SSI rocking frequency due to the re-interpretation of the soil properties is expected to lead to a higher building response.

On the other hand, the predicted increase in the vertical SSI natural frequency due to the re-interpretation of the soils data is not expected to have a significant effect on the building response as the UK ground spectrum shown in Figure 5 indicates that the main vertical SSI natural frequencies lie on the constant acceleration section of the spectrum.

Effect on Seismic Design Loads

These expected changes in the predicted SSI response of the Reactor Building, in particular the dominant rocking mode of vibration, can put into question any seismic design based on seismic loading information such as in-structure response spectra derived from an SSI building response analysis which used the Seeds and Idriss curves to define the non-linear behaviour of the soil. In order to assess the potential problem due to the re-interpretation of soils data, an SSI analysis of the Reactor Building using the "new" soil model shown in Table 1 was carried out. The resulting in-structure response spectra at typical locations on the building were compared with in-structure response spectra obtained using the "Seed and Idriss" soil model shown in Table 1.

The comparisons of response spectra for two locations are shown in Figures 6 to 9. These two locations comprise the top of the containment dome of the Reactor Building and the elevation of the polar crane respectively.

The comparisons of spectra at the two locations reflect the discussion in the previous section. The horizontal in-structure response spectra indicate that, as expected, there is a shift in the main spectral peak but more importantly it shows that the amplitude of the main spectral peak of the "new" spectra exceed the amplitude of the main spectral peak of the "Seed and Idriss" spectra by over 100%. Similarly the zero period acceleration (zpa) of the "new" spectra exceed the zpa of the "Seed and Idriss" spectra by over 40%. The comparison of the vertical in-structure response spectra indicate also the shift in the main spectral peaks and demonstrates that the effect of the re-interpretation of the soil data on the vertical response is not as significant as the effect on the horizontal response.

DISCUSSION

This particular case has illustrated that the re-interpretation of soils data, in particular the non-linear characteristics of soils, can have a significant effect on the predicted seismic SSI response of buildings and therefore any in-structure response spectra produced for use in seismic design. For an existing plant, it can put into question any seismic design based on seismic loads

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derived previously accepted and widely used generic soils data. Therefore, it is important for Geotechnical specialists to be aware of the consequences of a re-interpretation of soils data on the seismic response of buildings.

The evidence in the literature on the non-linear behaviour of soils under a seismic event is inconclusive. Whilst [1] and [2] suggest that the soil non-linearity observed under real earthquakes may not be as pronounced as that indicated by the Seed and Idriss curves other studies demonstrate that the same curves can predict accurately the behaviour of buildings under real earthquakes [6]. This latter reference uses the same procedure as used in this study to predict the response of a 1/4 scale model of a typical PWR Reactor Building on a soft site at Taiwan under two seismic events and compares the predicted response with its measured response under the two seismic events.

In view of a lack of consensus in the literature on the nonlinear behaviour of soils under seismic events, much of the impetus for revising the Seed and Idriss curves relies on subjective judgement. Therefore, the authors suggest that in view of the sensitivity of response to this revised interpretation, it would be worthwhile applying more effort in deriving a more rigorous position.

Although this study has concentrated on the seismic response of the Reactor Building on a typical soft site, similar results may be expected for other buildings and for other sites.

CONCLUSIONS

This study has shown that the departure from the previously accepted generic data on the nonlinear characteristics of soil is likely to result in a stiffer site with lower soil material damping. This in turn is likely to lead to an increase in the SSI natural frequencies of typical buildings and an increase in its seismic response.

This increase in the seismic response could put into question any seismic design based on seismic loads derived using the previously accepted generic soil data. It is therefore recommended that further consideration is given to any departure from the previously accepted data following on from the recent site response studies during seismic events.

