CANDU 6 Nuclear Power Plant: Reactor building floor response spectra considering seismic wave incoherency

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SUMMARY:
Within the scope of the refurbishment project of a CANDU 6 nuclear power plant (NPP), the new equipments should be designed to sustain a new seismic demand characterised by a uniform hazard spectra (UHS) which exhibits larger spectral ordinates in the high-frequency range. This paper presents a procedure developed at Hydro-Quebec for generating floor response spectra (FRS) using ambient vibrations calibrated detailed 3D finite element model. These FRS are based on ground motion time histories compatible with the mean UHS. Because the reactor building is founded on a large circular raft, it is possible to consider the effect of the seismic wave incoherency to filter out the high-frequency content, mainly above 10 Hz, using the incoherency transfer function "ITF" method proposed by EPRI (2006) and implemented herein into the software ABAQUS. This allows reducing significantly the non-necessary conservatism in resulting FRS which is an important issue for an existing NPP.

Keywords: CANDU 6 reactor building, Floor Response Spectra (FRS), Seismic wave incoherency.

1. INTRODUCTION

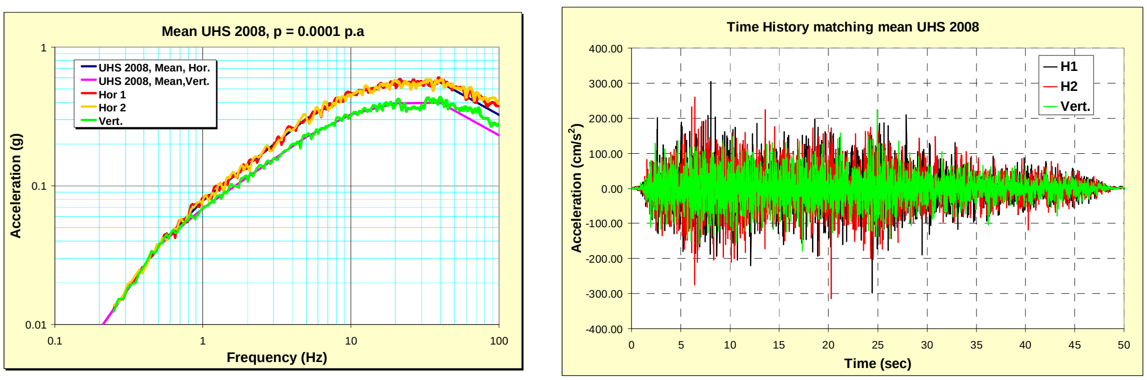
Within the scope of the refurbishment project of a CANDU 6 nuclear power plant (NPP), the new equipments should be designed to sustain a new seismic demand characterised by a uniform hazard spectra (UHS) obtained from a site specific study and defined for a return period of 1/10 000 years (Hydro Quebec, 2009-a). Compared to the original seismic design demand based on Newmark-Housner type of ground response spectra, the UHS for the site of study exhibits larger spectral ordinates in the high frequency range. However, the use of traditional techniques for generating floor response spectra (FRS) leads to very high peaks in the high-frequency range. These peaks may cause difficulties in qualifying equipments sensitive to this range of frequencies.

The CANDU 6 reactor building considered herein is founded on a very large raft foundation, as evidenced in the recent studies presented in EPRI (Electric Power Research Institute) reports (2005, 2006, 2007), the seismic wave incoherency filter out the high-frequency content of the input motions. Seismic compression and shear waves propagating from the hypocenter to the mat foundation encounter multiple reflections and refractions resulting in spatial incoherent variations as they encounter rock mass discontinuity. Moreover, as seismic waves reach the nearly rigid concrete foundation mat there is also an averaging effect on incoherent motions as they propagate to the supported reactor internal structure. This results in a significant reduction in FRS peaks, leading to a realistic determination of the seismic requirements for the reactor building equipments.

This paper presents a procedure developed at Hydro-Quebec using ambient vibrations testing to calibrate a detailed 3D finite element model (FEM) of a CANDU 6 NPP. This provides for the first time experimental data to characterised CANDU 6 type of NPP that are now in operation in several countries worldwide. The calibrated 3D FEM is then used for generating floor response spectra (FRS) based on ground motion time histories compatible with the mean UHS. Furthermore, the seismic wave incoherency effect is considered to reduce the ground motion intensity and filter out the high frequency content, mainly from 10 Hz and above, using the incoherency transfer function "ITF" method proposed by the Electric Power Research Institute (EPRI, 2006) and implemented herein into the commercial Finite Element (FE) code ABAQUS. This allows reducing significantly the non-necessary conservatism in resulting FRS which is an important issue for an existing NPP.

