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Seismic Sensitivity Study of a Generic CANDU Nuclear Power Plant: Soil-Structure Interaction

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SUMMARY

The seismic sensitivity and capability study for a generic CANDU Plant is part of an overall development program of design standardization. The purpose of this paper is to investigate the sensitivities of structural responses and floor response spectra (FRS) to variations of structural and soil parameters.

In the seismic design standardization, a wide range of soil conditions is considered and the envelopes of the resulting site spectra (soil-structure interaction effect) are then used for the design of the generic plant. The nuclear island structures considered herein have different relative stiffness and one of them has two layout/structure schemes: one is relatively flexible and the other is moderately stiff.

In the preliminary phase of the seismic sensitivity study presented hereby, the soil-structure interaction seismic analysis is based on the half-space modelling (soil-spring lumped-mass) method and the response spectrum method for the seismic responses. Distinct patterns and sensitivity of the site spectrum analysis for structure schemes of different relative stiffness and for different structural elevations are observed and discussed.

1. INTRODUCTION

The nuclear island structures of a generic CANDU Plant considered in the seismic sensitivity study encompasses a reactor building (R/B), a service building (S/B) and a common mat foundation. The S/B completely surrounds the R/B although they are structurally independent except that both are placed on a common mat. The R/B consists of two major components, namely, the containment structure (C/S) and the internal structure (I/S) which are structurally separated, except that both are supported on the base slab of the common mat. The C/S is formed by a cylindrical wall, a spherical dome at the top with a ring beam at the edge, and the base slab. The I/S includes walls, columns, slabs and beams, to provide shielding and structure support to the reactor and equipment. The common mat foundation design is to enhance the seismic stability of the structures and minimize any potential differential settlement.

Throughout the conceptual development of structure and equipment design, the building layouts were continuously revised for better facilitating equipment arrangement and structural strength requirements. For the I/S, two structural design schemes, designated as Version I and II, have been evaluated in terms of the soil-structure interaction effect. The significance of this design comparison is to show that considerable attention was paid to the layout of the generic plant to ensure the lowest possible seismic response in all critical areas of the plant, especially those particularly sensitive to vibratory motion or significantly affected by varying soil conditions.

In this paper, the results of the preliminary phase of the seismic sensitivity study are presented. The soil-structure interaction effect is evaluated based on the half-space modelling (soil-spring lumped-mass) method and the seismic responses (floor response and floor response spectrum (FRS)) are obtained by the response spectrum method developed in Ref. [1,2]. The time-history method and the finite boundary modelling method for soil media and its comparison with the soil-spring modelling method are covered in the next phase of study and are not reported herewith.

2. SEISMIC LUMPED-MASS MODEL

The seismic soil-spring lumped-mass model used here is shown in Fig. 1. The soil spring and dashpot constants for a homogeneous half-space medium are derived from equations given in Ref. [3]. For a layered elastic half-space, the equivalent soil spring constants are derived utilizing the approach of Ref. [4]. From these equivalent soil springs, for a layered elastic half-space, equivalent moduli of elasticity can then be determined for an equivalent homogeneous elastic half-space. Since the generic reference plant is designed to be adaptable for world-wide sites, a wide range of soil/rock properties is considered. These are represented by varying the soil-spring constants in the seismic model of Fig. 1. The equivalent elastic modulus (E) covers a range from $7 \times 10^3 \text{kg/cm}^2$ to $1 \times 10^5 \text{kg/cm}^2$. One more condition included is the case where the rock elastic modulus becomes infinite, i.e. each structure component is fixed at its base.

In Fig. 1, the structural components include the service building, the containment structure and the internal structure of the reactor building; they are structurally independent, except that all are supported on the common mat. Two structural schemes, Version I and II, are considered for the I/S. Version I is relatively flexible and has a fundamental frequency of 2.5 Hz which will be in resonance with the foundation-soil system for a soft soil condition. On the other hand, Version II is moderately stiff and has a fundamental frequency of 5.1 Hz which will be in resonance with a medium-hard rock.

