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CALCULATION OF EARTHQUAKE LOADS AND DEVELOPMENT OF CONSTRUCTIVE SOLUTIONS IN THE DESIGN OF SEISMIC RESIDENTIAL BUILDINGS

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Abstract.

The article analyzes complex approaches to calculating earthquake loads, selecting a structural system, and increasing seismic resistance in the design of residential buildings in seismically hazardous areas. The study developed a step-by-step algorithm for seismic calculation based on QMQ 2.01.03-19, QMQ 2.01.07-96, current design requirements for reinforced concrete structures, and the principles of Eurocode 8. In this case, the dynamic properties of the building, soil conditions, mass distribution by floors, structural regularity, center of rigidity and center of mass imbalance, foundation-soil interaction, and structural detailing requirements were taken as important criteria. The article evaluates the effectiveness of monolithic reinforced concrete frames, stiffening walls, diaphragms, and connecting elements for multi-story residential buildings, and proposes structural solutions that can be used at the design stage.

Keywords: seismic stability, earthquake load, residential building, reinforced concrete frame, stiffness wall, structural regularity, foundation, dynamic calculation.

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A large part of the territory of Uzbekistan is located in seismically active regions. Therefore, when designing residential buildings, it is necessary to assess the impact of earthquakes not as a simple additional load, but as a key factor that together determines the structural system of the building, the volumetric and planning solution, the foundation, materials and operational safety. The increase in the share of multi-storey residential buildings in urban areas with increasing population density requires the design of structural systems with greater reliability, high energy absorption capacity and monitoring during operation.

The central objective of earthquake-resistant design is to protect human life during an earthquake, prevent progressive structural failure, and ensure a level of damage that can be repaired. To achieve this goal, the calculated seismic effects must be determined in relation to realistic ground conditions, the building's mass, stiffness, period of vibration, structural regularity, and the plastic deformation capabilities of materials.

The main problems encountered in practical design are: the formation of the first floor as a soft floor in residential buildings, a significant imbalance between the center of rigidity and the center of mass, insufficient consideration of the foundation solution and soil conditions, insufficient connection of the beams acting as diaphragms, violation of the continuity of reinforcement in vertical structural elements, and poor quality control of execution during the design and construction process. This article summarizes computational and constructive proposals aimed at eliminating these problems.

Analysis of literature and regulatory documents

The national regulatory framework for seismic design is the main legal and technical basis for reducing seismic risk in residential buildings. The document QMQ 2.01.03-19 “Construction in seismic areas” defines seismic zoning, calculated seismic impact, selection of structural systems and requirements for earthquake-resistant structures. QMQ 2.01.07-96 “Loads and impacts” is used to form the main load combinations when taking into account permanent, temporary and special impacts.

In the Eurocode 8 concept, seismic design is based on the verification of the building's energy dissipation, ductile deformation capacity, structural regularity and limit states. The advantage of this approach is that it focuses not only on elastic strength, but also on the formation of plastic joints in controlled locations, sufficient column reserves and reliable operation of nodes.

The Resolution of the President of the Republic of Uzbekistan No. PQ-161 dated April 17, 2024 is aimed at increasing the seismic resistance of buildings and structures and improving the seismic hazard monitoring system. This document indicates the need to link seismic safety with scientific research, monitoring, expertise and practical construction processes. Therefore, it is advisable to provide for the possibility of structural monitoring, deformation control and technical condition assessment in the design of modern residential buildings, along with computational seismic inspections.

Purpose, objectives and scientific novelty of the research

The purpose of the research is to develop an algorithm for calculating earthquake loads in the design of seismically stable residential buildings, harmonized with regulatory requirements, and to substantiate a set of practical solutions for the structural system, foundation, and reinforcement.

The research objectives were defined as follows: to analyze the mass and stiffness parameters of the building when determining seismic loads; to calculate the distribution of seismic forces on floors; to assess structural regularity; to compare effective structural systems for residential buildings; to correlate the calculation results with the requirements for structural detailing; to formulate safety criteria to be used at the design stage.

The scientific novelty is that the article considers the stages of seismic load calculation, structural system selection, and structural detailing in a single algorithmic sequence. Also, a comprehensive model for increasing seismic resistance in residential buildings based on the interrelated operation of stiffening walls, diaphragm walls, foundation slab, and vertical element nodes was proposed.

