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VARIATION OF FLOOR VIBRATIONS DUE TO EARTHQUAKE IN REACTOR BUILDING STRUCTURES

Vilho Jussila[1], Ludovic Fülöp[2] and Yue Li[3]

[1] Research Scientist, VTT Technical Research Centre of Finland Ltd, Finland
[2] Principal Scientist, VTT Technical Research Centre of Finland Ltd, Finland
[3] Associate Professor, Department of Civil and Environmental Engineering, Michigan Technological University, USA

ABSTRACT

We have studied floor vibration of a generic reactor building subjected to seismic loads, with the aim of quantifying the variability of vibrations within each floor. A detailed 3D building model founded on the bedrock, was excited simultaneously to three directions by artificial accelerograms compatible with Finnish ground response spectra. The material model of the reinforced concrete walls, columns and beams was linear, whereas water in the spent fuel storage pools was modelled with mass elements. The dynamic simulation of 20 seconds was carried out using explicit time integration. The extracted results of the simulation were accelerations in three directions and pseudo-acceleration spectra (PSA) in several floor locations. At first, locations were estimated by engineering judgement to arrive to a feasible number of floor nodes and locations for post processing. It turned out that engineering judgment was not enough to depict locations, which resulted in conservative vibration estimates. For this reason we took a more systematic approach, where nodes of the floors were selected with a 2 m grid. With this method, besides the highest PSA peaks in all directions we are able to give the full plot of the vibration distribution in each floor. The statistical evaluation of the floor responses was also carried out in order to define floor accelerations and PSA's with high confidence of non-exceedance. The conclusion is that in-floor variability can be as high as 50-60% and more extensive models with enough dense node grids should be used in order to have the conservative estimate of floor vibration under seismic action.

INTRODUCTION

In the early days, when computational resources were limited, numerical studies needed to have a sharper focus on computational efficiency. In this context, dynamic models for nuclear buildings, with the purpose of obtaining in-structure response spectra, were carried out with reduced model sizes by condensation methods or component mode synthesis. Later it become feasible to carry out the modelling with full 3D models. Studies show that results with reduced models tend to overestimate response (Varpasuo, 1999, Nakamura et al., 2010). However, the floor vibrations may vary significantly within the same floor and this variability needs to be understood when analysing output from a 3D model. The building typology probably also plays a significant role. Major differences exist between the dynamic properties of a building typology influenced by torsional modes (Baušys et al., 2008) and a compact typology like the one analysed by Varpasuo (1999).

In this case we evaluated the floor vibrations for a reactor building designed for the advanced boiling water reactor (ABWR), with a compact configuration. The building is not prone to torsional effects, perimeter walls being very stiff. The intention was to keep the results generic for this building configuration.

OBJECTIVES

A generic challenge simulating full 3D nuclear power plant models under seismic action is the massive amount of information of the results. From the point of view of the accuracy of result it is important to introduce large number of nodes. How much is it possible to reduce the number of nodes

without losing the confidence of the analysis? This problem arises when analysing floor vibration sensitivity. Is it sufficiently accurate to use engineering judgement when select vibration output locations or is it required to use a more systematic approach?

In this study, our objective was to investigate the most obvious locations on the floor span subjected to heaviest floor response. We chose up to seven node locations at each floor and verified the feasibility of our node selection by comparative studies of the floor response in which several nodal grids were employed.

METHODS

It was assumed that the reactor building is on the bedrock, which is a requirement for a nuclear power plant location in Finland. As loads we used three component artificial accelerations, generated to comply with the target design spectra in the Finnish design guidelines (YVL 2.6, 2001, YVL B.7, 2013) . The horizontal peak ground acceleration (PGA) of $0.1 \cdot g$ ($\sim 1 m/s^2$) and 67% vertical component are designated for Southern Finland seismic conditions. The duration of the artificial accelerograms generated using a SIMQKE adaptation was calibrated for 6.5-7 magnitude earthquakes (ASCE 4-98, 2000). The total duration of the record was 18.5s with 1.5s rise time, 10s strong motion plateau and 7s decay time. However, the simulation length was 21s in order to observe decay of the vibration.

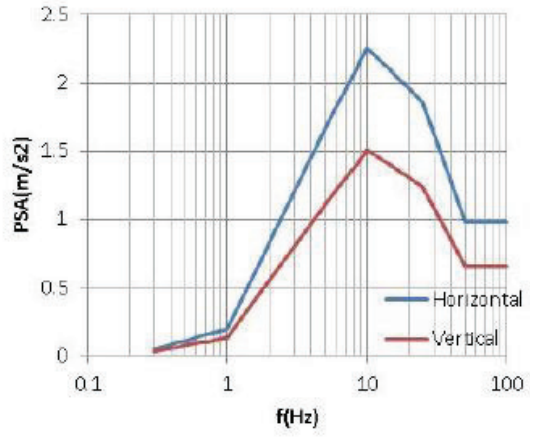


Figure 1. Target response spectra for accelerogram generation according to YVL 2.6 (2001) and YVL B.7 (2013) guidelines.

