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DESIGN FEATURES OF A SIX-STOREY RESIDENTIAL BUILDING IN A HIGH-SEISMICITY AREA WITH SOFT SOILS

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ABSTRACT

Introduction. The design of mid-rise residential buildings in Almaty requires an integrated assessment of seismic hazard, soil conditions, structural regularity and spatial response. This study considers a six-storey residential building with a technical basement located in a high-seismicity zone with relatively soft soil conditions. **Materials and Methods.** The structural behaviour was evaluated using a three-dimensional finite-element model developed in LIRA-SAPR 2024. The model incorporated the adopted architectural and structural layout, engineering-geological data, climatic parameters, seismic zoning characteristics and design material properties. Material behaviour was assumed to be linear elastic, which corresponds to code-oriented seismic verification at the design stage. Permanent, imposed, snow and seismic loads were applied in accordance with Kazakhstan and Eurocode-based provisions. Foundation boundary conditions were represented by subgrade reaction coefficients derived from engineering-geological data. The verification procedure included modal analysis, plan and vertical regularity checks, assessment of storey stiffness and mass variation, inter-storey drift evaluation, and overturning and sliding stability checks. **Results and Discussion.** The first two natural vibration modes were predominantly translational, while the torsional mode did not govern the structural response. The displacement-based plan-regularity indicators did not exceed 10%, and the vertical regularity coefficients remained below 1.25. No soft storey was identified, overturning and sliding stability were ensured, and inter-storey drifts remained within permissible limits. **Conclusions.** The results demonstrate that an integrated verification procedure combining soil-condition assessment, seismic zoning data and spatial finite-element modelling provides a reliable basis for substantiating seismic safety of mid-rise residential buildings under complex seismic and geotechnical conditions.

KEYWORDS: seismic design; soft soils; structural regularity; modal analysis; overturning; sliding stability.

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1 INTRODUCTION

Seismic design of residential buildings in urban areas requires a case-specific assessment of the interaction between architectural layout, structural system, foundation solution and soil conditions. Mid-rise housing is often treated as a relatively standard building type; however, studies published in 2022-2025 show that seismic performance can differ substantially depending on the selected lateral-load-resisting system, soil flexibility and regularity of the structural configuration [1-4].

Soft and deformable soils are a key design factor because they can modify the dynamic characteristics of a building and change the distribution of seismic demand. Soil-structure interaction may increase the fundamental period, alter storey drifts, change base-shear estimates and affect the interpretation of code-based verification results [5-8]. For this reason, seismic design cannot be limited to member strength checks only; it should also include regularity, torsional response, foundation stability and damage-limitation criteria.

A significant group of studies has demonstrated that soil and foundation stiffness can influence the seismic response of reinforced concrete buildings, including mid-rise structures [6,9-12]. The effect can be beneficial in some situations and detrimental in others, depending on the relative stiffness of the soil-foundation-structure system, the frequency content of the ground motion, the height of the building and the selected structural scheme [5,13]. These findings are particularly relevant for cities located in foothill and seismically active regions, where soft soils and high seismic intensity may occur simultaneously.

Another important design issue is structural regularity. Plan irregularity, torsional sensitivity and vertical irregularity may lead to unfavourable concentration of deformation and internal forces during earthquakes [14-17]. In reinforced-concrete buildings, the location and continuity of walls, stair-lift cores and diaphragms strongly influence the relationship between translational and torsional modes. Therefore, the evaluation of modal forms, diaphragm displacements and storey stiffness distribution is a necessary stage of design verification.

In reinforced-concrete wall and mixed wall systems, the seismic response is controlled by the combined behaviour of vertical lateral-load-resisting elements and horizontal floor diaphragms. Wall –diaphragm interaction affects the transfer and redistribution of seismic forces and may influence both elastic and inelastic response mechanisms of the structural system [18]. The role of floor diaphragms becomes particularly important in buildings with plan irregularity or non-uniform stiffness distribution, where diaphragm flexibility can change dynamic properties, lateral displacement demand and design seismic parameters [19]. In addition, coupled wall systems depend on the efficiency of coupling elements, which influence energy dissipation, residual displacement and inter-storey drift response under earthquake loading [20]. These findings confirm the need for an integrated verification procedure that combines modal analysis, regularity checks, diaphragm action assessment and foundation stability verification for buildings located in high-seismicity areas with soft soils.

A recent critical review of seismic soil–structure interaction analysis emphasizes that SSI can be considered through analytical, numerical and experimental approaches, and that the selection of the modelling strategy should correspond to the purpose of the seismic assessment, the available soil data and the required level of accuracy [35].

The seismic behaviour of reinforced-concrete buildings is also influenced by the interaction between stiffness distribution, deformation capacity, damage mechanisms and the effectiveness of the lateral-load-resisting system. Gkournelos et al. [36], in their state-of-the-art review on seismic upgrading of existing reinforced-concrete buildings, emphasized that the seismic performance of RC structures should be assessed through a combination of global

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response characteristics, deformation demand and structural system behaviour. Although the present study deals with a newly designed building rather than the upgrading of an existing one, this review confirms the relevance of evaluating modal behaviour, inter-storey drifts, regularity and stiffness distribution as key indicators of seismic reliability.

Although soil-structure interaction, structural regularity and diaphragm action have been widely investigated as separate seismic design issues, a reproducible code-oriented verification sequence for mid-rise reinforced-concrete wall buildings founded on soft soils in high-seismicity urban areas remains insufficiently discussed. Existing studies usually focus on parametric soil-structure interaction models, nonlinear seismic response or individual irregularity indicators, whereas practical design verification requires the combined assessment of modal behaviour, diaphragm displacement response, plan and vertical regularity, soft-storey formation and foundation stability within one spatial finite-element model.

The object of this study is a representative of a class of mid-rise reinforced-concrete wall residential buildings with moderate plan elongation and raft foundations constructed on soft foothill soils in high-seismicity regions.

The study aims to demonstrate and substantiate a code-compatible set of methods for verifying the seismic reliability of such buildings using a three-dimensional finite-element model. It was hypothesized that, for mid-rise wall-type reinforced-concrete buildings on soft soils, seismic regularity is governed primarily by the spatial distribution of stiffness rather than by moderate variations in foundation compliance.

In addition, the study considers the sensitivity of the dynamic characteristics and inter-storey drift response to changes in the relative foundation stiffness. This makes it possible to interpret the analysed building not only as a single design case, but also as an example of the interaction between a mid-rise reinforced-concrete wall system and a deformable foundation soil.

