RESPECTIVE ROLE OF THE VERTICAL AND HORIZONTAL COMPONENTS OF AN EARTHQUAKE EXCITATION FOR THE DETERMINATION OF FLOOR RESPONSE SPECTRA OF A BASE ISOLATED NUCLEAR STRUCTURE – APPLICATION TO GEN IV REACTORS

N.Moussallam[1], V.Vlaski[2]
[1]AREVA Engineering & Projects, Mechanical Engineering Lyon Department, Structural Analysis Section
[2]AREVA Engineering & Projects, Civil Structural Engineering Offenbach Department, Structural Dynamics Section
E-mail of corresponding author: nadim.moussallam@areva.com

ABSTRACT

Several nuclear energy systems, identified as GEN IV technologies, such as Liquid Metal Fast Breeder Reactor (LMFBR) must resist high temperature transients and do operate at relatively low internal pressure levels. Therefore, most of the components constituting these reactors are thin compared to their PWR counterparts. This induces a specific vulnerability to strong seismic loadings. For this reason, seismic base isolation is considered a very promising option. Its main goal, for this application, would be to decrease the loading on the components and systems by reducing the floor response spectra at their anchorage points. Despite some historical practices, the floor response spectra of a seismically isolated structure can not be properly determined using stick models or multi-degree of freedom spring mass models. Such models would actually lead to an over-estimation of the base isolation efficiency in the horizontal direction. Indeed, the vertical excitation component of the earthquake does excite some modes with significant local horizontal accelerations. As a result, the horizontal floor response spectra do exhibits significant peaks at frequencies higher than the isolation frequency. The representation of these local modes does generally require 3D modeling. The opposite phenomenon is also observed: the horizontal excitation does excite some modes with significant local vertical accelerations. Given that the horizontal excitation is filtered by the base isolation system, the vertical floor response spectra can be significantly reduced. By changing the vertical stiffness of the base isolation system or adding some damping in this direction useful design tools are available in order to influence both the horizontal and the vertical floor response spectra.

INTRODUCTION

In the recent decades, the seismic levels applied for the design of nuclear power plants have been constantly increased. Recent events in Japan, which have led to a halt in the functioning of the Kashiwazaki-Kariwa power plant in 2007 and the Fukushima accident in 2011 indicate that the design seismic levels may be subjected to further increase in a certain number of countries. As a result, it is becoming increasingly difficult to design a nuclear reactor in regions with high seismicity and the use of seismic base isolation system is expected to provide a much needed alternative to a constant strengthening of the structures, systems and components.

In the case of GEN IV reactors, and more specifically in the case of Liquid Metal Fast Breeder Reactors (LMFBR), several characteristics of their designs make the seismic problem even more stringent. Indeed, the primary and secondary circuits of these reactors are constituted of thin metallic vessels, shells and pipes, which are prone to buckling or plastic instability when submitted to dynamic loading. This is due for one part to the relatively low pressures inside these structures, when compared to the pressures encountered in usual light water reactors, and for the other part to the high thermal transients to which these structures may be submitted. Thin shells ensure a rapid conduction of the heat through the thickness, which keeps the peak thermal stresses in the allowable domain. A list of the design issues associated to the seismic loading for LMFBR is given in an AIEA report written by Gibert & Martelli [1].For LMFBR reactors of the 4th generation, whose safety level must be at least the same as the present safety level for GEN III reactors, it is foreseen that seismic base isolation systems will probably be required even for sites with moderate seismicity. The principal motivation in implementing these systems will be to lower the seismic loadings on the components and systems inside the buildings. In purely analytical terms, the isolation systems must be designed to produce as low as possible floor response spectra. This objective differs significantly from the one usually associated with seismic isolation systems in civil construction, which is to protect the buildings themselves. This may explain why the phenomena described in the present article seem to have been discovered only recently and are not addressed in the appropriate literature.

In the first part of this article, the expected “ideal” functioning of a seismic isolation system will be recalled, as well as some phenomena that are known to alter this “ideal” functioning. In the second part, it will be shown that the 3 dimensional nature of the seismic excitation might lead to spectra significantly different from the “ideal” ones for structures such as those encountered in the nuclear industry. The demonstration will be based on simple test cases. The third part illustrates the phenomena, as they are observed on a complete model of Gen IV nuclear island. A last part will concentrate on how the designer can improve the behavior of a seismically isolated structure.