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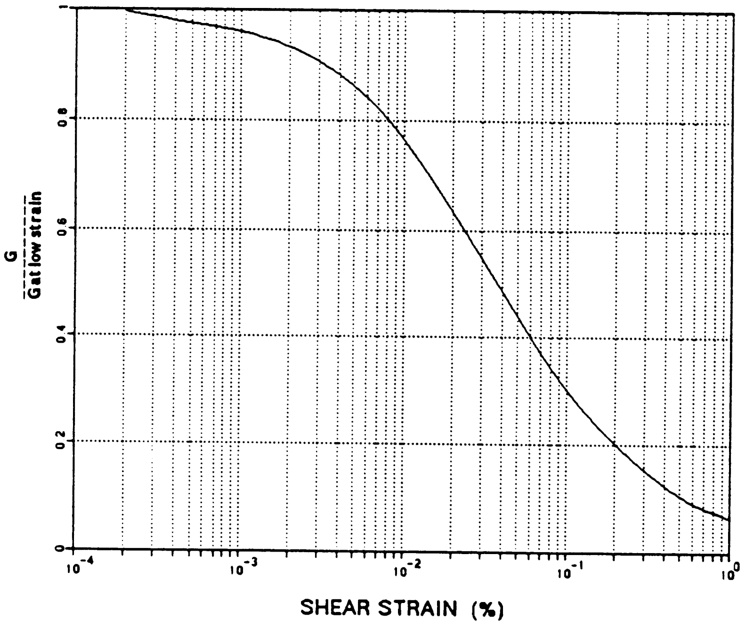

