Estimation of seismic resistance of multi-story buildings in the framework of the bimoment theory using the plate model

M.K. Usarov[1*], *D.M.* Usarov[1], *G.U.* Isaev[1], *M.Sh.* Kurbanbaev[1], and *B.* Yuldoshev[2]

[1] Institute of Mechanics and Seismic Stability of Structures of the Academy of Sciences of the Republic of Uzbekistan, 100125 Tashkent, Uzbekistan
[2] National Research University - Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, 100000 Tashkent, Uzbekistan

Abstract. This article is devoted to the development of a continual layered plate model of a multi-story building to dynamically assess the seismic resistance of multi-story buildings in a spatial statement. Seismic vibrations of a building are modeled as a motion of a thick anisotropic cantilevered plate, the deformation of which is described on the basis of the bimoment theory of thick plates.

1 Introduction

Multi-story buildings and structures erected in seismic areas must meet the requirements of seismic resistance. A significant part of the population of our republic lives in areas where strong earthquakes are possible. Sufficient knowledge about the dynamic operation of the structure is required to successfully calculate the seismic resistance of buildings and structures and to apply complex dynamic calculations in construction.

The article [1] considers the foundations of buildings and structures laid of weakly viscoelastic soils and the features of the theoretical justification of their deformations. The need for this study is due to the discrepancy between the theory of seepage compaction and field and laboratory experiments. Within the framework of the proposed model, designs are constructed for solving problems of loading the soil surface with typical loads that describe the stress-strain state of each phase of a two-phase medium (soil skeleton + pore water), taking into account the residual pore pressure. The deviation of the calculated residual pore pressures from the experimental data is no more than 5% (laboratory experiment) and 7% (field experiment). The calculation method presented in the article makes it possible to predict the deformation of the foundations from weak water-saturated soils.

In [2]. The analysis of design schemes was performed taking into account various types of installation errors. Forces in structural elements exceeding the allowable ones were determined taking into account the error in the installation of parts.

Articles [3, 4] are devoted to the dynamic problems of the deformed state of earth dams under seismic impacts. A method was developed for solving wave problems for determining

* Corresponding author: umakhamatali@mail.ru

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the stress-strain state of earth structures, in particular earth dams. Using the finite difference method, calculation formulas and an algorithm for solving problems were developed.

The study in[16] considers the contact interaction of deformable building structures or their parts. Such interaction is implemented, for example, in hydro-technical structures; suspended pile foundations, beams, rafters, sheet piles; friction bearings and kinematic bearings of seismically isolated buildings, etc. An extension of the existing formulations of the problems of contact without friction and contact with a known friction boundary is proposed in the form of a problem of linear complementarity to the formulation of frictional contact. As a result, a heuristic formulation of the contact problem with friction is obtained in the form of a linear complementarity problem.

In [6], the dynamic characteristics and oscillations of various axisymmetric and plane structures were considered, taking into account different geometries, spatial factors, and inelastic properties of materials.

In [7,8], the process of interaction of structures with non-linearly deformable soil was studied. Numerically, by the method of finite differences, the soil response and the stress-strain state of structures and soil were determined.

Article [9] is devoted to the dynamic problems of the deformed state of an earth structure under seismic impacts. A method was developed for solving wave problems for determining the stress-strain state of earth structures, in particular earth dams. Using the finite difference method, calculation formulas and an algorithm for solving problems were developed.

The study in [10] considers the organization and conduct of dynamic tests of a multi-story residential panel building. For dynamic tests, a software and hardware complex was developed that implements the standing wave method and makes it possible to determine the dynamic characteristics of a building by registering microseismic vibrations of building structures. Based on the results of dynamic tests, the actual natural (resonant) frequencies and modes of oscillations of building structures were determined. From the analysis of the distribution of peak values of the amplitudes of natural vibrations, we have identified dangerous zones for the occurrence of destructive processes in the ground of the building foundation, affecting its safe functioning.

Reference [11] considers damage and destruction of building structures by fire and other thermal effects. The research method consists in developing a cellular model of a heat-insulated plate based on the localization of a heat source in a certain position above the plate and characterized by the temperature distribution in the cells. The evolution of this distribution is a transition probability matrix that describes the change in thermal conductivity along with the plate in two directions and in terms of source functions.

