Application of «Soil» Dashpots in Modal Method Analysis of Civil Structures of Nuclear Power Plants

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*Abstract: Now in world practice there are two methods of dynamic analysis, which are intensively used, that are direct integration method and modal method. Advantage of a modal method is the opportunity of the account of normative values of attenuation in soil-structure systems by means of using special option *Modal Composite in Abaqus. However in modal method dashpot elements allowing to take into account radiating attenuation in a soil do not become active. In direct integration method there is an activization of dashpot elements, which are necessary for the account of radiating attenuation, but used in materials Reyleigh damping provides too conservative results in comparison with normative values. For overcoming the arisen problem in the present work opportunities of the new approach developed in Abaqus which is the combination of the named two methods realized with help of SIM architecture are investigated. The sense of the new approach consist in application of a modal method, provided that the matrix of attenuation is not diagonal, and fully populated. Further direct integration method is used for the decision of the related system of equations. In this study comparison of results of the analysis executed by a modal method, by method of direct integration and by the combined method realized with help of SIM architecture on a real structure of the NPP is made. As a result it is shown, that the new technology allows essentially to diminish conservatism which now is assumed at flow response spectrum analysis.*

Keywords: Radiation Damping, Rayleigh Damping, Modal Method, Direct Integration Method, SIM-architecture.

1. Introduction

The two methods of analysis of dynamic response and floor response spectra in civil structures of nuclear power plants are presently used in the world; they are: direct integration method and modal method. The modal method has advantage to apply normative values of damping in «soil-structure» systems. However dashpots, which allow to apply radiation damping in soil and which are determined from impedance functions from ASCE 4-98, are not active in the modal method. In direct integration method the dashpots, required for application of radiation properties of soil, become active, but Rayleigh damping used in materials of civil structures give too conservative results as compared with normative values. Besides, in solution of linear problems the direct integration method is rather ineffective. Nevertheless many designers prefer direct integration method in solution of above-mentioned problems and use it actively.

In this paper attempt has been made to argue against such fixed stereotype. With this aim Abaqus experts, have developed a new approach for dynamic analysis: this is a combination of the two above-mentioned methods with the help of SIM-architecture. The sense of innovative approach is to apply the modal method, provided that the projected viscous damping matrix is not any more diagonal as in conventional modal method, and is fully populated. Then when model was projected onto the eigenmodes used for its dynamic representation, the coupled set of equations will be solved with the use of the direct integration method. The new approach involve merits of both methods. It allows accurate use of normative values of damping in materials and simultaneously take into account radiation damping in soil due to activation of dashpot elements. In this paper we have used this new approach for problems of response spectra analysis in civil structures of NPP.

This paper gives comparison between results of the direct integration method and the combined method of analysis done with the help of SIM-architecture for the real NPP structure. Eventually it is shown that the new method allows substantially removing conservatism, which is now allowed for floor response spectra. It is also proven in this paper that the new approach is far more effective than the direct integration method. It is notable that Abaqus developers recommend to use the direct integration method primarily for solutions of nonlinear problems.

The paper also presents the universal way of distribution of equivalent rigidities and damping of soil along the base of foundation slab.

The discussed method was used in determination of floor response spectra for main buildings of Kudankulam NPP-3,4.

2. Method of analysis

The problem of response spectra analysis was solved in two steps.

Step 1: The following linear set of equations was solved to determine dynamic response with the use of the modal method:

$$KU + C\dot{U} + M\ddot{U} = -M\ddot{U}_0 \qquad (1.1)$$

In equation (1.1)

$$K = K_1 + K_2, \qquad (1.2)$$

where K_1 and K_2 are partial rigidity matrices for structure and soil respectively.

$$C = C_1 + C_2, \qquad (1.3)$$

where C_1 is damping matrix in «soil-structure» interaction caused by friction in material and characterized by little relative damping; C_2 is partial damping matrix caused by energy release into soil in vibration of stamp, that in its geometry is identical to foundation base, and is characterized by high radiation damping.

Full displacement U_i in system is as follows:

$$U_i = U + U_0 \tag{1.4}$$

We shall seek the solution of the system (1.1) in the form of:

$$U = \sum_{\beta} \phi_{\beta} q_{\beta}, \tag{1.5}$$

where ϕ_β is the eigenmode; q_β is generalized coordinate; β is variable index of the number of considered eigenmodes.

The modal dynamic procedure provides time history analysis of linear systems. The excitation is given as a function of time: it is assumed that the amplitude curve is specified so that the magnitude of the excitation varies linearly within each increment. When the model is projected onto the eigenmodes used for its dynamic representation we obtain the following coupled set of equations at time t:

$$\ddot{q}_\beta + C_{\beta\alpha}\dot{q}_\beta + \omega_\beta^2 q_\beta = (f_t)_\beta = f_{t-\Delta t} + \frac{\Delta f}{\Delta t}\Delta t \tag{1.6}$$

where α and β are indices in space of eigenvalues; $C_{\beta\alpha}$ is the projected viscous damping matrix, which in the general case is fully populated; q_β is generalized coordinate of mode β (amplitude of responses with this mode); $\omega_\beta = \sqrt{k_\beta / m_\beta}$ is the natural frequency of the undamped mode β, and Δf is change of f in time step Δt.

