20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division 5, Paper 2472

Seismic Analysis of ACR™ Nuclear Island Structures for Rock Sites in Eastern North America

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Keywords: seismic analysis, Eastern North America, seismic hazard, response spectra, time histories

1 ABSTRACT

The Advanced CANDU Reactor™, (ACR-1000™) is designed by Atomic Energy of Canada Limited (AECL™) to meet its customer requirements in Canada and worldwide. ACR-1000 product is based on 700 MWe class and 900 MWe class CANDU™ reactors, offering nuclear power plants to a broad segment of the power generation market. The seismic design of the ACR-1000 nuclear power plant (NPP) complies with Canadian standards and also with International Atomic Energy Agency safety design standards and guides.

The ACR-1000 standard design is based on a design ground response spectrum characterizing the richness of high-frequency in Eastern North America (ENA) rock sites, in addition to the design ground response spectra defined for soil and rock sites per the Canadian Standards Association (CSA). The standard design is based, as well, on seven design soil profiles defining the envelope of a wide range of foundation medium representing potential site conditions.

The seismic analysis of the ACR-1000 nuclear island structures and the generation of floor response spectra needed for seismic qualification of the structures, systems and components that are important to safety take the effects of seismic soil-structure-interaction (SSI) into account. Time histories that are compatible with the design ground response spectra are used in the seismic analyses. A set of three time histories is developed using the spectral matching technique to represent the ENA-based design ground response spectrum. Two more sets of three time histories are developed to be compatible with the CSA-based design ground response spectra for soil and rock sites.

This paper presents the findings of the seismic analyses of the ACR-1000 nuclear island structures. Lumped mass and consistent mass models representing the nuclear island are used in the analyses. A summary of the seismic SSI analysis methodology is presented. Key structural seismic response parameters for the nuclear island, founded on different design soil conditions, due to the design basis ground motions are determined and compared.

2 INTRODUCTION

The ACR-1000[1] is a light water cooled, heavy water moderated pressure-tube reactor. The conceptual arrangement of the ACR-1000, which includes the nuclear steam plant and balance of plant, is designed as a two-unit, plant containing all the facilities for day-to-day operations. Figure 1 shows a cut away view of ACR-1000 nuclear island. The nuclear island of the ACR-1000 NPP consists of the reactor building and the reactor auxiliary building located on a common base slab. The reactor building houses the reactor vault, the fuelling machine vault, steam generators enclosures, reactivity mechanism deck and reserve water supply tank. The reactor auxiliary building is a multi-story structure surrounding the reactor building and houses the electrical systems, new and spent fuel storage and associated fuel-handling facilities. The reactor building consists of two separate structures: the containment structure and the internal structure. The containment structure is a cylindrical prestressed concrete wall topped with a hemispherical dome. The internal structure consists of a combination of structural steel and reinforced concrete walls and floors. The containment and the internal structures are structurally separated from each other. The reactor auxiliary building is made of reinforced concrete walls and floors.

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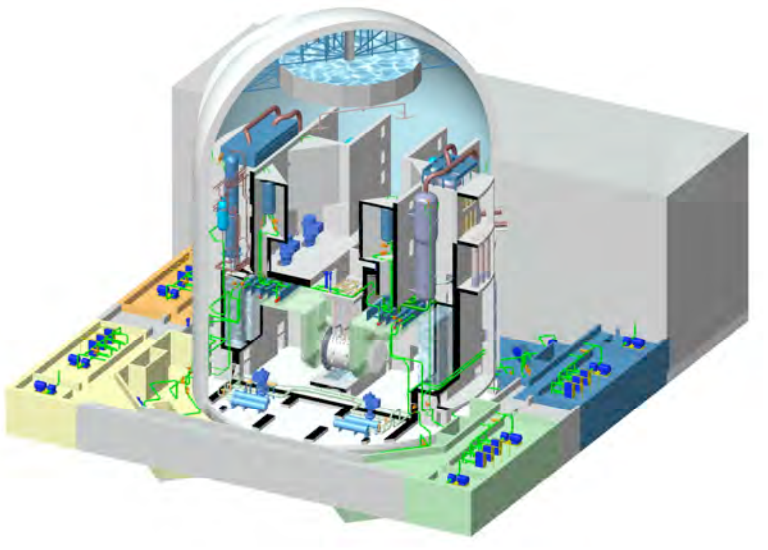

