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VALIDATION OF SEISMIC SOIL STRUCTURE INTERACTION (SSI) METHODOLOGY FOR A UK PWR NUCLEAR POWER STATION

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1 INTRODUCTION

The seismic loading information for use in the seismic design of equipment and minor structures within a nuclear power plant is determined from a dynamic response analysis of the building in which they are located. This dynamic response analysis needs to capture the global response of both the building structure and adjacent soil and is commonly referred to as a soil structure interaction (SSI) analysis. NNC have developed a simple and cost effective methodology for the seismic SSI analysis of buildings in a PWR nuclear power station at a UK soft site. This paper outlines the NNC methodology and describes the approach adopted for its validation.

2 OUTLINE OF NNC SEISMIC SSI ANALYSIS METHODOLOGY

The seismic SSI analysis methodology implemented by NNC for the response analysis of PWR buildings is based on the sub-structure (impedance) approach. In this approach, the soil adjacent to the building is analysed separately to determine its effective stiffness and a soil model is developed to reflect the dynamic stiffness of the soil underlying the building together with the soil surrounding the embedded portion of the building if applicable. The dynamic parameters of the soil model are added to a model of the building structure for the response analysis of the combined soil-structure system.

2.1 Soil Model

The NNC approach models the soil by a set of six frequency independent elastic springs and viscous dampers (ie. impedances) in each of the six rigid body degrees of freedom.

Frequency dependent impedances are calculated, in the first instance, using CLASSI/ASD assuming a rigid surface mounted basemat and taking account of both the geometry of the basemat and layering of the soil at the site. Best estimate soil properties compatible with the expected earthquake strain levels are used in the derivation of the impedances. The strain compatible soil properties are obtained from an equivalent linear deconvolution analysis using SHAKE. The frequency independent impedances are subsequently determined by plotting the intersection of the stiffness curve, as obtained from CLASSI, with a curve representing the mass or inertia of the building multiplied by the angular frequency squared, as shown in Figs 1 and 2. This intersection point is effectively the natural frequency for a mass supported by a frequency dependent spring, and the frequency is used to determine the equivalent frequency independent springs and dampers for the seismic SSI analysis of the building.

If appropriate these equivalent soil springs and dampers are modified to account for embedment effects before use in the seismic SSI analysis.

2.2 Building Model

The building structure is idealised by a simple finite element beam-mass model. However where flexible areas exist within a building, for example column supported floors which respond within the seismic frequency range, these are modelled explicitly using plate and beam elements.

2.3 Response Analysis

The soil springs and dampers are connected directly to the underside of the building basemat and the free field motion in the three orthogonal directions, ie. north-south, east-west and vertical, is applied via the springs and dampers.

The seismic response analysis is carried out in the time domain using the modal superposition method. A modified solution sequence in UAI/NASTRAN is used which incorporates composite structural and viscous soil damping together with cross coupling between modes. The response time histories at various pre-determined locations throughout the building are calculated in the analysis. The response analysis is repeated three times with different permutations of the three input time histories rotated to take account of the random nature of earthquake motion.

2.4 Generation of Design Floor Response Spectra

Floor response spectra (FRS) are generated from the building response time histories using the Duhamel Intergral. A NASTRAN post-processor developed by NNC is used for this purpose. The mean of the three FRS generated for each location in each of the three orthogonal directions are calculated and are subsequently frequency broadened to account for uncertainties in the methodology. The resulting broadened FRS are termed Design FRS and are used in seismic design.

In some cases the mean FRS at a number of locations within the building may be enveloped before the frequency broadening is applied.

3 VALIDATION OF NNC SEISMIC SSI ANALYSIS METHODOLOGY

Inherent in the NNC seismic SSI methodology outlined above are a number of simplifying assumptions that are required in order to permit a simple cost-effective design solution to what is a complex seismic analysis problem. Each of these assumptions was investigated by a separate parametric study to confirm that the assumptions were valid and would lead to an overall conservative but reasonable FRS for use in design. In addition, the complete NNC seismic SSI methodology, with all the inherent assumptions, was validated through a comparison of predicted response with the measured response of a quarter scale model containment building.