The study in [22] presents the results of experiments with samples of round concrete, and related to them differential (changing in depth) structural characteristics of concrete subjected to centrifugal molding and vibro-forming.

In [13], an analytical calculation of the brickwork of a barrel-shaped vault is considered, its structure of the material has a pronounced variability of elastic constants. In regulatory documents, brickwork is considered a complex two-component building material with elastic-plastic properties. However, there are no clear recommendations that take into account the variability of the elastic properties of brickwork.

[14] presents a technology for the production of anorthite-based building ceramics using semi-dry powder pressing based on the sintering of a raw mixture consisting of low-melting clay and blast-furnace sludge (BFS) in various proportions. Studies of the physical and mechanical properties of ceramic samples show that the addition of BFS to the composition of the mixture provides the compressive strength of the obtained samples up to 48.8 MPa, which is 25% higher than that of the control sample. The higher compressive strength is due to the formation of an anorthite phase, which is proven by X-ray studies. According to the

differential thermal analysis of the obtained samples, the exo-effect occurs during sintering at a temperature of 1050°C, which is typical for the formation of an anorthite phase.

In [15], free vibrations of Timoshenko beams loaded in the axial direction with many cracks under different boundary conditions are studied, namely: hinged-hinged, fixed-fixed, foxed-hinged and fixed-free conditions. The system of beams with cracks is presented in the form of several segments of beams connected by massless rotating springs with flexibility in cross-section.

Articles [16-19] are devoted to dynamic calculations of elements of the box-shaped structure of buildings for seismic resistance, taking into account the spatial work of box-shaped elements under the action of dynamic influences specified by moving their lower part according to a sinusoidal law. The equations of motion for each of the plate and beam elements of the box structure of the building are given on the basis of the Kirchhoff-Love theory. Expressions are given for the forces, moments and stresses of plate elements that balance the movement of box elements, as well as boundary conditions and full contact conditions through displacements and force factors in the contact zones of plate and beam elements.

Article [20] is devoted to the numerical solution of the problem of transverse vibrations of a multi-story building in the framework of a solid slab model under seismic action. A cantilevered anisotropic plate is proposed as a dynamic model of a building, the theory of which was developed within the framework of the three-dimensional dynamic theory of elasticity and takes into account not only forces and moments, but also bimoments [21].

When determining the reduced density and modulus of elasticity of the lamellar model, we use the technique developed in [20]. It is believed that the building consists of numerous boxes (rooms).

The reduced density of the building is determined by the following formula:

$$m_{\text{пр}} = \rho_{\text{пл}} V_1 = \rho_{\text{пр}} V_0 \tag{1}$$

Here V_1 is the volume of the slabs that form one floor of the building, V_0 is the volume of one floor of the building.

To calculate these volumes, we obtain the following formulas

$$V_0 = ab_1 H,\ V_1 = ab_1 h_2 + (n-2) H b_1 h_2 + aHh_2, \tag{2}$$

where a, H are the length and width of the building; b_1 – the height of one floor of the building; k is the number of internal transverse walls of the building; h_1 is the thickness of external load-bearing walls; h_2 is the thickness of the internal walls; $h_{пер}$ is the floor thickness.

In the general case, the reduced elastic characteristics of the building are determined by the following formulas [20]:

$$\begin{aligned} E_1^{прив} &= \zeta_{11} E_0, \quad E_2^{прив} = \zeta_{22} E_0, \quad E_3^{прив} = \zeta_{33} E_0, \\ G_{12}^{прив} &= \zeta_{12} G_0, \quad G_{13}^{прив} = \zeta_{13} G_0, \quad G_{23}^{прив} = \zeta_{23} G_0, \end{aligned} \tag{3}$$

the reduced density of the building is determined by the following formula

$$\rho_{\text{пр}} = \rho_0 \varsigma_0 . \tag{4}$$

It should be noted that the values of coefficients $\xi_{11}, \xi_{22}, \xi_{33}, \xi_{12}, \xi_{13}, \xi_{23}, \zeta_0$ for each cell (room) of the discrete part of the building are determined as functions of two spatial variables, E_0, G_0 are the moduli of elasticity and shear of the most stable load-bearing panel of the cell of the discrete part of the building.