Research methodology

The methodology used was normative analysis, computational-analytical approach, constructive comparison, and design risk assessment. In this case, the residential building was considered as a spatial structural system: the rafters were considered as horizontal diaphragms, columns and walls as vertical load-bearing elements, and the foundation was considered as a supporting system interacting with the soil.

When creating a computational model, the mass of the building by floor, the location of the stiffness elements, the period of vibration, soil conditions, the intensity of the seismic region, the ductile performance of the structural system and the operational function are taken into account. While the static equivalent method is convenient for initial assessment for simple and regular buildings, spectral-dynamic analysis is more appropriate for buildings with multi-storey, uneven or complex volumetric-plan solutions.

The study evaluated structural solutions based on three criteria: the first is the ability to absorb and dissipate earthquake energy; the second is to keep inter-story displacements within regulatory limits; and the third is to ensure structural continuity so that local damage does not lead to progressive failure.

Theoretical foundations of earthquake load calculations

The impact of an earthquake is manifested as inertial forces transmitted to a structure through ground motion. The greater the mass of the building and the more unfavorable the vibration patterns of the structural system, the higher the required design level of seismic action. Therefore, at the initial stage of seismic design, it is important to reduce the mass of the building, rationally place the stiffening elements, and ensure structural symmetry.

In the equivalent static method, the total seismic shear force is determined as a function of the design mass and spectral acceleration of the building. This approach is explained by the following generalized expression:

$$V = S_d(T_1) \cdot M \cdot \lambda / q$$

where V is the total design seismic shear force at the foundation level; S_d(T_1) is the design spectral acceleration corresponding to the first natural vibration period; M is the design seismic mass of the building; λ is the vibration mode and the mass coefficient involved; q is the behavior coefficient representing the ductile behavior of the structural system.

The mass and height of the floor play a key role in the distribution of seismic forces across floors. In most cases, inertia forces increase on higher floors, since the amplitude of vibrations increases as the floor is further from the foundation. The distribution of the total seismic force across floors is described by the following expression:

$$F_i = V \cdot (m_i \cdot h_i) / S(m_j \cdot h_j)$$

where F_i is the seismic force acting on the i-th floor; m_i is the mass of the i-th floor; h_i is the height of the i-th floor above the foundation level; Σ(m_j·h_j) is the sum of the mass and height products for all floors.

In residential buildings, the relative displacement between floors should be monitored separately. If the displacements between floors exceed the regulatory limits, serious damage will occur to wall partitions, engineering networks, facade elements and interior finishing layers. The relative displacement between floors is determined as follows:

$$\theta_i = (D_i - D_{i-1}) / h_i$$

where θ_i is the relative displacement index of the i-th floor; Δ_i and Δ_{i-1} are the horizontal displacements of the i and lower floors, respectively; h_i is the floor height. This parameter is an important indicator in assessing the operational safety and damage level of the building.

Table 1. Seismic calculation steps and basic checks

Stage	Account content	Basic parameters	Project result
1	Determining seismic region and ground conditions	seismic intensity, soil type, geological section	the calculated seismic impact level is determined
2	Choosing a building structural scheme	frame, stiffening wall, diaphragm, foundation	a spatially functional system is formed
3	Mass calculation by floors	share of permanent and temporary loads	a base is created for seismic inertia forces
4	Spectral or equivalent static analysis	T1, Sd(T), q, λ, V	horizontal forces are taken along the floors
5	Interstory displacement and deflection inspection	Δ, θ, eccentricity	Soft floor and reduced risk of torsion
6	Constructive detailing	fittings, knots, anchoring, yokes	provides a reserve against ductile deformation and progressive failure

Principles of choosing a constructive system

In seismic areas, the main task of the structural system of a residential building is to continuously and safely transfer horizontal inertia forces to the foundation. In this regard, the vertical and horizontal elements of the structural system should be spatially interconnected, and the beams should act as rigid diaphragms. Discontinuities between structural elements, sharp changes in stiffness across floors, and asymmetry in the plan aggravate the seismic response.

Monolithic reinforced concrete frames are widely used in residential buildings, as they provide freedom in architectural design and allow for continuous reinforcement of nodes. However, it can be difficult to limit inter-story displacements for high-rise buildings with a column-beam frame system alone. Therefore, it is effective to design a monolithic frame in conjunction with stiffening walls, elevator shaft cores, or seismic diaphragms.