3.1 Parametric Studies

The series of parametric studies carried out investigated assumptions covering all aspects of the seismic SSI methodology. These included simplifying assumptions made in the modelling of the soil, the modelling of the building structures and the basic analysis philosophy itself. Each parametric study examined a single assumption and the approach followed for each study was selected to best suit the investigation of the particular assumption under consideration. Several computer programmes were employed for these studies and these included finite element programmes such as NASTRAN and ANSYS together with specialist "state of the art" seismic SSI programmes such as ASD/CLASSI, SASSI and NNCDYNA3D, a version of DYNA3D developed specifically by NNC for soil structure interaction analyses.

3.1.1 Simplifying assumptions in the soil model

The complex response of the soil under a seismic event is represented in the building response analysis by a set of simple linear frequency independent soil impedances, as discussed in Section 2.1. Inherent in this simple representation are a number of assumptions involving: the layering of the site, frequency dependency of the soil impedances and non-linearity of the soil, which were investigated through a series of parametric studies.

These parametric studies examined the effect of these assumptions on the seismic response of the reactor building at the particular UK soft site and the conclusions of the more important of the parametric studies were as follows:

(a) The layering at the site has a significant effect on building seismic response and should be considered in the derivation of soil impedances.

(b) The frequency dependency of soil impedances can be adequately represented by frequency independent soil impedances, with the latter producing slightly more conservative results.

(c) Primary soil non-linearity can be represented by equivalent linear methods.

(d) Secondary soil non-linearity does not have a significant effect on building response and can be neglected.

These parametric studies demonstrated that it was valid to use linear frequency independent soil impedances so long as the layering of the site was considered in the derivation of the impedances. Typical results from the study carried out to investigate the frequency dependency of soil impedances are shown in Figs 3 and 4.

3.1.2 Simplifying assumptions in the building structure model

The building structures are mainly represented by simple beam and mass elements in the building response analysis, except for flexible areas, as discussed in Section 2.2. The main assumptions inherent in the representation of the building involve the use of the UAI/NASTRAN beam elements, the flexibility of the basemat, the possible loss of contact between the building foundation and the soil, and the separation between the foundation structural concrete and mass concrete.

The parametric studies examined the effect of these assumptions on the seismic response of the reactor building on the particular UK soft site, although for basemat up-lift the analysis was repeated for the fuel building. The conclusions of these studies were as follows:

(a) The UAI/NASTRAN beam elements were adequate to capture the global seismic response of the buildings.

(b) Basemat flexibility has a small effect on the seismic response of the buildings but the effects are adequately covered by the margins applied to produce the design FRS.

(c) Foundation lift-off does not have a significant effect on the seismic response of the buildings and can be neglected.

(d) The effects of separation between the structural concrete and mass concrete on the building seismic response are insignificant and can be neglected.

These parametric studies validated the main simplifying assumptions in the building model indicating that the combined effects of the assumptions were small and adequately covered by the margins applied in the generation of the design FRS.

3.1.3 Simplifying assumptions in the analysis philosophy

The need for a simple and cost-effective methodology required that a number of simplifying assumptions were made in the analysis philosophy. The more important assumptions involve the treatment of uncertainties in the soil and structural properties, structure-soil-structure interaction (SSSI) effects, and embedment effects.

The parametric studies carried out to investigate these more important assumptions for the particular site concluded the following.

(a) Soil property uncertainty has a significant effect on the response of buildings but frequency broadening of the best estimate FRS is sufficient to cover this effect.

(b) Structural property variations have an insignificant effect on the global seismic SSI response of the buildings and can be neglected.

(c) Structure-soil-structure interaction effects are not significant and do not require any additional margins in the production of design FRS.

(d) Embedment of the building significantly reduces the seismic response of the buildings. Conservatisms due to embedment effects remain present even when the soil impedances are modified to take account of the increased stiffening and radiation damping due to the embedment.