The research tasks were: 1) to systematize the site-specific climatic, geotechnical and seismic input data; 2) to develop a spatial finite-element model of the building-foundation system; 3) to determine the governing modal characteristics and identify possible torsional sensitivity; 4) to assess plan and vertical regularity using displacement- and stiffness-based criteria; 5) to verify the absence of soft-storey behaviour; and 6) to evaluate overturning and sliding stability of the raft foundation under seismic load combinations.

The calculation checks were carried out with reference to the national regulatory framework of the Republic of Kazakhstan. The sources listed as [21–32], are national technical and normative documents, including Code of Practice of the Republic of Kazakhstan (SP RK) and Normative and Technical Manual of the Republic of Kazakhstan (NTP RK). These codes and manuals were used as the basis for performing the required structural, seismic, geotechnical and design verification checks. Their application ensured that the adopted calculation procedures and assessment criteria were consistent with the regulatory requirements currently used in engineering practice in Kazakhstan

2 METHODS AND MATERIALS

The research was conducted on the example of a six-storey reinforced-concrete residential building with a technical basement located in Almaty, Republic of Kazakhstan, in an area characterized by high seismicity and soft soil conditions.

2.1 The area, climatic and geotechnical conditions

The investigated site is located within the foothill plain of the Trans-Ili Alatau in the Turksib district of Almaty, Republic of

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Kazakhstan. The area is characterized by a continental climate with hot summers, relatively cold winters, high annual and daily temperature amplitudes, dry air and a change in climatic characteristics with altitude.

According to the climatic data for the Almaty meteorological station, the construction area belongs to climatic region III-B [21]. The site is assigned to snow region II; the characteristic ground snow load is 1.2 kPa according to the national provisions for snow loads [22,23]. The normative seasonal freezing depth is 0.79 m for loams, 0.96 m for sandy loams, 1.03 m for coarse and gravelly sands and 1.17 m for coarse-grained soils [21]. The described conditions correspond to a cold semi-arid continental climate, which in the Köppen system is typically close to BSk. The key indicators are the strong continentality, low air humidity, hot summers, cold winters, and relatively limited precipitation, which are consistent with a steppe-type climate in the Almaty foothill area.

The normative and design values of the soil cohesion, c (MPa), internal friction angle, φ (degrees), and deformation modulus, E (MPa), are presented in Table 1. The design values of the specified characteristics were determined taking into account the soil reliability factor in accordance with the requirements of the current regulatory documents.

Table 1. Physical and mechanical properties of soils

No.	Soil type	Unit weight, kN/m^3			Cohesion, MPa			Friction angle, deg			E,MPa
		γn	γn	γn	cn	cn	cn	φn	φn	φn	
1	Hard/semi-hard subsiding loam above GWL	17.7	17.0	16.5	0.023	0.023	0.015	21.4	21.1	15.6	5.2
					0.019*	0.019*	0.013*	17.8*	17.8*	15.4*	4.7*
2	Hard/semi-hard loam below GWL	20.9	20.8	20.7	0.036	0.033	0.034	24.1	23.6	22.7	8.2
3	Stiff loam	20.2	19.9	19.8	0.021	0.020	0.028	21.8	21.3	21.0	5.3
4	Soft-plastic loam	20.3	20.2	20.2	0.022	0.022	0.021	18.0	17.5	17.1	4.1
5	Flow-plastic loam	20.0	19.8	19.8	0.015	0.015	0.014	15.4	14.9	14.6	2.9
6	Gravelly sand	18.5	18.5	18.3	0.001	0.001	0.0007*	38.0	38.0	34.5	30.0
					0.001*	0.001*	0.0007*	34.0*	34.0*	30.9*	30.0

*Note: * properties are given for soils in a water-saturated state.*

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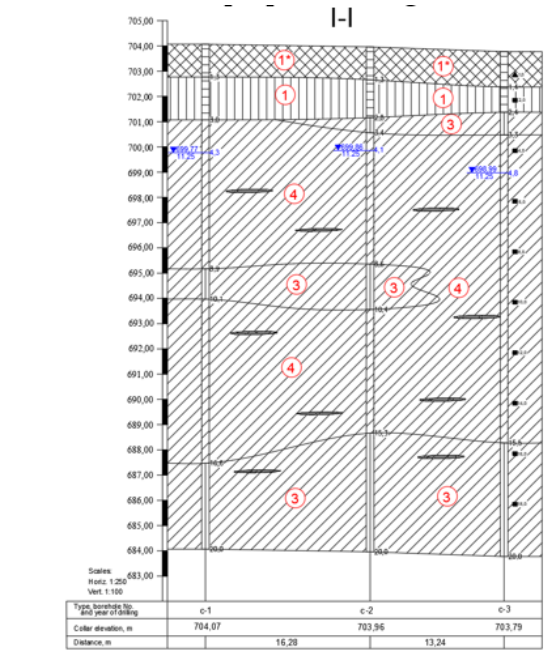


Fig. 1. Engineering-geological section along line 1-1. *Source: based on materials from the Engineering Geological Survey Report prepared by LLP "Almaty GIIZ", Archive No. 34–2025.*

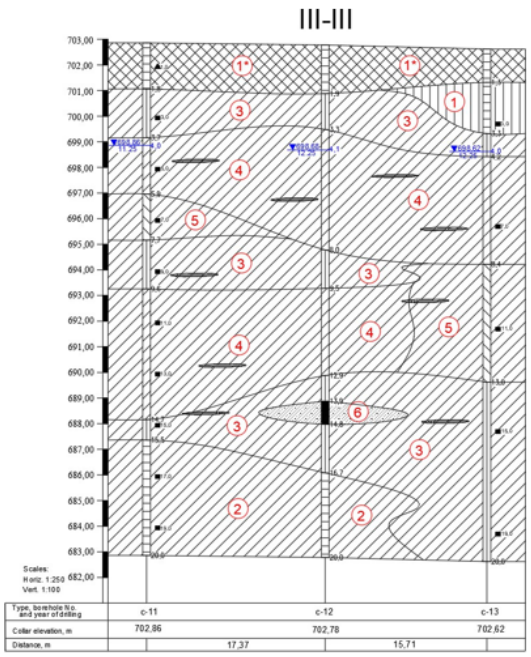


Fig. 2. Engineering-geological section along line 3-3. *Source: based on materials from the Engineering Geological Survey Report prepared by LLP "Almaty GIIZ", Archive No. 34–2025.*

According to the engineering-geological report and the seismic zoning provisions for Almaty, the regional seismic intensity is 9 points [24]. The site is located in zone III-A-1 of the seismic microzoning map SMZ-475 for Almaty [25]. The soil type by seismic properties is classified as Type III. The peak ground accelerations are 0.38 g for a 10% probability of exceedance in 50 years and 0.73 g for a 2% probability of exceedance in 50 years. The design horizontal peak ground acceleration was adopted as ag,d = 0.66 g, and the vertical design acceleration was adopted as avg,d = 0.594 g [26]. The refined seismic intensity of the construction site is 10 points.

