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Seismic Design and Analysis of CANDU Nuclear Power Plants

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ABSTRACT

The CANDU nuclear power plants seismic design complies with the Canadian standards developed for nuclear seismic design and also with relevant IAEA Safety Design Standards and Guides. In this paper, the Canadian seismic design philosophy and the seismic design approach for meeting the safety design requirements is reviewed. The results of the seismic design and analysis, including soil-structure interaction, employed in the CANDU seismic qualification program are presented. These studies indicate that the CANDU plants have significant seismic design margins and could be seismically qualified for a wide range of site conditions. The results also indicate that the design of the CANDU plants is capable of being qualified for 0.3g design basis earthquake acceleration, for site-specific applications.

INTRODUCTION

Through their world-wide operating records, CANDU Nuclear Power Plants (NPPs) have repeatedly demonstrated safe, reliable and competitive performance. Currently, there are twelve CANDU 6 single unit reactors operating or under construction world-wide. The CANDU 9 NPP is the next step in the evolution of the CANDU product line. The CANDU 9 is based on the proven Bruce B and Darlington stations 900 MWe class design, the single-unit features from the CANDU 6 and incorporates proven advanced technologies. Figure 1 shows the CANDU 9 reactor building.

The CANDU NPP design complies with Canadian standards developed for nuclear seismic design and also with relevant IAEA Safety Design Standards and Guides. In this paper, the Canadian seismic design philosophy and the seismic design approach for meeting the safety design requirements will be reviewed. Following the Canadian Standard CSA N289 [1,2 and 3] seismic design methodology, the CANDU 6 and CANDU 9 standard plants are conservatively qualified for a Design Basis Earthquake (DBE) with a peak horizontal ground acceleration of 0.2g for a wide range of soil/rock foundation conditions.

To illustrate the seismic analysis methodology used in CANDU plants seismic qualification, the seismic analysis results of the CANDU 9 will be presented. Several models of the CANDU 9 reactor building are used in this study, a lumped-mass model, an axi-symmetric finite element model and a 3D finite element model. In addition, the computer program SASSI was utilized in order to assess the Soil-Structure Interaction (SSI) effects between the reactor building and its supporting foundation media for both the CANDU 6 and CANDU 9.

SEISMIC DESIGN PHILOSOPHY

The seismic design philosophy of the CANDU 6 and 9 NPPs is consistent with the CANDU plants overall safety design philosophy. In this design philosophy, all plant systems are assigned to one of two groups. Group 1 systems sustain normal plant operation and power production and include two special safety systems. Group 2 includes the other two special safety systems and safety support functions. This grouping assignment maximizes protection against common cause events such as earthquakes and fires and minimizes physical and functional cross connections between the two groups.

The seismic safety functions which must be maintained in order to limit the release of radioactivity resulting from an earthquake to an acceptable value are, the ability to shut the reactor down and maintain it in a safe shutdown condition, the ability to remove decay heat, the ability to maintain a barrier to limit the release of radioactive material, and the ability to perform essential safety-related control and monitoring functions.

The CSA-N289 Standards require that NPP structures and systems important to these safety functions must meet more restrictive design requirements than those imposed by the National Building Code of Canada (NBCC) [4]. In the Canadian approach, three levels of earthquakes, each of different intensity and probability of occurrence, are used for the design of nuclear power plants. These three levels are defined as follows:

- Design Basis Earthquake :
  Design Basis Earthquake means an engineering representation of the potentially severe effects of earthquakes applicable to the site that have sufficiently low probability of heing exceeded during the lifetime of the plant. The DBE is equivalent to IAEA Seismic ground motion level S_2.
- Site Design Earthquake :
  Site Design Earthquake (SDE) means an engineering representation of the effects at the site of a set of possible earthquakes with an occurrence rate not greater than 0.01 per year, based on historical records. The SDE is an intermediate level earthquake, similar to IAEA seismic ground motion level S_1 and is used for the design of some specific systems.
- National Building Code of Canada :
  The NBCC design earthquake ground-motion acceleration is based on the seismic zoning requirements of the building code for nuclear power plant sites in Canada. The NBCC design earthquake is applied to those structures and major components which are not essential to safety following a seismic event and which have not been designed to the DBE or the SDE.

Safety-related structures, systems and components necessary to perform a safety function during and/or after an earthquake are seismically qualified to one of the two levels of earthquakes, DBE or SDE, as defined earlier.

