Comparative analysis of floor response spectra in civil structures of NPP using different methods of dynamic analysis.

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Abstract. JSC "Atomenergoproekt" has a great experience of NPP design. In this design the problem of floor response spectra calculation for analysis of loading on the equipment has a great importance. Well known, that this analysis is implemented in two steps. On the first step the accelerogramm in points of equipment location (replying accelerogramm) is determined, and after that on the second step maximum value of absolute acceleration for nonconcervative oscillator under different values of frequency and in fixed value of damping is calculated as floor response spectrum. In this case replying accelerogramm from the first step is used as initial action.

In the research the most important problem is to determine kinematic parameters of the 'soil-structure' system through the use of the following methods from SIMULIA(ABAQUS): direct integration method, modal method and advanced modal method (SIM-architecture), where projected damping matrix is considered as completely filled.

This paper offers theoretical description of the above-mentioned methods, their advantages and disadvantages, and the comparative analysis of their results for the schematic model of the 'soil-structure' system. Besides here one can find results of the calculation for a typical NPP building.

Key words: civil structures of nuclear power plants, floor response spectra, direct integration method, modal method, SIM-architecture, soil dashpot, Rayleigh damping, modal composite damping.

1. Introduction

At the present time, SIMULIA(ABAQUS) proposes three below-described methods of solution of dynamic problem in time domain, which are used for seismic analysis of civil structures of nuclear power plants.

The direct integration method is based on direct integration of equations of motion with fixed time increment by Abaqus/Standard. The method has the following advantages: the possibility to consider soil dashpots, simulating radiation damping in soil from vibrations of the building, and its applicability to all damping values in system without any restrictions. However, considering friction damping in the system, Rayleigh formula is used, it provides too conservative results, compared with the standard values for damping in materials. Besides the direct integration method is not very efficient; it is recommended mainly for analyses of nonlinear systems. However ,this method is recommended by ASCE4-98 [1].

The modal method is based on decomposition of solution of initial system of equations of motion by eigenmodes. As a result, the system reduces to independent equations for generalized oscillators, provided that damping matrix, projected on mode shapes is orthogonal. This method enables precise use of the normative values of damping in materials, however soil dashpots are not activated. Effect of soil dashpots, simulating radiation damping, is accounted approximately by assignment of damping in springs as relative damping in materials. Such damping is added to the frictional damping in soil. When the discussed method is used, it is often required to limit modal damping coefficients of systems, since the applied options of calculation of modal composite damping give nonconservative results. This method is recommended by ASCE4-98.

Another method (SIM-architecture), being a combination of the two above-described methods, is based on the assumption that projected damping matrix is completely filled. This method has advantages of the two above-described methods. The method enables account of soil dashpots, as well as normative damping in materials without use of Rayleigh formula. There are no reasons to limit modal composite damping in this method. This method gives trustworthy solution, but not specified in ASCE4-98.

It should be noted that the detailed theoretical justifications of the three above-described methods of dynamic analysis of civil structures of nuclear power plants is presented in papers [2,3,4], respectively.

2. FE model and input data for analysis

FE model is a three-level structure, consisting of absolutely rigid foundation slab 0.5 m thick and six columns resting on the foundation slab. Columns are supports for three floors at elevations 5 m, 10 m, 15 m, their thickness is 0.3 m. The model with sections of columns and beams, as well as points of output of response spectra (points 1, 2, 3), is shown in figure 1. Center of coordinates is in point of intersection of diagonals of the foundation slab.