2. GROUND MOTION TIME HISTORIES COMPATIBLES WITH MEAN UHS FOR CANDU 6 NPP

Atkinson (Hydro Quebec, 2009-b) has developed one broad band set of ground motion time history records to match the target spectrum for the CANDU 6 NPP site (1/10 000 p.a.), on rock, for the mean confidence level. This set is obtained from spectral matching technique by modifying the frequency content of historical recorded ground motions (M7.3 R42 km, Landers).



a. Response spectra

b. Time histories

Figure 1. Ground motion time histories compatibles with the mean UHS for the site of study.

As stated in (Hydro Quebec, 2010), this set of ground motions presented in Figure 1 meets the ASCE (4-98 and 43-05) as well as the CSA-N289.3 (2010) requirements for ground motion records to be used in seismic safety assessment of existing NPP facilities. Figure 1 shows the time history records that are matching the target response spectra in both, horizontal and vertical directions. The UHS target spectrum was developed initially for the horizontal motion component. The corresponding vertical spectrum for rock sites is defined following Atkinson (Hydro Quebec, 2009-b), based on the frequency-dependent V/H ratios published for rock sites in Eastern North America (ENA). This V/H ratio =1 at low frequencies, decreasing to slightly more than 2/3 at high frequencies (≥10 Hz).

3. CANDU 6 REACTOR BUILDING FRS BASED ON TIME HISTORY RECORDS COMPATIBLE WITH THE MEAN UHS

The CANDU 6 reactor building has the function of lodging the reactor, auxiliary equipments, machinery and the necessary facilities for handling fuel. As shown in Figure 2, it consists essentially of two distinct parts, the containment wall and the internal structure. The containment wall is essentially a prestressed concrete structure composed of a circular raft foundation, with a thickness of 1.5 m and a diameter of 47 m. It contains also a cylindrical wall, with a thickness of 1.05 m and an inner radius of 20.7 m as well as a spherical dome with a central thickness of 0.61 m with a radius of 41.5 m. Just below this dome there is a second reinforced concrete spherical dome having an opening in the center. This element serves as a water reservoir for emergency shut down with a capacity of about 2540 m^3. The internal structure is mainly a reinforced concrete structure, designed to support the reactor vessel and the various pieces of equipment.

3.1 Tridimensional finite element model for the CANDU 6 reactor building

As shown in Figure 2, the 3D FE model (FEM) of the reactor building includes the internal structure and the containment wall which share the same foundation (raft). It is prepared using the multi-physics FE software ABAQUS (2008). A detailed 3D FEM, if developed adequately and controlled for convergence (i.e. the missing mass effect is corrected by static corrections), is more accurate and less conservative than a traditional beam-column stick model with lumped masses for seismic analysis of NPP (Varpasuo, 1999). The 3D FEM is preferred to the stick model as the equipments requalification for an existing structure, depends directly on the generated seismic requirements (FRS). Because at this stage one is basically interested in the displacement field and its derivatives with respect to time (velocity and acceleration), the 10 node quadratic tetrahedral isoparametric solid element with a linear strain representation (C3D10) is used for the model. The developed mesh is shown in Figure 2.