The extent to which each structure and system remains functional is established by means of seismic categories for individual structures, systems or components. Two seismic categories are defined as follows:

- Category 'A' Structures, Systems or Components (SSC)
  Those SSC which must retain their pressure boundary integrity or structural integrity during and following an earthquake, and must not suffer cracking or excessive deformation, in order to ensure and maintain the safety function.
- Category 'B' Structures, Systems or Components
  Those SSC which must retain their pressure boundary or structural integrity and must function mechanically and/or electrically during and/or following an earthquake, in order to ensure and maintain the safety function.

The particular seismic requirements for each system component may involve combinations of, or departures from the general definition of "A" and "B" classification. Therefore, the detailed seismic requirements for each component, including whether it is required to operate after an earthquake or during and after an earthquake, are identified and the components are designed accordingly.

SEISMIC ANALYSIS

The seismic analysis of the CANDU 9 reactor building is carried out using two modeling approaches: lumped-mass modeling and finite element (consistent-mass) modeling. Three cases for the foundation medium are considered in order to cover a wide range of foundation medium characteristics. These cases represent hard, medium and soft rock conditions having dynamic shear moduli of 5000, 2750 and 500 MPa respectively. The ground response spectra per [3] for the DBE are shown in Figure 2 for different damping values. The DBE is applied in three directions: two horizontal and one vertical direction. The peak ground acceleration for the vertical direction is taken as two thirds of the horizontal direction.

Lumped-Mass Model

The lumped mass soil-spring method is utilized for generating the floor response spectra used for the qualification of the systems and components. The model consists of two sticks (Figure 3), one stick represents the containment structure and the other represents the internal structure. The geometric characteristics of these sticks are representative of the stiffness of the structure. The mass and mass moments of inertia about three axes at each node are determined by lumping the structures mass and the mass of major equipment. Six degrees of freedom are defined at each node. The nodes are connected by 3D beam elements that represent the stiffness characteristics of the structure. The eccentricity between the center of mass and the center of stiffness in the internal structure is taken into account. The analysis of the lumped mass model is performed using the STARDYNE computer program.

Soil structure interaction is considered in the analysis using soil springs attached to the base. Six springs are defined to represent the stiffness properties of the foundation medium in three translational and three rotational degrees of freedom. The stiffness of each spring is determined by applying the elastic-half space theory to the foundation medium [5].

Finite Element Models

The finite element models are used to evaluate the reactor building seismic response. Two finite elements are developed for the CANDU 9 reactor building: an axi-symmetric model and a 3D model. The axi-symmetric and 3D models are analysed using the computer program ANSYS. The axi-symmetric model is used to determine the design parameters of the containment structure. The 3D finite model is used in order to consider the asymmetrical effects due to the internal structure geometry and the containment structure buttresses and openings.

Axi-symmetric Finite Element Model

The axi-symmetric model consists of four main parts: the containment structure, the internal structure, the base slab, and the foundation medium (Figure 4). Six axi-symmetric solid elements are used across the thickness of the dome, the perimeter wall, and the base slab. The internal structure is modeled using axi-symmetric solid elements forming a cylinder of equivalent mass and stiffness. The total mass of the internal structure is used to determine the density of the material used for the idealized cylinder. The fundamental frequency of the internal structure is used to determine the modulus of elasticity of the material used for the idealized cylinder.

According to the requirements of CSA/CAN3-N289.3, the foundation medium is modeled using axi-symmetric solid elements forming a 224 m radius cylinder that is 192 m deep below the bottom surface of the base slab.

The Square Root of Sum of Squares (SRSS) method is used to determine the maximum seismic responses of the containment structure. The vertical component of the ground response spectrum is applied as a symmetric load. For the horizontal seismic component, which is asymmetric load, the ground response spectrum is applied in the positive radial direction and the negative hoop direction of the model in accordance with the algorithm of the ANSYS program.

3D Finite Element Model

The model consists of four main parts: the containment structure, the internal structure, the base slab, and the foundation medium (Figure 5). A structural shell element is used to model both the containment structure, the concrete internal structure and the base slab. A 3D solid element is used to model the foundation medium. A 3D beam element is used to model the concrete columns of the internal structure. In order to reduce the size of the model, the sub-structuring technique is used by defining the foundation medium as a super-element.

The boundary conditions are defined on the foundation medium super-element. All nodes on the bottom surface of the super-element are restrained in all degrees of freedom. Symmetrical restraints are defined on all nodes on the curved surface of the super-element.

The seismic load is represented by three seismic load cases; two horizontal cases and a vertical case. The Complete Quadratic Combination (CQC) method is used to determine the maximum seismic responses of the reactor building.

Analysis Results

The floor response spectra (FRS) at different floors and elevations are obtained from the seismic analysis of the lumped mass model. The FRS are generated using the methodology developed by Duff [6]. Two representative FRS for two key elevations are presented in Figures 6 and 7. Figure 6 shows the FRS at the steam generator platform (top of the internal structure). Figure 7 shows the FRS at the reserve water tank supporting structure (top of containment perimeter wall). The design FRS are envelopes of the FRS for the three foundation cases.