Figure 1: Seed and Idriss [4] Variation of Shear Modulus with Shear Strain

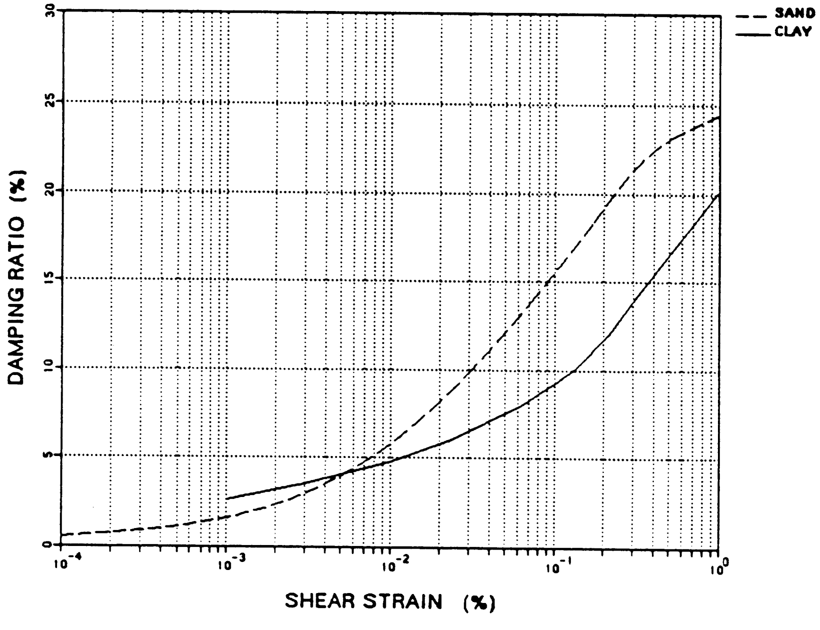

Figure 2: Seed and Idriss [4] Variation of Damping Ratio with Shear Strain

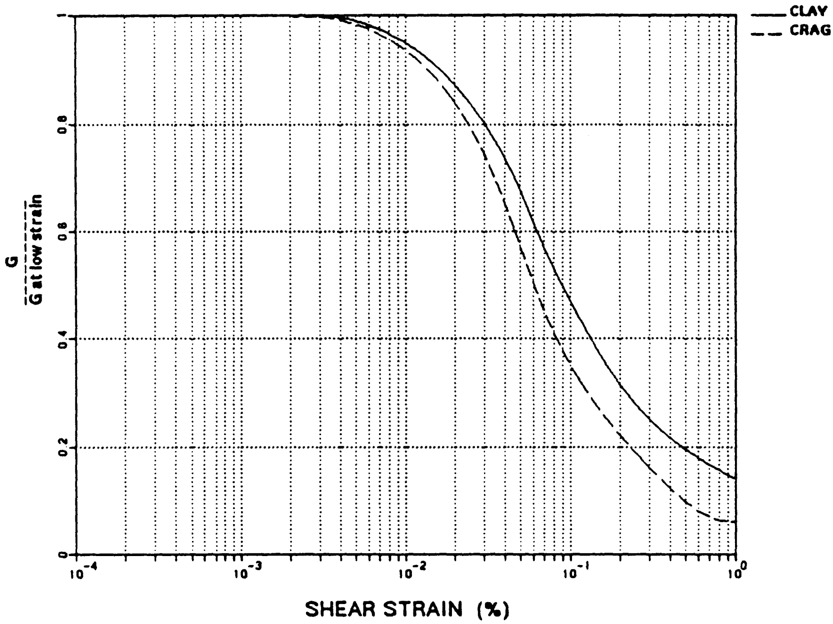

Figure 3: Variation of Shear Modulus with Shear Strain following a re-interpretation of soils data

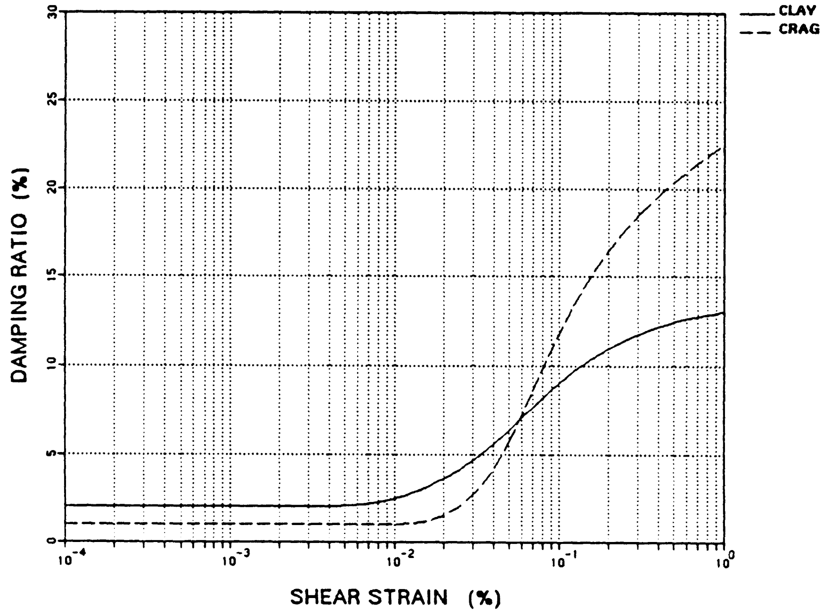

Figure 4: Variation of Damping Ratio with Shear Strain following a re-interpretation of soils data

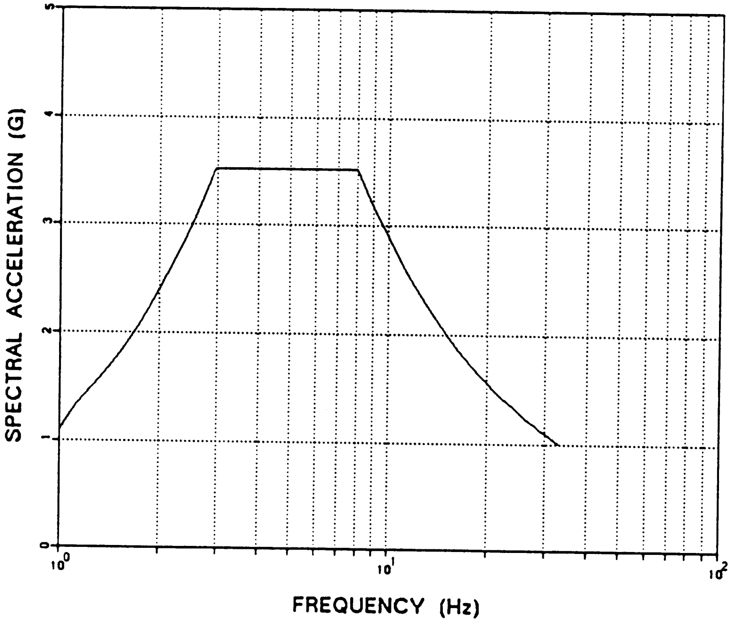

Figure 5: Seismic Ground Response Spectrum for a Typical UK Soft Site normalised to 1.0g (5% damping)