We write the formulas for determining coefficients $\xi_{11}, \xi_{22}, \xi_{33}, \xi_{12}, \xi_{13}, \xi_{23}, \zeta_0$ of the reduced moduli of elasticity of the discrete part of the building in the following form [20]:

$$\xi_{11} = \alpha \frac{S_{11}}{S_{01}}, \quad \xi_{22} = \alpha \frac{S_{22}}{S_{02}}, \quad \xi_{33} = \alpha \frac{S_{33}}{S_{03}}, \ \xi_{12} = \alpha \frac{S_{12}}{S_{01}},$$
$$\xi_{13} = \alpha \frac{h_{пер}}{b_1} \lambda^*, \quad \xi_{23} = \alpha \frac{h_2}{a_1}, \quad \zeta_0 = \frac{V_1}{V_0}. \tag{5}$$

where S_{01}, S_{02}, S_{03} are the cross-sectional areas of the building in three coordinate planes of one floor of the building; S_{11}, S_{22}, S_{33} are the total cross-sectional areas of the slabs in the coordinate planes that form one floor of the building; λ^* is the coefficient characterizing the voids in the cross-section of the floor slab. Coefficient α is determined depending on the cellular structure of the building structure.

Note that the above volumes and areas are determined using the methodology presented in [20], depending on the dimensions of the slabs, rooms and the building itself:

$$S_{01} = E_0 b_1 H, \quad S_{02} = E_0 a H, \quad S_{03} = E_0 a b_1, \tag{6}$$

$$S_{11} = b_1 h_2 E_b^{(2)} + H h_{пер} E_{пер}, \quad S_{12} = b_1 h_2 E_b^{(2)},$$
$$S_{22} = a h_2 E_b^{(2)} + (k-2) H h_2 E_b^{(2)}, \ S_{33} = a h_2 E_b^{(2)} + (k-2) b_1 h_2 E_b^{(2)}. \tag{7}$$

Here $G_{пер}$ is the shear modulus of the floor of the building; G_2 is the shear modulus of internal walls; $E_b^{(2)}$ is the

modulus of elasticity of internal walls; $E_{пер}$ is the modulus of elasticity of the floor.

Now let us determine the reduced moduli of elasticity and shear of the outer walls, taking into account window openings, using the technique given in [22] in the form of approximate formulas:

$$E_1^{прив} = E_1\left(1 - \frac{\eta}{\eta_0}\right), \ E_2^{прив} = E_2\left(1 - \frac{\eta}{\eta_0}\right), \ G_1^{прив} = G_1\left(1 - \frac{\eta}{\eta_0}\right), \ G_3^{прив} = G_3\left(1 - \frac{\eta}{\eta_0}\right). \tag{8}$$

where E_1, E_2, G_{12}, G_{13} are the moduli of elasticity and shear of the outer walls, η, η_0 are constant coefficients.

Thus, we have obtained formulas for representing the values of the reduced modulus of elasticity of the plate model of the building.

The values of coefficients $\xi_{11}, \xi_{22}, \xi_{33}, \xi_{12}, \xi_{13}, \xi_{23}, \zeta_0$ for each cell (room) of the building are determined as functions of two spatial variables, E_0, G_0 are the moduli of elasticity and shear of the strongest load-bearing panel of the building.

Therefore, we have obtained formulas (1) - (8) to determine the reduced modulus of elasticity of the discrete part of the plate model of the building. According to the obtained formulas (1) - (8), the reduced modulus of elasticity is 8–30 times less than the elastic modulus of the panels, and the reduced density of the plate model of the discrete part of the building is 7–20 times less than the density of the panel material, which is explained by the cellular structure of the building with a large number of voids.

2 Formulation of the problem

Let us assume that the seismic ground motion occurs in the direction of the OZ-axis (the width of the building). Based on this, we set the base acceleration $\ddot{u}_0(t)$ as an external impact on the lower fixed edge.