The common mat foundation was considered a rigid member in this study. This assumption was made in view of the common mat thickness and the stiffening effects contributed by the containment perimeter wall, the massive R/B internal structure walls at the lower floor, and the S/B walls. Furthermore, the combined effects of the common mat flexibility and the soil stiffness are compensated for by varying the soil stiffness to account for the worst condition and the envelopes of seismic responses are used for design of each individual structure component and equipment.

3. PARAMETRIC STUDY OF SOIL-STRUCTURE INTERACTION EFFECT

The structural floor response and the floor response spectra (FRS) are determined by the response spectrum method. Duff's [1,2] simple and efficient method is used to generate the FRS from the ground response spectra (GRS). As part of the seismic capability study for the generic plant, different ground response spectra, e.g. Ref. [5,6], have been used. In this report, the study was carried out for a design basis earthquake of 0.3 g and the GRS specified in Ref. [6].

Figures 2-7 show the site spectrum analysis (soil-structure interaction) for the peaks of the structural floor response and the FRS at representative elevations of the three structural components (the C/S, the S/B and the I/S). Figures 8-11 show the FRS. It is noted that the damping values used for Version I (I/S) are based on those specified in Ref. [5] which are in general lower than those specified in Ref. [6] used for Version II. However, this difference will not affect the conclusion described below.

From the results of the soil-structure interaction seismic analysis, some general and common features are given below:

(1) The rocking frequency of the foundation-soil system is about two times higher than the translational frequency. Therefore, the rocking effect is not significant in the soil-structure interaction.

(2) The effect of placing other structural components on the common foundation is to reduce the foundation-soil frequency and is more significant in the soft soil range.

(3) As the soil elastic modulus increases indefinitely, the dominant frequency, the composite damping, the structural floor response and the FRS all approach toward those of the limiting case where the structure is fixed at its own base.

(4) Coupling between the superstructure system and the foundation-soil system can be simulated approximately by a two-degree-of-freedom (2-DOF) model. For instance, the shifts of the coupled frequencies and the composite damping values of a 2-DOF system can provide significant clues to the soil-structure interaction behaviour of a particular structural component of a complex system like Fig. 1. Further study on the correlations between a 2-DOF model and the actual structure system is underway.

From Figs. 2-11, two significant patterns of seismic responses can be observed. The first pattern is associated with structures of relatively flexible, i.e. Version I of the I/S. The other is associated with moderately stiff structures, e.g. the C/S, the S/B and Version II of the I/S. Differences in the soil-structure interaction effect between these two patterns are listed in Table I. Features of site spectrum analysis can be further illustrated by the following comparison between the two versions of the I/S design.

(1) For the flexible structural scheme, Version I, the seismic response shakes down rapidly after the resonant condition in the site spectrum to the limiting case in which the structures are fixed at the base. On the other hand, for the moderately stiff structural scheme, the soil-structure interaction effect is prolonged.

(2) At the lower floor level, the fundamental frequency is higher, and therefore, the soil-structure interaction effect will be more prolonged than at higher floor levels, see the variations of the composite damping β in Figs. 4 and 5. For the lower levels of the moderately stiff structural scheme, the fundamental frequency becomes so high that its response virtually follows the foundation-soil system and the maximum response occurs in the soft soil range, see Figs. 5 and 7. In other words, for the flexible structural scheme (Version I), the responses of the top levels are governed by soft soil conditions (see Figs. 4 and 6) while the lower levels are governed by medium to hard rock conditions (see Figs. 5 and 7). On the contrary, for the moderately stiff structural scheme (Version II), the top levels are governed by medium to hard rock conditions (see Figs. 4 and 6) while the lower levels are governed by soft soil conditions (see Figs. 5 and 7).

(3) For both I/S schemes, at the top floor levels, the maximum FRS peak occurs at a soil condition harder than for the maximum structural floor response. Whereas, at the lower levels, it is just the opposite.

4. CONCLUSION

A flexible structural scheme has a narrow soil range of sharply changing soil-structure interaction behaviour. On the other hand, a moderately stiff structural scheme has a wide soil range of gradually changing soil-structure interaction which is less sensitive to variations and uncertainties of structural and soil parameters. Therefore, designs based on the latter concept are desirable.