“IDEAL” AND ACTUAL EFFECT OF A SEISMIC ISOLATION SYSTEM ON FLOOR RESPONSE SPECTRA FOR A PURELY HORIZONTAL EXCITATION

A seismic isolation system does basically act as a filter between the ground excitation and the isolated super-structure. An abundant literature exists on the subject, as for example the excellent book from Naeim and Kelly [2]. Many different systems are available, with low or high damping, pseudo-linear or completely non linear behavior. The principle is always to modify the dynamic behavior of a set of buildings denoted as the “super-structure” in order to increase the level of acceptable seismic loading. In the case of nuclear components design, the modification should uncouple the main buildings modes from the internal components modes, to avoid resonance phenomena. The range of components eigen frequencies being generally comprised between 3 and 20 Hz, the isolation system will classically be designed to shift the main horizontal building modes from a few Hz to below 1 Hz. This is achieved by introducing “soft” elements between the super-structure and the ground, the most classical of which are elastomeric rubber bearings. Isolation is usually not implemented in the vertical direction because the components sensitivity to vertical seismic loadings is lower.

The effect of the implementation of a horizontal isolation system below a super-structure is that the whole system “super-structure + isolation” have a behavior close to the one of a single degree of freedom oscillator. The super-structure being very stiff compared to the “soft” isolation system, it should almost not be excited by the filtered excitation signal. The floor response spectra in horizontal direction of such a structure are expected to:

- be constant along the height of the super-structure,
- exhibit a peak at the isolation frequency, which amplitude and width do only depend on the damping associated to the isolation system,
- exhibit a plateau after the peak, which value is equal to the value of the ground spectra for the isolation frequency.

An example of such expected “ideal” floor response spectra is given in Fig. 1, along with the ground response spectra corresponding to the time-history that have been used as an input. Such ideal floor response spectra can be obtained by simple spring-mass models.

Departing form this “ideal” behavior, it has been well established ([2], [3]) that even with a purely horizontal excitation, the floor response spectra of an isolated super-structure may exhibit some peaks at frequencies corresponding to the non isolated super-structure’s modes, i.e. frequencies higher than the isolation frequency. The excitation of these higher frequency modes is due to the still existing (even if largely reduced) participation factors associated to these modes in the horizontal direction and to the damping effects. Indeed, for systems with high damping values, the damping forces between the ground and the isolated super-structure become significant and the frequency content of these forces is not filtered. For low values of damping, an illustration of a typical actual floor response spectrum obtained with a purely horizontal excitation in given in Fig. 2.

Moreover, recent studies [4] have underlined the fact that for seismically isolated structures, the rocking excitation, which effects are assumed to be negligible in most seismic analyses, may become significant. This is because the horizontal excitation’s importance has been largely reduced by the isolation system. This aspect is difficult to treat since there is a lack of information and regulations concerning this type of excitation. No rocking excitation was considered in the analyses which results are presented here.