To describe the movement of multi-story buildings, we introduce a Cartesian coordinate system with variable x_1, x_2 and z. The origin of the coordinates is located in the lower-left corner of the median surface of the continuum plate. Let us direct the OX1 and OX2 axes along the length and height, and the OZ-axis - along the thickness (width of the building) of the plate model.

At the base of the building, the boundary conditions for flexural-shear vibrations have the following form:

$$\tilde{\psi}_1 = 0,\ \tilde{\psi}_2 = 0,\ \tilde{\beta}_1 = 0,\ \tilde{\beta}_2 = 0, \tilde{u}_1 = 0,\ \tilde{u}_2 = 0,\ \tilde{r} = u_0(t),\ \tilde{\gamma} = \frac{1}{3}u_0(t),\ \tilde{W} = u_0(t) \tag{10}$$

where $u_0(t)$ -displacement of the base of the building.

On the free side faces of the building, we have the conditions of equality to zero of forces, moments and bimoments and force factors:

$$M_{11} = 0,\ M_{12} = 0,\ P_{11} = 0,\ P_{12} = 0,\ Q_{13} = 0,\ \tilde{p}_{13} = 0,\ \tilde{\sigma}_{11} = 0,\ \tilde{\sigma}_{12} = 0,\ \overset{*}{\sigma}_{11} = 0 \tag{11}$$

On the free upper face of the building, we have the following conditions:

$$M_{12} = 0,\ M_{22} = 0,\ P_{12} = 0,\ P_{22} = 0,\ Q_{23} = 0,\ \tilde{p}_{23} = 0,\ \tilde{\sigma}_{11} = 0,\ \tilde{\sigma}_{12} = 0,\ \overset{*}{\sigma}_{22} = 0 \tag{12}$$

$$\tilde{\psi}_1 = 0,\ \tilde{\psi}_2 = 0,\ \tilde{\beta}_1 = 0,\ \tilde{\beta}_2 = 0,\ \tilde{r} = 0,\ \tilde{\gamma} = 0,\ \tilde{u}_1 = 0,\ \tilde{u}_2 = 0,\ \tilde{W} = 0,$$
$$\dot{\tilde{\psi}}_1 = 0,\ \dot{\tilde{\psi}}_2 = 0,\ \dot{\tilde{\beta}}_1 = 0,\ \dot{\tilde{\beta}}_2 = 0,\ \dot{\tilde{r}} = 0,\ \dot{\tilde{\gamma}} = 0,\ \dot{\tilde{u}}_1 = 0,\ \dot{\tilde{u}}_2 = 0,\ \dot{\tilde{W}} = 0.$$

For the numerical solution to the problem, we use the finite-difference equations of motion of the transverse vibrations of buildings, which are described with respect to the following nine unknown functions

$$\tilde{\psi}_1,\ \tilde{\psi}_2,\ \tilde{u}_1,\ \tilde{u}_2,\ \tilde{\beta}_1,\ \tilde{\beta}_2,\ \tilde{r},\ \tilde{\gamma},\ \tilde{W}:$$

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$$\frac{(M_{11})^k_{i+\frac{1}{2},j}-(M_{11})^k_{i-\frac{1}{2},j}}{\Delta x_1}+\frac{(M_{12})^k_{i,j+\frac{1}{2}}-(M_{12})^k_{i,j-\frac{1}{2}}}{\Delta x_2}-(Q_{13})_{i,j}=\rho\frac{H^2}{2}\frac{(\tilde{\psi}_1)^{k+1}_{i,j}-2(\tilde{\psi}_1)^k_{i,j}+(\tilde{\psi}_1)^{k-1}_{i,j}}{\Delta t^2},$$
$$\frac{(M_{12})^k_{i+\frac{1}{2},j}-(M_{12})^k_{i-\frac{1}{2},j}}{\Delta x_1}+\frac{(M_{22})^k_{i,j+\frac{1}{2}}-(M_{22})^k_{i,j-\frac{1}{2}}}{\Delta x_2}-(Q_{23})_{i,j}=\rho\frac{H^2}{2}\frac{(\tilde{\psi}_2)^{k+1}_{i,j}-2(\tilde{\psi}_2)^k_{i,j}+(\tilde{\psi}_2)^{k-1}_{i,j}}{\Delta t^2}, \quad (13)$$