The behaviour factor used to determine the design horizontal seismic loads was adopted as q = 4.2 in both the X - and Y - directions, in accordance with Table 2.1 of NTP RK 08-01.3-2021 [28]. For the structural system under consideration, which is characterized by a combination of coupled and uncoupled walls, the behaviour factor was adopted according to the conservative approach corresponding to a system with uncoupled walls.

2.2. Building description and finite-element model

The object of the study is a six-storey residential building with a technical basement. The total height from the ±0.000 level to the parapet or the upper point of the roof superstructure is 23.17 m; the height to the roof slab level, excluding the roof superstructure, is 19.90 m. The plan dimensions are 28.0 × 14.6 m.

The calculation model was developed in LIRA-SAPR 2024 Key No. 1030841252 as a three-dimensional finite-element model (Fig. 3–6). The model includes the main load-bearing and structural elements: raft foundation, reinforced-concrete walls, floor slabs, roof slab, columns, beams, stair-lift cores, parapet and roof superstructure. The model contains 26220 nodes and 26691 finite

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elements.

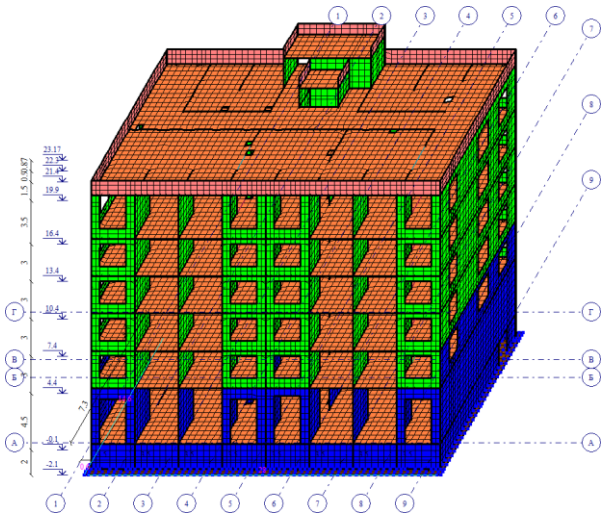


Fig. 3. Dimetric projection of the three-dimensional calculation model. *Source: authors' material*

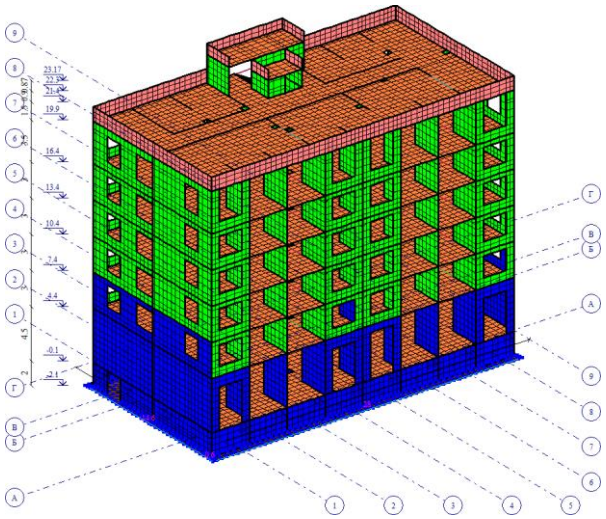


Fig. 4. Isometric projection of the three-dimensional calculation model. *Source: authors' material*



Fig. 5. Projection of the calculation model in the longitudinal vertical plane. *Source: authors' material*

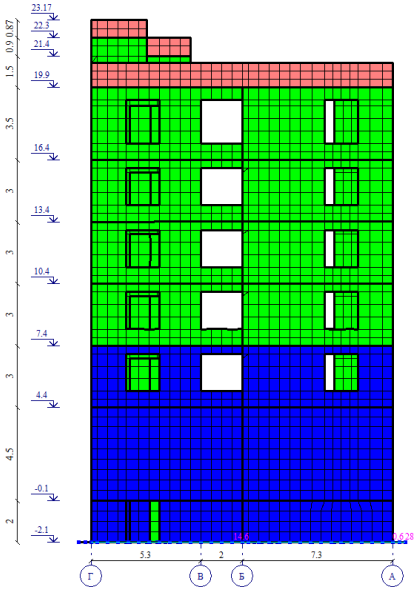


Fig. 6. Projection of the calculation model in the transverse vertical plane. *Source: authors' material*

The finite-element model was developed using plate, beam and bar-type finite elements. Plate finite elements were used to model reinforced-concrete floor slabs, walls and the raft foundation, while beam and bar-type elements were used for linear structural members and their equivalent bar analogues.

The adopted finite-element mesh size generally ranged from 0.30 to 0.50 m. A finer discretization, close to 0.30 m, was used in geometrically more complex zones and in areas where a more accurate transfer of stiffness and internal forces was required, whereas a mesh size close to 0.50 m was used

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in regular parts of the structural model.

Before performing the analysis, the calculation scheme was checked and packed in LIRA-SAPR. This procedure included merging coincident nodes, removing deleted or isolated nodes and ensuring the correct connectivity of adjacent finite elements. Such preprocessing was necessary to avoid artificial discontinuities in stiffness transfer between connected structural components.

The stiffness types and material properties used in the model are shown in Fig. 8. The material models adopted in the finite-element analysis were defined as linear elastic models. For reinforced-concrete structural elements, including walls, floor slabs, roof slabs, beams, columns and the raft foundation, an isotropic linear elastic constitutive law was used. The stress–strain relationship was described by Hooke's law using the elastic modulus, Poisson's ratio and unit weight assigned to the corresponding stiffness types in LIRA-SAPR 2024. The material parameters were adopted according to the design material classes specified in the structural design documentation and in accordance with the Kazakhstan and Eurocode-based provisions for reinforced-concrete structures, including SP RK EN 1992-1-1:2004/2011 [32] and the relevant seismic design provisions [26–29].

The reinforced-concrete elements were represented by equivalent elastic stiffness parameters at the global structural analysis stage. Reinforcement was not modelled as discrete bars in the spatial finite-element model; its influence was taken into account through the adopted design stiffness characteristics and subsequent structural verification procedures. Nonlinear cracking of concrete, reinforcement yielding, local crushing, cyclic stiffness degradation and nonlinear material behaviour were not included in the present model. This modelling assumption is consistent with the objective of the study, which is focused on code-oriented seismic verification, modal behaviour, regularity assessment, inter-storey drifts and foundation stability rather than on nonlinear performance-based seismic analysis.

