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Study on Seismic Response of CANDU 9 Reactor Building

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ABSTRACT

The effect of soil-structure interaction becomes important in the seismic design of critical structures such as nuclear power plants, which are constructed in the site composed of soft soil. Many methodologies have been developed to account for the proper consideration of soil-structure interaction effect. However it is difficult to estimate the soil-structure interaction effect accurately because of many uncertainties.

This paper presents the results of the study on dynamic responses and soil-structure interaction effect, which is an ongoing project. The analysis was conducted on the CANDU 9 reactor building which was conceptually designed by AECL(Atomic Energy of Canada Limited). Dynamic response characteristics of CANDU 9 reactor building were studied with the finite element model and the lumped mass stick model. The effect of soil-structure interaction was evaluated with the lumped mass stick model by use of computer program SASSI.

1. INTRODUCTION

There are potential opportunities for siting important facilities or buildings at sites that are composed of soft soil due to the increasing difficulty in acquiring new construction sites that consist of hard rock. When a structure is constructed at site composed of soft soil, the behavior of a structure is much affected by the motion of its supporting soil. This effect, which is caused by the flexibility of supporting soil, is more important in the case of stiff and massive structures. Therefore the effect of soil-structure interaction is an important consideration in the seismic design of a critical structure such as the nuclear power plants at sites composed of soft soil. The various finite element techniques have been used to solve the dynamic problems. The techniques have been extensively employed to analyze soil-structure interaction effects; to determine the stiffness functions, to study wave propagation problems in soil deposits, etc.

Several well-known methods have been developed and are currently being used to analyze structures at sites that are composed of soft soil, whose behaviors are influenced by soil-structure interaction. These methods include the soil-spring method, FLUSH(two-dimensional finite element method), SASSI(three-dimensional finite element substructure method), and CLASSI(more sophisticated half-space continuum impedance method). Each of these methods has its own limitation because of the assumptions used in formulation. The computer program SASSI was used in this study because it is more capable of analyzing dynamic responses of structures, considering soil-structure interaction.

This paper presents the results of the study on dynamic responses of structures and soil-structure interaction effects, which is an ongoing project. The implemented model is the CANDU 9 reactor building that was conceptually designed by AECL(Atomic Energy of Canada Limited). Dynamic response characteristics of CANDU 9 reactor building were studied with the finite element model and the lumped mass stick model. Also, dynamic responses of CANDU 9 reactor building, considering soil-structure interaction effects, were evaluated by using the three-dimensional finite element substructure method, program SASSI. The results show that the flexibility of supporting soil affects dynamic response characteristics of the reactor building and responses of the reactor building can be amplified due to the rotation of the foundation.

2. SASSI METHOD

When a structure is constructed at sites composed of soft soil, the behavior of a structure is much affected by the motion of its supporting soil. For past years, many sophisticated mathematical techniques and computer programs have been developed. Each method has the limitation due to the assumptions used in formulation and many uncertainties in the complicated soil properties and complex structure-foundation system. The computer program called SASSI was used in this study because it is more capable of analyzing dynamic responses of nuclear power plants considering three-dimensional soil-structure interaction.

The SASSI adopts a general three-dimensional finite element substructuring method using a discretized halfspace foundation model. The basic analytical method used in computer program SASSI is the complex response method, which works in the frequency domain, and the flexible volume method of substructuring. The flexible volume method employs a finite element substructuring technique in which the total system is partitioned into the structure and foundation models. The structure model consists of the finite elements for the superstructures and the basement except the excavated soil. The foundation model consists of the finite elements for the original site, i.e., the excavated soil for the basement is remained with the foundation model. With such a partitioning, the foundation medium retains the halfspace configuration which simplifies the calculations of the free-field motion and the foundation impedance. The soil-structure interaction occurs at every interaction nodes in the excavated soil volume, called the flexible volume. The foundation impedance is calculated for each interaction node and then coupled with the structural model to form the complete soil-structure interaction system. The computer program SASSI does not explicitly determine the scattered foundation input motions. It combines the determination of scattered foundation input motion with the solution for structural responses in the single-step interaction response solution.