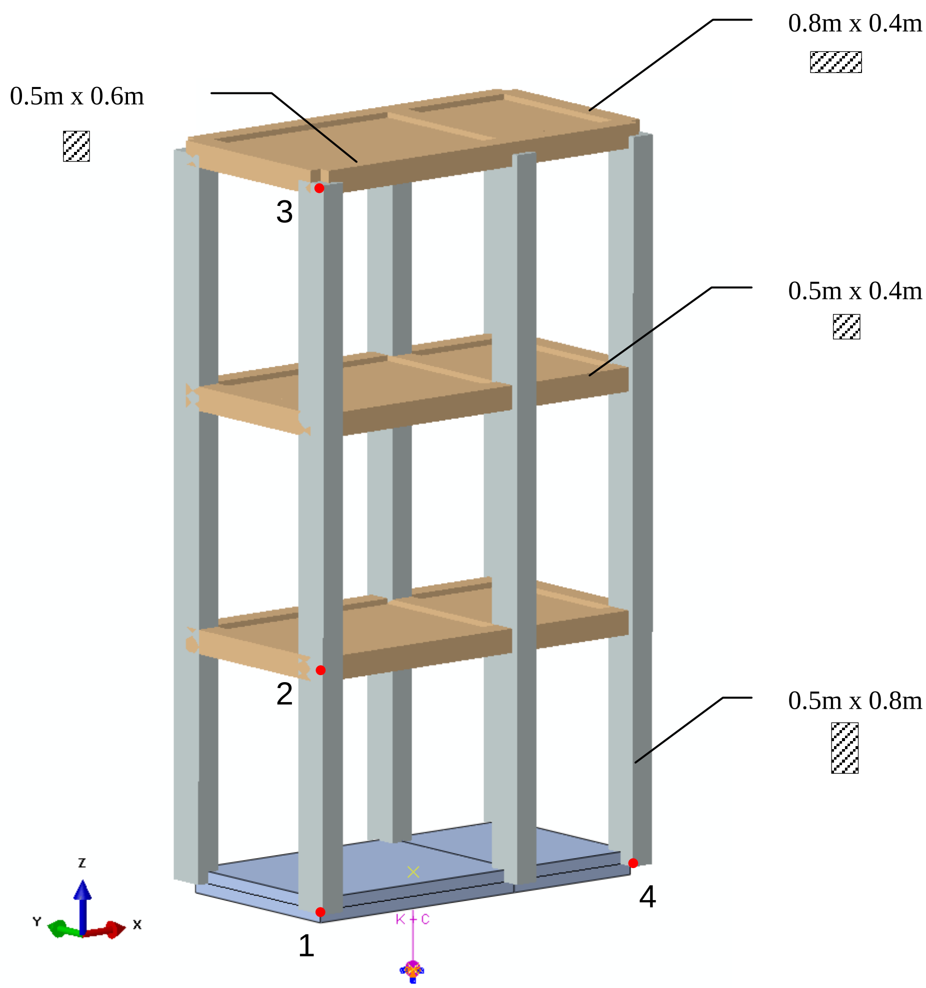

Figure 1. General view of the model.

The material used is concrete with the following properties: density is 2500 kg/m^3, Young's modulus is 3.1x10^{10} Pa, damping ratio is 7 %. Mass of the model is 295 tons. Lumped mass of 25 tons is placed in point 4 in the foundation slab to impart coupled vibrations to the model. In this case, out-of-diagonal terms of the projected damping matrix are to possess essential values and have an influence upon results of the calculation.

Soil has the following characteristics: density is 2000 kg/m^3, velocity of shear wave is 350 m/s, Poisson's ratio is 0.47, frictional damping ratio in soil is 5 % (according to EUR).

Soil was modeled by six springs and six dashpots with equivalent stiffness and equivalent dampings from ASCE 4-98 connected to the geometrical center of the foundation slab. Table 1 presents the appropriate characteristics of soil for the stamp with the following sizes: L=8 m, B=4 m.

Table 1. Equivalent rigidities and dampings for stamp.

Equivalent rigidity	Equivalent damping	Damping ratio
Kx=3.9 e+06 kN/m	*Cx=2.0e+04 kN·s/m*	*30%*
Ky=4.5 e+06 kN/m	*Cy=2.4e+04 kN·s/m*	*33%*
Kz=5.8 e+06 kN/m	*Cz=4.5e+04 kN·s/m*	*54%*
Kφx=2.6e+07 kN·m	*Cφx=3.2e+03 kN·s·m*	*0.2%*
Kφy=7.0e+07 kN·m	*Cφy=5.3e+04 kN·s·m*	*2%*
Kφz=5.2e+07 kN·m	*Cφz=5.3E+04 kN·s·m*	*6.7%*

As is seen from the table, there is essential energy outflow into soil during the process of vibrations of the system; especially high damping is realized during vertical vibrations (54%).

Initial seismic load is a three-component accelerogram with intensity of 0.22g, which takes into account high-frequency seismic load up to 100 Hz.