Retaining walls absorb most of the horizontal forces, reducing the overall deformation of the building. Their symmetrical arrangement in the plan reduces torsional vibrations. If the retaining walls are concentrated on only one side, the building will experience torsional moments during an earthquake, and the stresses in some vertical elements will increase sharply.

The foundation solution is a separate component of seismic stability. Plate foundation, lattice girder pile foundation or combined foundation systems are selected depending on the soil conditions and building height. In weak soils, not only the upper part of the structure, but also the soil-foundation-structure system should be analyzed together.

Table 2. Seismic efficiency of structural solutions for residential buildings

Constructive solution	Advantage	Limitation	Scope of application	Recommendation
Monolithic reinforced concrete frame	nodes are continuous, design freedom is high	If the stiffness is not sufficient, the displacement will increase.	medium and high-rise buildings	use in conjunction with a stiffening wall
Frame + stiffness walls	horizontal forces are effectively absorbed	If the plan is incorrectly placed, the risk of torsion increases.	7-16 storey residential buildings	symmetrical and continuous placement of walls
Nuclear system	the elevator and stair block act as a rigidity core	perimeter tightness may not be sufficient	multi-storey sectional houses	reliable connection of the outer shell with the core
Diaphragm valves	distributes horizontal loads to vertical elements	The more holes there are, the weaker the diaphragm becomes.	all seismic buildings	reinforcement of the diaphragm contour
Slab or pile foundation	reduces the risk of uneven sinking and tipping	requires geological survey	weak or complex grunts	soil-foundation-structure model inspection

Computational-constructive algorithm

The seismic calculation algorithm for a residential building should begin at the stage of the project assignment. Initially, the seismicity of the construction site, engineering and geological conditions, physical and mechanical properties of the soil and the level of groundwater are determined. At the next stage, the architectural and planning solution is analyzed from the point of view of constructive regularity. If the plan reveals sharp protrusions, long narrow blocks, large open first floors or uneven arrangement of stiffening elements, the project is revised in accordance with the requirements for seismic efficiency.

In the second stage, the structural system is selected. The optimal solution recommended for residential buildings is a monolithic reinforced concrete frame combined with an elevator-staircase core, stiffening walls and diaphragm walls. In this case, the vertical elements should be continuous from the foundation to the roof, the stiffness reduction by floors should be gradual, and the first floor should not become a soft floor.

At the third stage, the loads are calculated. Permanent loads include the weight of the structure itself, the weight of the walls and finishing layers, and engineering equipment. Temporary loads are determined by the operational loads of residential buildings and snow loads. In seismic calculations, a certain proportion of temporary loads is added to the design mass. As a result, the mass of the floors is determined and the coordinates of the center of mass are found.

In the fourth stage, a seismic analysis is performed. For regular, limited-height buildings, the equivalent static method is used as a preliminary calculation. For objects with complex plans, tall buildings, unevenly located stiffness elements, or complex ground conditions, a modal-spectral analysis should be performed. The calculation results include internal forces generated in columns, beams, walls, foundations, and rafters.

In the fifth stage, structural checks are carried out. Interstory displacement, torsion, overturning moment, foundation pressure, normal force and bending moments in vertical elements are checked. If interstory displacement exceeds the standard limit, the number and location of stiffening walls are revised or the cross-sections of structural elements are increased.

The sixth stage is structural detailing. In an earthquake-resistant building, reinforcement is not only a means of providing strength, but also a mechanism for absorbing energy and controlling plastic deformations. Therefore, the column-beam nodes, wall base, connection with the foundation, the contour of the diaphragm wall, and the openings must be designed based on a separate reinforcement scheme.