If the projected damping matrix is diagonal, equation 1.6 is transformed into the following uncoupled set of equations:

$$\ddot{q}_\beta + 2\xi_\beta\omega_\beta\dot{q}_\beta + \omega_\beta^2 q_\beta = (f_t)_\beta \tag{1.7}$$

where ξ_β is a value of damping ratio defined by the following relation:

$$2\xi_\beta\omega_\beta = \frac{c_\beta}{m_\beta}, \tag{1.8}$$

where c_β is modal coefficient of viscous friction and m_β is modal mass, which are compliant to mode β.

Let the matrix $C_{\beta\alpha}$ split into its diagonal and off-diagonal parts so that

$$C_{\beta\alpha} = C_{diag} + C_{off} \tag{1.9}$$

Matrix C_{off} defines the radiation damping into soil in the vibrations of building; it is defined with the help of special dashpots. Matrix C_{diag} defines friction in the system; it is understood as damping by modes. The matrix contains dashpot-type elements as well.

Step 2: Floor response spectra were determined as maximal absolute accelerations in modulus for linear nonconservative oscillator at various frequencies and fixed damping under effect determined in Step1. The resultant spectra expand by 15 % in the frequency range.

3. FE model

As an example we calculated floor response spectra in one of box-section buildings; the general view is shown in Fig. 1, and model of building without outer walls are Figures 2.1, 2.2. The following finite elements were used in the model:

- b31 is beam element to simulate columns and girders;
- s4 are quadrilateral plate/shell elements with account of transverse shear deformations to simulate walls and floors;
- spring2 and dashpot2 are spring and dashpot elements to simulate rigidity properties and radiation damping properties in soil with the use of the impedance method;
- mass is lumped mass element for account of inertial properties of equipment.

FE model has the following characteristics:

- the total number of nodes - 33131;
- the total number of equations - 169698;
- the total number of elements - 58453;
- the number of consided modes - 258.