Table 2 presents natural vibration frequencies of the system up to 100 Hz, effective masses of these modes and the corresponding modal damping coefficients for two cases: without soil dashpots (case 1) and with approximate account of soil dashpots (case 2). In both cases, the modal composite damping was determined as an average value proportional to elastic strain energy in finite element. As seen from the table, the modal damping ratios are generally below 7 % for case 1. The 8th mode is characterized by intensive deformation of soil in vertical direction, effective mass on this mode is 87 % of total mass of the system, the modal damping ratio exceeds 20 % (case 2). Therefore, we conservatively limited it by 20 % constraint.

Table 2. Modal damping coefficients of the system.

Tone No.	Frequency, Hz	Effective mass, t			Modal damping	
		X	Y	Z	Case 1	Case 2
1	2.16	2.12E+02	1.60E-04	2.86E-03	6.50%	6.93%
2	2.29	2.05E-04	2.02E+02	4.10E-03	5.55%	5.89%
3	3.37	4.13E-04	7.20E-01	5.94E-05	6.86%	6.99%
4	7.05	2.89E+01	4.34E-08	9.42E-06	6.96%	7.40%
5	8.97	1.31E-05	3.61E+01	1.32E-04	6.95%	7.77%
6	11.17	1.06E-02	1.02E+00	7.49E-06	6.75%	7.02%
7	12.00	7.62E+00	4.79E-06	1.28E-02	6.94%	7.29%
8	16.92	1.67E-03	5.18E-01	2.78E+02	5.85%	20.00%
9	17.17	8.36E-06	1.10E+01	1.47E+01	6.69%	9.22%
10	20.73	1.12E-01	1.44E+00	7.35E-04	6.54%	7.14%
11	21.57	1.49E-01	1.11E-01	3.18E+00	3.30%	4.85%
12	26.80	1.97E-02	2.27E+00	3.41E-02	4.29%	4.87%
13	27.08	7.62E-02	7.87E-03	1.77E+00	6.91%	7.42%
14	29.22	1.73E-01	7.34E-03	2.65E+00	6.94%	7.83%
15	32.64	2.25E+01	2.51E+01	3.60E-03	3.34%	20.00%
16	36.48	2.67E-01	1.30E-01	8.85E+00	6.81%	11.33%
17	36.58	4.26E+01	1.88E+01	1.59E-02	5.10%	20.00%
18	38.09	2.10E+00	7.12E-01	3.91E-04	6.87%	8.11%
19	38.79	5.31E-05	1.68E-01	1.19E-03	6.97%	7.04%
20	41.95	2.96E-01	1.80E-01	3.05E-01	6.81%	7.30%
21	42.81	5.69E-02	1.77E-03	1.77E-02	6.81%	6.86%
22	43.88	1.18E-02	2.76E-01	5.35E-06	6.98%	7.15%
23	44.40	1.90E-02	2.41E-02	2.20E-02	6.96%	7.01%
24	45.24	2.91E-03	5.45E-02	2.37E-04	6.98%	7.02%
70	92.68	1.94E-04	1.51E-04	1.41E-02	6.98%	7.03%
71	94.77	1.11E-04	1.21E-05	1.51E-01	6.92%	7.44%
72	95.31	2.60E-05	5.40E-04	1.24E-01	6.90%	7.34%
73	97.80	2.41E-05	4.31E-04	1.93E-01	6.91%	7.61%
74	98.91	8.14E-05	4.35E-03	1.06E-03	6.97%	6.99%
75	100.26	1.57E-04	5.96E-03	5.09E-02	6.87%	7.09%

Let us consider the problem of Rayleigh damping calculation, required when we use the direct integration method. The lower natural frequency of the system is f_1=2.16 Hz, and damping ratio is ξ_1=6.50 %, higher frequency of vibrations is f_2=100.26 Hz, and damping ratio is ξ_2=6.87%. Thus the coefficients α and β in Rayleigh formula will be:

$$\alpha = \frac{2\omega_1\omega_2(\xi_1\omega_2 - \xi_2\omega_1)}{\omega_2^2 - \omega_1^2} = 1.72477,$$

$$\beta = \frac{2(\xi_2\omega_2 - \xi_1\omega_1)}{\omega_2^2 - \omega_1^2} = 0.0002147,$$

$$\omega = 2\pi f.$$

Rayleigh function is shown in figure 2. Apart from this, dots represent the modal damping ratios for 75 modes of natural oscillations taken from table 2 (for case 1). It is seen from the figure that some modal damping ratios for rocking modes are significantly less than 7 %, which characterizes damping in concrete. The reason of this is that damping in soil of 5 % (due to friction) we attributed only to translational soil springs, however damping for rotational components of springs was conservatively taken as 0 %. That is why modal composite damping for such modes has a notable gap. Let us recall, that the results represented in figure 2 match with frictional damping in the system, and soil dashpots are responsible for radiation damping.