REFERENCES

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[4] Johnson, G.R., Christians, P. and Epstein, H.I., "Stiffness Coefficients for Embedded Footings", Journal of Geotechnical Engineering Division, GT.8, ASCE, August, 1975.

[5] Canadian Standards Association CAN3-N289.3-M81, "Design Procedures for Seismic Qualification of CANDU Nuclear Power Plants", September 1981.

[6] USNRC Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants", Revision 1, December 1973.

TABLE I: SITE SPECTRUM PATTERNS

MODERATELY STIFF STRUCTURE	RELATIVELY FLEXIBLE STRUCTURE
(1) Dominant frequency increases as soil elastic modulus (E) increases, and approaches asymptotically toward the natural frequency of structure.	(1) Dominant frequency varies insignificantly with soil elastic modulus, and is close to the natural frequency of structure.
(2) Composite damping drops as soil elastic modulus increases, and approaches toward the damping value of structure. Soil-structure interaction is strong, i.e., coupling effect, especially at soft and intermediate range of soil condition.	(2) Composite damping varies insignificantly with soil elastic modulus, and is close to the damping value of structure. Soil-structure interaction is weak, i.e., decoupling effect throughout the whole range of soil condition.
(3) Peak of structural floor acceleration occurs around the soil-structure resonant condition in a highly damped and coupled fashion. It drops slightly as soil elastic modulus keeps increasing.	(3) Peak of structural floor acceleration occurs around the soil-structure resonant condition in a decoupling fashion.
(4) FRS peak generally increases, but the increasing rate decreases, as soil elastic modulus increases with decreasing soil-structure interaction effect.	(4) Similarly to the structural floor acceleration, FRS peak occurs around the soil-structure resonant condition in a decoupling fashion.
(5) The pattern is less sensitive to small variations of structural parameters, e.g. natural frequency.	(5) The pattern, e.g. the maximum FRS peak and the associated elastic modulus, is sensitive to variations of structural parameters.