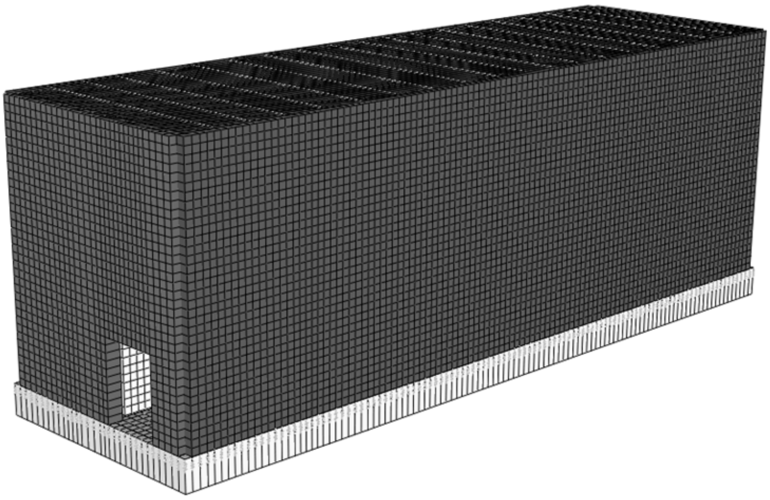

Figure 1. General view model of building

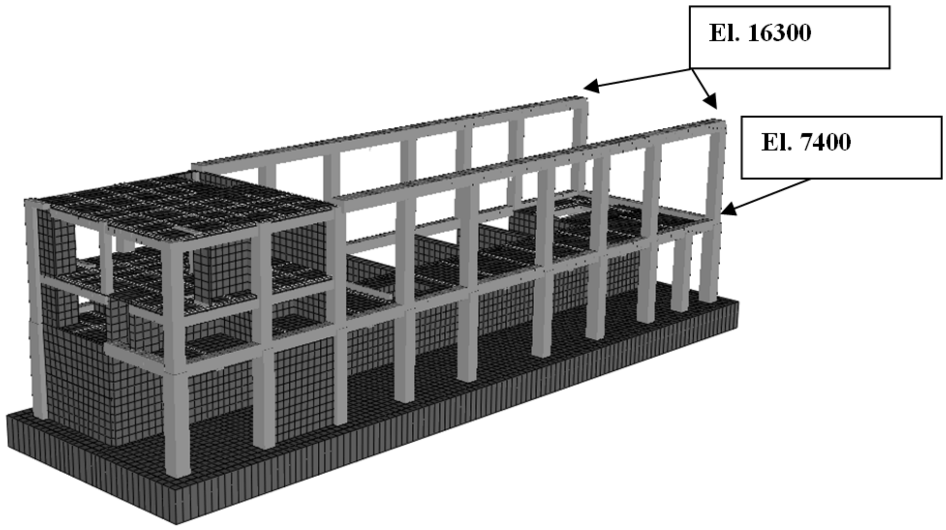

Figure 2.1. Building without outer walls

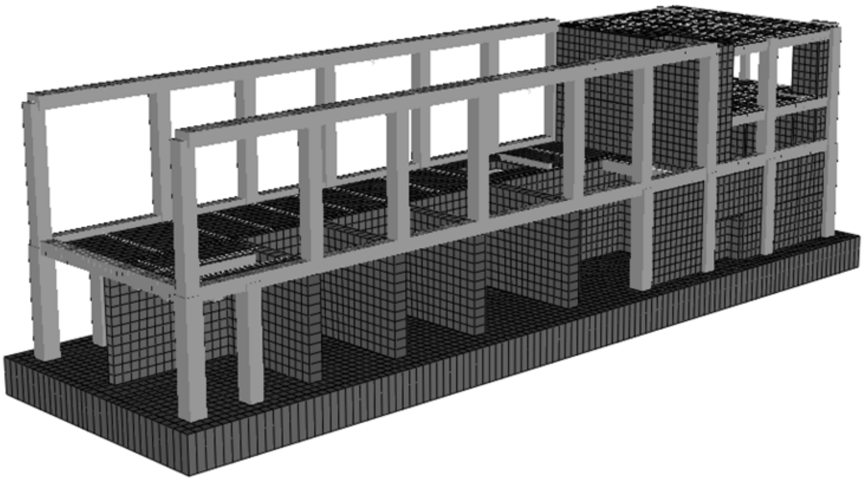

Figure 2.2. Building without outer walls

FE model of building was developed in the global coordinate system with the centre in geometrical centre of foundation base; axis X is directed along the longer side; axis Y along shorter side; axis Z along the normal upwards.

4. Consideration of soil

Formulas for equivalent rigidities and damping obtained in vibration of stamp (Figure 3) on elastic half-space were used to define K_2 and C_2 in equations (1.2) and (1.3)

$$\begin{aligned} K_2 &= \{k_x, k_y, k_z, k_{\varphi_x}, k_{\varphi_y}, k_{\varphi_z}\}, \\ C_2 &= \{b_x, b_y, b_z, b_{\varphi_x}, b_{\varphi_y}, b_{\varphi_z}\}. \end{aligned} \tag{1.10}$$

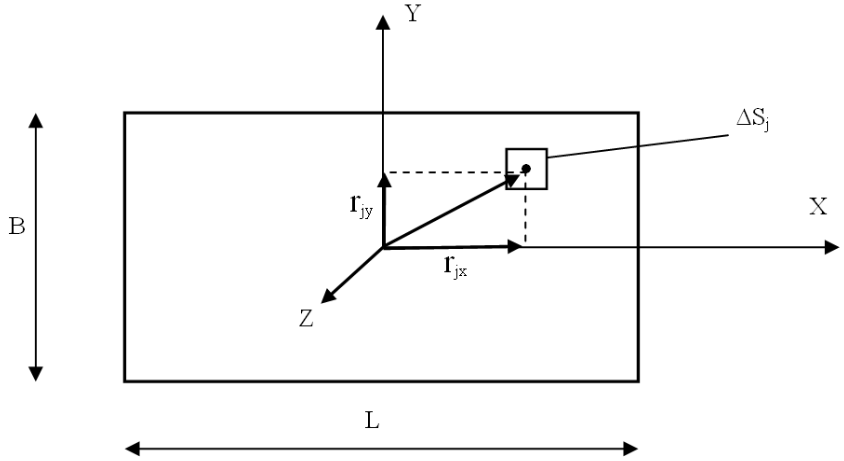

Figure 3. Rectangular stamp

Table 1 contains values of such equivalent rigidities and damping defined for soil according to ASCE 4-98 when velocity of S-waves is 650 m/s, density of soil is 2.63 t/m3 and Poisson ratio is 0.35 for the stamp L=64.8 m and B=20 m in size. As is seen from the Table-1 the system under consideration possesses high radiation damping, especially in vertical direction (91%).

Table 1. Equivalent rigidities and damping

$G_{average} = \rho V_s^2$	**Equivalent rigidities, ASCE-4-98**
k_x, t/m	$1.1 \cdot 10^7$
k_y, t/m	$1.4 \cdot 10^7$
k_z, t/m	$1.5 \cdot 10^7$
k_{φ_x}, t·m	$1.9 \cdot 10^9$
k_{φ_y}, t·m	$10.0 \cdot 10^9$
k_{φ_z}, t·m	$8.1 \cdot 10^9$

	Equivalent damping, ASCE-4-98
b_x, t·s/m	$2.0 \cdot 10^5$ (53%)
b_y, t·s/m	$2.5 \cdot 10^5$ (60%)
b_z, t·s/m	$3.9 \cdot 10^5$ (91%)
b_{φ_x}, t·s·m	$8.5 \cdot 10^6$ (14%)
b_{φ_y}, t·s·m	$120.0 \cdot 10^6$ (47%)
b_{φ_z}, t·s·m	$44.0 \cdot 10^6$ (21%)

It is required to distribute equivalent characteristics from Table 1 throughout the surface of the foundation slab.