7.14 см

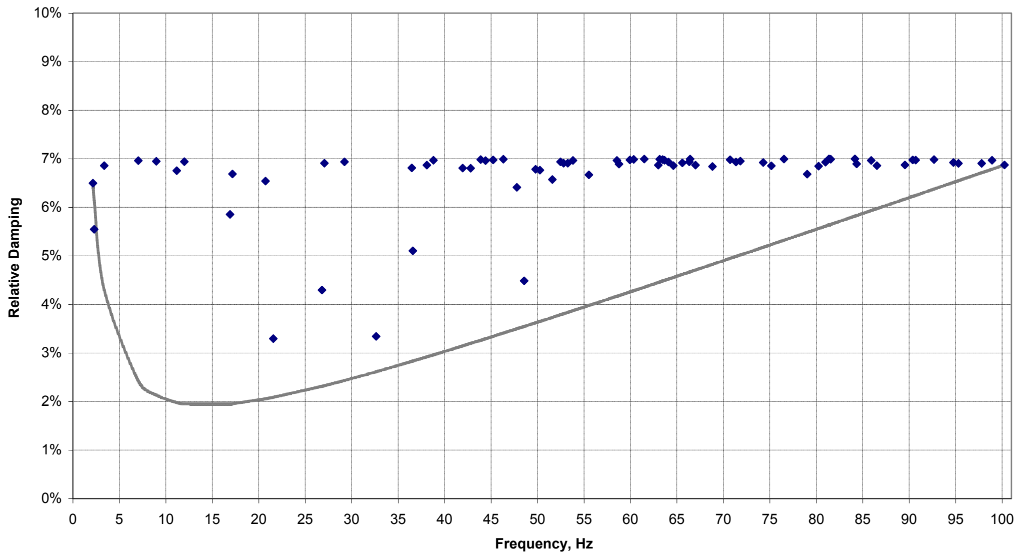

Figure 2. Comparison between Rayleigh damping and modal composite damping in materials.

3. Calculation results

Floor response spectra were obtained in the course of calculations for the structure shown in figure 1. The spectra were calculated by three above-described methods of dynamic analysis. The spectra are shown in figures 3…5.

Comparative analysis of the obtained spectra proves that calculations for upper parts of the structure (point 3) done by the direct integration method give the most conservative results. This is because of predominant influence of Rayleigh damping, which ensures conservative results as compared with specified damping in materials. Gap of Rayleigh damping defined in figure 2 confirms obtained conservatism of resulting response spectra. On the contrary, in point 1 more conservative are calculations done by modal method, since effect of soil dashpots predominates due to their immediate vicinity. Results of calculations with the use of SIM-architecture basically lead to reduced conservatism owing to precise account of soil dashpots, specified account of damping in materials and absence of limitations of damping values.

As the second example, we give results of calculation of response spectra for a typical box-type building. Internal structure of the building with points (A, B) of floor response spectra is shown in figure 6. Initial seismic load and soil properties in this example meet conditions of the 1st test problem. The resulting response spectra are shown in figures 7, 8. As is seen from figure 7, the modal method of calculation in point A at the edge of foundation slab gives representative excesses in operating frequencies within the range of 5…10 Hz as compared with calculations done by the direct integration method and SIM-architecture. The reason is some essential influence of soil dashpots. However, the modal method has 20 % limitation of modal composite damping, and it does not take into account damping on coupled vibration modes, that causes excess. In crane beam, point B, the vertical component of spectrum has similar excess in the modal method, since effect of soil dashpot is actually transmitted through the vertical column. For horizontal components of spectra, effect of soil is inessential, so only damping in materials influences results. Thus, the modal method gives lower results, since the appropriate modal composite damping includes noncoservatively effect of soil dashpots on resonant vibration tones. Comparison between the direct integration method and SIM-architecture in upper elevations shows excess of spectral accelerations in case 1, due to conservatism of the applied Rayleigh damping.

