Reanalysis and Evaluation of Seismic Capacity of the CANDU 700 MW NPP CERNAVODA

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ABSTRACT

The dynamic response of structures of the CANDU 700 MW NPP due to seismic loadings was conventionally analyzed in the time domain using modal substructure procedures. The frequency-independent parameters were tuned to the main frequencies of the soil-structure system. This is a common procedure widely used in the preliminary design of power plant structures and provides conservative results.

However, parallel to the rapid progress being made in upgrading the capability of data processing systems, methods and software tools have become available which work in the frequency domain using complex (soil-structure) mathematical models or models in which the soil is represented by frequency-dependent impedances.

In order to demonstrate the reserves existing in the design of the CANDU 700 reactor building, frequency-domain calculations were additionally prepared. The analyses were based on appropriate mathematical 3D-models of the coupled vibrating structures of the reactor building as well as the soil represented by frequency-dependent impedances.

The result obtained by using the time and frequency domain methods were compared and the safety margins of the CANDU design discussed.

1 INTRODUCTION

In recent years attention has focused on the conservatism in the seismic analyses and design methods used previously for the design of operating nuclear power plants. It is well known that former analyses of building structures were based on conservative procedures and assumptions, and that therefore the structures erected in the past possess sufficient capacity reserves to easily withstand higher seismic loadings. These reserves can very often be increased even further if the ductile capacity of the structures and the upper band of the material capabilities are considered.

These are welcome facts that are of great help for verifying and upgrading operating nuclear power plants for revised (higher) site-specific seismic input data. In order to demonstrate the higher capability of the structures and at the same time provide realistic (possibly not increased) structural response data for the requalification of all safety-related components and systems (which have to be upgraded or, in extreme cases, strengthened to accommodate increased seismic loading), more accurate analytical methods can be used.

In the course of requalifying a number of operating nuclear power plants at sites where the seismic input definitions were increased, it was shown that the conservatism of the various time domain methods (Figure 4) that generally assume frequency-independent soil parameters (stiffnesses and dampings) could be reduced significantly by means of complex methods using coupled mathematical models (Figure 5) in which the frequency dependency

of the soil parameters is realistically considered, and by calculation in the frequency domain. Unlike the substructure method, the complex method also allows realistic treatment of kinematic interaction effects and especially consideration of real embedment parameters of the building structure.

In order to demonstrate the margin of former calculations, the results obtained for the CANDU 700 MW reactor building by means of the two methods mentioned above will be compared.

2 DESCRIPTION OF THE STRUCTURAL SYSTEM

The reactor building comprises a prestressed-concrete containment structure and an internal structure supported on a common circular prestressed-concrete slab, supported in turn by a reinforced-concrete subslab connected to the common slab through reinforced-concrete keys (Figure 1).

The internal structure comprises two partially independent sections. The central part of the internal structure comprises a reinforced-concrete "Calandria Vault", providing direct support for the calandria vessel and core safety and control equipment. The Calandria Vault is connected to the internal structure at the floor at elevation +100 m. The remaining part of the internal structure supports the refueling machine and the majority of the equipment and distribution systems, including components of the primary and moderator systems, and comprises reinforced-concrete walls and slabs and some locally-braced, bolted steel frames. This part of the internal structure is supported at its base by the common base slab at elevation +93,90 m.

The internal structure has a vertical symmetry plan in one direction while in the other orthogonal direction the distribution of mass and stiffness is quite eccentric for each elevation.

The containment structure comprises a cylindrical shell of 1.07 m thickness, 41.50 m internal diameter and 51.7 m height which is capped by a spherical dome of 0.61 m thickness with a thickened sector in the transition zone to the cylindrical wall.

The soil under the foundation of the reactor building consists of white, hard, cracked and porous limestone in contact with the base slabs down to a depth of 16.5 m and clayish limestone between 16.5 m and 26.6 m below the foundation. From depth of 26 m down to about 100 m there are valangarian marls.

3 MATHEMATICAL MODEL AND LOADING CONDITIONS

In order to analyze the dynamic behavior properly and in view of the geometrical configuration of the reactor building internal structures, which are characterized by structural elements with different stiffness properties resulting in a complex mixed structure, an accurate and detailed model was necessary. To ensure adequate treatment of interaction effects, all the structures described in the previous section were therefore idealized in a single 3D finite element model (Figure 2). Modeling of the structures was sufficiently detailed and contained an adequate number of degrees of freedom to obtain the dynamic response at the locations of safety-related components and to evaluate the corresponding response spectra as well as the nodal forces and element stresses in the regions of interest.

The finite element model of the CERNAVODA reactor building has more than 6000 dynamic degrees of freedom. It comprises about 1640 trapezoidal as well as triangular elements and about 100 beam elements [1].