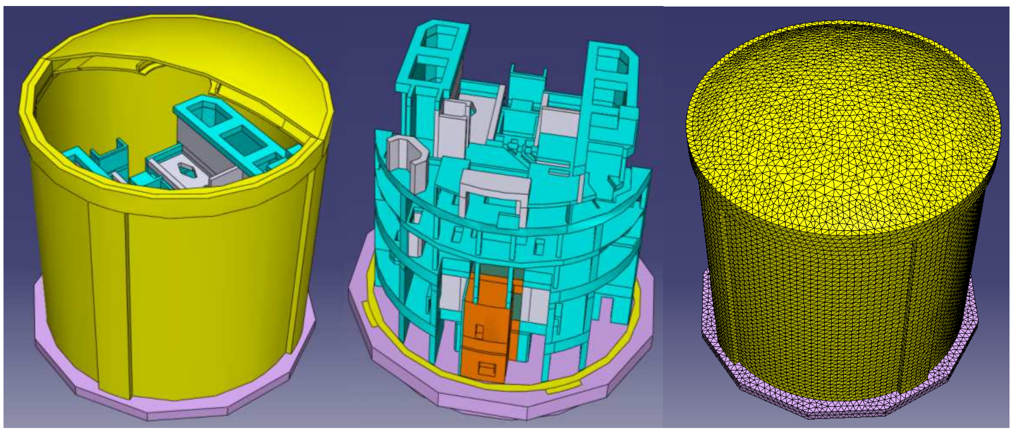


Figure 2. CANDU 6 reactor building and 3D finite element model.

One major advantage of this element is the fast automatic meshing, provided by the software, with regards to the complexity of the reactor building structure. Furthermore, the quadratic C3D10 solid element is more accurate than the linear 4 node tetrahedral solid element (C3D4).

The current seismic demand has significantly increased as compared to the initial design requirements. To develop an accurate seismic assessment of the reactor building (existing structure), one has to work to reduce to the minimum the uncertainties of the key parameters controlling the seismic behavior. Hence, the weight of the heavy equipments and their locations were assigned with special care. This issue has requested an exhaustive review of drawings as well as catalog of equipments (CANATOM, 1973).

The masses of equipments are introduced to the model in two ways, (i) nonstructural masses for the calandria vault system, the dousing water system and the live load for the different floors, and (ii) lumped concentrated masses for the important equipments. Note that the concrete calandria shell is part of the finite element model and fluid-structure interaction is not considered in this study. Therefore, the dousing water and the calandria fluid are modeled as nonstructural masses.

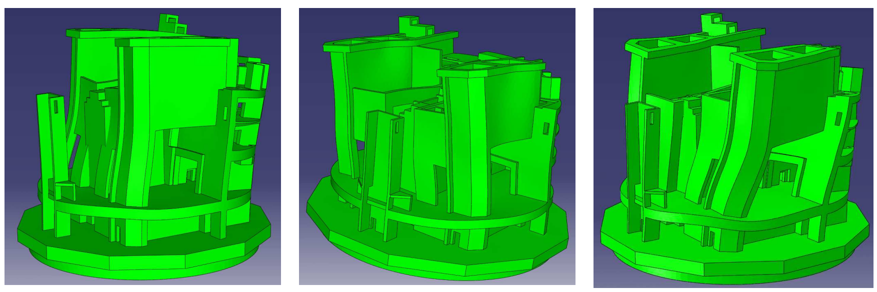
3.2 Linear seismic analyses of the reactor building

Linear seismic analyses are performed using the modal transient dynamic procedure with modal composite damping which allows assigning fractions of the critical damping for different materials, so an equivalent modal damping is computed from modal strain energy equivalence. Hence, for the modal dynamic procedure, one has considered a composite damping, 3% for the prestressed concrete structure, and 5% for the reinforced concrete structure (Hydro Quebec, 2010).

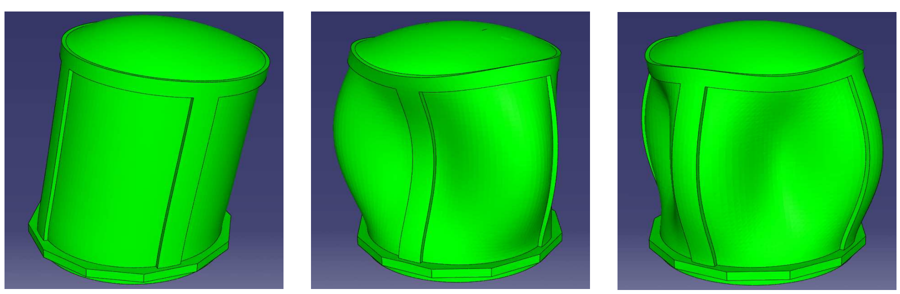
Because all equipments have small masses compared to the mass of the structure, equipment-structure interaction is neglected in this study. Thus, only the mass of the equipment (without stiffness) is considered in the numerical model. The Lanczos technique is used for the solution of the eigenvalue problem and all modes ≤ 50 Hz are considered. Therefore, the missing mass corresponding to modes above 50 Hz is captured through the static correction technique by introducing a residual mode in the modal analysis (as supported by ABAQUS).