The flexible volume substructuring technique used in program SASSI requires several steps of analysis: (1) site response analysis which determines the free-field motions in the flexible volume resulting from the prescribed seismic wave field ; (2) foundation impedance analysis which calculates the impedance matrix associated with the interaction nodes in the flexible volume ; and (3) soil-structure interaction response of the assembled soil-structure interaction system.

3. ANALYSIS OF SOIL-STRUCTURE INTERACTION

In this paper, the analysis was conducted on the CANDU 9 reactor building which was conceptually designed by AECL to investigate the dynamic response characteristics of the structure and the soil-structure interaction effects. CANDU 9 reactor building was modeled by a finite element model and a lumped mass stick model for various analyses. In order to obtain results of soil-structure systems, several soil-structure systems have been analyzed according to the variation of soil properties.

3.1 CANDU 9 Reactor Building

The CANDU 9 reactor building consists of the containment structure and the internal structure. Both structures are supported on a common base slab. The containment structure is made of prestressed concrete, and the internal structure is made of reinforced concrete and structural steel. The containment structure and the internal structure are structurally independent form each other at upper elevation. A view of the CANDU 9 reactor building is shown in figure 1.

The analysis of CANDU 9 reactor building was carried out using a three-dimensional finite element model of the whole reactor building and a lumped mass stick model. Figure 2 illustrates the finite element model of the containment structure. The properties of concrete used in the modeling of CANDU 9 reactor building are presented in Table 1.

Table 1. The properties of concrete used in the modeling of CANDU 9 reactor building

Modulus of elasticity	28.2 X 10^3 MPa
Poisson's ratio	0.15
Density	2700 kg/m^3
Damping coefficient	5% (reinforced) / 3% (prestressed)

In the analysis of soil-structure interaction effect, the lumped mass stick model was employed because the whole three-dimensional finite element model is not practical because of the long computational time. The lumped mass stick model of CANDU 9 reactor building is shown in figure 3. The lumped mass stick model of the containment structure consists of eight nodes and eight elements. The sectional properties, which include the area, moment of inertia, polar moment of inertia, shear factor, were calculated. Table 2 summarizes the sectional properties of the lumped mass stick model and table 3 summarizes lumped masses and mass moments for the containment structure.

Table 2. Stiffness properties of the lumped mass stick model for the containment structure

Element No.	Area (m^2)	Polar moment of inertia (m^4)	Moment of inertia (m^4)	Shear factor
1	228.799	54019.3	27009.6	0.53
2	2280869	143759.7	71879.8	0.53
3	228.663	188452.6	94226.3	0.53
4	275.675	236012.0	118006.0	0.53
5	275.675	236012.0	118006.0	0.53
6	275.675	236012.0	118006.0	0.53
7	275.675	236012.0	118006.0	0.53
8	275.675	236012.0	118006.0	0.53

The lumped mass stick model of the internal structure consists of sixteen nodes and ten elements. The sectional properties of the lumped mass stick model of the internal structure were calculated and masses and mass moments of inertia were determined. The detailed data for the lumped mass stick model of the internal structure is not presented in this paper.

Table 3. Lumped masses and mass moments for the containment structure.

Node No.	Mass (kg)	Mass moment of inertia J_x (kgm^2)	Mass moment of inertia J_y (kgm^2)	Mass moment of inertia J_z (kgm^2)
1	$3.129 X 10^6$	$3.942 X 10^8$	$3.942 X 10^8$	$7.365 X 10^8$
2	$6.283 X 10^6$	$1.499 X 10^9$	$1.499 X 10^9$	$2.714 X 10^9$
3	$6.320 X 10^6$	$2.343 X 10^9$	$2.343 X 10^9$	$4.583 X 10^9$
4	$1.001 X 10^7$	$3.880 X 10^9$	$3.880 X 10^9$	$7.667 X 10^9$
5	$6.759 X 10^6$	$2.938 X 10^9$	$2.938 X 10^9$	$5.792 X 10^9$
6	$6.779 X 10^6$	$2.938 X 10^9$	$2.938 X 10^9$	$5.792 X 10^9$
7	$6.759 X 10^6$	$2.938 X 10^9$	$2.938 X 10^9$	$5.792 X 10^9$
8	$6.809 X 10^6$	$2.938 X 10^9$	$2.938 X 10^9$	$5.792 X 10^9$