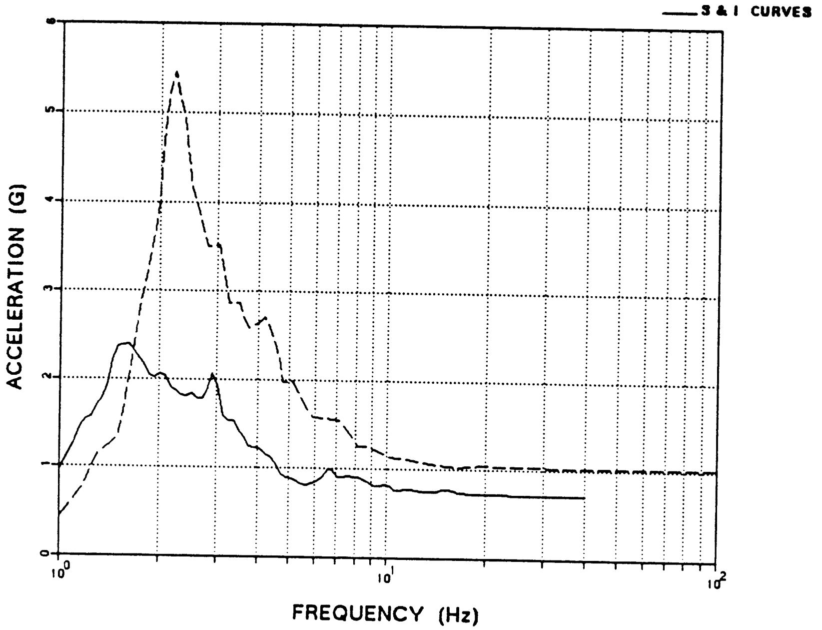

Figure 6: Comparison of Horizontal Response Spectrum at the Top of the Reactor Building Containment Dome (5% damping)

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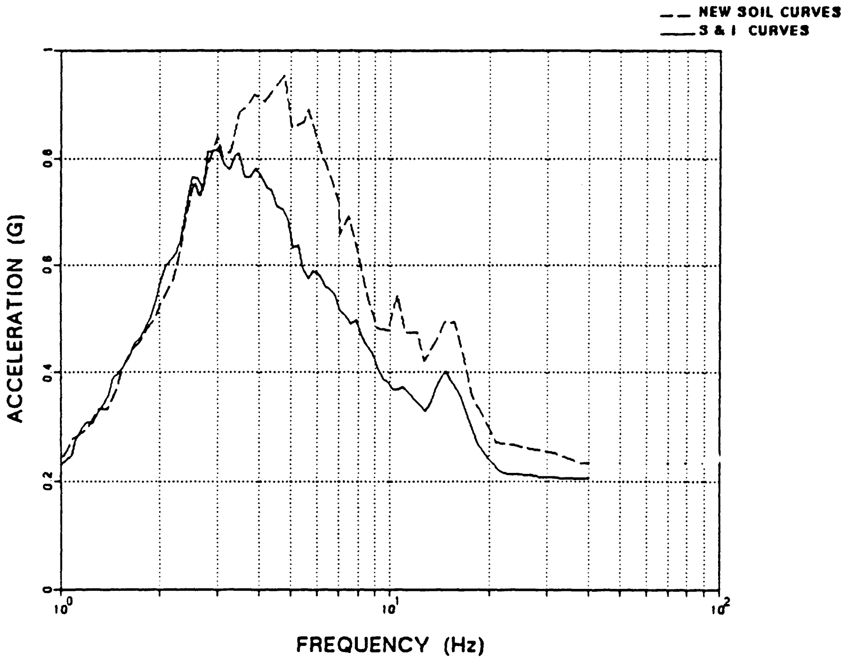