The parametric studies indicated that the analysis philosophy is valid and that the only margin required is frequency broadening to cover soil property uncertainty. Figs 5 and 6 show typical results from the soil property variation study indicating that 25% frequency broadening is sufficient to cover uncertainties in soil properties. Typical results from the structure-soil-structure-interaction study are shown in Figs 7 and 8.

3.2 Validation of Overall Methodology

The validation of the overall NNC seismic SSI methodology was carried out via a "blind" comparative study in which the response of a quarter scale model of a containment building at Lotung, Taiwan under two real seismic events was predicted using the NNC methodology and compared with the measured response. This work which is described in detail in Reference 1 indicated that the overall methodology predicted the frequency of the peaks of the building FRS accurately and resulted in conservative FRS for the Lotung building. Typical comparisons of predicted and measured FRS are shown in Figs 9 and 10.

4 CONCLUSIONS

This paper has outlined the methodology implemented by NNC for the seismic SSI analysis of buildings in a PWR nuclear power station on a soft site in the UK. The methodology was validated by a series of parametric studies together with a "blind" comparative study which compared the predicted response with the measured response of a containment model at Lotung, Taiwan. The parametric studies and comparative study demonstrated that the NNC seismic SSI methodology is valid. In addition the studies showed that the only margin required to produce Design FRS for this particular UK soft site, suitable for use in seismic design, was 25% frequency broadening.

REFERENCES

1. Llambias J.M. and Johnston, R.S., 'Comparison of calculated seismic response of a ¼ scale reactor building with the measured response', Proc. Int. Conf. on Earthquake, Blast and Impact, Manchester, UK, 1991, Elsevier, pp319-332.