3.2 Dynamic Characteristics of CANDU 9 Reactor Building

Dynamic behavior characteristics of CANDU 9 reactor building were investigated. Natural frequencies and mode shapes were obtained for the three-dimensional finite element model and the lumped mass stick model assuming that the degree of freedom(DOF) for the bottom of the foundation is fixed. The first mode has the natural frequency of 4.7 Hz and 5.1 Hz for the finite element model and the lumped mass stick model, respectively. The second mode has the natural frequency of 4.8 Hz and 5.1 Hz, and the third mode has 6.5 Hz and 7.2 Hz, respectively. These mode shapes are behaviors of the containment structure, and the deformed shapes for the two models were same. Natural frequencies were somewhat higher in the lumped mass stick model. The minor difference in natural frequencies of two models seems to be caused by the differences in the modeling of the opening and the buttress of CANDU 9 reactor building.

3.3 Soil-Structure Interaction Effect

In the analysis of soil-structure interaction effect, a simplified lumped mass stick model for a superstructure is employed because a whole three-dimensional finite element model is not practical because of the long computational time due to a large number of degree of freedoms. The containment structure and the internal structure were modeled with the lumped mass stick model and the foundation was assumed to be rigid. The columns and floor slabs of the internal structure were modeled with beam element. Figure 3 presents the lumped mass stick model of CANDU 9 reactor building and figure 4 presents the strain compatible dynamic rock properties for the potential sites. The sectional properties and lumped masses for the lumped mass stick model are summarized in table 2 and table 3.

Figure 5 presents the typical mode shapes of the lumped mass stick model at the site of case II. The first mode of CANDU 9 reactor building has the natural frequency of 2.37 Hz. The second and the third mode have the natural frequency of 2.56 Hz and 3.49 Hz, respectively. The natural frequencies of CANDU 9 reactor building are decreased and the mode shapes were changed significantly due to the flexibility of the supporting soil. These results show that the flexibility of the supporting soil affects the dynamic characteristics of CANDU 9 reactor building. The vertical response due to the flexibility of the supporting soil changed as well.

The nuclear power plant has been conservatively qualified for a Design Basis Earthquake(DBE) peak horizontal ground acceleration of 0.2g. The N-S component of the ground acceleration recorded at El Centro during the 1940 Imperial Valley Earthquake was used as an input motion with peak ground acceleration adjusted to 0.2g. Fig 6 presents the comparison of the response accelerations at the top of the containment structure for different soil models. Fig 7 presents the comparison of the response accelerations at the top of the internal structure for different soil models. The acceleration of the containment structure on the soft soil (case III) is larger than that on the soft rock (case II) due to the rotation of the foundation and the bending of the seismic wall. These results illustrate the effect of soil properties. However, there is slight difference between the layered model (case I) and the equivalent uniform halfspace model (case II).

4. CONCLUSIONS

Nowadays, there are potential opportunities for siting important facilities or buildings at sites composed of soft soil due to the increasing difficulty in acquiring new construction sites composed of hard rock. When a structure is constructed at sites composed of soft soil, the behavior of a structure is much affected by the motion of its supporting soil. This effect caused by the flexibility of supporting soil is more important in the case of stiff and massive structures. Therefore the effect of soil-structure interaction is an important consideration in the seismic design of a critical structure such as the nuclear power plants at sites composed of soft soil. This paper presents the results of the study on dynamic responses of CANDU 9 reactor building and soil-structure interaction effects, which is an ongoing process.

Dynamic response characteristics of CANDU 9 reactor building was studied with the three-dimensional finite element model and the lumped mass stick model. The model used for the analysis was CANDU 9 reactor building which was newly and conceptually designed by AECL. Also dynamic responses of CANDU 9 reactor building considering soil-structure interaction effect were evaluated by using three-dimensional finite element substructure method, program SASSI. As regards the results, flexibility of the supporting soil affects dynamic response characteristics of CANDU 9 reactor building and response of CANDU 9 reactor building can be amplified due to the rotation of the foundation and the bending of the seismic wall.