Figure 1. ACR-1000 nuclear island

Three horizontal design ground response spectra are defined for the seismic design of the standard ACR-1000 plant, Figure 2. Two design ground response spectra are based on the Canadian Standard CSA-N289.3 (2003). These are the CSA-based design ground response spectrum for rock and soil sites. In addition, one typical design ground response spectrum follows the ENA-based spectrum proposed by Atkinson and Elgohary (2007). The CSA-based spectra in the vertical direction are taken as two-thirds of the horizontal spectra. The ENA-based spectrum in the vertical direction is obtained by applying frequency-dependent factor to the horizontal spectrum. The factor ranges from 1.0 (frequencies ≤ 0.25 Hz) to 0.71 (frequencies ≥ 10 Hz), (Siddiqqi and Atkinson 2002).

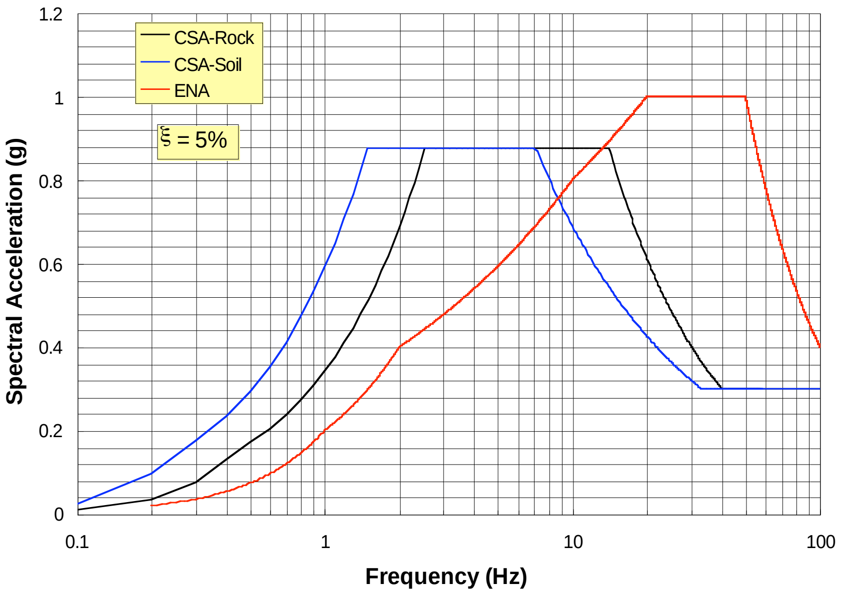

Figure 2. ACR-1000 design basis ground response spectra

The ACR-1000 is designed to envelope a wide range of potential rock-soil site conditions. Hence, the generic design of the ACR-1000 is based on a set of design soil profiles representing a variety of foundation conditions. These foundation conditions range from shallow rock sites to deep soil sites. The design soil profiles are classified based on the total thickness of the soil layers overlying bedrock. In addition, for each design soil profile, the shear wave velocities of the soil layers vary along the depth to bedrock. Table 1 gives a summary of the properties of the different soil-rock profiles.

Table 1. Design soil profiles

Profile	Depth-to-bedrock (m)	Shear wave velocity (m/sec)		
		Top	Bottom	Half-space
HR	-	-	-	2500
A-1	14	533	637	1524
B-1	42	533	845	1524
B-2	42	457	724	1524
B-3	42	305	506	1524
C-1	70	205	370	1524
D-1	114	152	300	1524

3 SPECTRA COMPATIBLE TIME HISTORIES

Three sets of time-histories are developed to be compatible with the three design ground response spectrum shown in Figure 2. Each set includes two horizontal components plus a vertical component. Two sets of time-histories that are compatible with the CSA-based design ground response spectra for rock and soil sites are generated to satisfy the CSA-N289.3 acceptance criteria. The set of spectra-compatible time histories for the ENA-based design ground response spectrum is developed to meet the requirements of the CSA-N289.3 standard and of SRP 3.7.1 (USNRC 2007). Details of the development of the design spectra-compatible time-histories can be found in the companion paper.

Figure 3 shows a selected set of the design time-histories that are developed to be compatible with the horizontal design ground response spectra. The figure presents one of the two horizontal components of each of the three developed sets of spectra compatible time histories.