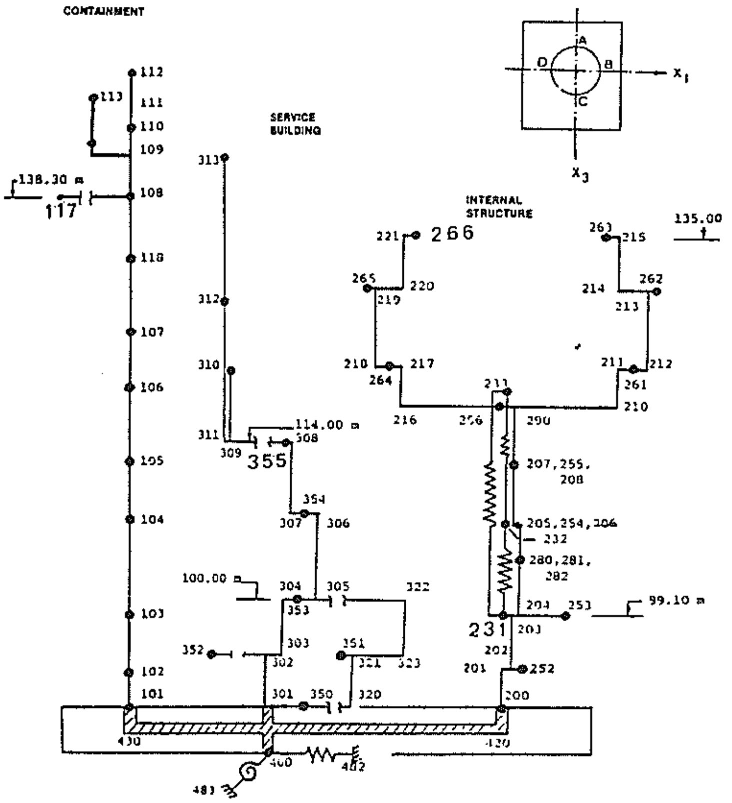

Figure 1. Soil-Spring Lumped-Mass Model of Nuclear Structures

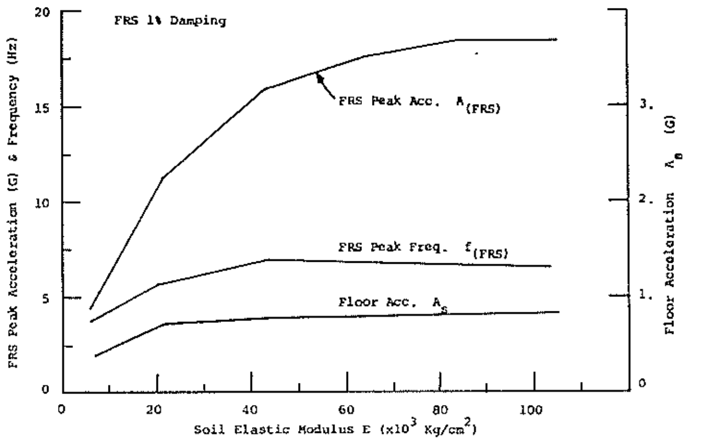

Figure 2. Site Spectrum of Seismic Response at Node 117 of C/S (I)

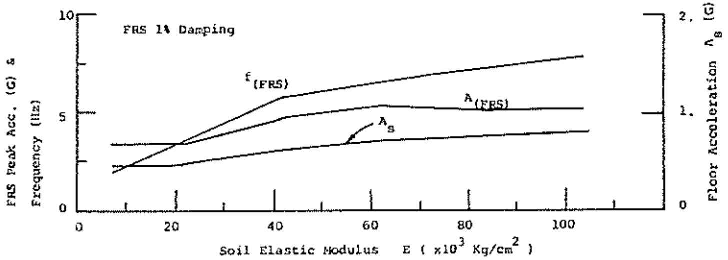

Figure 3. Site Spectrum of Seismic Response at Node 355 of S/B (I)

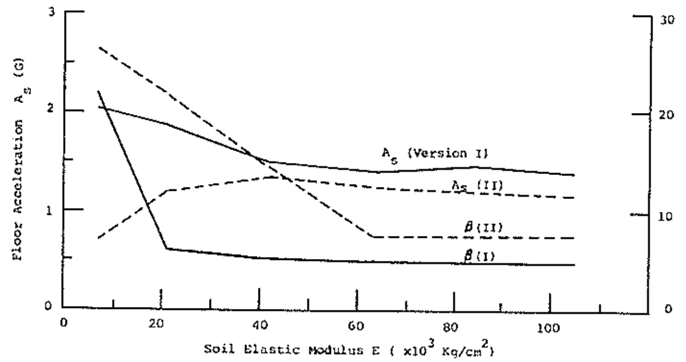

Figure 4. Floor Response and Dominant Damping Value for Node 266 (Top of I/S)

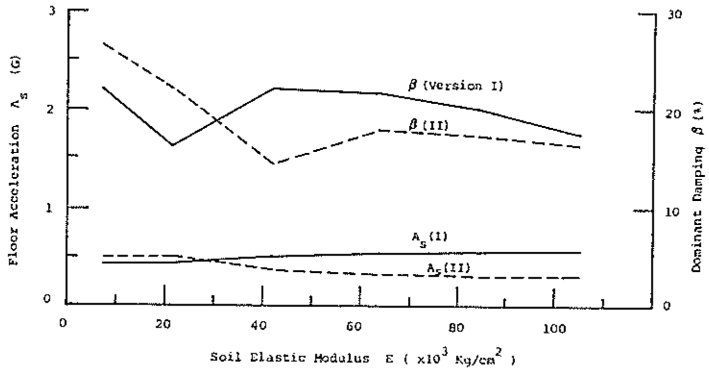

Figure 5. Floor Response and Dominant Damping Value for Node 231 of I/S (Grade Floor)