$$\frac{(Q_{13})^k_{i+\frac{1}{2},j}-(Q_{13})^k_{i-\frac{1}{2},j}}{\Delta x_1}+\frac{(Q_{23})^k_{i,j+\frac{1}{2}}-(Q_{23})^k_{i,j-\frac{1}{2}}}{\Delta x_2}=\rho\frac{(\tilde{r})^{k+1}_{i,j}-2(\tilde{r})^k_{i,j}+(\tilde{r})^{k-1}_{i,j}}{\Delta t^2}, \quad (14)$$

$$\frac{(P_{11})^k_{i+\frac{1}{2},j}-(P_{11})^k_{i-\frac{1}{2},j}}{\Delta x_1}+\frac{(P_{12})^k_{i,j+\frac{1}{2}}-(P_{12})^k_{i,j-\frac{1}{2}}}{\Delta x_2}-3(\tilde{p}_{13})_{i,j}=\rho\frac{H^2}{2}\frac{(\tilde{\beta}_1)^{k+1}_{i,j}-2(\tilde{\beta}_1)^k_{i,j}+(\tilde{\beta}_1)^{k-1}_{i,j}}{\Delta t^2},$$
$$\frac{(P_{12})^k_{i+\frac{1}{2},j}-(P_{12})^k_{i-\frac{1}{2},j}}{\Delta x_1}+\frac{(P_{22})^k_{i,j+\frac{1}{2}}-(P_{22})^k_{i,j-\frac{1}{2}}}{\Delta x_2}-3(\tilde{p}_{23})_{i,j}=\rho\frac{H^2}{2}\frac{(\tilde{\beta}_2)^{k+1}_{i,j}-2(\tilde{\beta}_2)^k_{i,j}+(\tilde{\beta}_2)^{k-1}_{i,j}}{\Delta t^2}, \quad (15)$$

$$\frac{(\tilde{p}_{13})^k_{i+\frac{1}{2},j}-(\tilde{p}_{13})^k_{i-\frac{1}{2},j}}{\Delta x_1}+\frac{(\tilde{p}_{23})^k_{i,j+\frac{1}{2}}-(\tilde{p}_{23})^k_{i,j-\frac{1}{2}}}{\Delta x_2}-\frac{4(\tilde{p}_{33})_{i,j}}{H}=\rho\frac{(\tilde{\gamma})^{k+1}_{i,j}-2(\tilde{\gamma})^k_{i,j}+(\tilde{\gamma})^{k-1}_{i,j}}{\Delta t^2}, \quad (16)$$

where $M_{ij},\ Q_{i3}\ (i,j=1{,}2)$ are bending moments and shear forces; $P_{ij},\ (i,j=1{,}2)$ are the longitudinal bimoments, $p_{i3}\ (i,j=1{,}2)$; p33 are the intensities of transverse bimoments.

The system of equations of motion with respect to three generalized functions $\tilde{u}_1, \tilde{u}_2, \tilde{W}$ is approximated as

$$(\tilde{u}_1)_{i,j}=\frac{1}{2}\left(21(\tilde{\beta}_1)_{i,j}-7(\tilde{\psi}_1)_{i,j}\right)-\frac{1}{30}H\frac{\tilde{W}_{i+1,j}-\tilde{W}_{i-1,j}}{\Delta x_1},$$
$$(\tilde{u}_2)_{i,j}=\frac{1}{2}\left(21(\tilde{\beta}_2)_{i,j}-7(\tilde{\psi}_2)_{i,j}\right)-\frac{1}{30}H\frac{\tilde{W}_{i,j=1}-\tilde{W}_{i,j-1}}{\Delta x_2}, \quad (17)$$

$$\tilde{W}=\frac{21}{4}(\tilde{\gamma})_{i,j}-\frac{3}{4}(\tilde{r})_{i,j}-\frac{H}{20}\left(\frac{E_{31}}{E_{33}}\frac{(\tilde{u}_1)_{i+1,j}-(\tilde{u}_1)_{i-1,j}}{\Delta x_1}+\frac{E_{32}}{E_{33}}\frac{(\tilde{u}_2)_{i,j=1}-(\tilde{u}_2)_{i,j-1}}{\Delta x_2}\right). \quad (18)$$

The calculations were performed for multi-story buildings, the plan of which is shown in Fig. 1 (a plan of a continuum plate model of a multi-story building).