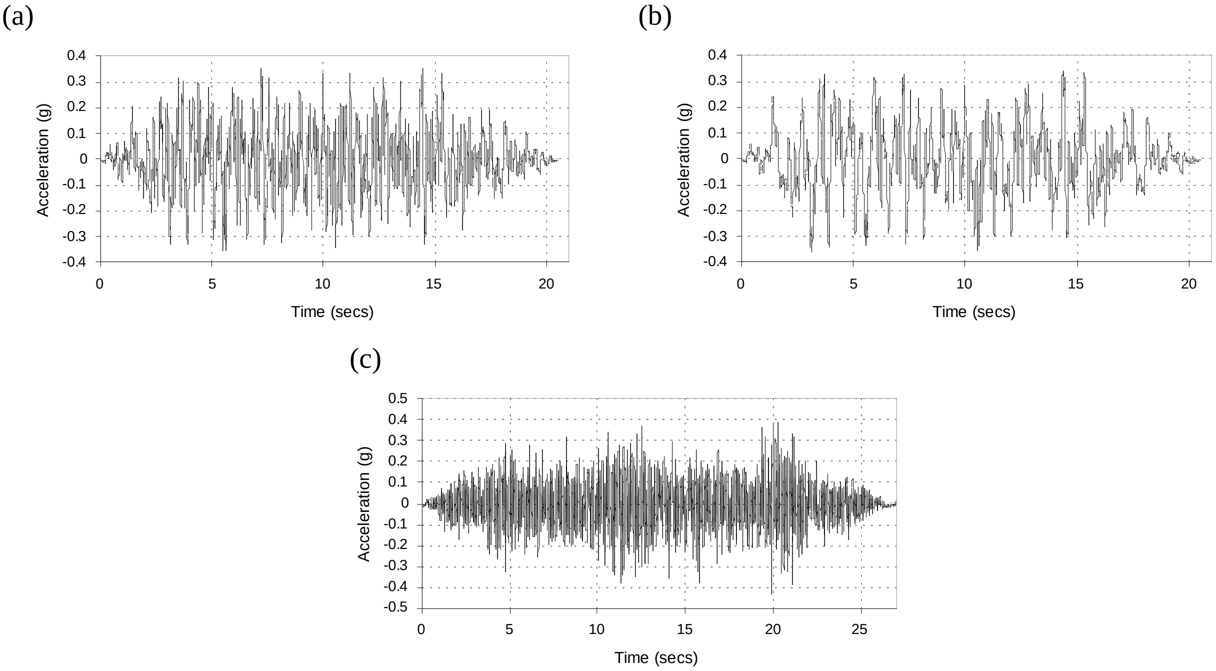

Figure 3. Selected horizontal components of the design time-histories: (a) CSA-based for rock sites, (b) CSA-based for soil sites, and (c) ENA-based for rock sites

4 NUCLEAR ISLAND DYNAMIC MODELS

Three-dimensional finite element analysis models of the ACR-1000 nuclear island are developed and used in the seismic soil-structure-interaction analyses. Figure 4 presents two analysis models used in this study: the lumped-mass model and the consistent-mass models.

The lumped mass model, Figure 4(a), consists of ‘sticks’ representing both the reactor building and the reactor auxiliary building. Each stick consists of beam elements connecting between nodes located at the centre of stiffness for each floor. The beam elements represent the stiffness characteristics of each structure. Each node has six degrees of freedom: three displacements and three rotations. The mass and mass moment

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of inertia at each floor are determined by lumping the mass of the walls, the concrete floors, steel platforms, major equipment, and equivalent masses of the superimposed live loads at a node. Each mass node is connected by a rigid link to the stiffness node when the centre of mass at the floor is not coincident with its centre of stiffness. Two stick models represent the containment and internal structures forming the reactor building. The reactor auxiliary building is idealized with two stick models rigidly connected at each floor. The model includes two additional stick models representing the spent fuel bay and storage tank. To account for the soil-structure interaction effects, the base slab and embedded walls are modelled with solid elements for the part supporting the reactor building and with shell elements for the part embedded within the supporting design soil layer.

The consistent-mass model, Figure 4(b), consists of shell finite elements representing the walls and floors of each containment structure, the internal structure, the reactor auxiliary building, and the common base slab. Both mass density and thickness associated with the shell finite elements captures the dynamic properties of the nuclear island structures. The model takes into account the spatial features of the containment and internal structures, and predicts the torsion effects accurately. The nuclear island model accounts for interaction effects that might arise during seismic events between the containment structure, the internal structure, and the reactor auxiliary building structures. To account for the soil-structure interaction effects, in case of elastic half-space hard rock conditions, six springs and dashpots are used to idealize the soil stiffness and damping characteristics according to CSA-N289.3.