In the analysis of soil-structure interaction effect, a simplified lumped mass stick model for a superstructure is more proper because a whole three-dimensional finite element model is not practical because this model requires excessive computational time due to a large number of degree of freedoms. There were not significant differences in results for the layered model of site and the equivalent uniform halfspace model. However, it is difficult to estimate the soil-structure interaction effect accurately because of many uncertainties in the complicated soil properties and complex structure-foundation system, therefore further researches are required.

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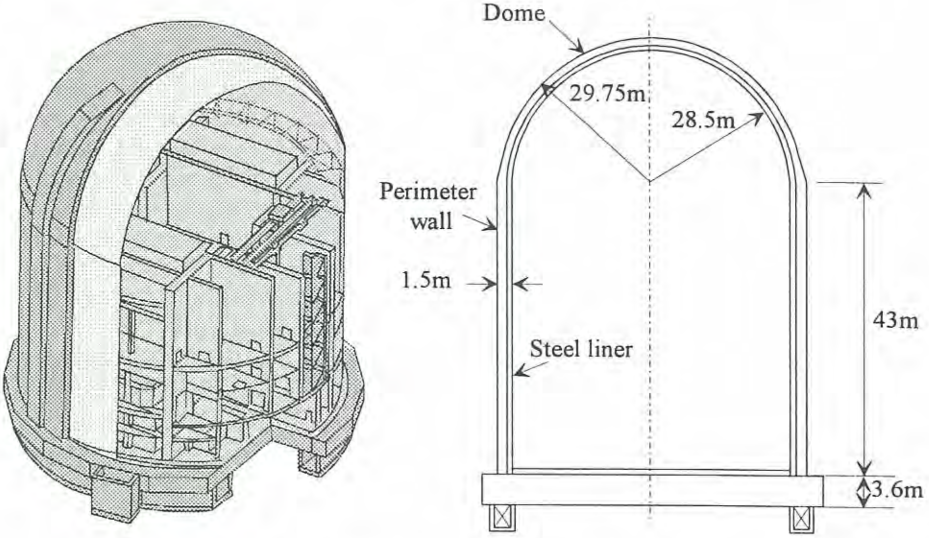