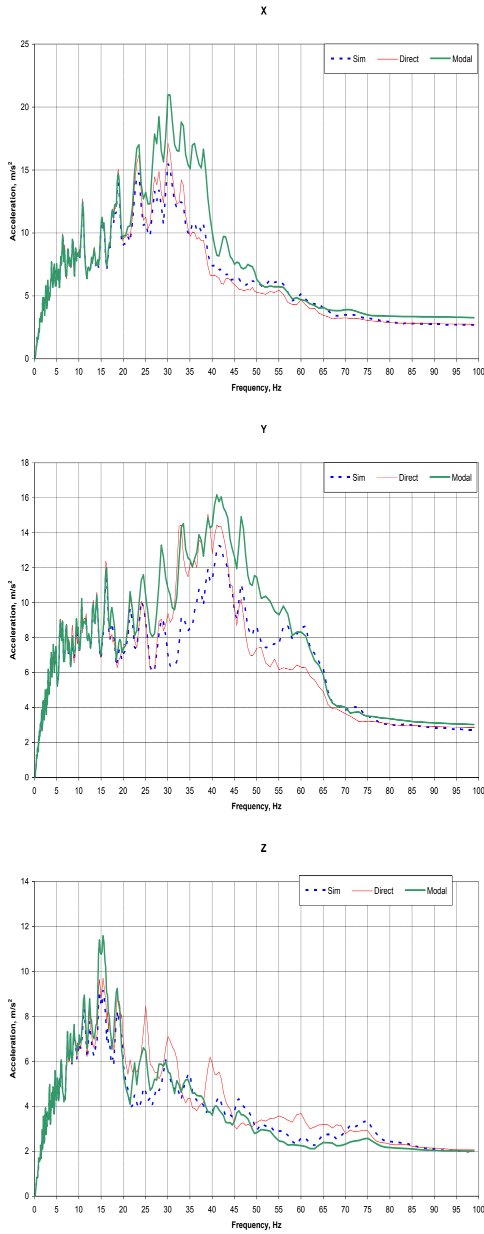

Figure 3. Floor response spectra in point 1.

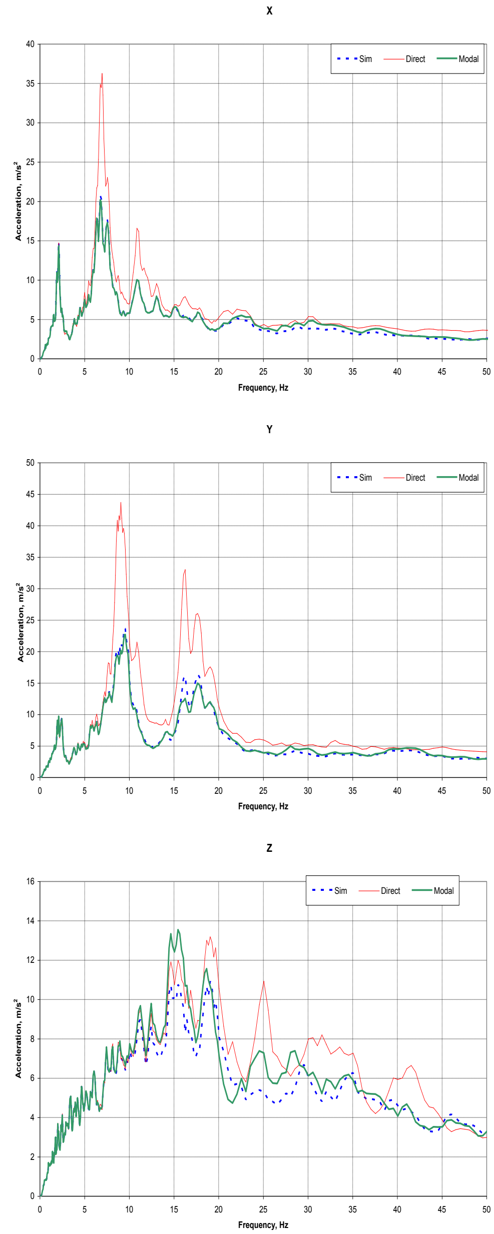

Figure 4. Floor response spectra in point 2.