The weight of the structure is composed of the deadweight of the structure itself, the weight of mechanical and electrical components as well as various live loads. The total weight of the model is approximately 840000 kN.

For the soil properties and layering of the soil at the CERNAVODA site (Table 1), earthquake- strain-adapted G values and impedance functions were obtained [2]. The global

stiffnesses and damping values were derived from the impedance functions and distributed accordingly over the nodes of the discretized foundation mat.

The seismic excitation was represented using three artificial acceleration time histories (one for each translational direction) acting simultaneously. The time histories were generated from the site-specific free-field spectra (Figure 3). The maximum acceleration was at 0.20 g and 0.13 g for the horizontal and the vertical direction respectively. These free-field artificial acceleration time histories formed the basis for the excitations determined at the foundation level. The applied excitation time histories have a duration of 40 s and were digitized using a time interval of 0.01 s.

4 ANALYSIS PROCEDURES

4.1 Time-Domain Calculation

The starting point of the analysis was the 3D mathematical model for the building structure above mentioned supported by frequency-independent soil springs (Figure 4). The frequency-independent springs and dampers were distributed appropriately at nodes of the discretized foundation of the buildings (CERNAVODA).

The dynamic analyses were conducted using the STRUDYN finite element program [4]. In accordance with German standards (KTA 2201.4), the analysis was performed assuming a cut-off damping of 15 % and 30 % for the horizontal and vertical directions, respectively.

4.2 Frequency Domain Calculation

The structural model of the building described above was coupled with the mathematical model of the soil to form one complex finite element model (Figure 5). The numerical computations were performed using the SASSI [3] computer code which solves the equation of motion in the frequency domain. In SASSI the flexible volume method is adopted for coupling the two structures and allows a horizontally layered halfspace representing the soil region under the foundation to be taken into account.

The impedance matrix for the soil was determined by inverting the flexibility matrix calculated for interaction nodes which are common to the structure and soil region. The impedance matrix was added to the stiffness matrix of the structure, and this resulted in a final complex matrix for all degrees of freedom needed to describe the behaviour of the system.

The Fast Fourier Transform technique was applied to obtain the response at any node in the model. The equations of motion were only solved at selected frequencies and the results for all "in-between" frequencies were interpolated.

5 COMPARISON OF RESULTS

The aim of this study was to demonstrate the influence on the results of different assumptions regarding the representation of the soil-structure system as well as the interaction effects on the dynamic response of the CANDU 700 reactor building during earthquake excitation of the site CERNAVODA.

The maximum accelerations as well as response spectra for characteristic regions (on the foundation plate and the top of the reactor hall as well as on the top of the inner structure) were computed by both procedures and compared.

It is evident that the lower structural response obtained (in the frequency domain) using coupled soil-structure models is due to the realistic representation of the soil capabilities as well as consideration of the real damping capacity of the coupled soil-structure system.

In order to compare and evaluate the results obtained in both calculations, the response spectra for the soft and hard soil obtained for characteristic regions (foundation level and typical elevations) were plotted together always in one graph. In addition, displacements were also determined at relevant points of the structure.

A comparison of the respective spectra for 2 % (Figures 6 to 23) shows that there is a significant difference between the dynamic response results obtained by means of the two methods (time and frequency domain). It can be observed that there is a slight shift in the fundamental frequency of the partial structures and a reduction in the spectral accelerations obtained by frequency-domain calculations procedures.

Because of the greater effect of soil damping (material and radiation damping) on the dynamic behaviour of the lower part of the building, the reductions are more pronounced at the foundation level than on the upper floors of the building.

However, on the lower floors the reduction in the peak acceleration is by about 20 to 40 % in the horizontal and up to 10 - 20 % in certain frequency regions of the vertical direction. The reduction in the rigid body part of the spectra is nearly the same.

6 CONCLUSION

Various dynamic analyses were performed for the reactor building of the CANDU 700 NPP in order to determine the dynamic response and assess the aseismic capacity of the structures. Different types of mathematical models for idealizing the soil and the building structures were used. The analyses demonstrated here were based on appropriate mathematical models of the coupled vibrating structures of the reactor building and the layered soil. On the basis of this study, it can be concluded that time-domain analyses using frequency-independent impedances and cut-off modal damping usually provide conservative results.

In general, complex model analysis (considering the frequency dependency of the soil parameters) yielded - also in the case of CERNAVODA Unit 1 - lower accelerations, especially in the frequency range above the fundamental frequency when compared to the accelerations obtained through conventional substructure approaches:

This is due to the following influences:

- Consideration of the real damping capacity
- Consideration of kinematic interaction effects by the complex mathematical model
- Consideration of the real stiffness of the foundation plate
- Filtering effects of the soil

On the basis of this study, it can be concluded that the time-domain approaches using substructure models and frequency-independent (discrete) stiffnesses and dampings as well as cut-off modal damping provides conservative results. On the other hand, the frequency domain approach, in which the soil-structure interaction effects are represented more realistically, provides more reliable results.