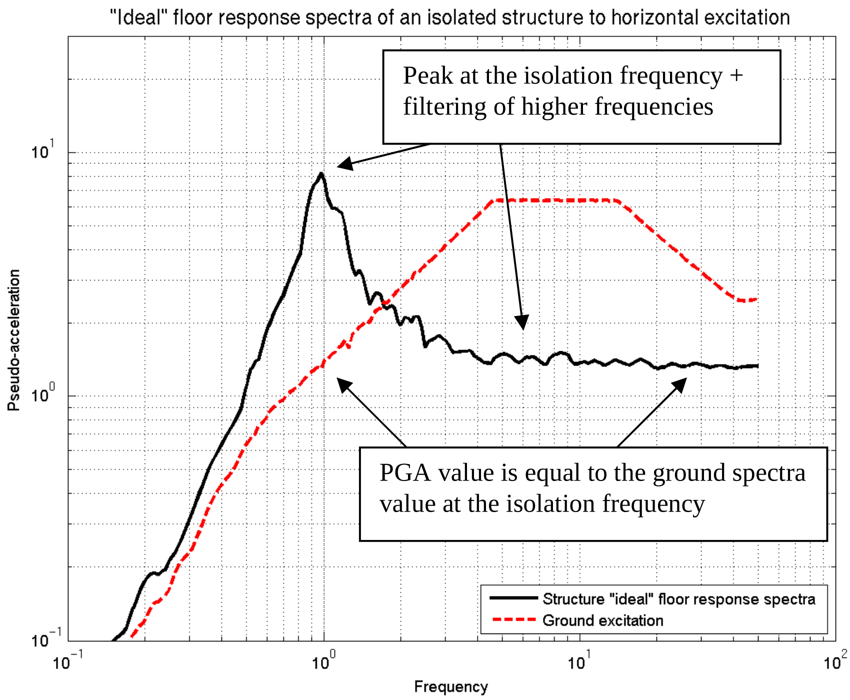


Fig.1: "Ideal" floor response spectra of an isolated structure to a purely horizontal excitation (time-history)

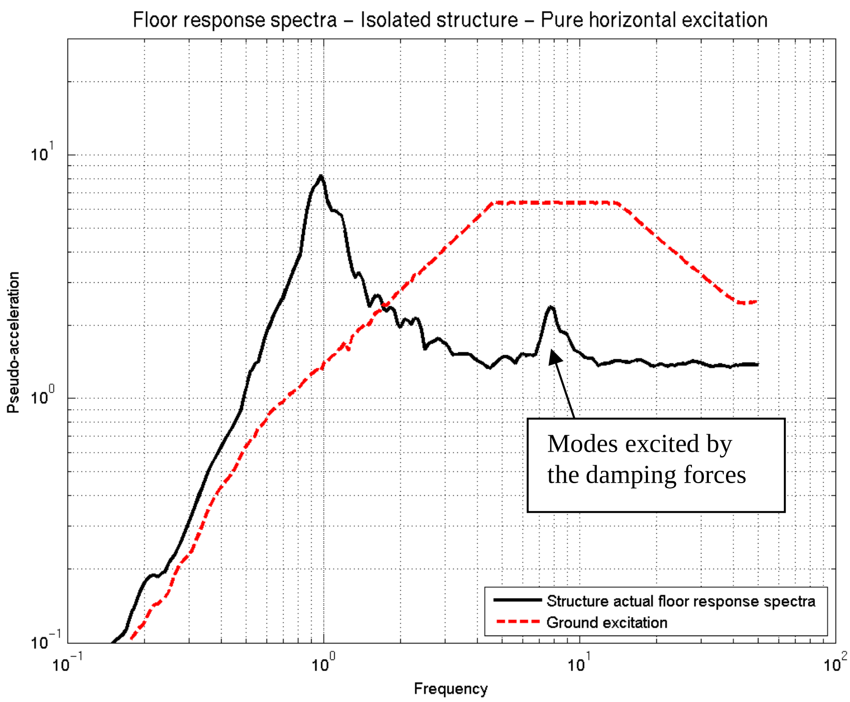


Fig.2: Actual floor response spectra of an isolated structure to a purely horizontal excitation (time-history)

INFLUENCE OF THE VERTICAL EXCITATION ON HORIZONTAL FLOOR RESPONSE SPECTRA - TEST CASES

If the whole system "super-structure + isolation" is assumed to be linear, the contribution of the vertical and horizontal seismic excitation can be computed separately and then linearly added to obtain the 3-dimensionnal response of the structure. This method is typically the one employed in many calculations of the behavior of a seismically isolated structure. The problem lies in the fact that it is very commonly assumed that floor response spectra in the horizontal direction are mainly due to the horizontal excitation and floor response spectra in the vertical direction are mainly due to the vertical excitation. Horizontal and vertical floor responses spectra are then computed with different simplified models, typically stick models, and it is assumed that the interaction is negligible. It will be demonstrated hereafter that this assumption is not valid for base isolated structures. Let us consider three very simple 2D structures:

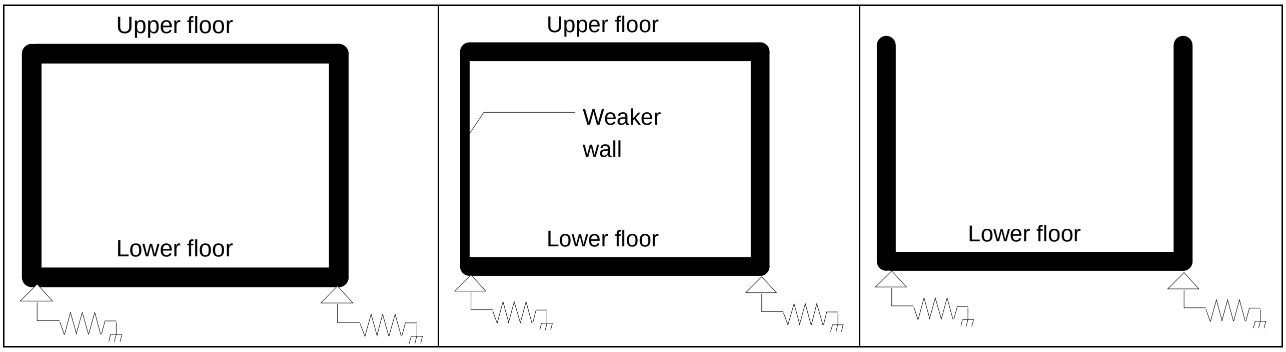
- The first case is a perfectly symmetrical rectangular frame constituted of two lateral walls and two horizontal floors. It represents an autonomous well balanced building with a stiffness distribution exactly fitting its mass distribution and a regular stiffening of the walls by the floors. The structure is illustrated in Fig. 3a. The first vertical mode of this structure is illustrated in Fig 4a. A possible corresponding structure in a power plant is a containment building uncoupled from all other external buildings, as illustrated in Fig. 5a.
- The second case is similar to the first one, except for one lateral wall, which stiffness is twice lower than in the previous case. It represents the very common situation of a building linked to another structure on one side and self standing on the other side. It is also representative of any discrepancy between the stiffness distribution and the mass distribution within a building. Such discrepancy leads to modes which have significant participation factors in both the horizontal and the vertical directions. A purely vertical excitation of the structure will lead to significant horizontal displacement of certain points of this structure. The structure is illustrated in Fig. 3b. The first vertical mode of this structure is illustrated in Fig 4b. A possible corresponding structure in a power plant is a fuel building, rigidly linked to another stiffer building (containment or airplane crash shell) on one of its side, as illustrated in Fig 5b.
- The third case is similar to the first one, except for the upper floor that has been suppressed. It represents the case of large halls with wide lateral walls and a lack of floors linking these walls. It is also representative of any symmetrical structure for which a purely vertical mode with no participation in the horizontal direction can generate symmetrical horizontal displacement of several points of the structure. The structure is illustrated in Fig. 3c. The first vertical mode of this structure is illustrated in Fig 4c. Possible corresponding structures in a Gen IV power plant are the steam generator buildings, which are located outside the reactor building. The design of the steam generator might result in rather elongated buildings linked to the reactor building up to a certain altitude. A schematic of this configuration is given in Fig 5c.

For each of these three cases, the structure is supported on its two lower corners. The support for each corner is either fixed or mounted on a spring representing a horizontal isolation device. The isolation frequency is 1 Hz in the horizontal direction. All three structures have a main horizontal mode located at 1 Hz and representing more than 99 % of the participating mass in this direction. In the vertical direction, the isolation devices are 100 times stiffer than in the horizontal direction.