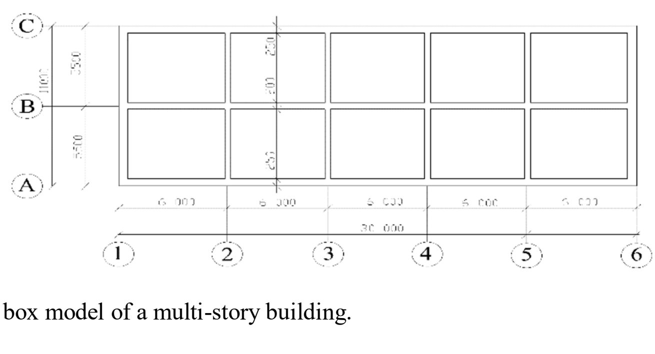

Fig. 1. Plan of a box model of a multi-story building.

3 Analysis of numerical results

The mechanical and geometric characteristics of the materials of the room panels are taken as: bending load-bearing panels have an elastic modulus of $E = 20000\,MPa$; density $\rho = 2700\ \text{kg/m}^3$; Poisson's ratio $\nu = 0.3$. For a shear panel the modulus of elasticity is $E = 7500\,MPa$; density $\rho = 1200\ \text{kg/m}^3$; Poisson's ratio $\nu = 0.3$.

The results of calculations of forced vibrations of the building within the framework of a thick plate model are given for the following dimensions of the slabs and the building:

$$h_1 = 0.40\,m,\ h_2 = 0.25\,m,\ h_{\text{пер}} = 0.2\,m,\ a_1 = 5\,m,\ b_1 = 3\,m,\ a = 30\,m,\ H = 13\,m.$$

Then the calculated coefficients ξ_0, ξ_{11}, ξ_{22}, ξ_{33}, ξ_{12}, ξ_{13}, ξ_{23} according to the corresponding formulas are:

$$\xi_{11} = 0.11,\ \xi_{22} = 0.137, \xi_{33} = 0.09,\ \xi_{12} = 0.077,\ \xi_{13} = 0.067,\ \xi_{23} = 0.04,\ \xi_0 = 0.142$$

The reduced elastic characteristics of the building are determined by the following formulas:

$$E_1^{\text{пр}} = \xi_{11}E_0,\ E_2^{\text{пр}} = \xi_{22}E_0,\ E_3^{\text{пр}} = \xi_{33}E_0,\ G_{12}^{\text{пр}} = \xi_{12}G_0,\ G_{13}^{\text{пр}} = \xi_{13}G_0,\ G_{23}^{\text{пр}} = \xi_{23}G_0.$$

Modulus of elasticity and density of concrete are $E = 20000\ MPa,\ \rho = 2500\ kg/m^3$. Then, according to the formulas, the reduced characteristics of the building are:

$$E_1^{\text{пр}} = 1323.08\,MPa,\ E_2^{\text{пр}} = 1643.08\,MPa, E_3^{\text{пр}} = 1120.00\ MPa,$$

$$G_{12}^{\text{пр}} = 369{,}23\ MPa,\ G_{13}^{\text{пр}} = 320.00\ MPa,\ G_{23}^{\text{пр}} = 192{,}00\ MPa,\ \rho_{np} = 351.02\ kg/m^3.$$

The heights of nine-story, twelve-story and sixteen-story buildings are assumed to be 30 m, 40 m, and 51 m, respectively.

4 Seismic impacts

External seismic impacts on the lower fixed edge are set as the base acceleration $\ddot{u}_0(t)$ in the following form:

$$\ddot{u}_0(t) = a_0 \cos(\omega_0 t),$$

where $a_0 = k_c g$ and $\omega_0 = 2\pi\nu_0$, k_c, g and ν_0 are the coefficient of seismicity, acceleration of free fall and the natural frequency of the soil base. From the expression of acceleration, the displacements of the base of the building are determined in the following form:

$$u_0(t) = \frac{A_0}{2}(1 - \cos(\omega_0 t)).$$

Here A_0 and ω_0 are the amplitude and circular frequency of the base displacement.