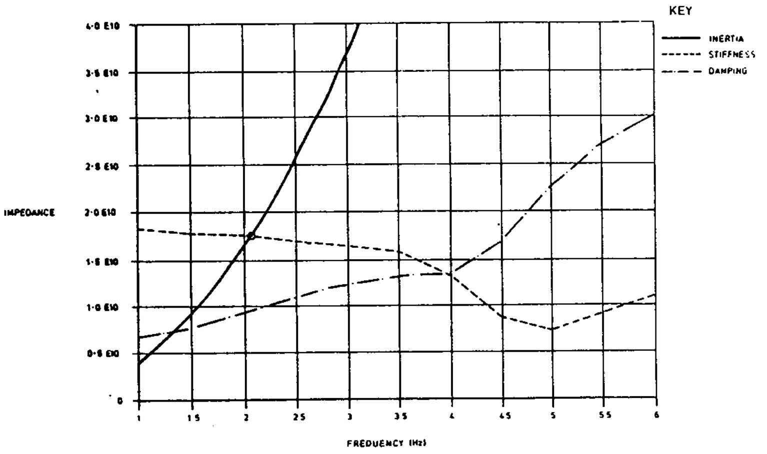

Fig. 1 Variation of Horizontal Stiffness and Damping Coefficient with Frequency

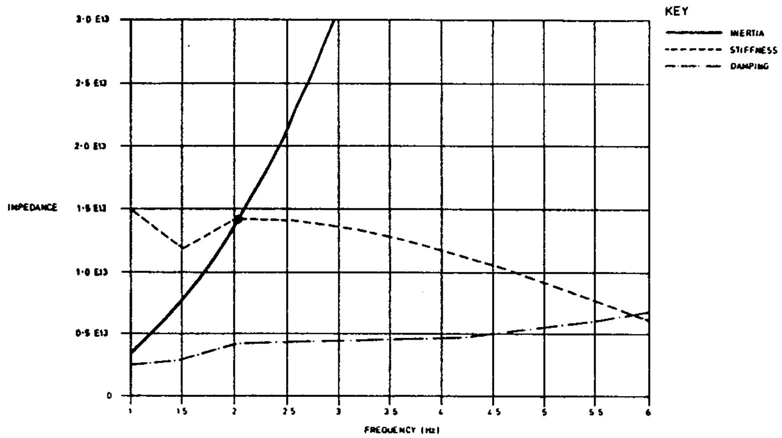

Fig. 2 Variation of Rotational Stiffness and Damping Coefficient with Frequency

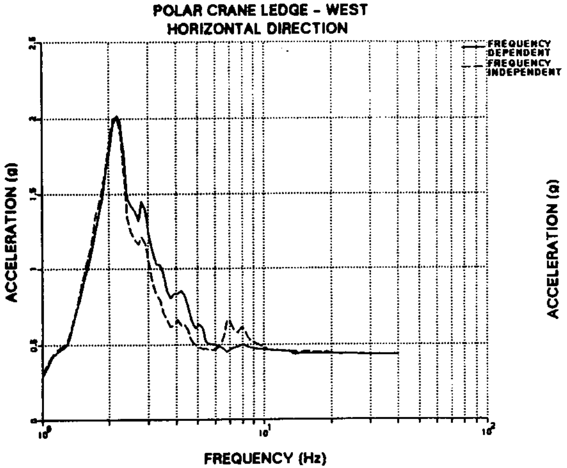

Fig. 3 Effect of Frequency Dependency of Soil Impedances on the Reactor Building Horizontal FRS for the Polar Crane Elevation

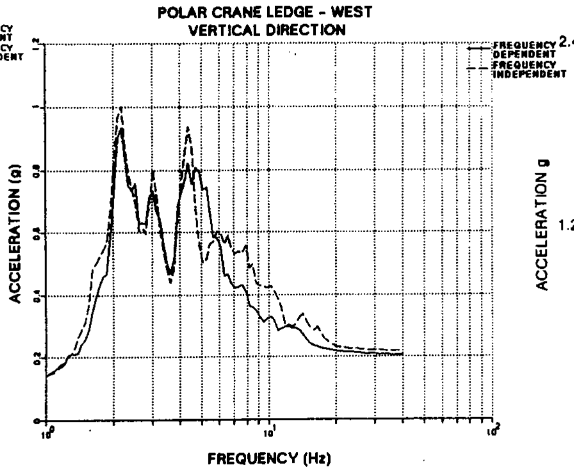

Fig. 4 Effect of Frequency Dependency of Soil Impedances on the Reactor Building Vertical FRS for the Polar Crane Elevation

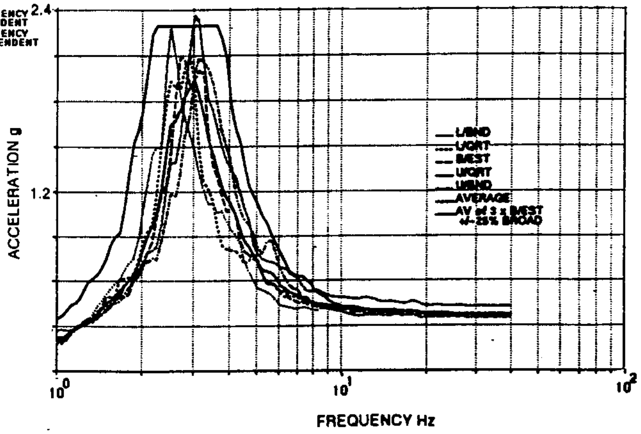

Fig. 5 Effect of Soil Property Uncertainty on the Fuel Building Horizontal FRS for the 21.13m Elevation

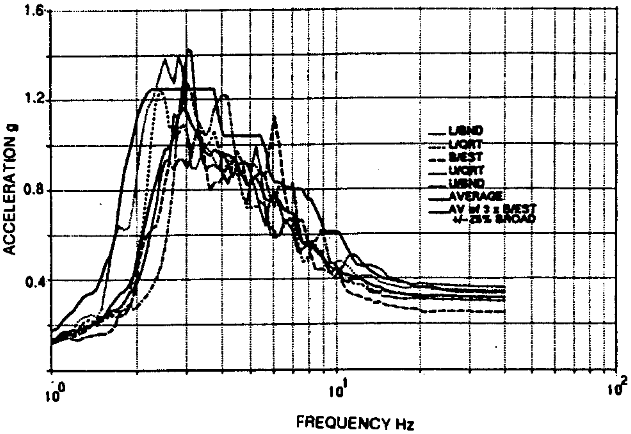

Fig. 6 Effect of Soil Property Uncertainty on the Fuel Building Vertical FRS for the 21.13m Elevation