The analysis models are verified by comparing the SSI analysis results for the case of a rigid foundation on hard rock with that of the dynamic characteristics of the fixed-based structure evaluated using ANSYS (2005). To assess the performance of the lumped mass model for the case of ground motions characterized with high frequency, additional 3D finite element coarse mesh model is being prepared. The results of this assessment will be presented in future papers.

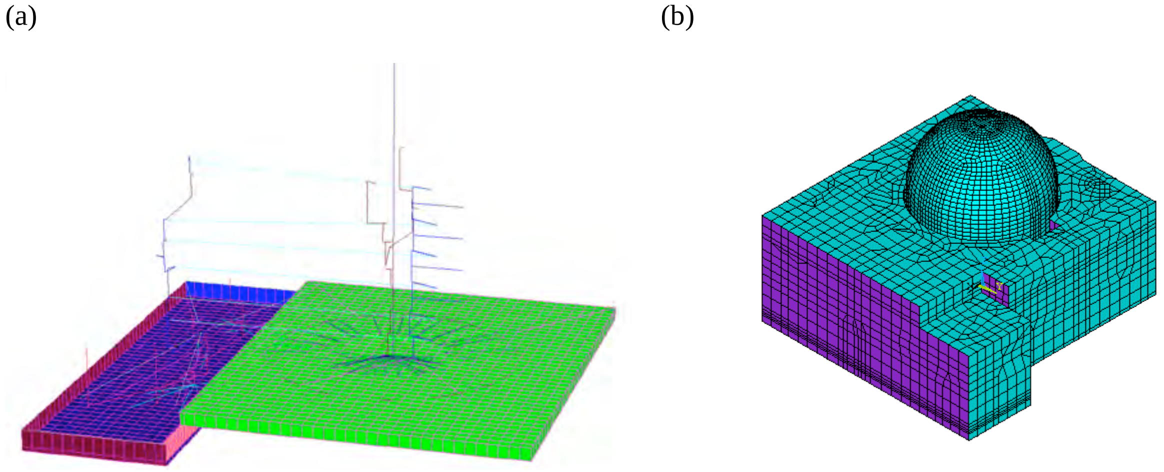

Figure 4. ACR-1000 nuclear island models: (a) Lumped mass, (b) Consistent mass

5 SEISMIC ANALYSIS PROCEDURES

Seismic analyses of the ACR-1000 nuclear island are conducted using ACS SASSI (Ghiocel 2008) and ANSYS (2005). ACS SASSI is based on the original SASSI code developed by Lysmer and co-workers at the University of California, Berkeley and is one of the programs used in the EPRI/DOE technology innovation study on wave incoherency effects in SSI analysis (Short et al. 2006, 2007). For the layered design soil conditions, the SSI analyses are conducted using the flexible interface (i.e., subtraction) solution approach that is one of the ACS SASSI solution algorithms. For the elastic half space hard rock condition, the seismic analysis of the nuclear island is analyzed using ANSYS.

Table 2 presents a summary of the combination of applicable design ground motion, design soil profiles, and the analysis software. In addition, the following major assumptions are made in performing the SSI analyses:

- The control motion is specified as an outcrop motion at the bottom of the base slab under the reactor building sticks.

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- The part of the base slab under the reactor building is treated as a surface foundation, whereas the other part of base slab is embedded within the supporting design soil layer.
- Transfer functions are computed at a satisfactory number of frequency points to ensure that the transfer functions are well defined over the frequency range of interest. In addition, interpolated transfer function curves at characteristic nodes are inspected to ensure no spurious peaks are present.
- Wave incoherency effects that are known to generally decrease the response in the high frequency range are not accounted for in this analysis phase.
- The damping values used in the analyses for the structure are 5% and 7% for prestressed, and reinforced concrete; respectively.
- The defined shear wave velocity profiles are assumed to be the strain-compatible values. These are, however, used in multiple free-field de-convolution analyses to derive reasonably conservative hysteretic soil damping estimates.
- The cut-off frequency for the harder rock profiles is taken at 50 Hz. Apart from the D-1 soil profile, the cut-off frequencies for other design soil profiles are chosen larger than 25 Hz.
- The displacement and acceleration transient responses to each directional component are combined algebraically to obtain the response to the three-component ground motion.