Let us assume that translational values of rigidities and damping will be distributed arbitrarily: $z = f(x, y)$. Then we can write the expression for the reduced rigidity for jth point of the foundation base (Figure 3) as follows:

$$k_{ij} = C_i f_{ij}(x, y)\Delta S_j . \tag{1.11}$$

$i = x, y, z$ and $j = 1...N$ are valid in formula (1.11), where N is the number of nodal points on the foundation base and C_i is constant value. $f_{ij}(x, y)$ is value of function $f(x, y)$ in point j along direction i .

We shall define constant value C_i from the following condition:

$$\sum_j C_i f_{ij}(x, y)\Delta S_j = k_i \tag{1.12}$$

From (1.12) follows:

$$C_i = \frac{k_i}{\sum_j f_{ij}(x, y)\Delta S_j} \tag{1.13}$$

With the account of (1.13) expression (1.11) can be rewritten as follows:

$$k_{ij} = \frac{k_i f_{ij}(x, y)\Delta S_j}{\sum_j f_{ij}(x, y)\Delta S_j} \tag{1.14}$$

Formula (1.14) makes it possible to define rigidity in jth point of the foundation when it has arbitrary distribution on the foundation base. By analogy, we shall represent expression for damping as:

$$b_{ij} = \frac{b_i f_{ij}(x,y)\Delta S_j}{\sum_j f_{ij}(x,y)\Delta S_j} \tag{1.15}$$

From ratios (1.14) and (1.15) it is easy to obtain:

$$\sum_j k_{ij} = k_i\,,\ \sum_j b_{ij} = b_i\,, \tag{1.16}$$

i.e. summary (integral) translational rigidities and damping in all the points of the foundation base exactly match the equivalent values.

From (1.15) it is also easy to obtain the special case of uniform distribution of equivalent damping throughout the foundation base with $f_i(x,y) = 1$. These ratios will look like:

$$b_{ij} = b_i \frac{\Delta Sj}{S}\text{, where } S = BL\,. \tag{1.17}$$

However for distribution of translational values of equivalent rigidities more exacter law was used; $z = f(x,y)$ was defined in proportion to contact pressure.

Translational nodal rigidities and damping create the integral angular rigidity and damping:

$$\begin{aligned}
C_{\varphi_x} &= \sum_j k_{zj} \cdot r_{jy}^2 \\
C_{\varphi_y} &= \sum_j k_{zj} \cdot r_{jx}^2 \\
C_{\varphi_z} &= \sum_j (k_{xj} \cdot r_{jy}^2 + k_{yj} \cdot r_{jx}^2) \\
D_{\varphi_x} &= \sum_j b_{zj} \cdot r_{jy}^2 \\
D_{\varphi_y} &= \sum_j b_{zj} \cdot r_{jx}^2 \\
D_{\varphi_z} &= \sum_j (b_{xj} \cdot r_{jy}^2 + b_{yj} \cdot r_{jx}^2)\,.
\end{aligned} \tag{1.18}$$

Here r_{jx} and r_{jy} are components of radius-vector of j th point, which comes out of geometrical center of foundation base.

Integral characteristics (1.18) differ from equivalent characteristics, so validity of the stamp theory we shall balance the difference as follows:

$$\begin{aligned}
&\Delta c_{\varphi_x} = k_{\varphi x} - C_{\varphi_x}; \quad \Delta b_{\varphi_x} = b_{\varphi_x} - D_{\varphi_x} \\
&\Delta c_{\varphi_y} = k_{\varphi y} - C_{\varphi_y}; \quad \Delta b_{\varphi_y} = b_{\varphi_y} - D_{\varphi_y} \\
&\Delta c_{\varphi_z} = k_{\varphi z} - C_{\varphi_z}; \quad \Delta b_{\varphi_z} = b_{\varphi_z} - D_{\varphi_z}.
\end{aligned} \tag{1.19}$$

We shall distribute uniformly the obtained differences throughout the foundation base.