The three test cases were submitted simultaneously to synthetic acceleration time histories in the horizontal and vertical directions. The time histories correspond to the spectral curves of the European Utility Requirements [5] document for hard soil. The horizontal response spectra obtained on the upper part of the structure are given in Fig. 6a to Fig. 6c. On each part of the figure, the envelope response spectra of all points located on the upper part of the structure are given for one test case, with and without seismic isolation devices. Several observations can be derived from these figures:

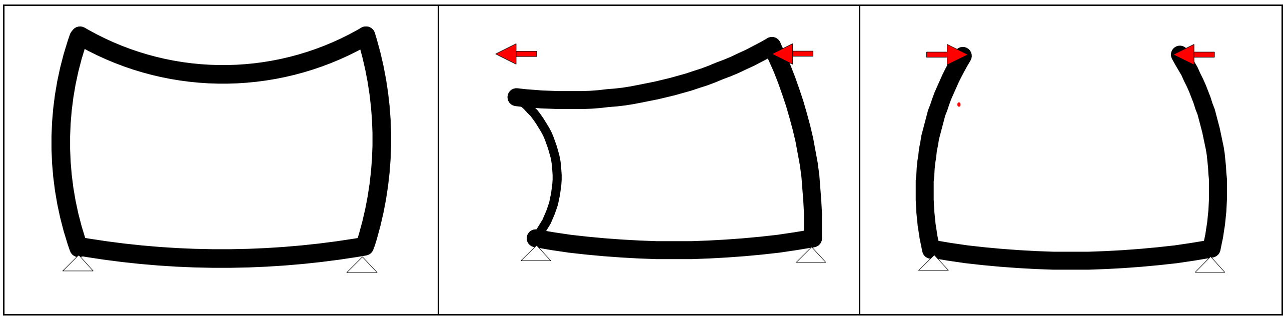
- In all cases, except in the vicinity of the isolation frequency, the implementation of isolation devices in the model is resulting in significantly lower floor response spectra.
- Even though a modal analysis of these three isolated structures would define them as having a unique participating mode in the horizontal direction, it does not mean that the horizontal floor response spectra of these structures are identical. This is because, for an isolated structure, the vertical loading results in horizontal local displacements of the structure which are not negligible.
- The effect of the vertical acceleration on horizontal floor response spectra might significantly reduce the effectiveness of the seismic isolation system and become the leading constraint on the design of

components and systems. Therefore, the vertical and horizontal analysis shall be combined, if not carried at once, for determining the floor responses spectra of base isolated structures.



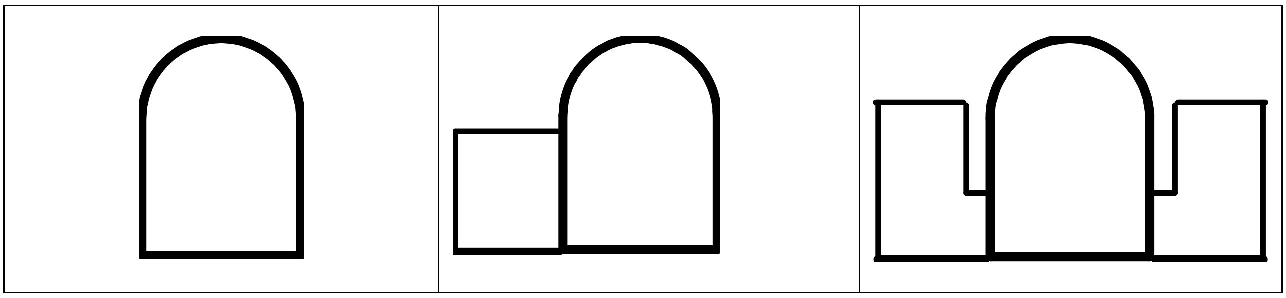
a) b) c)

Fig.3: Simple test case structures for the analysis – Horizontal support springs are either infinitely stiff (clamped structure) or tuned to produce a first translational mode at 1 Hz (isolated structure) - a) symmetrical closed frame b) unsymmetrical closed frame structure c) symmetrical open frame



a) b) c)

Fig.4: Principal mode of the structure when excited in the vertical direction – Associated local horizontal displacement highlighted by the arrows - a) symmetrical closed frame b) unsymmetrical closed frame structure c) symmetrical open frame



a) b) c)

Fig.5: Examples of possible arrangement of buildings for Gen IV reactors which have a behavior similar to the test cases - a) self standing containment building, assimilated with the symmetrical closed frame b) coupled fuel and containment building associated with the unsymmetrical closed frame structure c) Elongated steam generator buildings associated with the symmetrical open frame