Table 2. Combinations of design ground motions, design soil profiles, and analysis software

Design Soil Profile	Design Basis Ground Motion	Analysis Software
HR	Rock CSA-based & ENA-based	ANSYS & ACS SASSI
A-1 B-1 B-2	Rock CSA-based & ENA-based	ACS SASSI
B-3 C-1 D-1	Soil CSA-based	ACS SASSI

6 CONTAINMENT STRUCTURES SEISMIC RESPONSE

Selected seismic responses for the containment structure and the concrete internal structure are presented in this paper. The presented responses include variation of structural acceleration response along the height and floor response spectra at representative key locations for only three soil conditions: the hard rock condition (HR) and the B-2 and C-1 design soil profiles. The seismic responses of the containment and internal structures to both ENA-based and CSA-based design ground motions and for different soil conditions are compared. The impact of including the high frequency input motion, i.e. the ENA-based design ground response spectra and the time-histories compatible with the ENA-based spectra; on the seismic behaviour of ACR-1000 containment structure is investigated in this study.

6.1 Acceleration Response

The horizontal acceleration responses of the containment structure due to both the ENA-based and CSA-based horizontal design ground motion are shown in Figure 5 for the hard rock condition. The acceleration responses are determined while the SSI effects are idealized using both constant soil springs and frequency-dependent impedance functions. The horizontal acceleration response of the containment structure due to the applicable horizontal design ground motion is shown in Figure 6 for the three design soil conditions: HR, B-2, and C-1, while the SSI effects are idealized using frequency-dependent impedance functions. Figure 7 compares the vertical acceleration response of the containment structure for the hard rock condition when the two approaches accounting for the SSI effects are followed. The vertical acceleration response of the containment structure to the applicable vertical design ground motion for the three design soil conditions: HR, B-2, and C-1, are shown in Figure 8, while the SSI effects are idealized using frequency-dependent impedance functions.

Similarly, the horizontal and vertical acceleration responses of the internal structure to applicable design ground motions and for different soil conditions are shown in Figures 9 to 12.

The containment and internal structures respond to the design ground motion in cantilever mode. In the case of hard rock condition, the variation of the horizontal acceleration response along the height takes an “S” shape that is attenuated in the case of softer design soil profiles such as B-2 and C-1. This behaviour can

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be attributed to the fact that ENA-based design spectrum amplifies higher modes. In addition, the structural responses obtained for the hard rock conditions while the SSI effects are idealized either by constant soil springs or by frequency-dependent impedance functions are found to be consistent.

The variations of the horizontal and vertical acceleration responses along the height, for different design soil conditions including the hard rock condition, show that the CSA-based design ground motion, rather than the ENA-based design ground motion, governs the seismic design.

6.2 Floor Response Spectra

Figure 13 shows a set of 5%-damped floor response spectra at the top of the containment structure due to the applicable horizontal design ground motion and for the three design soil conditions: HR, B-2, and C-1. The set consists of three spectra in the three spatial directions of the ground motions: two horizontal components and one vertical component. Similar sets of floor response spectra at the top of the internal structure and at the base slab are shown in Figures 14 and 15.

The sets of floor response spectra in the horizontal directions show that the impact of incorporating the ENA-based design ground motion is minor when compared with the floor response spectra due to the CSA-based design ground motion. This observation is true for higher floor; however, for floors close to the base slab, the ENA-based design ground motion causes same seismic load levels but at higher frequencies. The sets of floor response spectra in the vertical direction show that, for the internal structure, incorporating the ENA-based design ground motion increases the seismic load levels at higher frequencies, while for the containment structure, and the base slab, there is minor impact on the seismic load levels. This will only affect high-frequency sensitive components supported on the floors of the internal structure.

The sets of horizontal floor response spectra at the top of both the containment and internal structures are generally governed by the CSA-based design ground motion, rather than the ENA-based design ground motion. The horizontal floor response spectra at the base slab are characterized with just shifted peaks to higher frequency levels. The sets of floor response spectra in the vertical direction indicates that the ENA-based design ground motion, rather than the CSA-based design ground motion, would governs the seismic design of safety-related components supported on the concrete floors of the internal structure.

