Seismic resistance evaluation of multi-story buildings using the modern LIRA-SAPR SP

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Abstract. This article presents the results of evaluating the seismic resistance of high-rise buildings on real records of the accelogram and on regulatory documents using the LIRA-SAPR SP. The maximum and minimum values of bending moments, longitudinal forces, shear stresses are determined, and the most vulnerable areas where cracking in load-bearing structures is possible are determined. It was found that the values of force factors arising in buildings under the action of the accelogram turned out to be 2 times less than the values obtained from the data based on regulatory documents. Along with this, it was found that the results of the calculation for the seismic resistance of high-rise buildings according to real accelerograms and according to regulatory documents showed that the higher the building, the greater the magnitude of displacements, bending moments and longitudinal forces on the upper floors of buildings. This requires the development of appropriate measures to reduce the vibrations of the upper floors of multi-story buildings.

1 Introduction

Due to the fact that the Republic of Uzbekistan is located in a seismically active zone, it is necessary to ensure the safe operation of buildings and structures, which could be achieved by stage-by-stage solving tasks in the design, construction and operation. A significant part of the population lives in the territory of the republic that, according to the forecast of possible strong earthquakes, is of an intensity of 9 points and higher. However, this problem has not been completely solved to date. At present, due to the increasing frequency of earthquakes in the region and the mass construction of multi-story buildings, there is a need for systematic scientific and practical research to develop improved methods for calculating such buildings for seismic effects, although some of these works have been conducted before. This explains the relevance of the article.

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Buildings are complex objects of study in structural mechanics. To date, there are no universal approaches for their calculation that would cover the entire dynamic process. The existing methods of dynamic calculation of the stress-strain state, due to the large number of elements and the complex structure of high-rise large-scale buildings, are a difficult task. It is known that in the modern practice of designing buildings and structures, there are various linear and nonlinear static and dynamic methods of the problem solution [1]. Therefore, the theory of seismic resistance of buildings and structures continues to develop as one of the topical areas of structural mechanics. Numerous studies on the development of the theory of seismic resistance of buildings and structures continue in developed countries to fully cover the dynamic process and behavior of a complex structure [2].

Various methods were developed to calculate buildings and structures for seismic effects, taking into account important factors of seismic load, soil conditions of the site and design features of building structures. These studies are considered in [3-7].

The article [8] is devoted to the dynamic problems of the deformed state of earth dams under seismic influences. A method for solving wave problems was developed to determine the stress-strain state of earth structures, in particular, earth dams. Using the method of finite differences was developed calculation formulas and an algorithm for solving problems.

The study in [9] considers the problem of seismic resistance of multi-story buildings with a sliding support. The calculation takes into account the vertical component of seismic effects in the form of real accelerograms. As a result of the calculation, the dynamic characteristics of the building with seismic isolation were determined.

In [10], the results of assessing the technical condition of existing buildings of preschool institutions built in seismically active regions of the republic in different years are presented; they take into account the requirements of various standards of earthquake-resistant construction. As a result, relevant recommendations are given for strengthening structures and ensuring the seismic resistance of load-bearing structures.

In [11], the organization and conduct of dynamic tests of a multi-story residential panel building in Krasnoyarsk are presented. Software and hardware complex for dynamic tests was developed that implements the standing wave method, which 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 the oscillations of building structures were determined. From the analysis of the peak values distribution of the amplitudes of natural oscillations, the danger zones of the occurrence of destructive processes in the ground of the building foundation, affecting its safe functioning, were determined.

The study in [12] is devoted to the static consideration of higher modes of oscillations in the problems of the dynamics of building structures under an external harmonic load. Using a computer complex, the displacements of nodes and internal forces in the elements of the structures under consideration were determined. The influence of displacements, fractures of the axes of wall panels during their installation on the operation of large-panel structures was considered in [13]. 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 regarding the error in the installation of parts.

In [14], a method was developed for calculating structures with self-isolation under seismic effects within the framework of nonlinear dynamics using the finite element method (FEM). Articles [15, 16] are devoted to the dynamic problems of the strained state of earth dams 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.