In calculations, the foundation of the building is assumed to be absolutely rigid.

Tables 1, 2 and 3 show the values of natural frequency p_0 and the maximum values of normal and shear stresses σ_{11}, σ_{22} and σ_{12} (in MPa), obtained under transverse vibrations of nine-, twelve- and sixteen-story buildings, corresponding to seven-, eight- and nine-point earthquakes $k_c = 0{,}1;\ 0{,}2;\ 0{,}4$ and $\nu_0 = 2{,}7;\ 2{,}4;\ 1{,}8$.

Let us determine the maximum stress values in the outer walls of a large-panel two-story building.

The amplitude of external impact A_0 depends on the magnitude of the earthquake, determined from condition $A_0\omega_0^2 = 2k_c g$, where k_c, g are the seismicity coefficient and the free fall acceleration.

For a seven magnitude earthquake, $k_c = 0.1;\ \nu_0 = 2.7Hz$. Then, the amplitude of the external impact is:

$$A_0 = \frac{2k_c g}{\omega_0^2} = \frac{2\cdot 0.1\cdot 9.8}{16.95^2} = 0.68\,cm$$

For an eight magnitude earthquake, $k_c = 0.2;\ \nu_0 = 2.4Hz$. Then the amplitude of the external impact is:

$$A_0 = \frac{2k_c g}{\omega_0^2} = \frac{2\cdot 0.2\cdot 9.8}{15.07^2} = 1.74\,cm$$
.

For a nine magnitude earthquake, $k_c = 0.4;\ \nu_0 = 2Hz$. Then the amplitude of the external impact is:

$$A_0 = \frac{2k_c g}{\omega_0^2} = \frac{2\cdot 0.4\cdot 9.8}{12.56^2} = 5{,}03.cm$$

The problem is solved by the finite difference method. Calculation steps are introduced according to the formulas: $\Delta x_1 = \frac{a}{N},\ \Delta x_2 = \frac{b}{M}$ – calculation step, N, M – number of partitions, Δt – time step.

The following dimensionless variables were introduced $x = x_1/a,\ y = x_2/b,\ \tau = \frac{ct}{H}$, where $c = \sqrt{\frac{E}{\rho}}$.

Table 1 shows the values of natural frequency $p_0 = 3{,}2\,Hz$ and the maximum values of normal and shear stresses σ_{11}, σ_{22} and σ_{12} (in MPa) obtained under transverse vibrations of a twelve-story building for seven-, eight- and nine-point earthquakes with a base acceleration frequency ν_0 = 2.7 Hz.

Calculations performed within the framework of a continual spatial plate model using an explicit scheme of the finite difference method showed that under external dynamic impacts of large amplitude, dangerous stresses appear at different lower points in the contact zone surfaces of the outer walls of a nine-story building and the foundation at seven- and eight-point earthquakes.

Table 1. Values of the first natural frequency, maximum and minimum stresses of a nine-story large-panel building during 7-8-9 points earthquakes.

№	*H, m*	k_s	ν_0, *Hz*	p_0 *Hz*	Coordinate *(x,y)*	σ_{11}, MPa		σ_{12}, MPa		σ_{22}, MPa	
						[min]	[max]	[min]	[max]	[min]	[max]
1	13	0.1	2.7	3.2	*[a/4,0]*	-1.2	1.2	-0.9	0.9	-6.02	6.02
2		0.2			*[a/4,0]*	-3	3	-0.8	0.8	-12.13	12.14
3		0.4			*[a/4,0]*	-5	5.1	-1.8	1.7	-25.03	25.04
4		0.1			*[a/2,0]*	-1.5	1.5	-0.1	0.1	-6.12	6.20
5		0.2			*[a/2,0]*	-2.8	2.9	-0.2	0.2	-12.33	12.41
5		0.4			*[a/2,0]*	-7	7	-0.3	0.3	-25.15	25.07

Table 2 shows the results of calculations of the maximum normal and shear stresses σ_{11}, σ_{22} and σ_{12} (in MPa), obtained during seven-, eight- and nine-point earthquakes at a base acceleration frequency ν_0= 2.4 Hz and a natural vibration frequency $p_0 = 2.2Hz$, obtained under transverse vibrations of a twelve-story building.