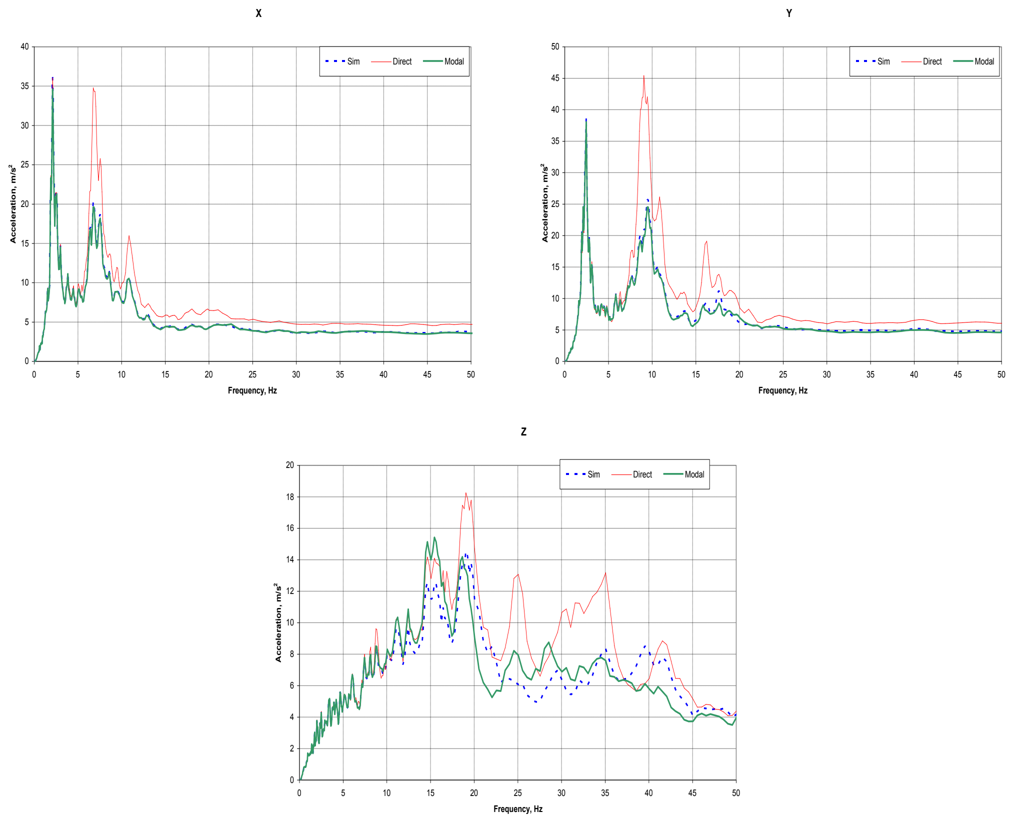

Figure 5. Floor response spectra in point 3.

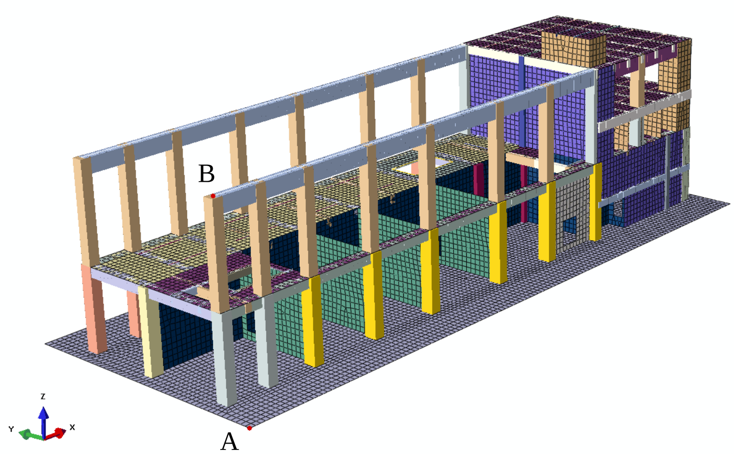

Figure 6. View of typical NPP model.