The recorded data in the simulation was nodal accelerations. The data is presented in three result formats: (a) sensitivity of the floor acceleration as a function of distance from the external wall , (b) pseudo-acceleration spectra computed with Newmark explicit time integration (Bathe, 2006) (Chopra, 2008), and (c) cumulative distribution function in order to study the minimum feasible number of nodes required to a realistic analysis of the floor vibrations.

Power plant model

The finite element model (FEM) of the eight storey generic building is as follows:

- Plan lateral dimensions are 61x58 m.
- Elevation to the top of the dome is 56 m.
- Outer wall thickness is 2 m.
- Structure is supported by bedrock to the vertical direction but the surrounding soil provides horizontal support.

- Total mass of the model is 222425 ton. 97% of the total mass covers mass of the structure, 0.96% covers the mass of the small spent fuel tank, 1.57% covers the mass of the large spent fuel tank and 0.36% covers the mass of the pressure vessel.
- Prevailing mesh size of shells is ~0.67 m.
- The model had 151158 elements and 143144 nodes with six degree of freedom. 6870 were linear line elements, 144272 were quadrilateral elements and 16 were triangular elements.
- The global coordinate system has following components: x and y spans the horizontal plane and z is the vertical direction.

The walls and floors were modelled with a linear concrete material model ignoring the steel reinforcement bars. This is feasible choice when the deformation of the building is assumed to remain in the elastic range under the seismic excitation. However, support steel frames of the structure were modelled. Water of the spent fuel storage was modelled with point masses attached to the reservoir walls. Locally these masses yield shear stresses which cannot be produced by the sloshing water. But, because the focus of the study was to assess global the vibrational response, the modelling of water with the point masses is acceptable. Finally, the pressure vessel was a rigid member providing inertia effects. A full description of the modes is given in by Jussila and Fülöp (2014a) and Jussila et al. (2014).

All wall-floor connections are assumed to be rigid. Connections, material non-linearity and other energy dissipating effects are covered with Rayleigh damping. This decision is simple but poses some undesired side effects. Firstly, Rayleigh damping increases simulation time when the damping factor at the controlling frequency is large. Secondly, for smaller frequencies than the controlling frequency ω_1 or larger frequencies than the controlling frequency ω_2, the damping increases rapidly. In effect, the floor outputs can be relied upon only within the interval ω_1 to ω_2. The target of the damping factor is less than 4% within observation range of the frequencies of 3-50Hz (ASCE 4-98, 2000).

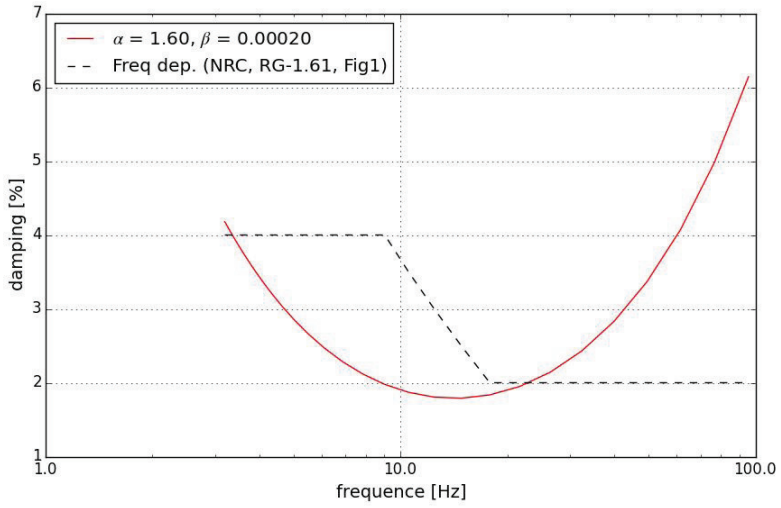


Figure 2. Rayleigh damping

Explicit time domain analysis was carried out with ABAQUS. The time domain was used, instead of the more customary frequency domain, because this study has been extended to the non-linear range of material responses later (Jussila and Fülöp, 2014b). Our intention was to keep compatibility between the stages of the modelling.