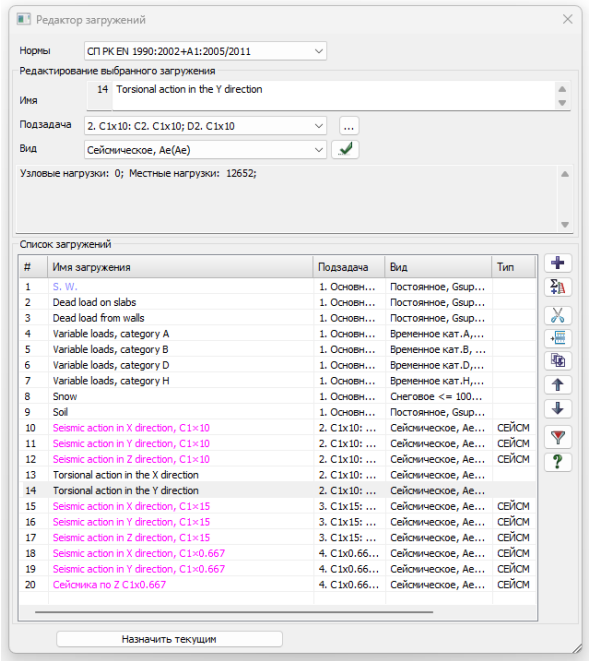


Fig. 7. Load case editor showing static and dynamic load cases. *Source: authors' material*

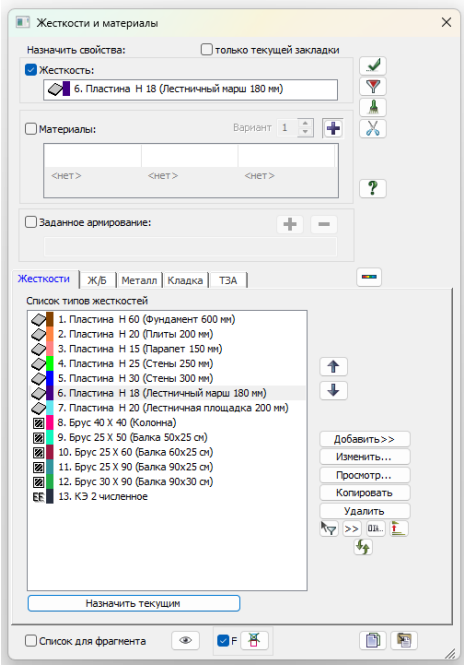


Fig. 8. List of stiffness types and material properties used in the model. *Source: authors' material*

Fourteen load cases were considered, including nine static actions and five dynamic

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actions related to seismic loading and torsion. The combinations of actions and seismic effects were assigned in accordance with the relevant Kazakhstan seismic design and Eurocode-based provisions.

The boundary conditions of the foundation were represented by vertical subgrade reaction coefficients $C_{1\ z}$ assigned at the base of the raft foundation. The initial static subgrade reaction coefficient was adopted as $K_{stat} = 350$ tf/m^3 . In accordance with Appendix D of SP RK 2.03-30-2017* [24], when experimental data on elastic wave propagation velocities are not available, the deformation modulus obtained from static tests may be increased by a factor of 10 to form the equivalent elastic stiffness of the foundation soil. Therefore, the basic equivalent stiffness used in the seismic calculation model was adopted as $K_0 = 10\ K_{stat} = 3500$ tf / m^3 .

To account for the possible variability of soil stiffness, three calculation variants of the "building–foundation–soil" system were considered: a basic model with $K_0 = 3500$ tf/m^3, an increased-stiffness model with K_1=1.5 K_0=5250 tf/m^3, and a reduced-stiffness model with K_2=K_0/1.5= 2333 tf/m^3. In all three variants, the geometry, structural stiffness and loading scheme of the building were kept unchanged. This approach made it possible to evaluate the sensitivity of the global seismic response to changes in the foundation stiffness.

To quantify the influence of foundation compliance, a relative foundation stiffness parameter was introduced as:

$$\eta = \frac{k_s}{k_{s,0}}, 0 \qquad (1)$$

where: k_s - is the adopted subgrade reaction coefficient and $k_{s,0}$ is the basic equivalent foundation stiffness used in the reference model. The analysed values were $\eta = 0.67$, 1.00, and 1.50, corresponding to the reduced, basic and increased stiffness models, respectively. For each model, the natural periods, modal sequence, maximum floor displacements and inter-storey drift increments were compared with the basic model.

The sensitivity of the dynamic characteristics was additionally interpreted using the dimensionless frequency parameter:

$$\alpha_0 = \frac{wr}{V_s}, \qquad (2)$$

where: ω - is the circular natural frequency of the corresponding vibration mode; r - is the characteristic foundation dimension, and V_s - is the shear-wave velocity of the soil. In the absence of direct field measurements of V s, this parameter was used as an interpretative indicator linking the structural frequency, foundation size and soil deformability. Lower values of α_0 correspond to a relatively more flexible soil-foundation system, whereas higher values indicate a stiffer dynamic interaction regime.

A reduction in foundation stiffness primarily increased translational flexibility while having a limited influence on torsional response, indicating that the investigated structural system is more sensitive to global translational compliance than to torsional instability.

2.3 Post-processing and evaluation procedure

The post-processing stage was organized as a sequence of extraction, comparison and verification of global response parameters obtained from the finite-element model. The extracted output data included natural periods and mode shapes, modal vibration directions, maximum roof displacements, maximum and minimum diaphragm displacements, average floor displacements, inter-storey displacement differences, equivalent storey stiffness values, storey masses, regularity coefficients, overturning moments, resisting moments, sliding forces and foundation stability coefficients. These parameters were selected because they directly characterize the spatial seismic behaviour of the building, including translational and torsional response, stiffness distribution, diaphragm displacement uniformity, soft-storey risk and global foundation stability.

The extracted results were evaluated by comparing them with the adopted code-based verification criteria. The modal characteristics

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were used to identify whether the first vibration modes were translational or torsional. The diaphragm displacement indicators were used for the plan-regularity assessment, while inter-storey displacement differences and mass–stiffness ratios were used for the vertical-regularity assessment. Equivalent storey stiffness values were analysed to identify possible storeys with reduced lateral stiffness. Overturning and sliding stability were assessed by comparing the calculated destabilizing effects with the corresponding resisting effects. Therefore, the post-processing procedure was not limited to the extraction of numerical results, but was used as the basis for the integrated assessment of regularity, spatial behaviour and seismic reliability of the building.