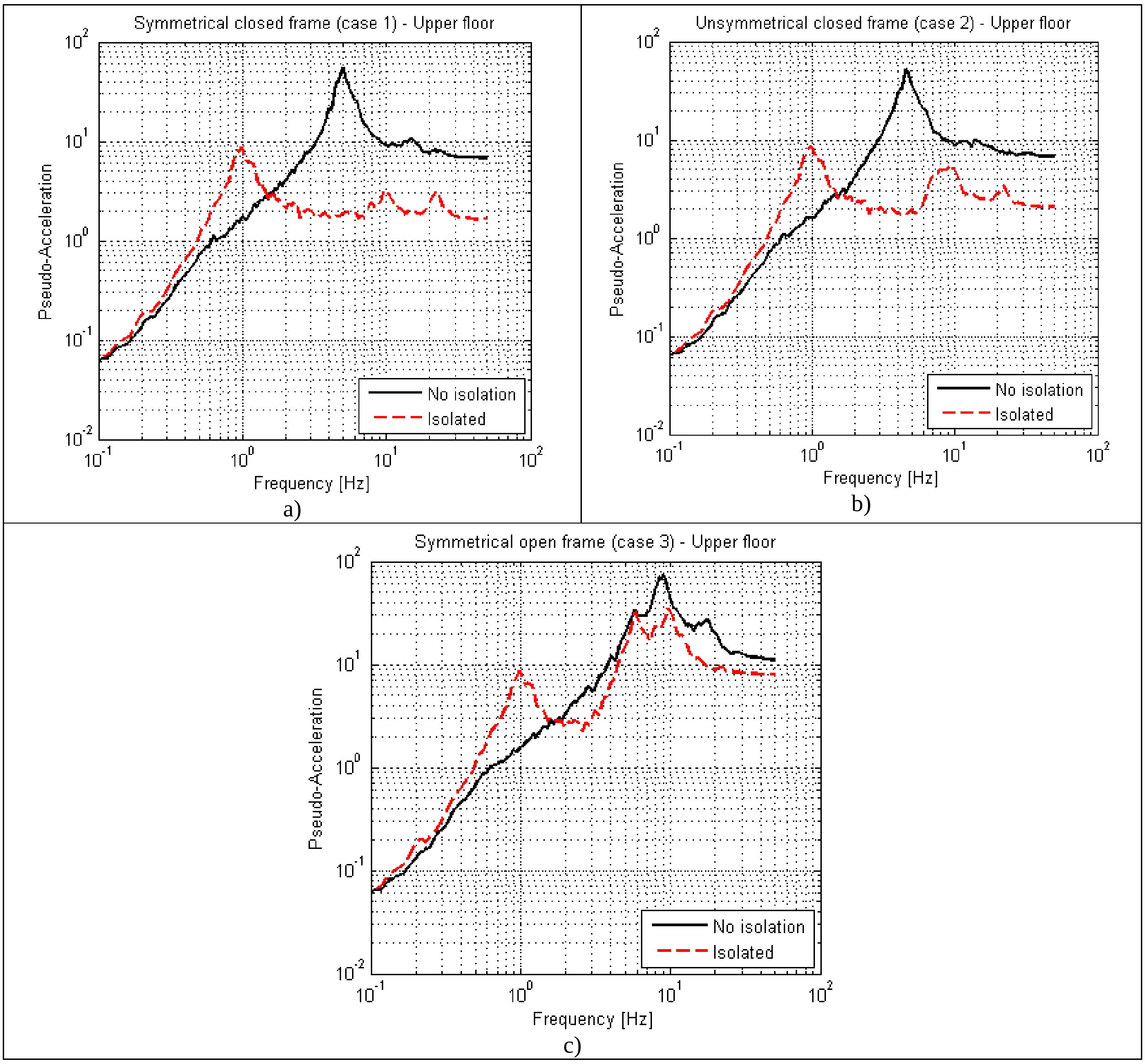


Fig.6: Horizontal response spectra on the upper part of the test case structures – a) symmetrical closed frame b) unsymmetrical closed frame structure c) symmetrical open frame

EXTENSION TO GEN IV BUILDINGS – RESPECTIVE INFLUENCE OF THE VERTICAL AND HORIZONTAL EXCITATIONS

LMFBR nuclear islands, such as planned today, may be prone to the kind of phenomena described in the previous paragraph. A dynamic analysis conducted on the preliminary design of a sodium fast reactor nuclear island developed by AREVA was conducted. Several time histories were given as input and the floor response spectra at different locations and altitudes inside the buildings were determined. The calculations were performed with and without the implementation of a seismic isolation system. The model was 3D and the seismic excitation was applied simultaneously in 3 orthogonal directions.