Reference [17] proposes a method for using the POLYANS polymer reagent in concrete; it is produced from waste in polyacrylonitrile fiber production. The results of the reagent influence on the capillary absorption of concrete are presented, which contribute to the high resistance of cement concrete in saline media. The studies in [18, 19] propose a method for experimental research of bent reinforced concrete beams made of ordinary heavy concrete, equipped with fiberglass composite reinforcement. Data on methods for measuring the resulting deformations, cracks and deflections of beam prototypes under the action of transverse forces are presented.

Articles [20-22] are devoted to the theoretical calculation of the box-shaped structure of large-panel buildings for dynamic impacts, taking into account the spatial work of transverse and longitudinal walls under the dynamic impact, given by the base movement according to a sinusoidal law. Methods for numerical solutions to the problem of contact interaction of beam and plate elements of a box structure of a building were developed.

The study in [23] is devoted to the numerical solution to 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 the building. The model was developed within the framework of the three-dimensional dynamic theory of elasticity and takes into account not only structural forces and moments but also bimoments.

Articles [24, 25] consider the development of the theory and method for calculating thick lamellar structures. A detailed analysis of well-known publications devoted to this problem is given. A theory and a method for estimating the stress-strain state of thick lamellar structures within the framework of the three-dimensional theory of elasticity were developed. In this study, the results of the calculation of a multi-story building for seismic resistance, obtained using the linear-spectral method (LIRA-SAPR SP), are presented. The choice of constructive solutions for the buildings, their design and calculation for seismic resistance should be conducted with the participation of specialized research-and-design organizations. In accordance with the current norms and principles for ensuring the seismic resistance of multi-story residential buildings, special attention must be paid to interpreting the law of seismic action on the basis of calculations. Applying LIRA–SAPR SP when solving new problems of seismic resistance of buildings, it is necessary to choose one of the six features given in the design schemes (version 2018 and above, application P4).

In [26], four-story and nine-story buildings were studied with a set of three earthquake records and it was shown that the use of a sliding foundation does not always lead to a significant decrease in the shear force on the floors of the building and that the vertical component of the seismic action has a significant effect on the shear vibrations of the building.

In [27], the influence of linear and nonlinear models of the foundation interaction with the foundation soil on the vibrations of a multi-story building under seismic effects was studied. In the studies, the building was designed for seismic impacts, taking into account rigid, elastic, elastic-plastic and viscoelastic models of the interaction between the foundation and the foundation soil.

2 Methods

When designing multi-story or high-rise buildings, special attention is paid to a complete understanding of the entire complex structural system and the work of the supporting

operating system "base - foundation - building". With available computer technology, basic analytical calculations for simple and complex high-rise structures are performed using software packages. Simplified (manual) calculation methods are not recommended.

When calculating the seismic resistance of buildings using LIRA-SAPR, it is possible to solve the problem by two calculation methods:

a) dynamic method - according to real or simulated seismic effects;

b) spectral method – according to seismic effects for perfectly elastic systems.

For buildings with a height of more than 40 m or for massive residential buildings with new structures, a dynamic calculation method should be applied. The required parameters for individual regions are selected from special tables.

In normative document [1], paragraph 2.7, it is written that "for buildings (structures) with fundamentally new constructive solutions with a height of more than 40m the dynamic method of calculation should be used, and when designing mass construction objects with a height of up to 40m the dynamic method of calculation is recommended". The choice of a structural system, design, and calculation of buildings (structures) for real or synthesized seismic effects should be done with the participation of research organizations specializing in the field of earthquake-resistant construction. This article presents the numerical results of the seismic calculation of a 20-story high-rise building based on the dynamic method of calculating seismic effects in the form of a real accelerogram recorded in the seismically active zone of Tashkent at the construction site of the high-rise building.

Synthesized accelerogram and its response spectra correspond to quasi-sinusoidal oscillatory process with a continuous and increasing (in a certain way) frequency. The rate of its change, set in different frequency intervals, provided the required depth of the oscillator resonance for the selected frequency zones. At the same time, the response spectra in these zones increased smoothly and continuously (without significant drops and peaks), reached a constant level, and finally decreased. At the beginning of the process, the amplitude of the accelerogram was maximum, and then quickly decreased by half to its new value [28].