To account for the actual dynamic properties of the structure, the numerical model is first calibrated by adjusting the effective stiffness of structural components with ambient vibrations measurements. Then, the different load conditions are introduced in the model. Only few NPP around the world were tested for ambient vibrations and it is a first for a CANDU NPP to the best of the author's knowledge.

From the numerical model, the first natural frequencies are computed and compared to results obtained from ambient vibration testing. This step is required to ensure that the inertia and the stiffness of the numerical model correspond to the real structure. Figure 3 shows the first natural frequencies obtained from the calibrated numerical model (internal structure and containment wall) as well as their corresponding mode shapes (Nour et al., 2010; Hydro-Quebec, 2010; IZIIS, 2009).



a. Internal structure.



b. Containment wall.

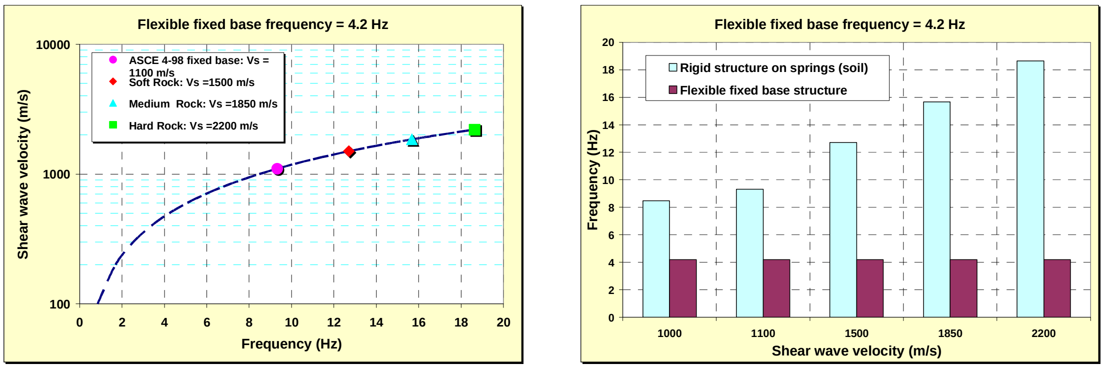
Figure 3. Calibration of the finite element model (FEM) with ambient vibrations (Amb. Vib.) results.

3.3 Fixed base model justification

According to AECL (1974), the reactor building is built on a rock site where the shear wave velocity Vs varies from 1500 m/s to 2200 m/s, thus the free field deconvolution and the soil structure interaction are neglected. Therefore, a fixed base mathematical model is adopted as explained below:

- In the NS-G-3.6 safety guide of the IAEA (2004), it is mentioned that for type 1 sites (Vs > 1100 m/s), a fixed base could be adopted for the numerical model.

- In the section 3.3.3.2 of the ASCE 4-98 (2000), it is well indicated that the bottom rigid boundary of the numerical model could be defined at the soil layer having Vs > 1100 m/s. Because the shear wave velocity of the underlying soil layer of the site under study is greater than 1500 m/s, this rigid boundary coincides with the foundation base of the reactor building. Furthermore, as shown in Figure 4, the section 3.3.1.1 of ASCE 4-98 (2000) requirements are satisfied, then a fixed base could be adopted for the numerical model.



a. b.

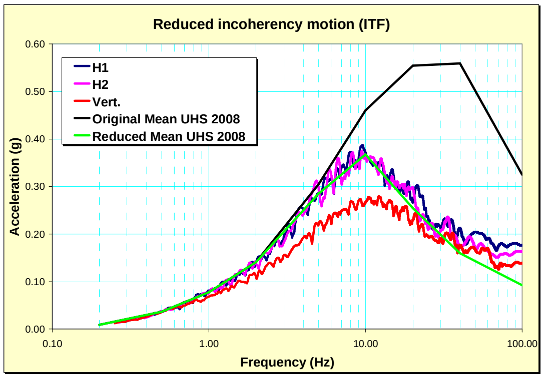
Figure 4. Fixed base model justification (mode 1 ≅ 4.2 Hz in Figure 3).