Before entering to the discussion of the floor vibration analysis, the main results of the computed natural vibration modes are presented. Altogether four significant global horizontal modes were

found. 1st global mode set in y- and x-direction has frequency of 3.20 Hz and 3.59 Hz with participating mass of 72% and 75%. 2nd global mode set has natural frequencies in y- and x-direction of 7.05 Hz and 7.62 Hz with participating mass of 9% and 5% respectively. These frequencies will induce significant dynamic response in the horizontal direction. It is more difficult to synthetize the modal results in the vertical direction, where several modes (5.93 Hz, 7.62 Hz, 8.36 Hz, 9.17 Hz) have significant participation factors. The first 100 modes have been reviewed for the model with total participation factor from all modes of 91%, 92% in the x- and y- directions, but only 80% in the z-(vertical) direction.

Floor nodes in vibration analysis

The floor response was investigated using pseudo-acceleration spectra (PSA). The structure has eight storeys. 1st, 2nd and 4th floor slab is dominated by a circular opening of the primary containment vessel. The 4th floor slab has three additional large rectangular openings in three corners. On the 6th storey the spent-fuel storage tanks form large rectangular opening in x direction. The 7th and 8th storeys have floors strips in x direction next to the external wall creating in the middle a large opening which disconnects floors in y direction. The plan contains a semi-floor which was included to analysis. It is located between 4th and 5th floors. Selective examples of the floors are given in Figure 3. The values of the x and y-axes were scaled with the width of the building.

The nodes present in the FEM mesh are indicated in blue and the red circles are nodes selected for the data analysis. We considered four node selection sets in the analysis: (a) few nodes were selected by engineering judgement, larger node sets were selected by the (b) 6 m, (c) 4 m and (d) 2 m grids. Thus, the 2 m set yields the densest grid to further analysis.

Pseudo-acceleration spectra

PSA's are commonly used in seismic engineering to estimate dynamic load-effects and dynamic amplification on a structure idealised as a single-degree of freedom (SDOF) oscillator.

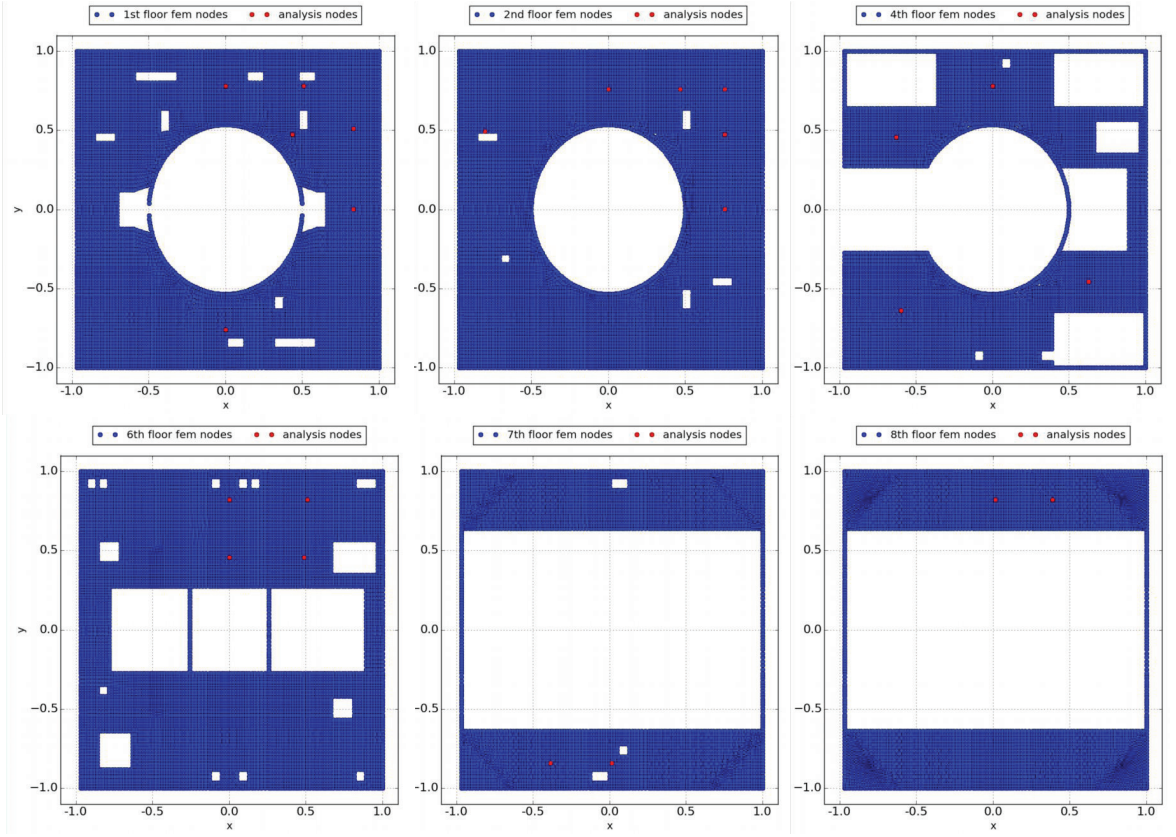
The PSA spectra are based on calculating the response of a set of independent SDOF spring-mass systems, each with a different natural frequency. In this PSA analysis, n=250 systems with frequency range from 0.1 Hz to 100 Hz were employed. The equation of motion of a SDOF spring-mass system in generalized coordinate system is