The accelerogram is not selective to the natural frequencies of a high-rise building when their values deviate in one direction or another. Due to structural changes or modeling errors, the levels of the object's response (including floor-by-floor accelerograms and response spectra) to this effect will not have sharp changes. Analog accelerograms, on the contrary, are frequency-selective. The response of an object under such impacts can vary greatly depending on its natural frequencies.

With three orthogonal accelerograms, it is possible to model a synchronous three-component seismic action for conservative calculations of complex spatial high-rise buildings. The use of analog accelerograms is associated with significant uncertainties in the selection of components according to their frequency characteristics, durations, intensities, phase combinations, and times of manifestation of the greatest influence. The use of a group of joint three-component records of accelerograms eliminates the above uncertainties. However, such records are extremely rare, and they do not solve the problem of sufficient conservativeness (reliability) of the calculation.

Below in the table 1 was given acceleration for the 8-point seismic zone of Tashkent, which in this form can be used for dynamic analysis of the seismic resistance of an object using various numerical integration methods. The digitization is set with a constant time step (0.01 s), it uses two scale factors: the first (multiplier) - converts it to the original physical norm of accelerations (in fractions of g); the second one scales the accelerogram to the calculated level.

Table 1. Accelogram of the 8-point seismically active zone of Tashkent. Digitization step DTA= 0.01 s. Scale of digitization RMA= 0.01, Amax=0.25g, T=10.06 s.

Scale factor to the accelerogram RM=0.01.
A, cm/s2 0 -6,79945 -2,91589 -0,87408 0,32685 1,87581 3,20597 3,78898 2,39764 -1,03577 -5,24415 -8,55219 -10,26675 -10,50885 -10,382 -10,65944 -11,46016 -12,17498 -12,22266 -11,3495 -10,08052 -9,37254 -10,05656 -11,78509 -12,73287 -10,31278 -3,11543 7,6181 18,19471 24,60862 24,8671 19,90296 12,57611 5,88072 1,73183 0,83189 3,13821 ..... -248,51137 -193,54057 -129,13869 -73,19337 -31,58348 -6,02845 4,82913 5,92771 4,50612 5,96236 11,21583 16,73863 17,86521 11,76906 ..... -8,58643 -11,13676 -13,45225 -15,57634 -17,65816 -19,83244 -22,14356 -24,47337 -26,57287 -28,06752 -28,59883 -27,88813 -25,91017 -22,87122 -19,28957 -15,72722 -12,58465 -9,70501 -6,74982 -3,51514 -0,33183 2,4512 4,51225 6,10094 7,58989 9,68359 12,88235 16,6823 19,43296 21,20136

Below are the accelerograms in the form of a graph in the horizontal and vertical directions (Figs. 1-2).