2.4 Justification of finite-element modelling assumptions

The adopted finite-element modelling assumptions were selected in accordance with the objective of the study, which is focused on code-oriented seismic verification at the design stage rather than on nonlinear performance-based seismic assessment. The use of plate finite elements for reinforced-concrete walls, floor slabs and the raft foundation makes it possible to represent the spatial stiffness of the main load-bearing system and the diaphragm action of floor slabs. Beam and bar-type finite elements were used for linear structural members and equivalent bar analogues, which is appropriate for the global analysis of the building's spatial response.

The assumption of linear elastic material behaviour is suitable for the considered verification task because the main control parameters of the study are natural periods, modal shapes, floor displacements, inter-storey drifts, regularity coefficients and foundation stability coefficients. These parameters are primarily governed by the global stiffness distribution and mass configuration of the structural system. Nonlinear cracking of concrete, reinforcement yielding, cyclic stiffness degradation and nonlinear soil behaviour were not included in the present model; these effects are beyond the scope of the adopted design-stage verification procedure and are explicitly treated as limitations of the study.

The foundation-soil interaction was represented by vertical subgrade reaction coefficients C_{1z} assigned at the base of the raft foundation. This simplified elastic representation is appropriate for comparing the influence of foundation stiffness on the global seismic response of the building. To reduce the uncertainty associated with soil stiffness, three variants of the "building-foundation-soil" system were analysed using the basic, increased and reduced values of the equivalent foundation stiffness. Thus, the adopted modelling assumptions provide a reproducible and sufficiently detailed basis for assessing the global seismic behaviour of the investigated mid-rise reinforced-concrete building under the selected code-based verification criteria.

3 RESULTS AND DISCUSSION

3.1 Modal behaviour of the building

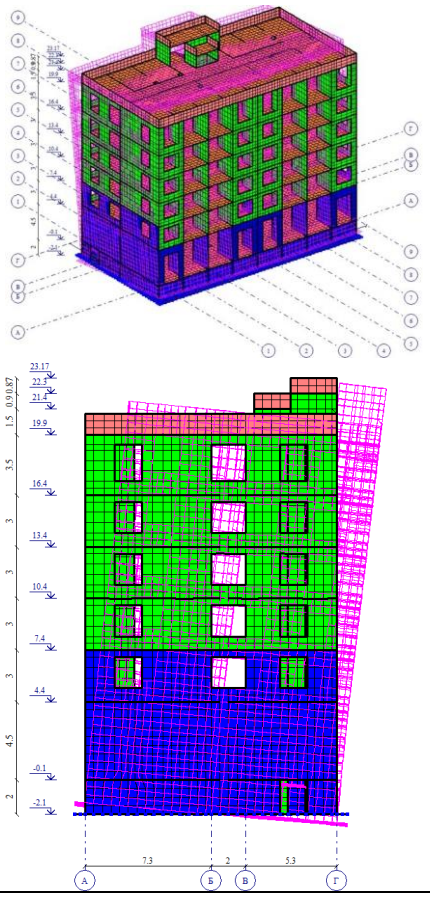
Modal analysis is a key stage of seismic verification because it makes it possible to identify the governing dynamic characteristics of the structural system before performing regularity and displacement-based checks. For buildings located in high-seismicity areas, the evaluation of natural vibration modes is particularly important for determining whether the global response is governed by translational or torsional behaviour. The sequence and type of the first vibration modes provide an indication of the spatial stiffness distribution, the effectiveness of the lateral-load-resisting system and the possible sensitivity of the building to torsional effects.

In the present study, modal analysis was performed to determine the main dynamic characteristics of the building, including vibration directions, natural periods, the

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distribution of mass and stiffness participation, and possible torsional effects. The first two modes of the basic-stiffness model are predominantly translational and are shown with mode-shape illustrations in Table 2. Table 3 presents the corresponding sensitivity analysis for the reduced and increased foundation stiffness coefficients. In all considered cases, the third mode remains torsional and has a shorter period than the first two modes. This modal sequence indicates that the torsional response does not govern the global dynamic behaviour of the building and that the adopted reinforced-concrete wall system provides a sufficiently regular spatial stiffness distribution at the elastic analysis stage.

Table 2. Results of natural vibration mode analysis

Mode No.	Vibration type	Direction	Period, s	Mode shape illustration
1	Translational	In the Y direction	0.4251	

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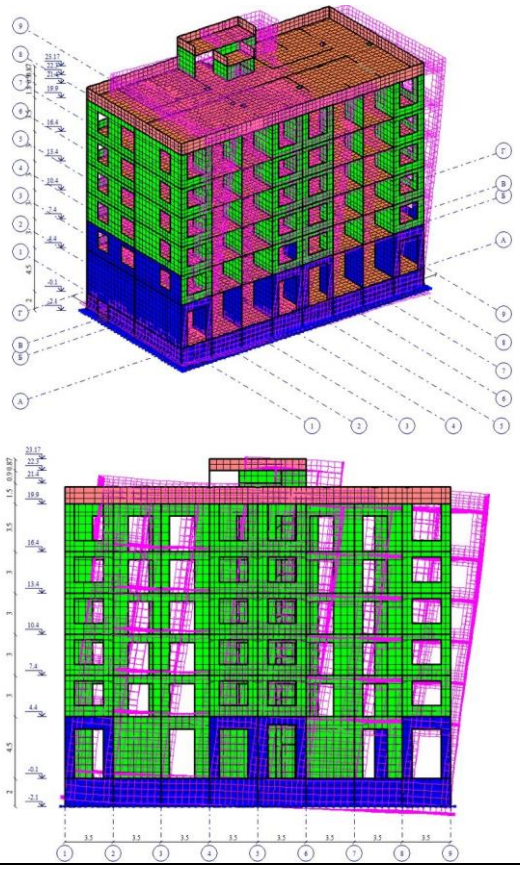
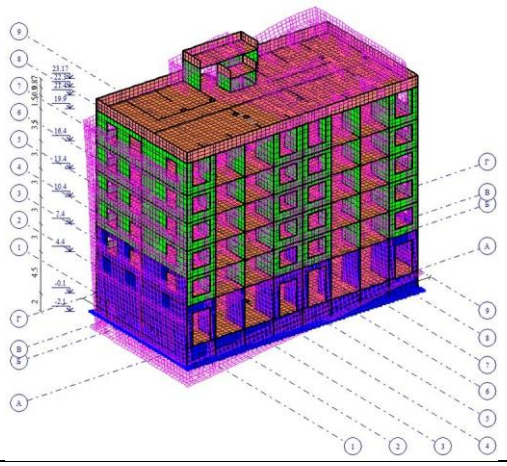
2	Translational	In the X direction	0.3259	
3	Torsional	About axis Z	0.2465	