$$\ddot{Y}_n(t) + 2 \cdot \xi_n \cdot \omega_n \cdot \dot{Y}_n(t) + \omega_n^2 \cdot Y_n(t) = a(t) \tag{1}$$

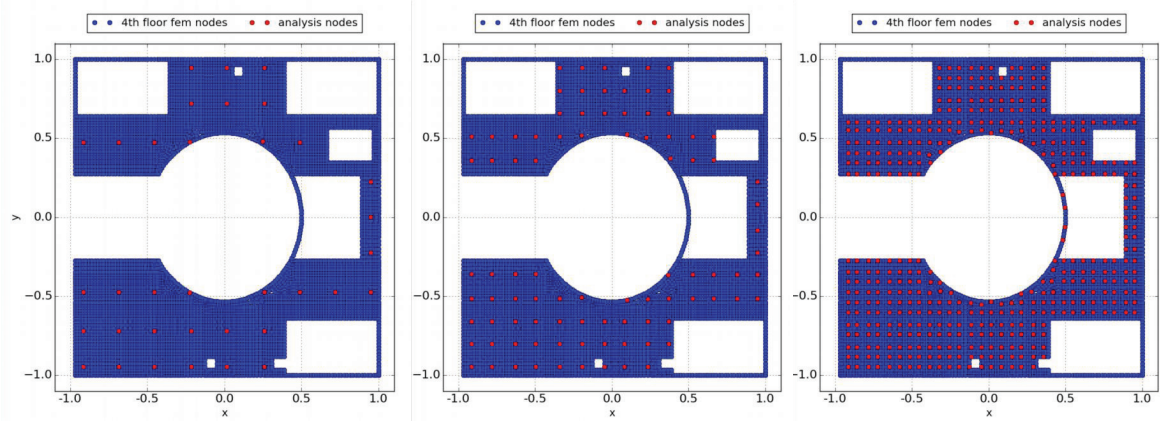
In Eq. 1 ω_n is a frequency, ξ_n is damping, $a(t)$ is the acceleration history applied to the base, $\ddot{Y}_n$, $\dot{Y}_n$ and Y_n acceleration, velocity and displacement respectively. For each frequency in a range from 0.1 Hz to 100 Hz with n=250 logarithmic step, acceleration, velocity and displacement was calculated with Newmark's explicit time integration method (Bathe 2006, Chopra, 2008). The accelerations of the floor nodes were applied as the excitation signal. The damping was 5%. Based on the solutions of Eq. 1 one could describe PSA with

$$a_{PSA\_n} = \omega_n^2 \cdot \max_n (Y_n) \tag{2}$$

Eq. 2 takes into account only maximum displacement of the mass-spring system with specific frequency under the simulation excitation.



(a)