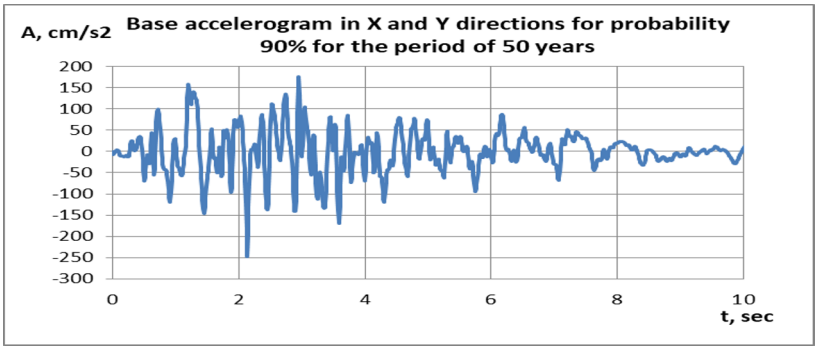

Fig. 1. Accelerogram in X and Y directions

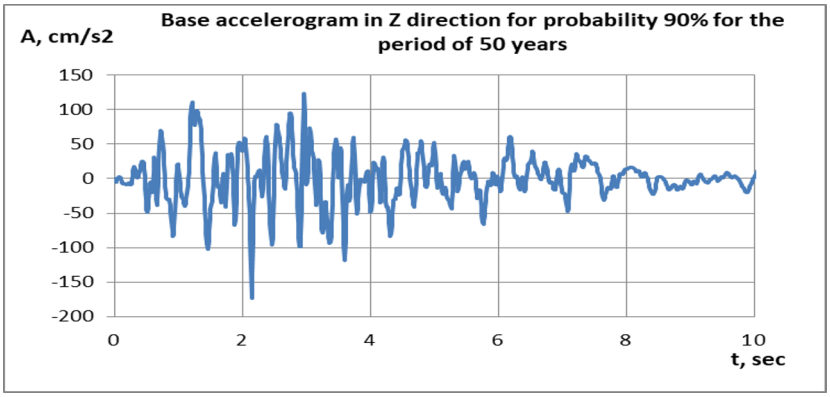

Fig. 2. Accelerogram in Z direction

The object of study is a 20-story high-rise building; it has a solid foundation 1.2 m thick made of class A-III reinforcement, concrete class is B20. The cross-sectional area of the columns is 0.4x0.4; 0.4x0.6; 0.5x0.6 m. Longitudinal columns with a cross-section of 0.4x1.6 and 0.4x1.8 m are made of class A-III reinforcement. The concrete class of vertical structures is B25. The cross-section of the bearing beams is 0.4x0.5 m, they are made of class A-III reinforcement. Concrete class of the beams is B25. The floor thickness is 0.16 m

and consists of longitudinal reinforcement A-III and transverse reinforcement A-I. Concrete class of the floors is B25. The thickness of the stiffening diaphragm, which perceives horizontal seismic loads, at the level of the basement floor is 0.4 m, from the first floor to the top, it is 0.3 m. The walls of the basement are made of reinforced concrete, their thickness is 0.4 m. The outer partitions are made of light gas blocks, their thickness is 0.3 m. The outer walls are made with thermal insulation using mineral basalt fiber fabric.

As external loads, a constant load (self-weight of structures), long-term temporary loads (load of equipment, furniture and people), short-term loads (snow load, wind load in the horizontal direction), instantaneous load (wind pulsation) and seismic effects in the form of accelerograms were obtained in X, Y, and Z directions. As a result of the calculation, the numerical values of internal force factors are given according to the dynamic method based on the real accelerogram and according to the method of the normative document KMK 2.01.03-19 in the load-bearing structures of a high-rise frame building.

3 Results and discussion

Below are the numerical results of the stress-strain state of a 20-story high-rise building based on dynamic calculation in the form of a three-component accelerogram with an equivalent intensity of 8 points. The amplitude of movement of the top of the building is 0.16 m in the longitudinal direction X, in the transverse direction 0.21 m, and 0.03 m in the vertical direction Z, the angular displacement relative to the UY-axis was 2.97 rad, relative to UX - 4.09 rad, and relative to the UZ-axis - 1.23 rad. In beam elements, including columns in the middle of the basement floor, the maximum value of the normal force N under compression is 50.4 tf, the shear force Qy in the Y direction is 58.6 tf, in the Z direction, it is 96.4 tf, the bending moment Mx in the X direction is 6.74 tf*m, the bending moment My in the Y direction is 44.8 tf*m, the torque Mz in the Z direction is 20.2 tf*m.

Calculation of a 20-story high-rise building on seismic impact was performed according to the KMK 2.01.03-19 regulatory document method.

The displacement amplitude and internal force factors in the bearing structures of the building calculated according to the KMC turned out to be almost 2 times greater than the results of the dynamic method obtained from the accelerogram.

4 Conclusion

1. An improved method for calculating a high-rise building for seismic resistance according to spectral theory using the LIRA-SAPR software package was proposed.

2. Calculations for seismic resistance of high-rise buildings were conducted on the basis of earthquake accelerograms and according to the method of normative documents; it was determined that the values of force factors arising in buildings under the action of the accelogram turned out to be 2 times less than the values obtained by the normative method. This is due to the use of additional coefficients that take into account the geometric parameters and design features of buildings.

3. The results of the calculation of a 20-story high-rise building on real accelerograms made it possible to determine the maximum and minimum values of bending moments, longitudinal forces, shear stresses and determine the most vulnerable areas where cracking in the supporting structures is possible.

4. The results of the calculation for the seismic resistance of high-rise buildings, obtained from real accelerograms and according to regulatory documents, showed that the higher the building, the greater the magnitude of displacements, bending moments and

longitudinal forces on the upper floors of buildings. This requires the development of appropriate measures to reduce the vibrations of the upper floors of multi-story buildings.

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