Table 3. Sensitivity of modal characteristics to relative foundation stiffness

Model	Relative foundation stiffness η	T_1, s	ΔT_1, %	T_2, s	ΔT_2, %	T_3, s	ΔT_3, %
Reduced stiffness	0.67	0.4877	+14.7	0.3552	+9.0	0.2620	+6.3
Basic stiffness	1.00	0.4251	0.0	0.3259	0.0	0.2465	0.0
Increased stiffness	1.50	0.3810	-10.4	0.3073	-5.7	0.2390	-3.0

The comparison shows that the reduction of the relative foundation stiffness to η = 0.67 increases the first translational period by 14.7%, the second translational period by 9.0%, and the torsional period by 6.3% compared with the basic model. Conversely, increasing the foundation stiffness to η = 1.50 reduces the corresponding periods by 10.4%,

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5.7%, and 3.0%, respectively. The greatest sensitivity is observed for the first translational mode, which confirms that the analysed building–foundation system is primarily affected by global translational compliance. At the same time, the torsional mode remains the third mode in all stiffness variants, indicating that moderate changes in foundation stiffness do not change the governing type of dynamic response.

3.2 Plan regularity

The plan regularity was evaluated using displacement-based criteria for floor diaphragms. The governing values were compared with the 10% limit (Table 4).

Table 4. Floor diaphragm horizontal displacements for natural modes 2 (SX) and 1 (SY) and plan-regularity check according to condition ≤10%.

Level, m	Mode 2 (*SX*)				Mode 1 (*SY*)			
	δ_{min} *SX* mm	δ_{max} *SX* mm	δ_{avg} *SX* mm	*Condition* ≤ 10%, *SX*	δmin *SY* mm	Δmax *SY* mm	δ_{avg} *SY* mm	*Condition* ≤ 10%, *SY*
-2.10	0.00	0.00	0.00	-	0.00	0.00	0.00	-
-0.10	0.70	0.77	0.73	4.63	1.99	2.00	2.00	0.25
4.40	3.20	3.74	3.47	7.22	6.73	6.79	6.76	0.44
7.40	5.30	6.22	5.76	7.40	10.40	10.50	10.45	0.48
10.40	7.58	8.93	8.26	7.56	14.30	14.30	14.30	0.00
13.40	9.77	11.50	10.64	7.52	18.10	18.10	18.10	0.00
16.40	11.70	13.80	12.75	7.61	21.70	21.80	21.75	0.23
19.90	13.70	15.90	14.80	6.92	25.80	25.80	25.80	0.00

Analysis of Table 4 shows that the ≤10% requirement is satisfied. According to this criterion, the building is classified as regular in plan.

Table 5 presents the results of checking the building's compliance with the plan regularity requirements according to the 10% limit criterion.

Table 5. Plan-regularity check according to condition ≤ 10%, for seismic actions in the principal directions.

Level, m	Condition ≤ 10%, along axis X (Mode 2, S_X)	Condition ≤ 10%, along axis Y , (Mode 1, S_Y)
-2.10	0.000	0.000
-0.10	7.000	2.370
4.40	0.129	2.660
7.40	0.339	2.240
10.40	0.506	1.660
13.40	0.442	1.510
16.40	0.449	1.680
19.90	0.342	2.090

The analysis of the calculated horizontal displacements of the floor diaphragms

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presented in Table 4, performed with due consideration of their actual in-plane deformability, showed that the difference does not exceed 10% at all considered levels. According to this criterion, the building is classified as regular in plan.

3.3 Vertical regularity and stiffness distribution

Table 6 presents the results of checking the building for compliance with the criteria of structural regularity in elevation.

The assessment was carried out based on the analysis of the vertical distribution of displacements, interstorey displacement differences, and stiffness coefficients between adjacent levels.

Table 6. Storey regularity check along the building height according to condition ≤ 1.25

Level, m	Storey height, m	Horizontal displacement in direction X, mm	Inter-storey displacement difference in direction X, mm	Regularity coefficient in direction (Condition ≤ 1.25)	Horizontal displacement along axis Y, mm	Inter-storey displacement difference in direction Y, mm	Regularity coefficient in direction Y (Condition ≤ 1.25)
-2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-0.10	2.00	0.61	2.85	0.81	1.96	4.90	0.88
4.40	4.50	3.46	2.32	0.93	6.88	3.72	0.98
7.40	3.00	5.78	2.49	1.07	10.60	3.80	1.00
10.40	3.00	8.27	2.33	1.06	14.40	3.80	1.03
13.40	3.00	10.60	2.20	1.22	18.20	3.70	1.05
16.40	3.00	12.80	2.10	0.80	21.90	4.10	0.90
19.90	3.50	14.90	0.00	0.00	26.00	0.00	0.00

According to the data presented in Table 7, the regularity coefficients in the X and Y directions do not exceed 1.25 at all considered levels. According to this criterion, the building is classified as regular in elevation.

3.4 Check of the variation in stiffness and mass along the height

The check of the variation in stiffness and mass along the height was performed by comparing the horizontal stiffness values (C_i , X , C_i , Y)and masses (mi)of adjacent storeys, with an assessment of their relative variation between levels. The results are presented in Table 8.

The criterion is considered to be satisfied if the values of C_i, X, C_i,Y , and mi, as a rule, remain approximately constant or gradually decrease from the base to the top of the building without abrupt changes exceeding 30%, that is, provided that the following conditions are met: $\Delta C_{i,X} / C_{i,X} \leq 0.30$, $\Delta C_{i,Y} / C_{i,Y} \leq 0.30$, $\Delta m_i / m_i \leq 0.30$ for adjacent storeys.

Table 8. Check of horizontal stiffness and mass variation along the building height

Level, m	$a_{x,i}$ m	$a_{y,i}$ m	$F_{x,i}$ tf	$F_{y,i}$ tf	$C_{x,i}$ tf / m	$C_{y,i}$ tf / m	$\Delta C_{i,X} / C_{i,X}$ %	$\Delta C_{i,Y} / C_{i,Y}$ %	m_i t	$\Delta m_i / mi$ %

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-0.10	0.02	0.03	398.55	398.55	18799.53	13464.53	not defined	not defined	1082.00	not defined
4.40	0.25	0.10	398.55	398.55	1626.73	3832.21	15.57	8.90	807.00	2.11
7.40	0.21	0.10	398.55	398.55	1879.95	4173.30	0.00	0.31	790.00	0.00
10.40	0.21	0.10	398.55	398.55	1879.95	4160.23	0.00	0.42	790.00	0.00
13.40	0.21	0.10	398.55	398.55	1879.95	4142.93	0.93	1.33	790.00	8.99
16.40	0.21	0.10	398.55	398.55	1862.38	4087.69	–	–	861.00	–

According to the data presented in Table 8, the relative variation in the horizontal stiffness values $C_{i,X}$, $C_{i,Y}$, and masses m_i between adjacent storeys does not exceed 30%. Therefore, for the storey part of the building, the requirement for a gradual variation in stiffness and mass along the height is satisfied.