Figure 1 View of CANDU 9 reactor building and its dimensions

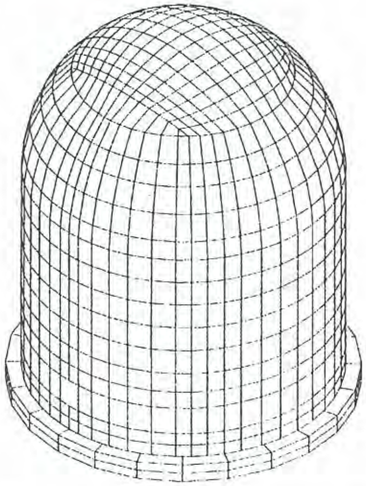


Figure 2 3-D finite element model of CANDU 9 reactor building

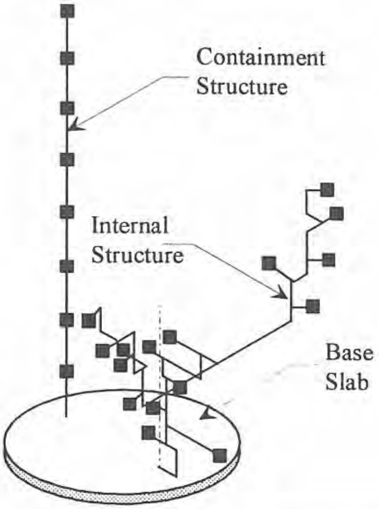


Figure 3 Lumped mass stick model of CANDU 9 reactor building

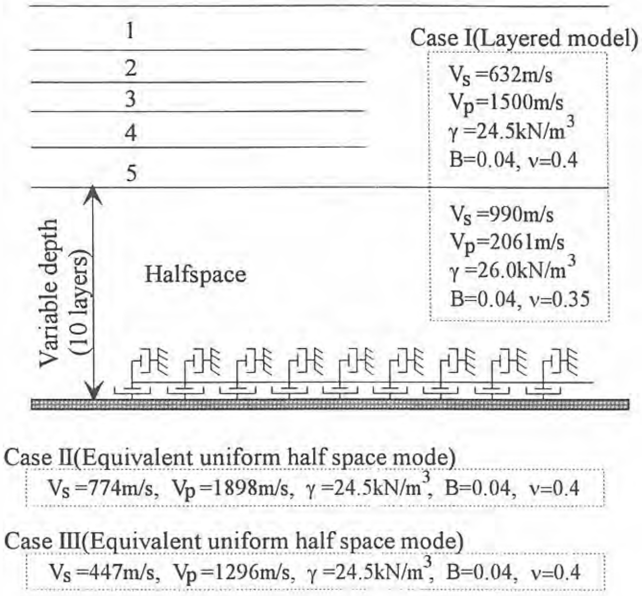
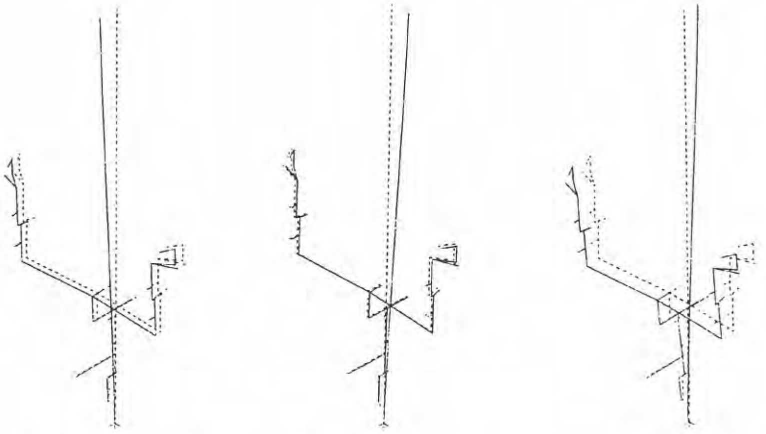


Figure 4 Dynamic properties for the potential sites



(a) 1st mode shape (b) 2nd mode shape (c) 3rd mode shape

Figure5 Mode shapes of the CANDU 9 resctor building

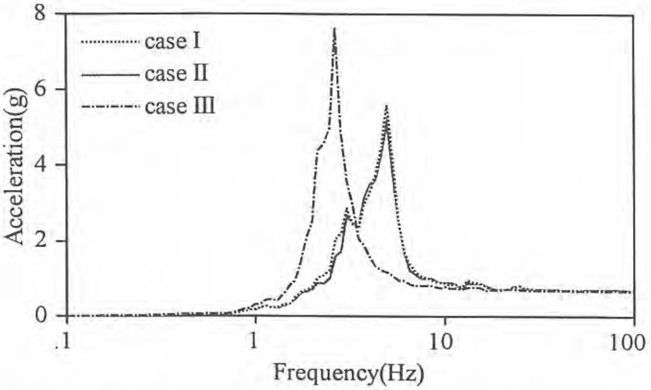


Figure 6 Absolute acceleration at the top of the containment structure

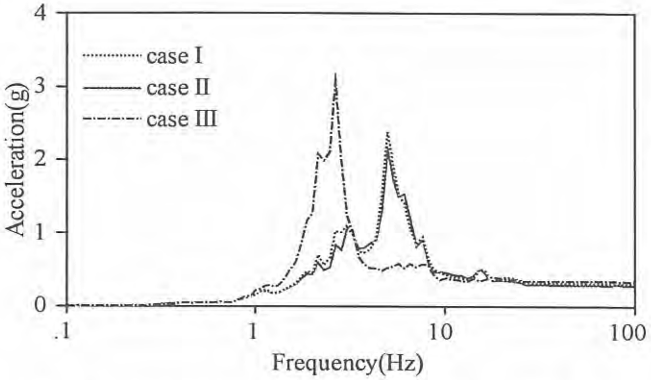


Figure 7 Absolute acceleration at the top of the internal structure