Table 3. Risk factors and mitigation measures identified at the project stage

Risk factor	**Seismic aftermath**	**Detection method**	**Constructive measure**
Soft first floor	floor mechanism and local collapse risk	Comparison of hardness by floor	adding a wall/diaphragm on the first floor, strengthening the column section
Center of mass and stiffness imbalance	torsional vibrations	eccentricity analysis by plan	symmetrical placement of stiffening walls
Vertical element break	the power flow is interrupted	structural scheme analysis	continuous continuation of columns and walls to the foundation
Big holes in the oraopma	the diaphragm weakens	check the travel plan	hole perimeter contour reinforcement and additional connecting elements
Weak ground and uneven subsidence	foundation deformation and slope displacement	geological survey, sedimentary calculation	slab or pile foundation, soil reinforcement

Proposed constructive solutions

1. Spatial frame-core system. In a residential building, a monolithic reinforced concrete core is formed around the elevator and stair blocks, and the external and internal columns are connected to the core by beams and struts. Such a system distributes part of the horizontal forces to the core and part to the frame, reducing the overall deformation.

2. Symmetrical rigid wall system. Rigid walls are placed in a balanced manner along the two main directions of the building. The wall should not be abruptly interrupted from floor to floor, but should be continuous from the foundation to the upper floors and monolithically connected with the surrounding diaphragms. It is not recommended to concentrate the walls along only one facade.

3. Reinforced concrete diaphragm walls. Monolithic reinforced concrete diaphragm walls distribute horizontal loads to the stiffening walls and frame elements. If the diaphragms have large engineering openings, contour reinforcement and additional connecting elements are used around them.

4. Ductile reinforcement. The main reinforcement against compression and bending in columns is carried out continuously, the yokes are tightened in the nodal zones, and the strong column - relatively ductile beam principle is applied so that plastic joints in beams are formed not at the columns, but at the controlled beam ends. This approach reduces the risk of progressive collapse.

5. Joint assessment of the foundation and soil. In weak soils, the deformation of the foundation has a significant impact on the overall seismic response of the building. Therefore, the choice of foundation slab, pile-grid or soil reinforcement measures is based on engineering and geological results. It is necessary to pre-evaluate the sharp unevenness of the stiffness and uneven settlements at the foundation level.

6. Monitoring-friendly design solution. In a modern seismic safety approach, a building should be monitored not only during the design and construction stages, but also during operation. In important residential complexes, it is advisable to include in the design control schemes for deformation joints, subsidence monitoring points, accelerometric monitoring, and assessment of the technical condition of structures.

Results and discussion

The analysis shows that the reliability of a seismically stable residential building is not limited to determining the calculated seismic force value. Real safety is achieved only when the calculation result is combined with the structural scheme, spatial connection of elements, quality of detailing and execution control during the construction process. Especially in monolithic reinforced concrete buildings, the quality of nodes, anchoring of reinforcement and compliance with the design grade of concrete play a key role.

The use of stiffening walls and core systems reduces inter-story displacements, but if they are incorrectly placed, the torsional response can increase. Therefore, it is necessary to place the stiffening elements in a balanced manner according to the plan, minimizing the eccentricity between the center of mass and the center of stiffness. This situation indicates that in residential buildings, the architectural plan should be developed in conjunction with the structural logic.

The influence of the foundation solution on the seismic response is also important. A strong superstructure may not provide the required stability due to weak soil or an incorrectly selected foundation. Therefore, the geological conditions of the construction site, groundwater, the possibility of subsidence and liquefaction of the soil, and the pressures under the foundation should also be evaluated in parallel with the seismic calculation.

The proposed algorithm for practical design combines the stages of seismic load determination, floor distribution, inter-floor displacement verification, structural system optimization, and ductile detailing into a single system. This approach strengthens the connection between the theoretical calculation and the real structural solution, which is important for scientific and practical research at the OAK level.

Conclusion

1. When designing seismically stable residential buildings, the calculation of earthquake loads should be performed in relation to the structural system of the building, soil conditions, distribution of mass across floors, and structural regularity.

2. The use of a monolithic reinforced concrete frame in combination with stiffening walls, an elevator-staircase core, and rigid diaphragm walls is an effective structural solution for multi-story residential buildings.

3. Interstory displacement, torsional response, soft floor risk, and continuity of vertical elements should be the main inspection criteria when evaluating seismic design results.

4. Ductile reinforcement, strengthening of nodal zones, proper anchorage lengths, and the formation of plastic joints in controlled locations increase seismic resistance.

5. Consideration of foundation and soil-structure interaction is an essential condition for seismic safety, especially in areas with weak soils.

6. Incorporating seismic monitoring, deformation control, and operational technical inspection capabilities at the design stage will increase the safety of residential buildings throughout their entire service life.

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