3.5 Soft-storey assessment

Equivalent horizontal stiffness was evaluated in both principal directions to identify possible storeys with reduced lateral stiffness (Table 9).

Table 9. Storey equivalent horizontal stiffness and verification coefficients in the X and Y directions

Level, m	$a_{x,i}$ m	$a_{y,i}$ m	$F_{x,i}$ tf	$F_{y,i}$ tf	$C_{x,i}$ tf/m	$C_{y,i}$ tf/m	$\eta^{(1)}_{x,i}$ ≥0.7	$\eta^{(1)}_{y,i}$ ≥0.7	$\eta^{(2)}_{x,i}$ ≥0.8	$\eta^{(2)}_{y,i}$ ≥0.8
-0.10	0.02	0.03	398.55	398.55	18799.53	13464.53	11.56	3.51	10.47	3.32
4.40	0.25	0.10	398.55	398.55	1626.73	3832.21	0.87	0.92	0.87	0.92
7.40	0.21	0.10	398.55	398.55	1879.95	4173.30	1.00	1.00	1.00	1.01
10.40	0.21	0.10	398.55	398.55	1879.95	4160.23	1.00	1.00	1.09	1.08
13.40	0.21	0.10	398.55	398.55	1879.95	4142.93	1.01	1.01	1.71	1.68
16.40	0.21	0.10	398.55	398.55	1862.38	4087.69	1.30	1.23	3.90	3.69
19.90	0.28	0.12	398.55	398.55	1433.63	3321.25	not defined	not defined	not defined	not defined

Based on the storey-by-storey comparison of the equivalent horizontal stiffness values $C_{x,i}$ and $C_{y,i}$ presented in Table 9, it was established that, for all levels for which the check was performed, the criteria confirming the absence of storeys with reduced stiffness are satisfied.

3.6 Foundation stability and basement wall verification

Overturning and sliding stability checks were carried out for the special seismic load combination, considering the actual raft dimensions, design building weight and the adopted resistance components. Table 10 presents the input data and the calculated stability coefficients, which make it possible to compare the resisting and overturning effects in the X and Y directions.

Table 10. Overturning stability check

Parameter	Value along axis X	Value along axis Y
Building height, m	H = 23.17	
Foundation slab size, m	L_x = 28.65	L_y = 15.80

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Total design building weight (seismic combination), t_f	P_z = 5577.08	
Total resisting moment, $t_f \cdot m$	$M_{res,\ x}$ = 44059.00	$M_{res,\ y}$ = 79891.70
Horizontal seismic forces, t_f	P_x = 1226.00	P_y = 1288.00
Overturning moment, $t_f \cdot m$	$M_{over,\ x}$ = 19895.30	$M_{over,\ y}$ = 18937.60
Overturning stability coefficient	k_x = 2.215> 1.8	k_y = 4.219 > 1.8

The check of the building stability against overturning, presented in Table 10, showed that in both directions, the obtained values exceed the required value of 1.8. Therefore, the building stability against overturning is ensured under the adopted accidental load combination.

Check of stability against sliding at the foundation base level

To confirm the foundation stability against sliding, a check of the ratio between the total resisting and sliding forces was performed, as presented in Table 11.

Table 11. Sliding stability check at the foundation base level

Calculation variant (assumptions)	$\sum F_{res}$, tf	$\sum F_{sd}$, tf	$k = \frac{\sum F_{res}}{\sum F_{sd}} \geq 1.5$
Basic case considering passive earth pressure (E_p), active earth pressure (E_a), friction, and cohesion	3897.57	1146.11	3.40
Conservative case: soil acts on one side only, (E_p=0)	3244.85	1146.11	2.83
Conservative case: (E_p=0), (E_a=0), (c=0)	2185.60	1297.84	1.68

According to the data presented in Table 11, the foundation stability against sliding is ensured in all considered cases.

Sensitivity analysis of soil-structure interaction parameters

The obtained first translational periods of 0.4251 s and 0.3259 s, together with the torsional period of 0.2465 s, indicate a relatively stiff reinforced-concrete wall system in which the torsional mode does not govern the dynamic response. The obtained response suggests that the combination of continuous floor diaphragms and distributed wall stiffness reduces eccentricity between the centres of mass and rigidity, thereby limiting torsional amplification. This result is consistent with recent soil - structure interaction studies showing that the global seismic response of reinforced-concrete buildings depends on the relative stiffness of the soil–foundation–structure system, foundation modelling assumptions and seismic input characteristics [33,34].

Requena García de la Cruz et al. [33] showed that the consideration of soil-structure interaction may modify the seismic vulnerability and global response of mid-rise reinforced-concrete buildings. Zhang and Far [34] also demonstrated that dynamic soil-structure interaction can have both beneficial and unfavourable effects depending on soil stiffness, structural system and earthquake input.

In the present study, the influence of foundation stiffness was considered through three variants of the "building-foundation-soil" system: K_0 = 3500 tf / m^3, K_1 = 1.5, K_0 = 5250 tf / m^3 and $K_2 = K_0 / 1.5$ = 2333 tf / m^3. In all variants, the geometry, structural stiffness and loading scheme of the building were kept

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unchanged.

The influence of foundation stiffness was further assessed by comparing the relative increments of inter-storey drifts with respect to the basic model. The relative foundation stiffness was expressed as $\eta = k_s / k_{s,0}$, where $k_{s,0}$ corresponds to the basic equivalent stiffness of the foundation soil. The reduced, basic and increased stiffness models therefore corresponded to $\eta = 0.67$, 1.00, and 1.50, respectively.

The inter-storey drift increment was calculated as

$$\Delta\theta_i = \frac{\theta_i(\eta) - \theta_i(1.0)}{\theta_i(1.0)} \times 100\% \quad (3)$$

where: $\theta_i(\eta)$ - is the inter-storey drift of the i-th storey for the considered foundation stiffness model, and $\theta_i(1.0)$ is the corresponding value in the basic model. This normalization made it possible to compare the sensitivity of different storeys independently of the absolute drift values.

The obtained results indicate that the decrease in foundation stiffness leads to an increase in inter-storey drift demand, especially in the lower and middle storeys, where the interaction between the raft foundation and the vertical wall system has the greatest influence on the global deformation shape. Conversely, the increase in foundation stiffness reduces the drift increments but does not significantly change the distribution pattern along the building height. Thus, the response is not governed by a local soft-storey mechanism, but by the overall translational flexibility of the soil–foundation–structure system.