First of all, the efficiency of the seismic isolation system for reducing the horizontal floor response spectra in the frequency range of interest was confirmed. Fig. 7a illustrates the difference of horizontal floor response spectra at a given floor of the structure with and without isolation system. Reductions up to a factor 10 are achievable. Still, the potential for reduction is not as high as it would be expected because of the peaks due to the vertical excitation. These peaks are altitude dependant, as illustrated in Fig. 7b. Fig. 7c shows the horizontal response spectra that would have been obtained with respectively purely horizontal and purely vertical excitations. The predominance of the vertical excitation on the higher frequency range is clear. Since the model is linear, the total response spectrum corresponds to an addition of the response spectra obtained with purely horizontal and purely vertical excitation.

Finally, if the vertical excitation has been demonstrated to have an influence on the horizontal response spectra, there is no reason for the horizontal excitation not to have the same kind of influence on the vertical response spectra. Indeed, some modes inducing significant local vertical accelerations are excited by the horizontal excitation. The implementation of a seismic isolation system does effectively filter the horizontal excitation, which means that these modes will be less excited. As a consequence, the vertical floor response spectra of the structure were found to be generally decreased by the implementation of the horizontal isolation system. This fact is illustrated in Fig. 7d. No mention of it was found in previous literature. Still, since the isolation system does also have a finite vertical stiffness, the change of vertical floor response spectra will also depend on this stiffness. The authors do not exclude that in some cases, because some vertical modes could be shifted toward lower frequency by the adjunction of this stiffness, the vertical floor response spectra might be actually augmented instead of decreased.