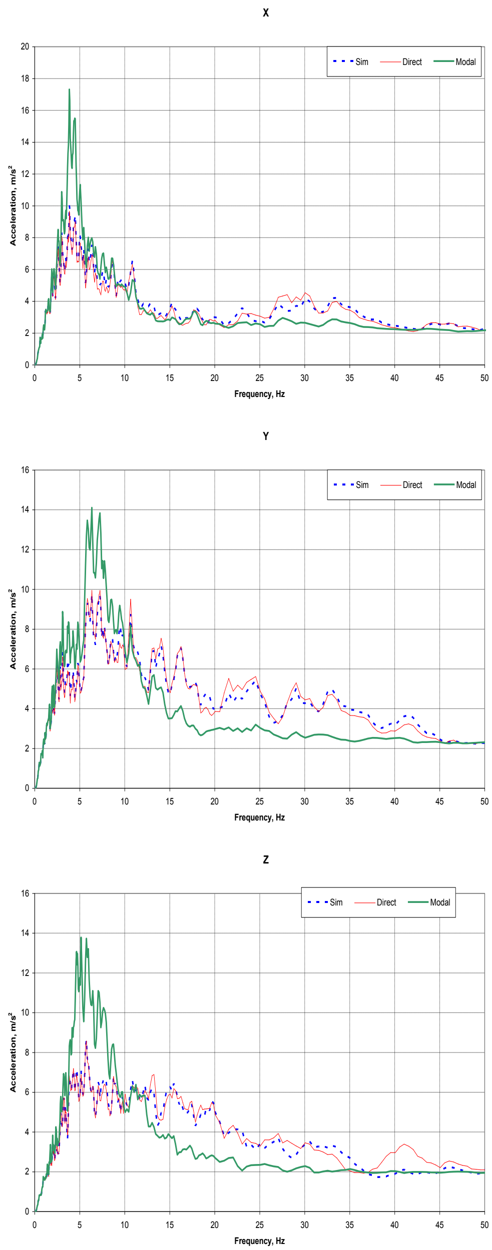

Figure 7. Floor response spectra in point A.

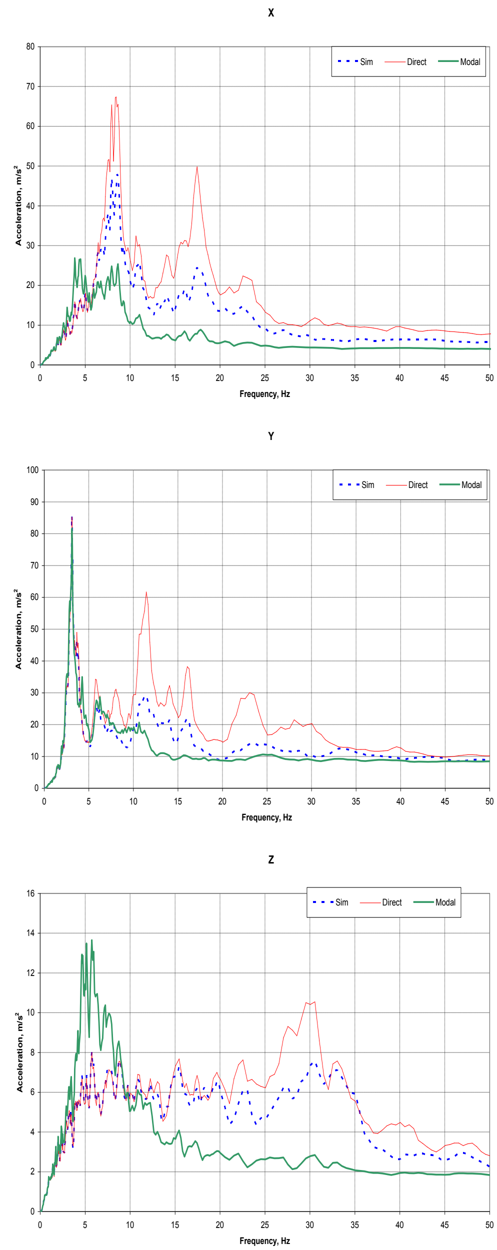

Figure 8. Floor response spectra in point B.

4. Conclusions

Based on the results of research, we can come to the following conclusions. Theoretically, SIM-architecture contains advantages of both the direct integration methods and the modal method. It allows precise account of soil dashpots and specified damping in materials, and there are no reasons for limitation of a modal composite damping value. In practical calculations through the use of SIM-architecture, in the majority of cases, spectral accelerations are lower than in calculations through the modal method and the direct integration method. In any case, SIM-architecture ensures more trustworthy results, if we apply theoretical considerations. Among disadvantages of the direct integration method, the use of Rayleigh damping, giving rather conservative results, should be mentioned. Weaknesses of the modal method is untrustworthy simulation of soil dashpots and limitations imposed on values of modal composite damping.

In view of the above-mentioned, the authors recommend to include SIM-architecture into ASCE and Russian standards on designing seismic resistant nuclear power plants, as an innovative solution.

5. References

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