3.4 Procedure for the development of FRS for the CANDU 6 reactor building considering wave incoherency effect

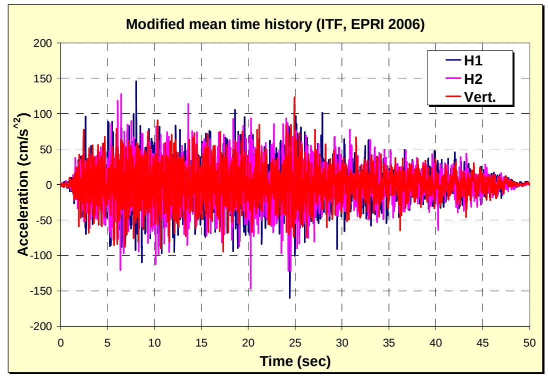
For the development of the reactor building FRS, one performs first a transient modal seismic analysis by computing the structural response history in the time domain. Then, for the desired point, and for a predefined viscous damping ratio of the equipment, a floor response spectrum (FRS) is computed from the transient accelerations. As recommended by ASCE 4-98 and CSA-N289.3 (2010), the frequency content of the generated FRS should be broadened to ±15% to account for structural uncertainties.

In addition, it is possible to take advantage of the beneficial effect of the seismic wave incoherency as the reactor building is founded on a large raft. In this sense, the high frequencies are filtered out and peak FRS are significantly reduced. This incoherency can be incorporated into the finite element model using the "Incoherency Transfer Function" (ITF) method documented in EPRI (2006), approved by the U.S. NRC and recommended by the Canadian standard for CANDU CSA-N289.1 (2008, see clause B7). This method consists to modify the seismic motion at the foundation base to account for the ground motion incoherency via a simplified approach. Moreover, this latter can be easily implemented in some commercial software without performing the exhaustive soil-structure interaction procedure available in the SASSI (System for Analysis of Soil Structure Interactions) (EPRI, 2007) computer program. The EPRI report (2006) develops an equivalent method (ITF) to the integrated approach in SASSI to consider the seismic wave incoherency. As demonstrated in this EPRI report, the ITF method gives results slightly conservative but comparable to results obtained from the SASSI program.

Figure 5.a shows the scaling functions based on ITFs in the frequency domain. These scaling functions are applied to modify the amplitude of the Fourier transform coefficients of the free-field ground motions (Figure 1.b). The modified ground motion (Figure 5.b) is used herein in standard seismic response analyses, using the ABAQUS commercial software (2008), as an alternate means of including effects of seismic wave incoherency. It is worthy to note that different scaling functions are applied for horizontal and vertical motions corresponding to rock site condition. However, it is anticipated that seismic demand will be significantly reduced for high-frequency, mainly from 10 Hz and above.

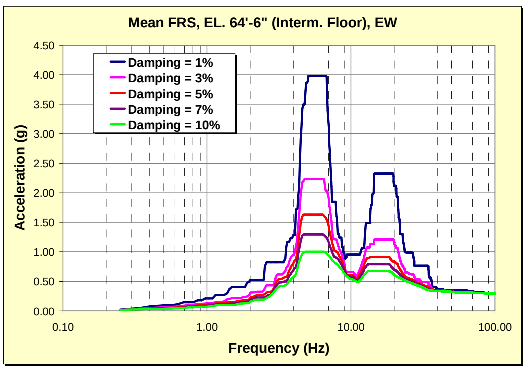


a.

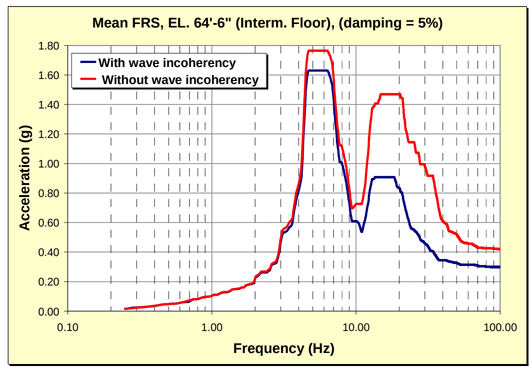


b.