The frequency-domain approach, yields a realistic and efficient design which is not only safe but also economical. It may be recommended for use especially in situations requiring verification of existing building structures due to upgraded seismic input data.

7 REFERENCES

- [1] Mathematical Model and Dynamic Characteristics of the Reactor Building Cernavoda, Unit 1, KWU NDA2/95/130b
- [2] Soil Profile for the Load Case Earthquake and Impedance Function for the Reactor Building of NPP Cernavoda, KWU NDA2/95/E0184
- [3] SASSI, A Computer System for Dynamic Soil-Structure Interaction Analysis, Siemens KWU Version 1/1991 (Original source M. Tabatabaie-Raissi, J. Lysmer, University of California, Berkeley)
- [4] STRUDYN, Linear-Elastic, Static and Dynamic Analysis of Structures, User Information Manual 1991

Fig.1 CANDU 700 MW Reactor Building of CERNAVODA NPP – Vertical Section

Intensity Functions

Fig. 3
CANDU 700 MW Reactor Building
Seismic Input Definition for the Site CERNAVODA

Fig. 4
CANDU 700 MW Reactor Building
Mathematical Model for the Decoupled Soil-Structure Systems

Fig. 2 CANDU 700 MW, CERNAVODA NPP
Idealization of Structures

Fig. 5 CANDU 700 MW Reactor Building
Mathematical Model of the Coupled Soil-Structure System

Soil Layer		Shear Modulus G (MN/m ²)	
N°	Thickness (m)	Case A	Case B
1	16.5	740	3500
2	10.1	600	2100
3	∞	900	2100

Tab. 1 Soil Data for CERNAVODAP Site

Mode N°	Freq. [Hz]	MAX DOF	Modal X1	Modal X2	Modal X3	Modal Damping %
1	2.55	4400-1	443965.22	359.22	4465.35	35.45 15.00
2	2.59	4778-2	645.64	445481.24	407.17	24.60 15.00
3	3.21	774-1	6025.54	424.45	789410.48	75.79 30.00
4	3.74	479-2	73.42	107.18	24.49	17.79 15.00
5	3.85	1232-1	2504.69	9.05	17.74	7.00 7.00
6	4.44	1765-2	49.09	24573.96	5.54	10.54 10.54
7	4.83	1107-2	243.21	5.47	59.46	5.47 5.47
8	4.89	1107-2	135.44	1593.17	52.59	4.39 4.39
9	5.14	7563-2	264.45	0.43	10.13	5.13 5.13
10	5.20	1752-2	19174.93	15.44	32.82	4.57 4.57
11	5.29	7564-1	15.43	62.47	4.14	5.14 5.14
12	5.46	1212-1	1863.80	63142.47	44.29	11.46 11.46
13	5.46	1752-2	2310.00	158113.77	3.85	11.69 13.00
14	5.48	4778-2	262213.76	4694.27	1234.27	24.94 15.00
15	6.13	7564-3	45.02	172.22	2.48	5.11 5.11
16	6.14	7564-3	22.52	1012.33	6.19	5.23 5.23
17	6.26	1717-2	77.94	36366.43	0.13	12.22 12.22
18	6.76	479-1	10461.09	186.54	30.97	4.10 4.36
19	6.87	477-2	1583.54	6.12	22.10	5.12 5.12
20	6.92	477-2	4701.71	89.45	39.11	5.45 5.45
21	6.97	7561-3	75.59	12.70	19.34	5.43 5.43
22	7.02	479-1	107.98	44.02	1310.99	5.77 5.77
23	7.04	479-1	12.73	15.47	287.44	5.49 5.49
24	7.22	479-1	189.60	1354.33	492.77	5.44 5.44
25	7.30	479-1	1069.01	144.75	355.75	5.43 5.43
26	7.40	479-1	3328.22	246.21	382.82	5.70 5.70
27	7.45	7571-3	461.49	1343.70	18.76	5.24 5.24
28	7.49	822-2	34.56	127.23	0.35	5.04 5.04
29	7.74	831-2	53.52	14.94	2.10	5.01 5.01
30	7.76	5464-2	1.29	2.00	0.54	5.17 5.17
31	7.84	5467-2	0.00	0.14	0.20	5.17 5.17
32	8.42	1164-1	0.01	4.09	1.06	5.04 5.04
33	8.44	7562-3	0.02	2.24	2.35	5.54 5.54
34	8.52	7565-3	1.17	0.44	0.34	5.40 5.40
35	8.57	7564-3	0.01	0.24	4.49	5.01 5.01
36	9.30	1735-2	26.95	141.47	3.76	5.42 5.42
37	9.34	1756-2	50.42	29.38	1.56	5.34 5.34
38	9.36	7564-3	0.13	0.13	0.00	5.00 5.00
39	9.52	1105-2	0.00	0.00	0.00	5.00 5.00
40	10.45	7562-3	162.54	31.50	28.44	7.23 7.23
41	10.49	5464-3	0.51	0.00	0.10	5.05 5.05
42	10.63	8774-1	0.04	0.03	0.06	5.04 5.04
43	10.83	879-3	34.61	14.27	145.14	5.82 5.82
44	11.04	1220-2	154.40	1.45	195.12	7.00 7.00
45	11.49	1243-3	14.87	43.74	7.85	6.04 6.04
46	11.62	1243-3	11.47	26.40	39.43	5.30 5.30
47	11.65	1249-3	83.87	22.00	0.40	5.21 5.21
48	11.80	479-2	41.31	1.24	0.33	5.29 5.29
49	12.92	479-2	8.52	2.44	8.93	5.09 5.09
50	13.94	479-2	2.14	144.79	17.61	5.34 5.34
51	12.06	479-3	7.45	82.41	13.76	5.28 5.28
52	12.24	479-2	0.44	15.23	93.28	5.22 5.22
53	12.19	479-2	0.00	43.94	20.44	5.42 5.42
54	12.33	1272-1	11.04	21.40	24.42	5.40 5.40
55	12.50	604-1	6.55	29.49	31.03	5.42 5.42
56	12.57	7564-3	1.20	2.74	0.96	5.01 5.01
57	13.44	1774-2	6.50	77.55	0.40	5.74 5.74
58	12.73	7735-2	15.44	9.84	1.93	5.04 5.04
59	12.80	7562-3	3.12	2.45	1.91	5.03 5.03
60	12.42	7560-3	0.01	4.74	0.38	5.03 5.03
61	12.84	604-1	4.37	22.43	6.57	5.21 5.21
62	12.92	6476-3	24.74	0.31	0.09	5.03 5.03
63	12.95	6464-3	17.11	74.14	1.43	5.14 5.14
64	13.05	1262-2	9.74	0.10	0.09	5.14 5.14
65	13.11	832-2	7.97	0.00	0.44	5.14 5.14
66	13.25	7574-3	0.03	0.82	0.02	5.02 5.02
67	13.24	521-1	7.44	11.22	0.19	5.09 5.09
68	13.34	1244-3	4.44	9.01	1.44	5.10 5.10
69	13.80	444-2	0.29	2.34	1.74	5.05 5.05
70	13.81	5277-1	0.00	0.71	0.15	5.10 5.10