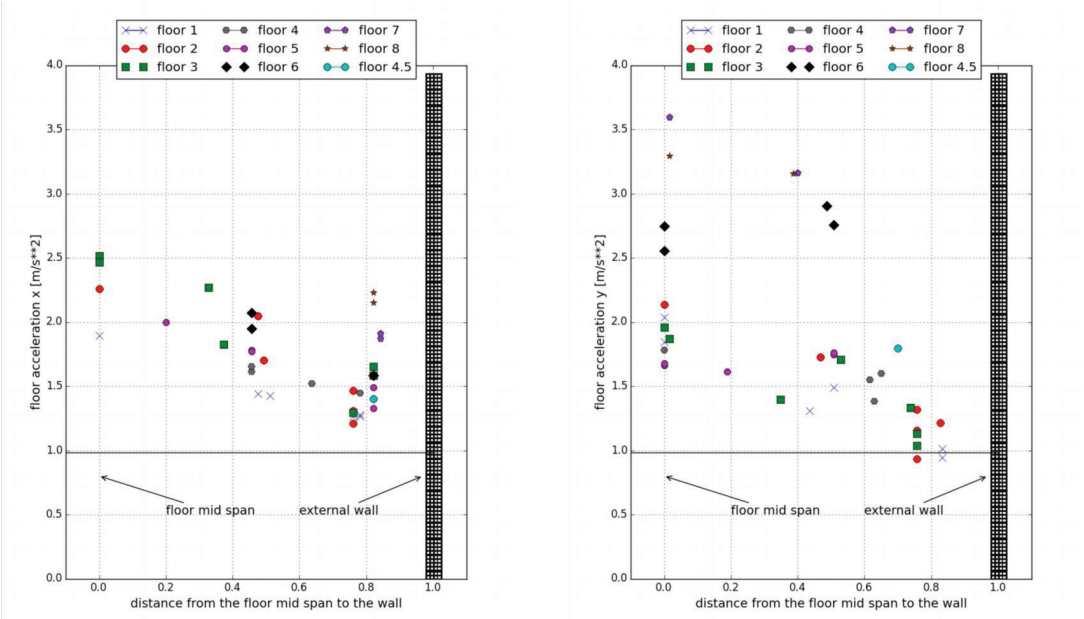
(b)

Figure 3. (a) Selected geometries of the 1st, 2nd, 4th, 6th, 7th and 8th floors. In blue are all FEM nodes on the floor and red are nodes for floor vibration analysis. (b) The 2m, 4m and 6m node grids are given for the 4th floor.

Results of floor vibrations

First we analysed results from the nodes which were hand-picked (Figure 3). There were 1 to 7 nodes on each floor. Peak floor acceleration in x and y directions are plotted as a function of a distance from the external wall in Figure 4. The horizontal PGA of 0.1·g, applied to the base of the structure, is indicated with horizontal solid black line. The plot in x direction shows increasing trend towards to the floor mid span. Similar trend can be found in y direction. In addition, floors six, seven and eight

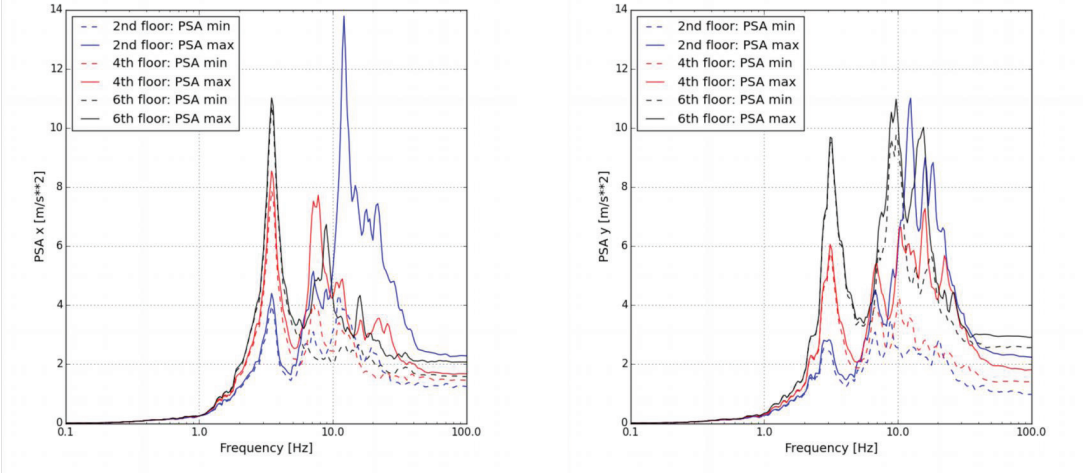
has larger floor accelerations than any other analysed floor. It can be noticed that variation within one floor can be as high as 50-60%.



(a) (b)

Figure 4. (a) Floor acceleration in x direction has increasing linear trend with distance to external wall. (b) Floor acceleration in y direction has similar trend. 6th, 7th and 8th floor have higher acceleration.

Next we computed PSA according to Eq. 1 and 2. The equation of motion (Eq. 1) of the spring-mass systems was solved on each frequency. The excitation was the floor node acceleration in x and y direction. For each frequency and for each floor, we computed smallest and largest value in x and y direction. The dynamic amplification has clear increasing trend at the close vicinity of natural frequencies, 3.59 Hz and 7.62 Hz in the x direction (Figure 5.a). Corresponding values in y direction are 3.20 Hz and 7.05 Hz (Figure 5.b). However, PSA spectra show dynamic amplification in x direction at the 2nd floor which is outside of the natural frequencies, and correspond to the amplification peak in the input spectra. Similar trend can be seen in the y direction.