However in contrast to Δc_{φ_x}, Δc_{φ_y} and Δc_{φ_z}, values Δb_{φ_x}, Δb_{φ_y} and Δb_{φ_z} can be negative. In this case let us assume that:

$$\Delta b_{\varphi_x} = \Delta b_{\varphi_y} = \Delta b_{\varphi_z} = 0 \tag{1.20}$$

From (1.20) it is possible to obtain expressions for corrected values of damping, which have the following view:

$$\bar{b}_{z_1} = \frac{b_{\varphi_x}}{\sum_j \frac{\Delta S_j}{S} \cdot r_{jy}^2} \tag{1.21}$$

$$\bar{b}_{z_2} = \frac{b_{\varphi_y}}{\sum_j \frac{\Delta S_j}{S} \cdot r_{jx}^2} \tag{1.22}$$

$$\bar{b}_x = \bar{b}_y = \frac{b_{\varphi_z}}{\sum_j \left(\frac{\Delta S_j}{S} \cdot r_{jy}^2 + \frac{\Delta S_j}{S} \cdot r_{jx}^2 \right)} \tag{1.23}$$

From (1.21) and (2.22) we shall give due consideration for minimal damping. We can show that the corrected translational damping obtained from formulae (1.21)-(1.22) are less than the respective equivalent damping; and angular damping caused by the corrected linear damping correspond to equivalent values or somewhat less. It confirms conservatism of condition (1.20).

Equivalent corrected damping are indicated in Table 2.

Table 2. Equivalent corrected damping

	Equivalent damping (corrected)
$\bar{b}_x$, t·s/m	$1.2 \cdot 10^5$ (31%)
$\bar{b}_y$, t·s/m	$1.2 \cdot 10^5$ (31%)
$\bar{b}_z$, t·s/m	$2.6 \cdot 10^5$ (60%)
$\bar{b}_{\varphi_x}$, t·s·m	$8.5 \cdot 10^6$(14%)
$\bar{b}_{\varphi_y}$, t·s·m	$90 \cdot 10^6$(35%)
$\bar{b}_{\varphi_z}$, t·s·m	$44 \cdot 10^6$(21%)

From comparison of equivalent damping presented in Tables 1 and 2 it is seen that damping values from Table 2 participated in the calculation are much cut off as compared with the original values, especially for translational components (up to 50%).

Three-component accelerogram which was used as the initial effect is shown in Figure 4.