7 CONCLUSION

In this study, the seismic response of the ACR-1000 nuclear island structures is investigated. Lumped mass and consistent mass models representing the structures of the nuclear island are used in the analyses. The soil structure interaction effects, representing each of the design foundation conditions, are idealized using both constant soil springs and frequency-dependent impedance functions. Both CSA-based and ENA-based design ground motions are used in the seismic analyses. The ENA-based design ground motion is rich with high frequency content characterizing seismic hazards in ENA rock sites. The acceleration response of the containment and internal structures is determined. In addition, the floor response spectra at key locations of the nuclear island structures are generated. The structural responses to the ENA-based ground motion are compared with the structural responses to CSA-based ground motion. The CSA-based design ground motion, rather than the ENA-based design ground motion, governs the seismic acceleration response of the containment and internal structures. The impact of incorporating the ENA-based design ground motion on the floor response spectra is, generally, minor when compared with the floor response spectra due to the CSA-based design ground motion; particularly for higher floors. For floors close to the base slab, the ENA-based design ground motion causes same seismic load levels but at higher frequencies. In addition, for the vertical floor response spectra of the internal structure, incorporating the ENA-based design ground motion increases the seismic load levels at higher frequencies. The study demonstrates the robustness of the ACR-1000 nuclear power plant seismic design including sites in ENA characterized with rich high frequency content and hard rock foundation condition.

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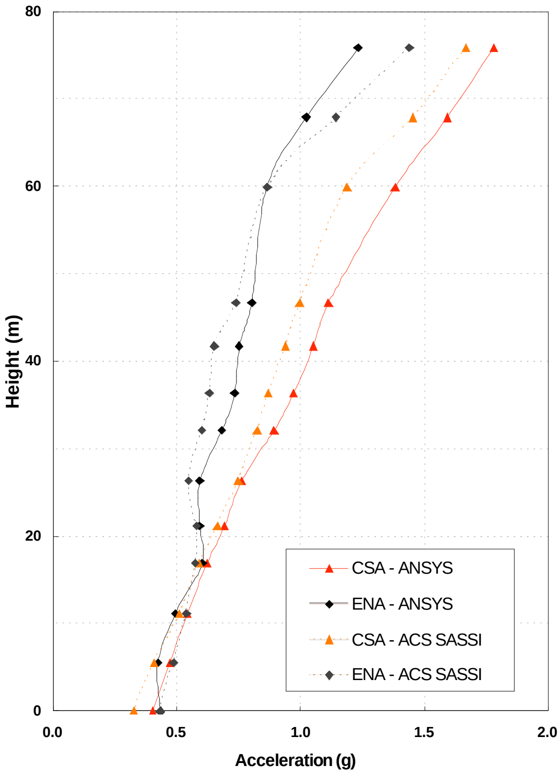