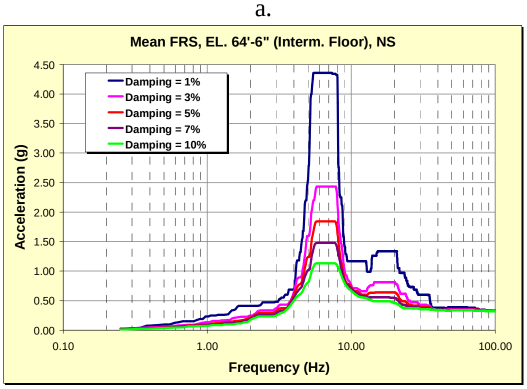
Figure 5. Reduced incoherency motion using the ITF method.



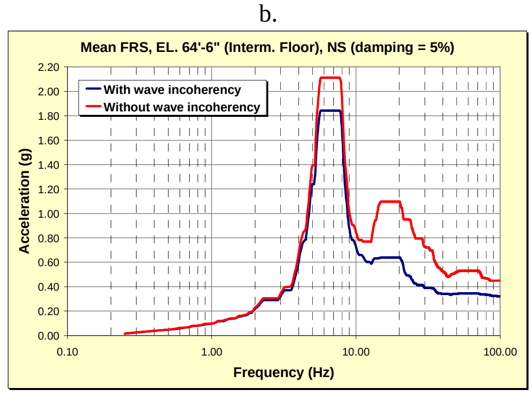
a.



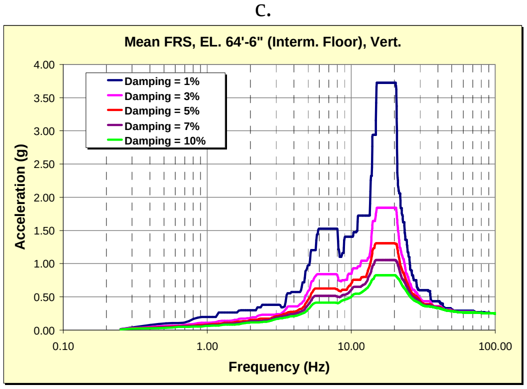
b.



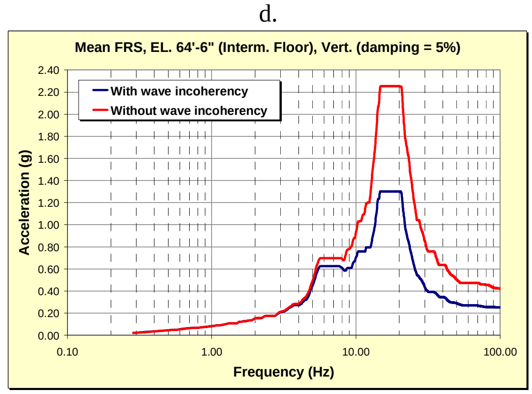
c.



d.



e.



f.

Figure 6. FRS for the floor 64’-6” of the internal structure considering the wave incoherency effect.

As shown in Figure 6, the results of this procedure are described for a single floor, i.e. for the 64’-6” level and for the three components EW, NS and vertical. Figures 6.a, 6.c and 6.e show the calculated FRS at this level for different values of damping considering the effect of wave incoherency. Whereas, Figures 6.b, 6.d and 6.f illustrate, for a given damping value of 5%, the issue of considering or neglecting the effect of wave incoherency.

In the high-frequency range, it is well demonstrated that the consideration of the beneficial effect of the wave incoherency for the reactor building leads to a significantly reduced seismic demand and, therefore, to a realistic design of equipments sensitive to high-frequency content, namely for 10 Hz and above.

4. CONCLUSIONS

This paper, presents an original procedure for generating floor response spectra (FRS) for a CANDU 6 reactor building in operation. To extend the lifetime of this building for additional 25 years, a special attention is given to adequately represent the dynamic response to seismic events. Hence, a 3D finite element model is used instead of a stick model, and the numerical model is calibrated with ambient vibrations measurements results instead of using nominal dynamic material properties. The calibrated 3D FEM is then used for generating floor response spectra (FRS) based on ground motion time histories compatible with the mean UHS.

Furthermore, the seismic wave incoherency effect is considered to reduce the ground motion intensity and filter out the high frequency content, mainly from 10 Hz and above, using the incoherency transfer function "ITF" method which can be easily implemented in commercial software. It is well demonstrated that the consideration of the beneficial effect of the wave incoherency for the reactor building leads to a significantly reduced seismic demand and, therefore, to a realistic design of equipments sensitive to high-frequency content, namely for 10 Hz and above.

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