SOIL STRUCTURE INTERACTION

The application of the computer program SASSI [7] has been investigated with respect to the SSI analysis of the CANDU 6 NPP reactor building [8]. SASSI has been employed for CANDU seismic qualification because the program is best capable of rigorously analyzing 3-D SSI response for surface-supported or embedded structures with rigid or flexible foundations.

The SASSI computed FRS for the CANDU 6 reactor building at key points have been computed for a potential 0.25g site [8]. A GRS (Figure 2) spectrum compatible time history was used as the input motion. The unbroadened 2% damped FRS at the top of the containment structure in the B/D direction and at El. 100.00 of the internal structure for a 0.25g peak ground acceleration DBE are shown in Figures 8 and 9. For comparison purposes, the figures also show the broadened standard plant FRS, determined for a 0.20g DBE level, and the potential site FRS, determined using the standard soil-spring method. It is noted that SASSI generated FRS for a 0.25g DBE site generally falls within the standard CANDU 6 design envelope.

The SASSI SSI analysis of the CANDU 9 reactor building also utilizes a lumped mass stick model. A 3-D finite element model has been used to model the base slab foundation. The seismic input used in the analysis is GRS (Figure 2) spectrum compatible time history. The control point for the time history input was applied at the ground surface. The input motion is assumed to consist of a vertically propagating SV-wave field. The control motion is scaled to 0.2g.

Representative FRS for the CANDU 9 reactor building at key elevations are shown in Figures 10 and 11. These figures show the FRS at the top of the reactor building containment structure and internal structure for 5% damping. These FRS are generated using the soil-spring models (envelope of three rock conditions) and the FRS generated using the SASSI computer program for the same three rock conditions. The figures show that using state of the art analysis methods and computer tools for SSI analysis indicates that there is significant conservatism in the design in the frequency range of interest (i.e. 3-10 Hz) for sites where the SSI effects are significant.

HIGHER SEISMCITY

CANDU NPPs have been assessed for higher seismic design requirements. The results of the assessment indicate that the standard CANDU 6 plant, which is designed for a DBE acceleration of 0.2 g, can withstand an earthquake with a horizontal DBE acceleration of 0.3 g. Simple design modifications in the reactor and fuel handling system can be implemented to enhance the seismic capability of the system [9]. The reactor building can be strengthened to withstand 0.3 g DBE without any major layout changes. Design changes such as a thicker base slab and a fixed connection between the base slab and the perimeter wall (currently a hinged connection) and minor strengthening of some internal walls can be easily implemented during the detail design phase of the project.

The CANDU 9 NPP was also assessed for higher seismic input. It was found that the Standard CANDU 9 reactor building, which is designed for a DBE acceleration of 0.2 g, can withstand an earthquake with a horizontal DBE acceleration of 0.3 g without any conceptual layout or design modifications. The impact of the higher seismic input on critical components such as the reactor and fuel handling system was assessed using conservative input parameters. The results show that minor design modifications (e.g. material changes) may be required but these can be easily implemented during the detail design phase.

CONCLUSIONS

- The CANDU nuclear power plants seismic design is based on sound principles and practices, some of which are uniquely suited to CANDU systems and component but are consistent with international codes and standards.
- The application of the Canadian seismic approaches including the state-of-the art tools and techniques has ensured a robust design of the CANDU 6 and CANDU 9 NPPs.
- The results of the SSI analyses indicate that there is significant conservatism in the design of the CANDU plants for sites where the SSI effects are significant.
- This study has shown that under certain conditions where SSI effects are significant, the SASSI SSI analysis method can reduce the predicted seismic loads significantly, thereby providing increased seismic design margins, and allowing the standard CANDU 6 and CANDU 9 NPPS to be located at sites having higher seismicity.
- The CANDU 6 and CANDU 9 plants can be designed for higher seismic inputs without any major modifications to the plant layout or the basic design of its structures, systems and components.