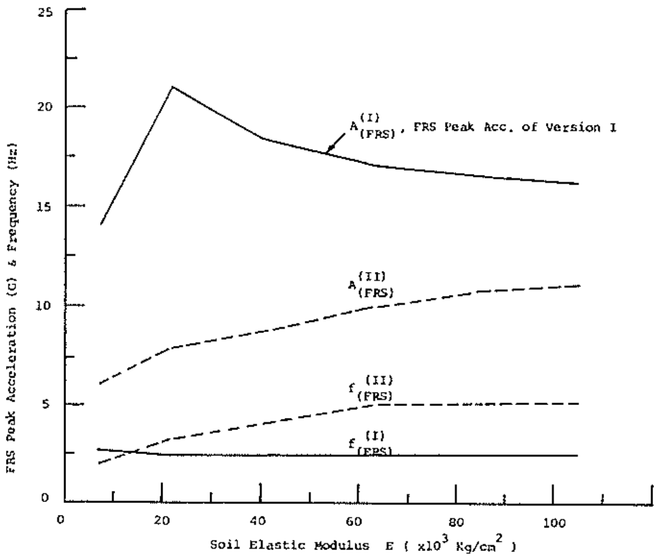

Figure 6. Peak Acceleration and Frequency of FRS (1%) for Node 266 (Top of I/S)

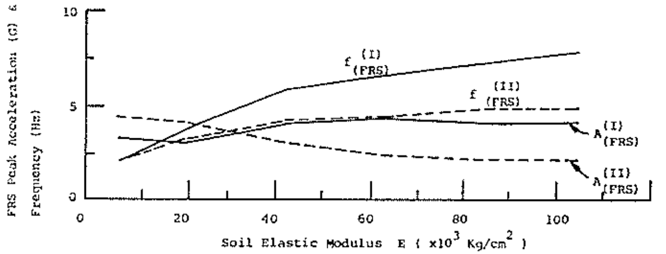

Figure 7. Peak Acceleration and Frequency of FRS (1%) for Node 231 of I/S (Grade)

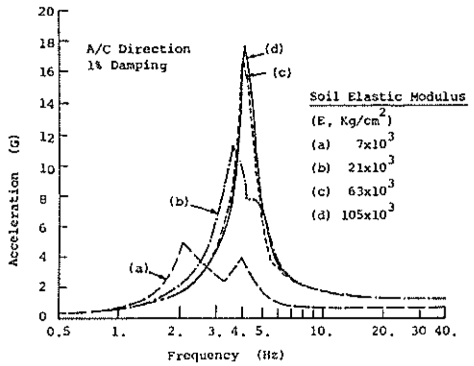

Figure 8. Floor Response Spectra for Node 117 of C/S (I)

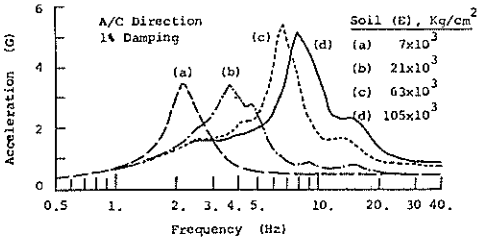

Figure 9. Floor Response Spectra for Node 355 of S/B (I)

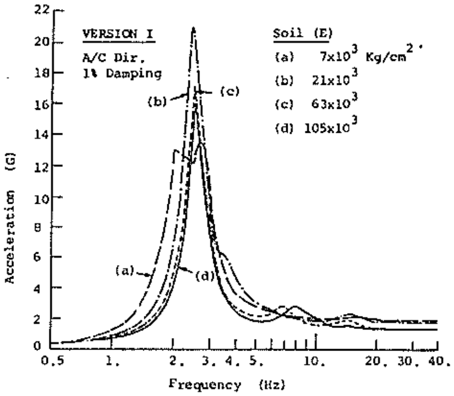

Figure 10. Floor Response Spectra for Node 266 of I/S (I)

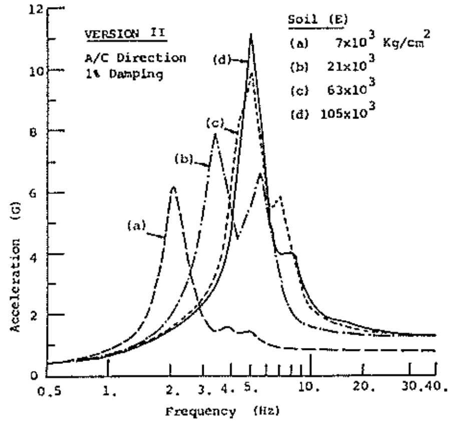

Figure 11. Floor Response Spectra for Node 266 of I/S (II)