(a) (b)

Figure 5. (a) Dynamic amplification in x direction at the first natural frequency of 3.59 Hz increases with floor height (b) Similar trend can be observed in y direction.

We compared PSA curves in horizontal and vertical directions at the 4th floor with 2.0m node grid and with the node set selected by engineering judgment. PSA curves of 2.0m node grid are given as function of computed 5% and 95% percentile exceedance. However, in the case of the engineering selection maximum and minimum PSA curves are plotted. In the x direction 2.0m node grid yields slightly larger acceleration at the first global mode of vibration (Figure 6.a). At the higher frequencies the node set selected with engineering judgement cannot predict the acceleration as precisely as the 2.0m node grid. In y direction both 2.0m node grid and the engineering selection yields overlapping result in terms of 95% percentile exceedance and maximum value respectively (Figure 6.b). Finally in the vertical direction the engineering selection cannot predict acceleration accurately as shown in Figure 6.c.

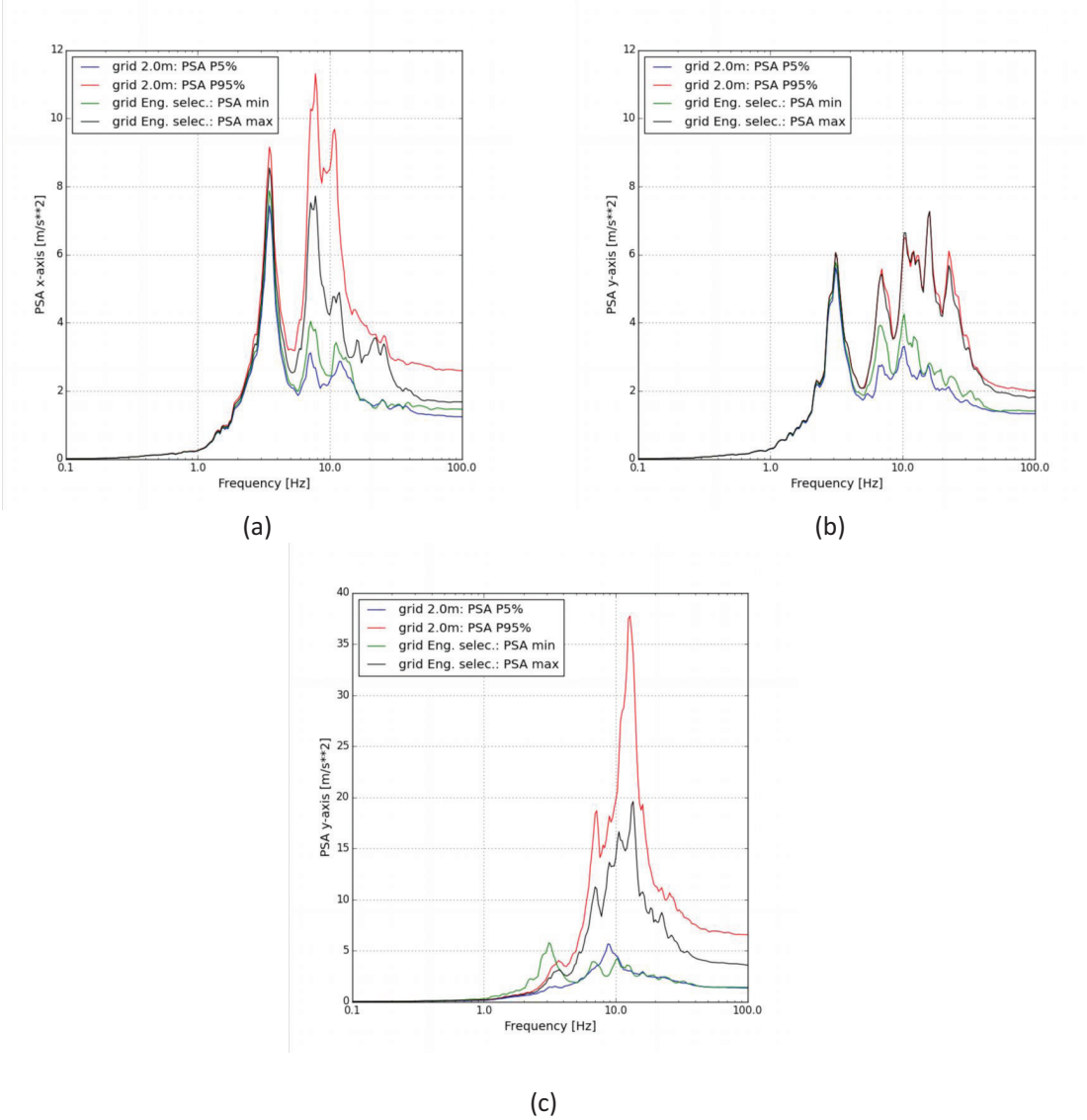
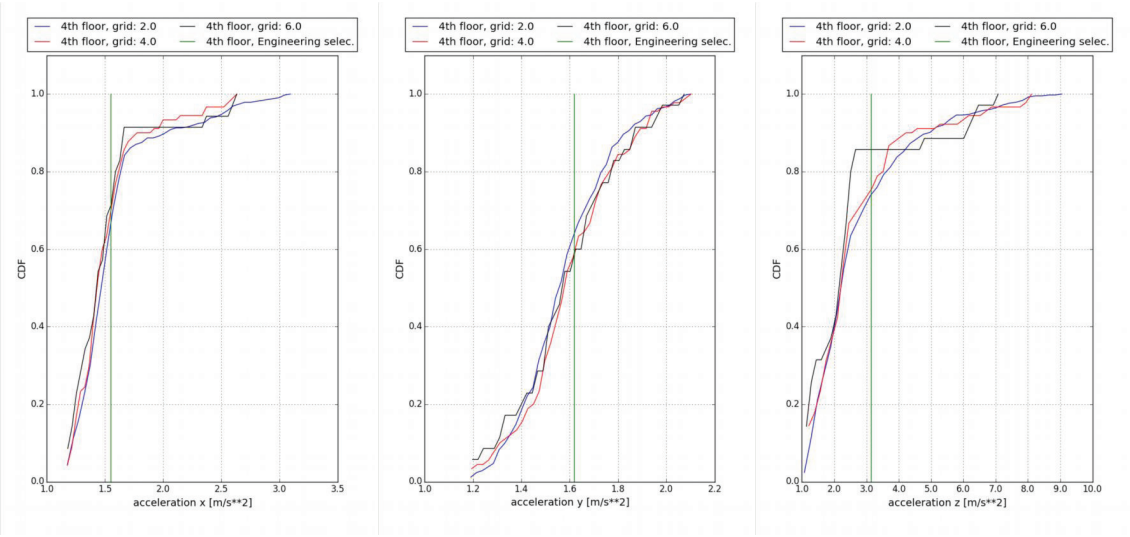