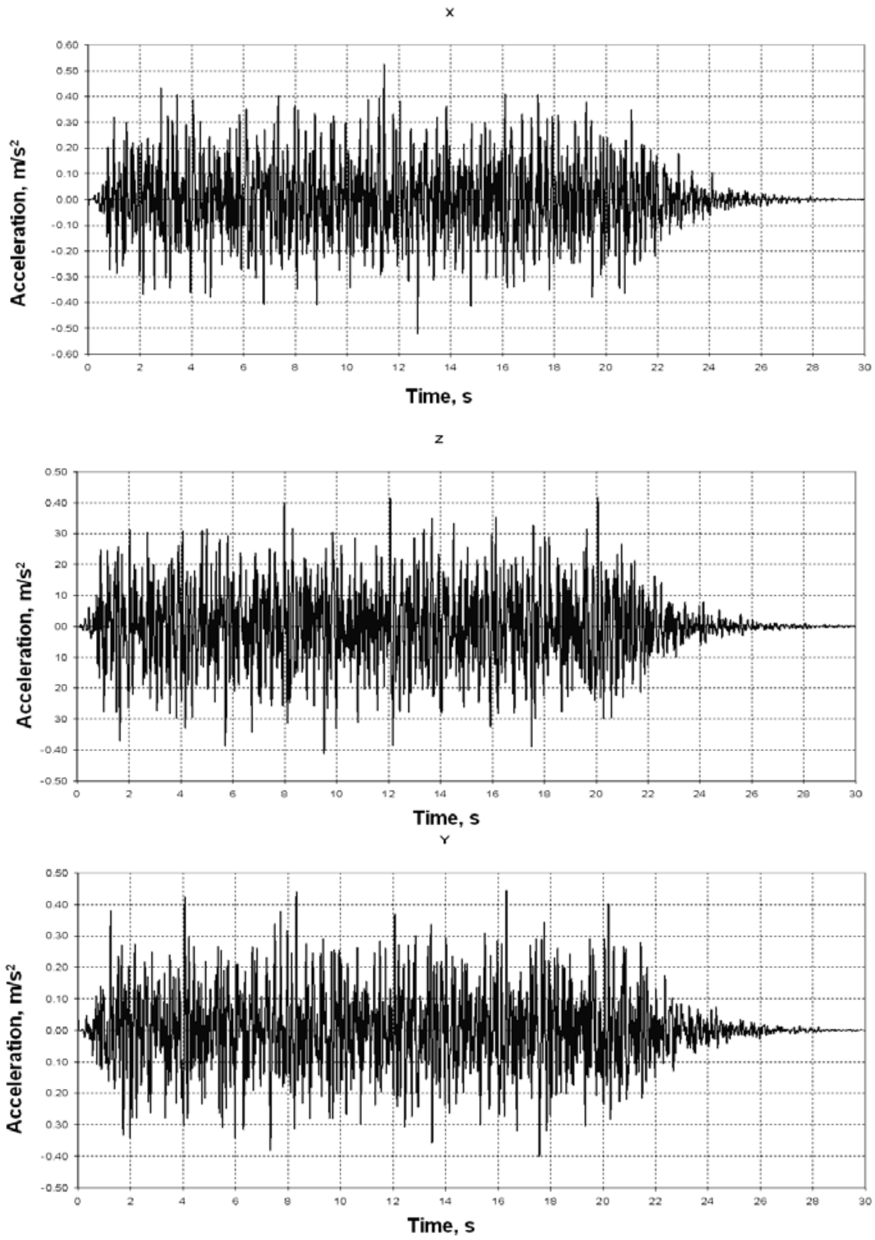

Figure 4. Initial accelerogram

5. Results

Floor response spectra were defined in the result of the analysis. Figures 5-7 give the comparative analysis between response spectra obtained in the combined method calculation with the help of SIM-architecture and obtained in the direct integration analysis with account of Rayleigh damping for two boundary frequencies: 33 Hz and 50 Hz, at normative damping in materials - 4 %. The respective curves of Rayleigh functions are shown in Figure 8.

Rayleigh damping matrix was defined with the use of formula $C_1 = \alpha M + \beta K$, where

1) $\alpha = 0.7225$, $\beta = 0.000365$, $f_1 = 1.63Hz$, $f_2 = 33Hz$

2) $\alpha = 0.73487$, $\beta = 0.000246$, $f_1 = 1.63Hz$, $f_2 = 50Hz$

The comparative analysis proves substantial decrease of spectral accelerations when SIM-architecture is used as compared with the direct integration method. Almost half spectral accelerations decreases are observed at the crane elevation. It should be noted that increases of boundary frequency to 50 Hz did not have substantial influence on the results.

Analysis of effectiveness of results showed the following:

Total running time is 10 h 35 min through the use of the direct integration method and 5 min through the use of SIM-architecture. Such great reduction of time is explained not only by high efficiency of SIM technology, but by new eigenvalue solver AMS as well.

6. Conclusions

Proceeding from the results of research we can conclude that the new technology of assessment of dynamic response and floor response spectra in civil structures of a nuclear power plant used in Abaqus, as SIM-architecture, allows remove conservatism and radically increase effectiveness of results. So this new technology can ensure considerable benefits for equipment designers and civil structures designers, if they would use it in place of direct integration method.

This paper describes the universal method of distribution of equivalent rigidities and damping of soil throughout the foundation base, that allows to obtain precisely their integral translational components under any laws of distribution.

The use of the above-stated innovative technology can be recommended in analysis of both dynamic response in civil structures of nuclear power plants and floor response spectra.