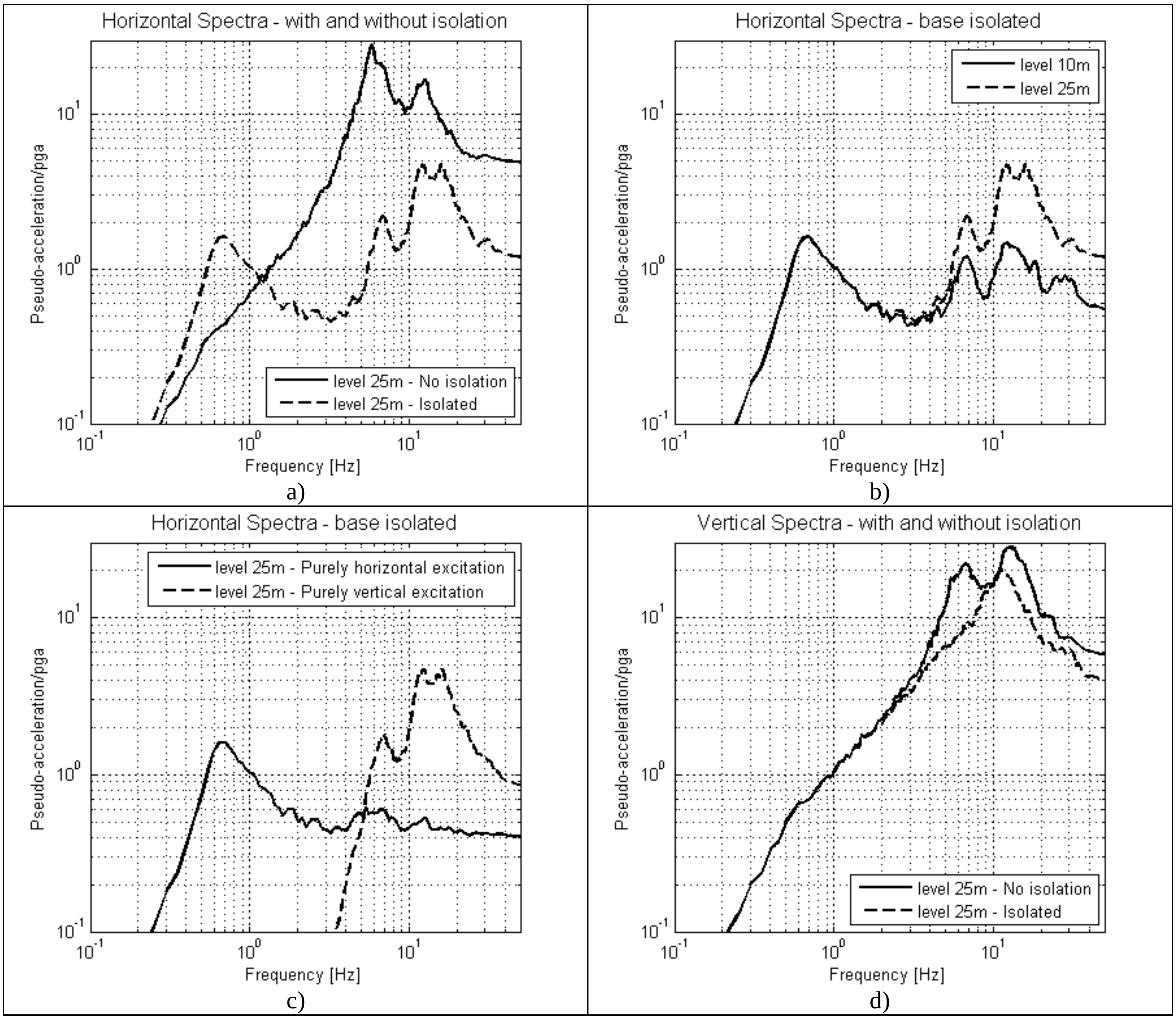


Fig.7: Calculated floor response spectra for a GEN IV structure – a) Horizontal floor response spectra with and without isolation. b) Horizontal spectra at two altitudes. c) Separation of the effects of the vertical and horizontal excitation on horizontal response spectra. d) Vertical floor response spectra with and without isolation.

DESIGN TOOLS TO ENHANCE THE BEHAVIOR OF A SEISMICALLY ISOLATED STRUCTURE

Based on the results presented in the previous paragraphs, it seems that some parameters are of unexpected importance for assessing, and possibly enhancing, the efficiency of a seismic isolation system. First of all, the soil-structure interaction in the vertical direction shall not be neglected. This interaction would affect the main vertical modes and therefore the positions of the peaks on the horizontal response spectra. The soil damping will directly affect the amplitude of these peaks. The vertical stiffness of the isolation system, generally considered of secondary importance, might prove a valuable tool to displace the peaks on the horizontal spectra as well as on the vertical spectra. Depending of the technology chosen for the isolation, it is more or less complicated to change the stiffness without moving the isolation frequency. The adjunction of damping devices, working in the vertical direction only and located in parallel with the isolation system allows a reduction of both the vertical and the horizontal response spectra. Finally, the building design can be modified to reduce the coupling between directions. Some changes of the sodium fast reactor design are typically envisaged for reducing the peaks on the horizontal response spectra.

CONCLUSION

Based on simple test cases and complete 3D calculation of a Gen IV reactor with base isolation system, the present paper demonstrates that the determination of the floor response spectra in an isolated structure requires a correct assessment of the influence of both the horizontal and vertical excitations. The vertical excitation results in some peaks at higher frequencies of the horizontal floor response spectra that would be missed by separated directional analyses traditionally performed with stick models.

The implementation of seismic isolation system in the horizontal direction has been found to also decrease the vertical response spectra of the structure. This is because some horizontal modes inducing vertical local acceleration are less excited.

Finally, the importance of the soil-structure interaction and of the stiffness of the isolation system in the vertical direction is underlined. Indeed, these parameters would significantly affect both the vertical and the horizontal floor response spectra. From a designer point of view, changing the vertical stiffness of the isolation system along with the possible adjunction of damping devices working in this direction might prove valuable tools to further decrease the floor response spectra.

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