Figure 7: Comparison of Vertical Response Spectrum at the Top of the Reactor Building Containment Dome (5% damping)

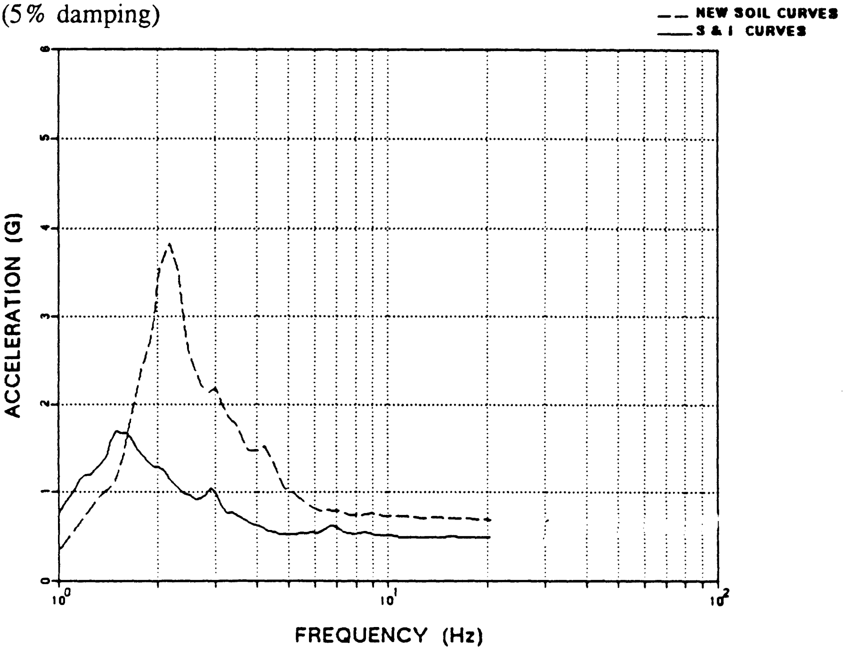

Figure 8: Comparison of Horizontal Response Spectrum at the elevation of the Polar Crane in the Reactor Building (5% damping)

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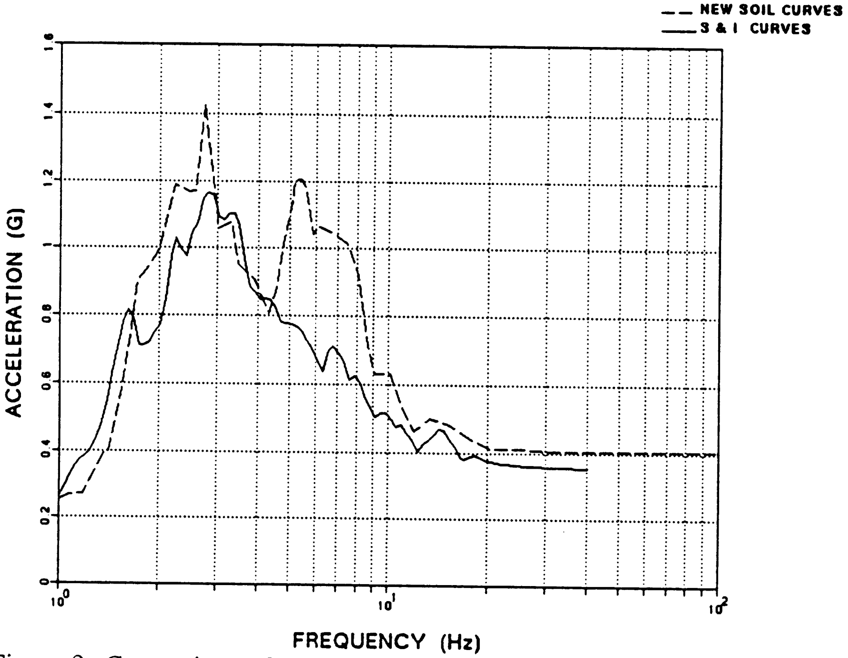

Figure 9: Comparison of Vertical Response Spectrum at the elevation of the Polar Crane in the Reactor Building (5% damping)