Table 2. Values of the first natural frequency, maximum and minimum stresses of a twelve-story large-panel building during 7-8-9 points earthquakes.

№	*H, m*	k_s	ν_0, *Hz*	p_0, *Hz*	Coordinates *(x,y)*	σ_{11}, MPa		σ_{12}, MPa		σ_{22}, MPa	
						[min]	[max]	[min]	[max]	[min]	[max]
1	13	0.1	2.4	2.2	*[a/4,0]*	-1.5	1.5	-0.7	0.7	-7.51	7.51
2		0.2			*[a/4,0]*	-3	3	-1.6	1.6	-15.07	15.07
3		0.4			*[a/4,0]*	-6	6	-2.8	2.8	-30.14	30.14
4		0.1			*[a/2,0]*	-1.8	1.8	-0.1	0.1	-8.09	8.07
5		0.2			*[a/2,0]*	-3.5	3.5	-0.15	0.15	-16.22	16.19
5		0.4			*[a/2,0]*	-7	7	-0.35	0.35	-32.31	32.28

Table 3 shows the numerical values of the maximum normal and shear stresses σ_{11}, σ_{22} and σ_{12} (in MPa) obtained during seven-, eight- and nine-point earthquakes with a base acceleration frequency ν_0= 2.0 Hz and a natural vibration frequency $p_0 = 1.5Hz$, obtained under transverse vibrations of a twelve-story building.

Table 3. Maximum and minimum stress values of a sixteen-story large-panel building during 7-8-9 points earthquakes.

№	*H, m*	k_s	ν_0, *Hz*	p_0, *Hz*	Coordinates *(x,y)*	σ_{11}, MPa		σ_{12}, MPa		σ_{22}, MPa	
						[min]	[max]	[min]	[max]	[min]	[max]
1	13	0.1	2	1.5	*[a/4,0]*	-1.5	1.5	-0.8	0.8	-6.12	6.11
2		0.2			*[a/4,0]*	-2.5	2.5	-1.5	1.5	-12.13	12.12
3		0.4			*[a/4,0]*	-5	5	-2.7	2.7	-25.05	25.02
4		0.1			*[a/2,0]*	-1.5	1.5	-0.08	0.08	-6.52	6.51
5		0.2			*[a/2,0]*	-2.7	2.7	-0.15	0.15	-12.52	12.50
5		0.4			*[a/2,0]*	-5.5	5.5	-0.3	0.3	-21.53	21.52

It should be noted that in the calculations of a sixteen-story building with the same magnitude of seismic impact that acts on a twelve-story building, relatively small stresses arise compared to the stresses obtained in a twelve-story building. This circumstance is explained by the fact that the frequency of external impact differs significantly from the resonant frequency of a sixteen-story building.

The calculation step for dimensionless coordinates is $\Delta x = 1/N,\ \Delta y = 1/M$. The stability of the calculation in dimensionless time is ensured by an explicit scheme with step

$$\Delta\tau = \frac{c\Delta t}{H} = 0.01.$$

In conclusion, we note that the plate model of the building adequately reflects the modes of vibrations of the building under seismic effects. In calculations, the number of partitions into steps of difference schemes in dimensionless coordinates is taken as follows: for a nine-story building $N = 30, \quad M = 30$, for a twelve-story building $N = 30, \quad M = 42$, a sixteen-story large-panel building $N = 30, \ M = 52$.

5 Conclusion

A technique, an algorithm for the numerical calculation of the stress state of a multi-story building within the framework of a continual spatial plate model was developed using an explicit scheme of the finite difference method.

Numerical results of stresses in the characteristic sections of plate elements (in external walls) of a multi-story building were obtained.

Calculations showed that under external dynamic impacts of large amplitude, dangerous stresses appear at different lower points of the contact zone surfaces of the outer walls of a multi-story building and the foundation during seven- and eight-point earthquakes.

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