Figure 6 Comparison of PSA curves with 2.0m grid and hand-picked by engineering judgement. Subfigures (a) and (b) spans the horizontal plane and (c) is the vertical direction.

At last we studied the influence of the grid size on the confidence of the analysed results. Altogether the 4th floor has 5999 nodes in the finite element model. The 6m, 4m and 2m grid contain 35, 90 and

424 nodes respectively. Once again the peak floor acceleration was picked-up from the time history of each node response. The cumulative distribution of the data was computed using 40 bins. Finally, as shown in Figure 7, the cumulative distribution was plotted as a function of the floor acceleration. In order to visualize the effect of number of selected nodes we also added the maximum acceleration value from the nodes chosen by engineering judgement (Figure 7). The figures shows that 4m and 6m grid cannot pick the highest floor acceleration in x or z direction. In addition, in x direction 4m and 6m grid shows some scatter compared to 2m grid. However, in y direction the cumulative distributions are overlapping very well regardless of the grid size. The node set selected by engineering judgement predicts half of the maximum acceleration observed with the 2m grid. About 30% and 40% of the nodes have larger acceleration than observed with the engineering node selection. In z direction the 6m scatter compared to 2m is clearly visible. In this case the engineering selection covers 75% of all nodes. It should be noted that 75% coverage in the vertical direction yields three time lower acceleration than 2m node grid. This is quite intriguing, as engineering judgement nodes were initially placed to the mid-spans of floors in order to maximize the vertical vibration.



(a) (b) (c)

Figure 7. Cumulative distribution for peak floor accelerations in the x, y and z direction. Grid size of 2, 4 and 6 m were considered.

DISCUSSION

There are several factors that have influence on the results. We identify the following:

1. Decision of implementing linear material model. This decision gave two options to define dissipation of energy. They were mass and stiffness proportional Rayleigh damping or modal damping. We decided to use traditional Rayleigh damping despite the disadvantages because the modal superposition dynamics requires heavy computing of the natural mode shapes to achieve 95% mass participation in horizontal and vertical directions. In later stages of the study, the model was extended to non-linear material models too, when modal dynamics would not have been available.
2. The response spectra based on YVL guidelines (YVL 2.6, 2001, YVL B.7, 2013) has the peak amplification at 10Hz in horizontal and vertical direction.
3. The walls of the structure are more rigid than the floors and have contribution to the results together with local differences in stiffness. Joints and discontinuities in the structure have energy dissipative effects. They are covered by the damping.
4. The first horizontal global mode shapes have influence because of the high mass participations in y and x directions.