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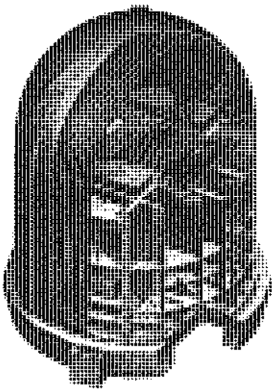

Fig. 1: CANDU 9 Reactor Building

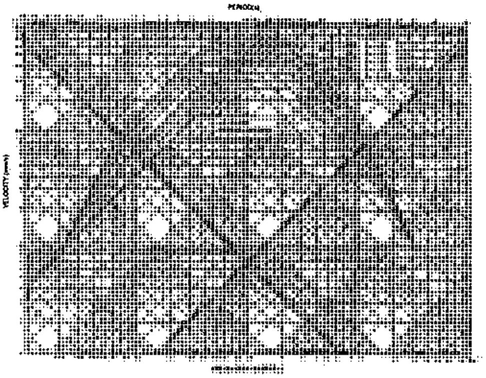

Fig. 2: GRS for CANDU 9 Seismic Design

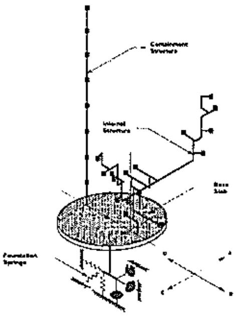

Fig. 3: CANDU 9 Lumped Mass Model

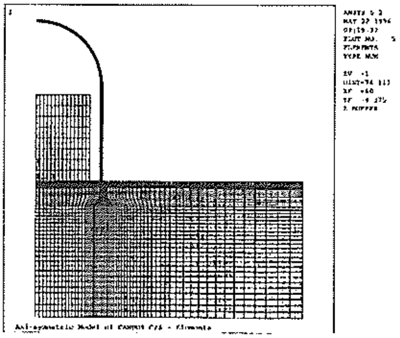

Fig. 4: CANDU 9 Axi-symmetric Model

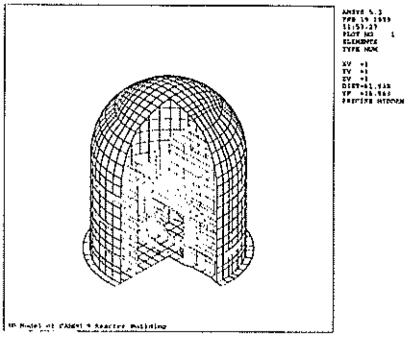

Fig. 5: CANDU 9 3D Model

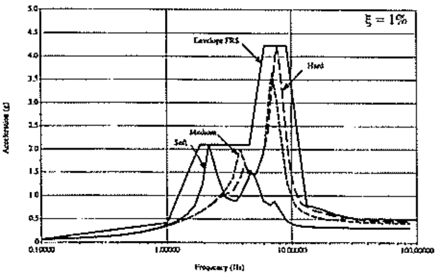

Fig. 6: FRS at Stream Generator Platform

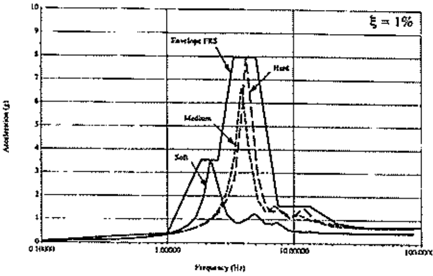

Fig. 7: FRS at Reserve Water Tank

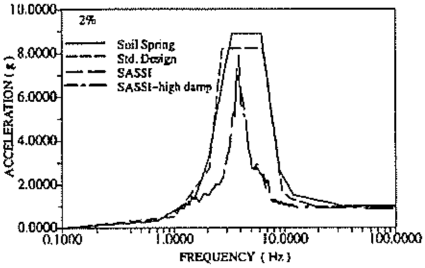

Fig. 8: FRS at Top of Containment Structure

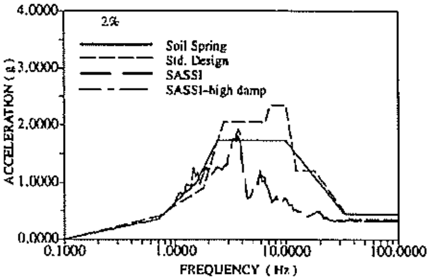

Fig. 9: El. 100.00 of Internal Structure

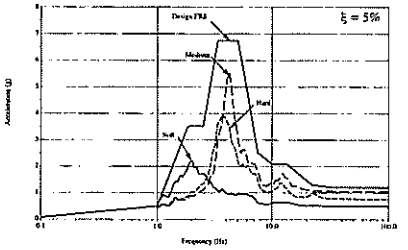

Fig. 10: FRS at Top of Containment Structure

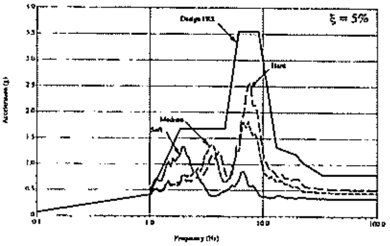

Fig. 11: FRS at Top of Internal Structure