The same tendency can be interpreted through the dimensionless frequency parameter $\alpha_0 = \omega r / V_s$. A decrease in soil stiffness is associated with a reduction in the effective shear-wave velocity and, consequently, with a change in the dynamic interaction regime. However, within the considered range of foundation stiffness variation, the modal sequence remained stable: the first two modes were translational and the torsional mode did not become governing. This confirms that the analysed mid-rise wall-type building is more sensitive to changes in translational compliance than to torsional instability.

The adopted approach corresponds to a simplified elastic representation of foundation compliance using vertical subgrade reaction coefficients. According to Bharti et al. [35], soil-structure interaction may be studied using analytical, numerical and experimental approaches with different levels of complexity. Therefore, the use of subgrade reaction coefficients and stiffness-variation models is appropriate for global design-stage seismic verification, while more advanced nonlinear soil–structure interaction modelling may be considered in future research.

In addition, the review by Gkournelos et al. [36] supports the need to interpret the seismic reliability of reinforced-concrete buildings through combined indicators of global response, deformation demand and structural system behaviour, rather than through isolated strength checks only.

The results should be interpreted within the assumptions of the adopted linear-elastic model. The analysis did not include nonlinear cracking of reinforced concrete, reinforcement yielding, cyclic degradation of stiffness, nonlinear soil behaviour, possible separation or sliding at the soil–foundation interface, or nonlinear time-history analysis. Therefore, the proposed verification sequence is suitable for design-stage substantiation of seismic reliability, but it should not be interpreted as a full nonlinear performance-based seismic assessment.

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4 CONCLUSION

The investigated building may be considered representative of a class of mid-rise reinforced-concrete wall residential buildings with moderate plan elongation and raft foundations constructed on soft foothill soils in high-seismicity regions. The study aimed to demonstrate and substantiate a code-compatible set of methods for verifying the seismic reliability of such buildings using a three-dimensional finite-element model. The study comprised the following investigations: (1) the systematization of site-specific climatic, geotechnical, and seismic input data; (2) the development of a three-dimensional finite-element model of the soil–structure system; (3) the determination of the governing modal characteristics and the identification of potential torsional sensitivity; (4) the assessment of plan and vertical regularity in accordance with displacement- and stiffness-based criteria; (5) the verification of the absence of soft-storey behavior; and (6) the evaluation of the overturning and sliding stability of the raft foundation under prescribed seismic load combinations.

Based on the obtained results, the following conclusions can be drawn.

1. A code-oriented sequence of finite-element verification methods was structured for a six-storey reinforced-concrete residential building located in Almaty, Republic of Kazakhstan, under high-seismicity and soft-soil conditions. The proposed sequence combines site-specific seismic input data, geotechnical parameters, modal analysis, plan and vertical regularity checks, soft-storey assessment, and foundation stability verification within a single spatial calculation model.

2. The modal analysis showed that the first two vibration modes were predominantly translational, with periods of 0.4251 s and 0.3259 s, while the third mode was torsional with a shorter period of 0.2465 s. This indicates that the torsional response did not govern the global dynamic behaviour of the investigated building. The obtained modal sequence indicates that, for mid-rise reinforced-concrete wall buildings founded on soft soils, the spatial continuity and symmetric distribution of wall-type lateral-load-resisting elements may suppress torsional dominance even under reduced foundation stiffness.

3. The displacement-based plan-regularity assessment confirmed that the adopted reinforced-concrete wall system provided a balanced distribution of horizontal stiffness. The maximum plan-irregularity indicators did not exceed the adopted 10% limit, with governing values of 7.00% and 2.66% in the principal directions.

4. The vertical-regularity and soft-storey checks showed that no abrupt discontinuity of storey stiffness or deformation demand occurred along the building height. The maximum regularity coefficients were 1.22 and 1.05 for inter-storey displacement behaviour and 1.07 and 1.14 for mass-stiffness distribution, which remained below the adopted limit of 1.25. It was established that, for mid-rise reinforced-concrete wall buildings on soft soils, spatial continuity and balanced distribution of wall-type lateral-load-resisting elements play a more important role in maintaining seismic regularity than local increases in floor stiffness.

5. The foundation stability verification demonstrated sufficient safety margins under seismic load combinations. The overturning stability coefficients were 2.215 and 4.219 in the two principal directions, exceeding the required value of 1.8. The sliding stability coefficients were 3.40, 2.83 and 1.68 for the considered calculation assumptions, confirming stability even under the limiting conservative variant. The performed sensitivity analysis showed that the reduction of foundation stiffness increases the global translational flexibility and produces measurable increments in inter-storey drift demand. However, within the considered range of relative foundation stiffness, the

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modal sequence remained stable and the torsional mode did not become governing. The interpretation using the dimensionless frequency parameter $\alpha 0 = \omega r / V s$ confirms that the seismic response of the analysed building is controlled mainly by the relationship between translational structural stiffness, foundation compliance and soil deformability, rather than by torsional instability.

6. The scientific contribution of the study consists in the integrated presentation of a reproducible verification sequence for mid-rise reinforced-concrete wall buildings on soft soils in high-seismicity areas. The obtained results show that seismic reliability in such conditions should be assessed not by isolated strength checks, but by the combined evaluation of soil conditions, modal behaviour, diaphragm displacements, regularity criteria, soft-storey risk and foundation stability.

7. The limitations of the study are related to the linear-elastic character of the finite-element model and the absence of nonlinear material behaviour, nonlinear soil response and nonlinear time-history analysis. Further research should include a wider parametric variation of the dimensionless frequency parameter $\alpha 0$, nonlinear soil behaviour, cracking and cyclic stiffness degradation in order to quantify the transition from code-oriented elastic verification to performance-based seismic assessment.

8. The study confirms that seismic reliability of mid-rise buildings on soft soils is governed by the interaction between foundation compliance, diaphragm action, wall stiffness distribution and modal characteristics rather than by isolated strength parameters alone. The proposed verification sequence may be applied to other mid-rise reinforced-concrete residential buildings with raft foundations and wall-type lateral-load-resisting systems located on deformable soils in high-seismicity regions. The applicability of the obtained results is limited to wall-system buildings with a height of approximately 20-30 m, regular geometric configuration, a linear-elastic formulation, and no pronounced asymmetry.

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During the preparation of this manuscript, the authors used [tool name, version] solely for language editing and grammar checking. The authors reviewed and edited the output and take full responsibility for the scientific content, analyses, interpretations and conclusions of the article.

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