Figure 5. Containment structure horizontal acceleration response – HR condition

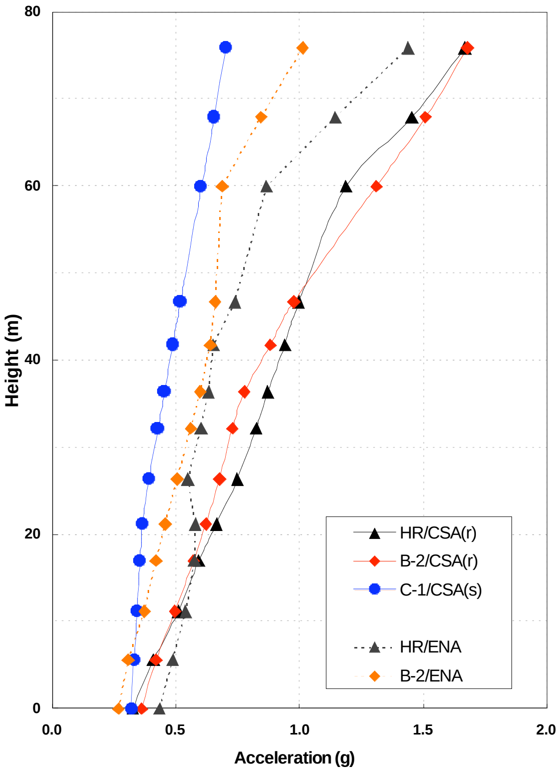

Figure 6. Containment structure horizontal acceleration response – HR, B-2 & C-1

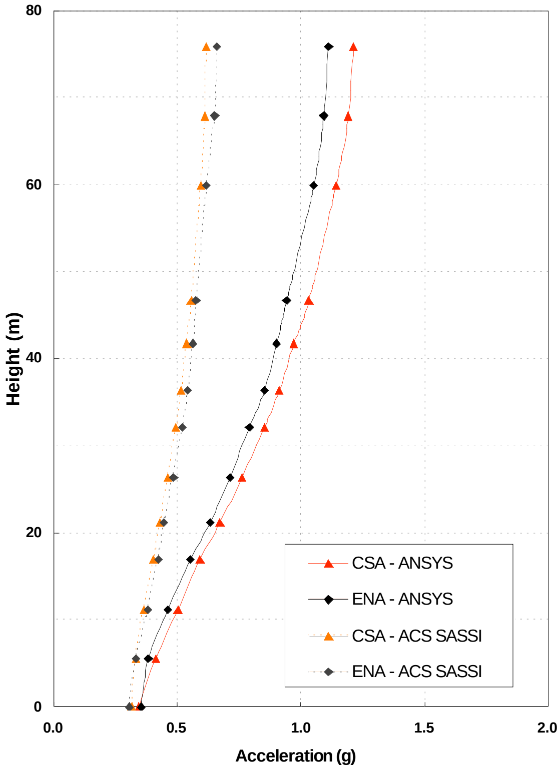

Figure 7. Containment structure vertical acceleration response – HR condition

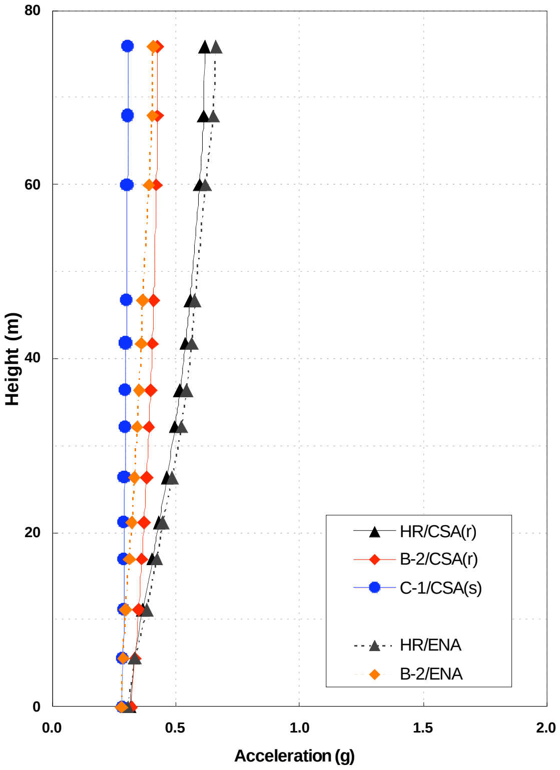

Figure 8. Containment structure vertical acceleration response – HR, B-2 & C-1

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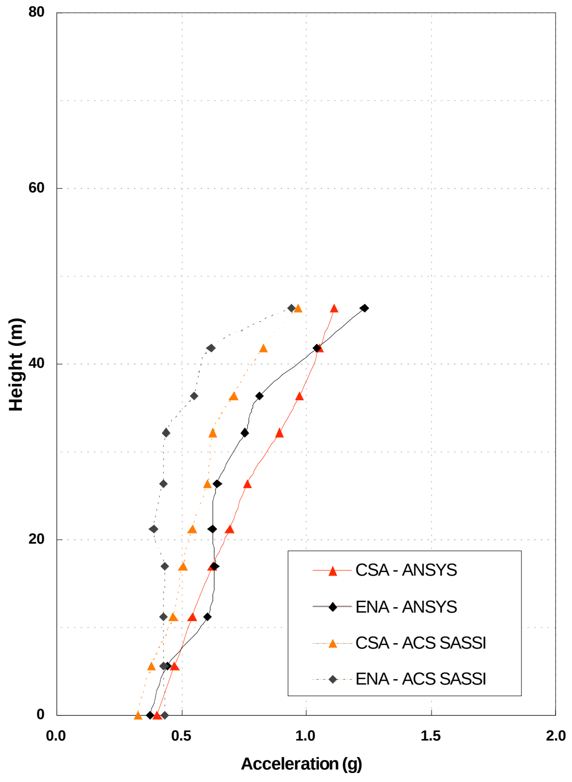