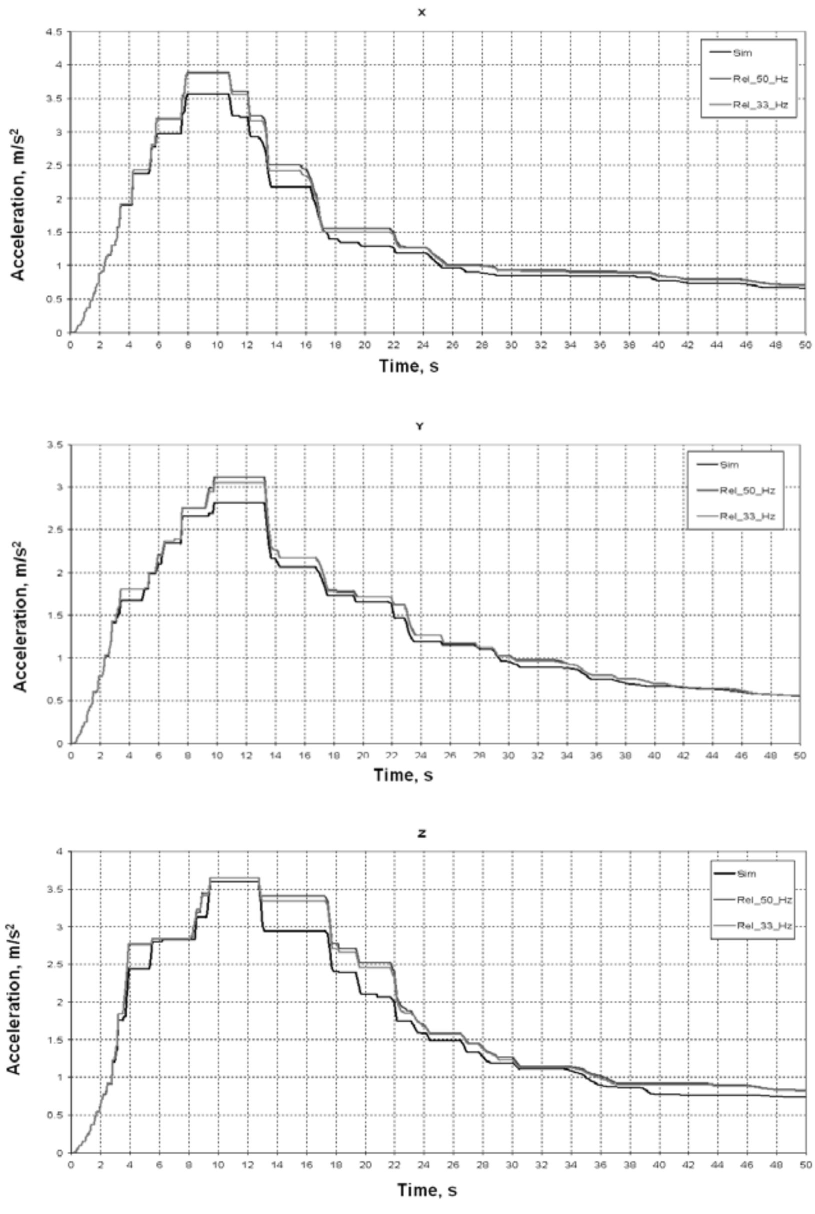

Figure 5. Foundation

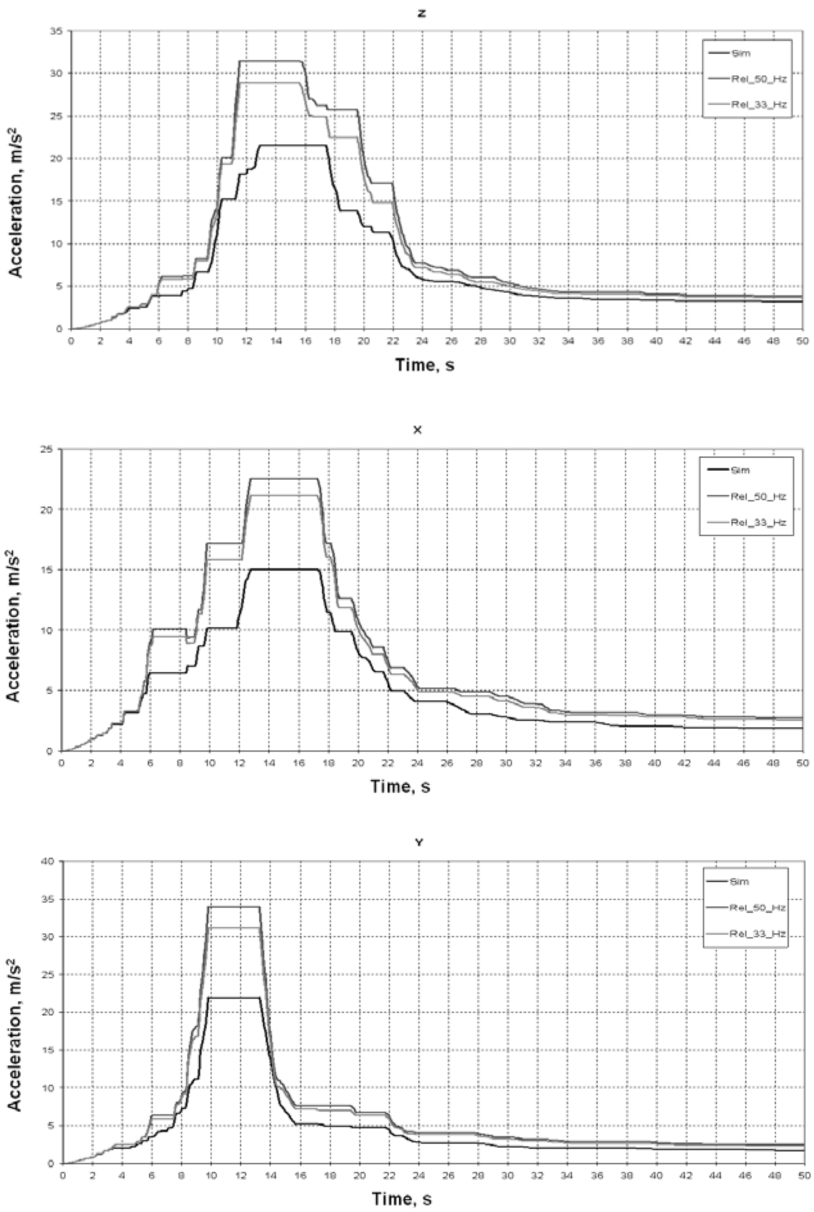

Figure 6. Elevation 7400

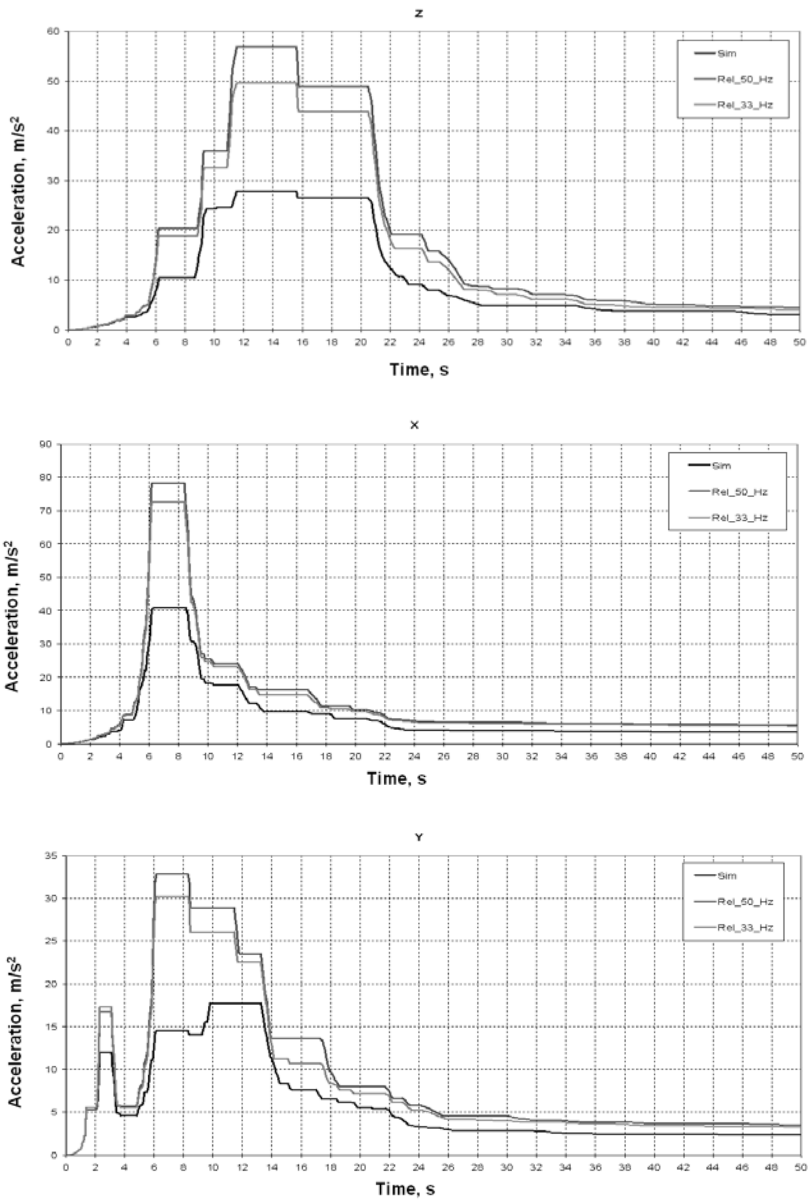