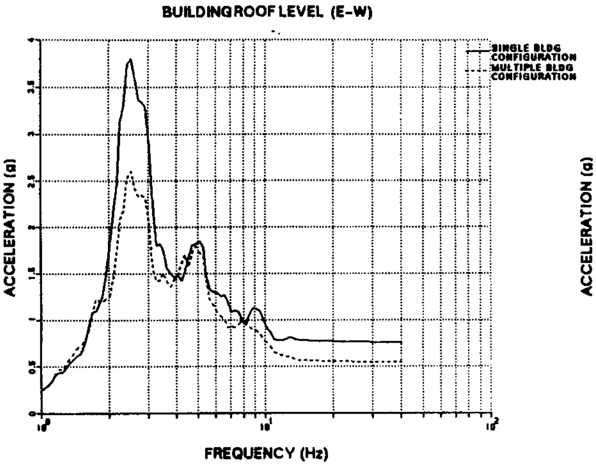

Fig. 7 Effect of Structure-Soil-Structure Interaction on the Fuel Building Horizontal FRS for the Roof Elevation

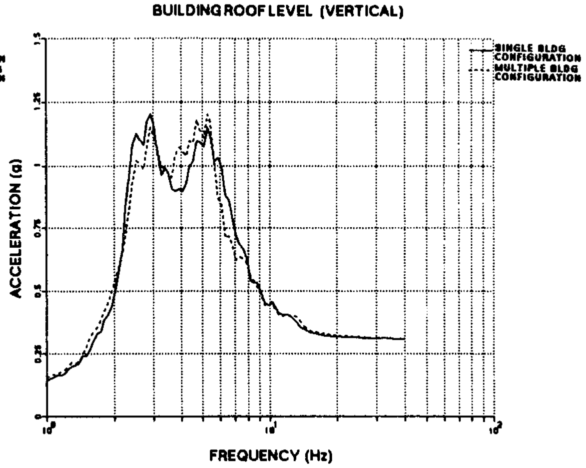

Fig. 8 Effect of Structure-Soil-Structure Interaction on the Fuel Building Vertical FRS for the Roof Elevation

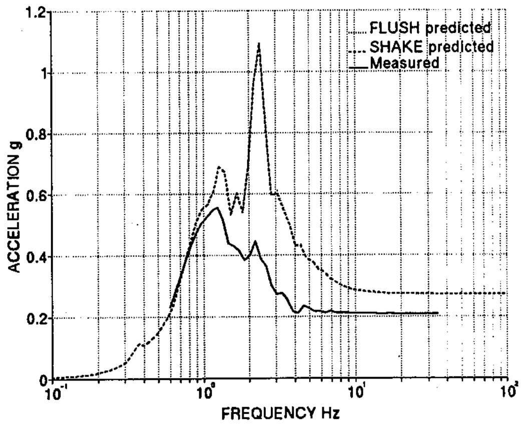

Fig. 9 Comparison of Predicted and Measured Horizontal Response of the Lotung Containment model

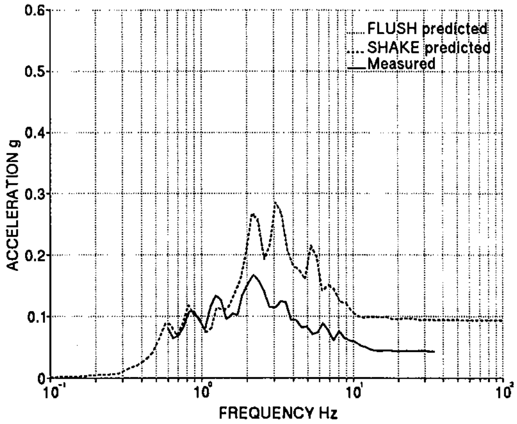

Fig. 10 Comparison of Predicted and Measured Vertical Response of the Lotung Containment model