Figure 9. Internal structure horizontal acceleration response – HR condition

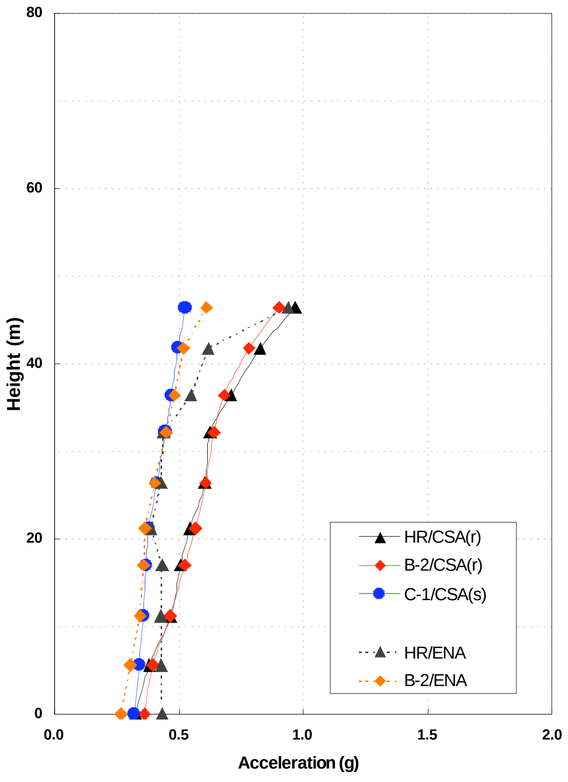

Figure 10. Internal structure horizontal acceleration response – HR, B-2 & C-1

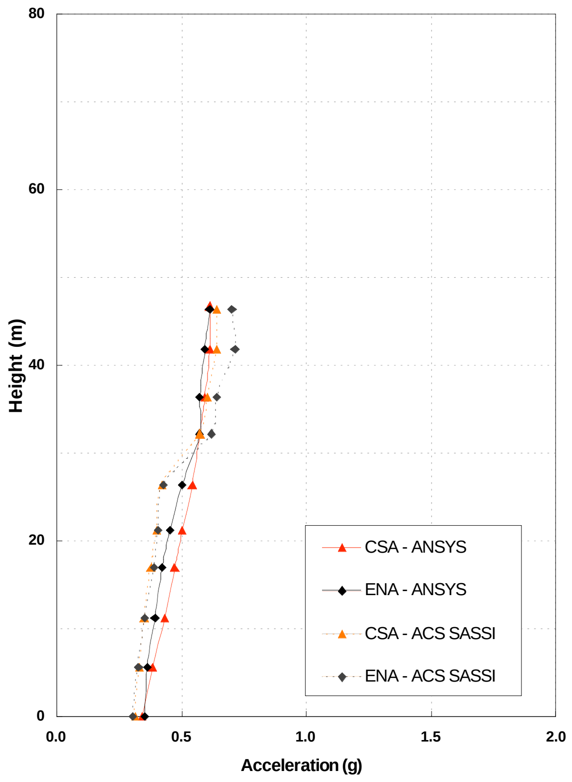

Figure 11. Internal structure vertical acceleration response – HR condition

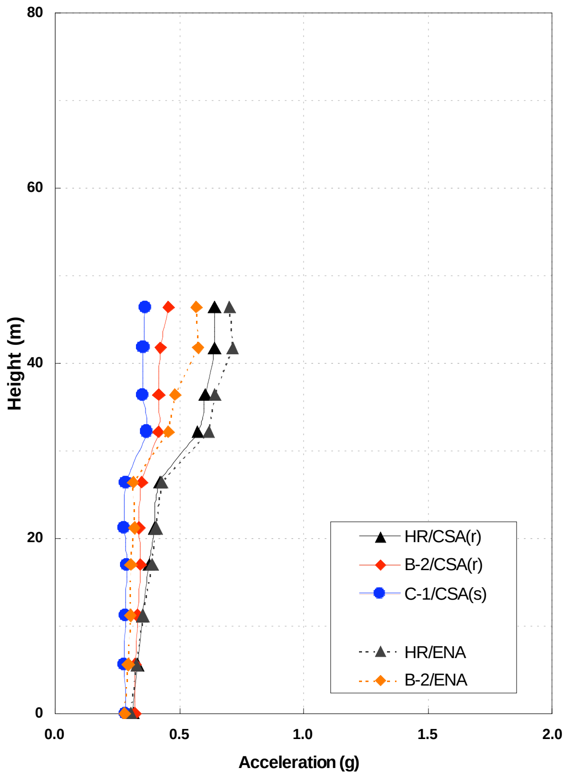

Figure 12. Internal structure vertical acceleration response – HR, B-2 & C-1

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