Tab. 2 Eigenfrequencies and Modal Values for G_A

Fig. 6 CANDU 700 MW Reactor Building CERNAVODA Foundation Mat, Direction X1, Level 94.0 m

Fig. 7 CANDU 700 MW Reactor Building CERNAVODA Foundation Mat, Direction X2, Level 94.0 m

Fig. 8 CANDU 700 MW Reactor Building CERNAVODA Foundation Mat, Direction X3, Level 94.0 m

Fig. 9 CANDU 700 MW Reactor Building CERNAVODA
Basis of Calandria Vault , Direction X1, Level 100 m

Fig. 10 CANDU 700 MW Reactor Building CERNAVODA
Basis of Calandria Vault , Direction X2, Level 100 m

Fig. 11 CANDU 700 MW Reactor Building CERNAVODA
Basis of Calandria Vault , Direction X3, Level 100 m

Fig. 12 CANDU 700 MW Reactor Building CERNAVODA
Main Cooling Pumps, Direction X1, Level 117 m

Fig. 13 CANDU 700 MW Reactor Building CERNAVODA
Main Cooling Pumps, Direction X2, Level 117 m

Fig. 14 CANDU 700 MW Reactor Building CERNAVODA
Main Cooling Pumps, Direction X3, Level 117 m

Fig. 15 CANDU 700 MW Reactor Building CERNAVODA
Steam Generator, Direction X1, Level 125.0 m

Fig. 16 CANDU 700 MW Reactor Building CERNAVODA
Steam Generator, Direction X2, Level 125.0 m

Fig. 17 CANDU 700 MW Reactor Building CERNAVODA
Steam Generator, Direction X3, Level 125.0 m

Fig. 18 CANDU 700 MW Reactor Building CERNAVODA
Containment, Direction X1, Level 135.0 m

Fig. 19 CANDU 700 MW Reactor Building CERNAVODA
Containment, Direction X2, Level 135.0 m

Fig. 20 CANDU 700 MW Reactor Building CERNAVODA
Containment, Direction X3, Level 135.0 m