Figure 7. Elevation of crane (16300)

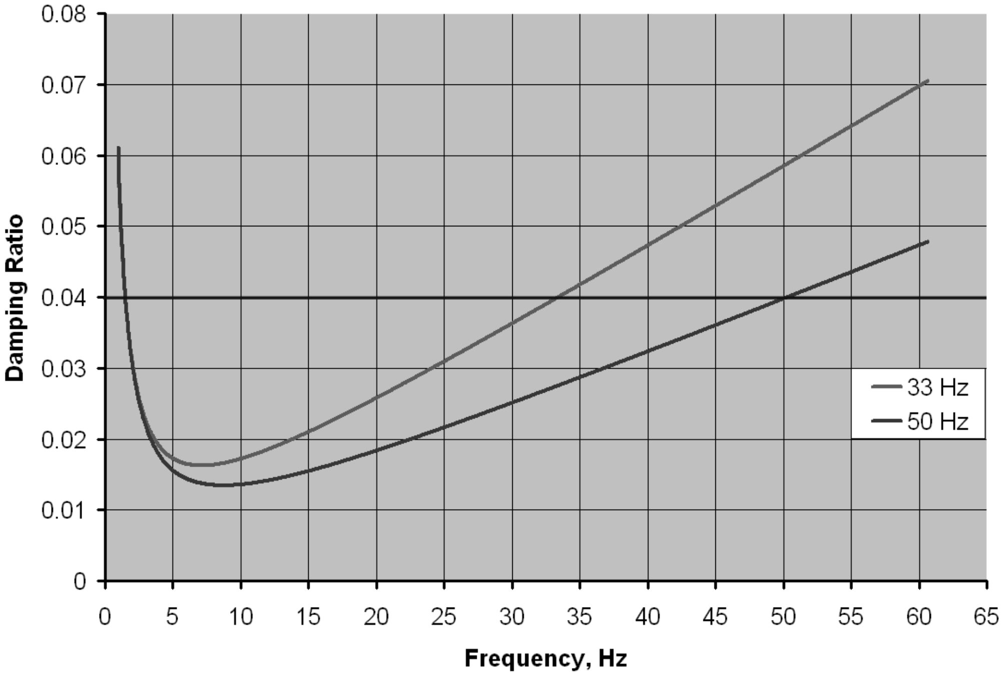

Figure 8. Rayleigh functions for the two boundary frequencies