A close vicinity to the external walls of the reactor building has stiffening effect to the floors. For this reason, higher floor accelerations were observed close to the mid-span of the floor compared to vicinity of the walls (Figure 4). The nodes at the 1st, 2nd and 3rd floor close to the external walls have peak floor accelerations almost equal to the peak ground acceleration (PGA). Dynamic amplification does not have significant influence to these locations.

The large openings of the 6th, 7th and 8th storeys as shown in Figure 3, reduces the floor stiffness significantly. As a consequence the dynamic amplification increases in the y direction. This is the cause of the amplified floor acceleration shown on the right side of Figure 4.b.

The result in Figure 5 shows increase in the dynamic amplification as a function of floor elevation, especially at the first global horizontal mode. The reason can be found from the mode shapes. At the base the mode shape vectors have small deformation values, gradually increasing with elevation. Thus, the contribution of the first global mode to the response of the floor increases too.

Figure 5 also shows that at the higher floors, the high frequency components have been filtered out. The peak amplification at 10Hz in the YVL spectra does not control the response as in the case of lower floors. This is the effect of the damping but also of the flexibility at higher levels. It should be noted the PSA at the 2nd storey has peak amplification almost at 10Hz. The decay of the floor PSA follows closely to YVL spectra, which indicate limited influence on the response of damping or own vibration modes of the structure.

In order to understand the influence of number of nodes on the results of floor acceleration, several grid sizes were studied including the node set selected by engineering judgement. The results were plotted in Figure 6 and Figure 7. In the x and z direction denser grid was able to capture local peaks of the floor accelerations. In this case the grid behaves as a filter which rules out some of the peak values. For this reason the grid sizes of 4m and 6m and our engineering selection has lower peak floor acceleration in PSA and CDF plots than 2m grid (Figure 6a, Figure 6c, Figure 7a and Figure 7c). If the floor accelerations are quite even and localization in spots does not exist, then grid size do not have significant role as shown in Figure 6b and Figure 7b. The localization is interpreted as local changes in the flexibility of the floors. The grid size has notable effect to all CDF plots, in the sense that there is more scatter as grid becomes coarser. This effect cannot be corrected by choosing different bin sizes for the computation of CDFs. Especially, vertical direction CDF plot have scatter when the grid size was decreased because the course grid cannot take into account the flexibility of the floors. Such floor flexibility in the vertical direction can be result of an opening or flexibility of the supporting beams under the floor.

The nodes selected based on engineering judgement give valuable information on the dynamic behaviour in a global sense. It was able to catch influence of the large openings which spans from wall-to-wall. On the other hand, the PSA curves show global trend in increase of the dynamic amplification as a function of the storey elevation. However, the comparison of 2m node grid and engineering selection yields significant difference in vertical direction as shown CDF curves in Figure 6c and PSA curves in Figure 7c. As a consequence, our engineering selection yields non-conservative results than denser grids.

Based on the grid size analysis it can be said that capturing localized flexibility densest grid yields best result. However, it is not necessary to analyse all floor nodes which in this case was 5999. This is revealed by the smoothness of the CDF plot of the 2 m grid, achieved in a structure with prevailing floor spans of 8-10m. It appears that the grid size in the range of span/4 yields sufficient accuracy even in the vertical direction.

CONCLUSION

We have studied floor vibrations of the reactor building equipped with the advanced boiling water reactor (ABWR). The excitation was seismic action conforming to spectra in the Finnish guidelines (YVL B.7, 2013). We assumed that the response of the reactor building remain in the linear range. The energy dissipation occurring in the structure was accounted Rayleigh damping.

The factors that have influence to the results were: 1) decision of using linear material model 2) the YVL spectra has the peak amplification at the relatively high frequency of 10Hz, 3) the structural typology is compact and characterised by stiff external walls with floors where openings may reduce, in relative terms, local stiffness.

In these conditions, according to our analysis, the nodes selected based on engineering judgement predict non-conservative behaviour of the floors in the reactor building. In the horizontal directions, the under estimation was two times whereas in the vertical direction it was three times. In order to capture localized behaviour of the floors characterized by local change of stiffness densest grid gave best results. We suggest a minimum grid of span/4 for observing localized effects like local floor vibrations in the vertical direction.

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