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Optimizing Foundations: The Case for Slab Selection in Multi-Story Residential Buildings: Mengoptimalkan Pondasi: Kasus Pemilihan Pelat pada Bangunan Tempat Tinggal Bertingkat

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This study investigates the optimal foundation design for multi-story residential buildings through a comparative analysis of two foundation variants under specific geological conditions. Employing the finite element method via SCAD software, we assessed the structural integrity and load-bearing capacities of the foundation options. Material consumption was quantified for each variant, and the consistency of settling calculations for the slab foundation was evaluated. The results indicated that the slab foundation not only minimizes material usage but also simplifies design complexity according to normative standards. Based on technical and economic assessments, the slab foundation is recommended as the most cost-effective and structurally efficient option for such construction projects. This research provides a pivotal foundation design perspective that could influence future architectural and engineering practices in residential building construction.

Highlights:

- SCAD software validates foundation integrity via finite element analysis.
- Slab foundations offer superior cost and material efficiency.
- Simplifies design, enhancing construction process efficiency.

Keywords: Structural Integrity, Slab Foundation, Reinforcement, Monolith, Building

Introduction

Atyrau is a city of the European Kazakhstani part and an administrative center of the Atyrau region. The city is located in the western part of the country along the Ural river shore. Atyrau is one of the biggest cities in Western Kazakhstan.

Geotechnical aspects of building design on loose soil that is typical for the Atyrau region territory are greatly important due to the reason that foundations analysis is not carried out properly without the foundations' interactions with the ground segment buried in mind [1].

Due to the development of computing tools, conjoined analysis of foundations and buildings comprise the building design [2]. However, requirements for the accuracy of foundation deformity

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analysis are significantly lower than those for construction analysis.

Joint analysis of foundations and buildings enables the determination of structural deformations in a building project and the calculation of risk zone dimensions for adjacent building sites [3]. This type of analysis optimizes potential expenses during the initial pre-project stage (preliminary assessment of the geotechnical situation) and validates them during the building design process (geotechnical justification) [4].

10 to 65% of building expenditures undergo reduction due to the enhancement of the project's engineering proposals [5]:

1. The correlation between soil characteristics and ground segments facilitates the development of cost-effective construction solutions.

2. Alternative engineering suggestions.

As a result, the importance of the study encompasses investigating the distinctive structural design features of foundations, considering soil conditions in engineering-geological contexts, to determine technical-economic parameters and select the most cost-effective option [6].

a. Research Objectives

To devise an optimal structural design for a foundation in a residential monolithic multistoried building amidst evolving design requirements dictated by construction conditions and layout schemes [7].

1.To conduct variable foundation design of a residential monolithic multistoried building by the specified layout scheme in specified engineering-geological conditions of Atyrau city.

2.To calculate two alternate designs foundations of a residential monolithic multi-storied building reinforcement.

b. Academic Novelty

1.In general cases, for the calculation of rectangular foundation plate bed it is recommended to count the size of finite elements not less than b/10 where b is the smallest size of the plate (length and width). Therefore, for the practical calculations of a foundation by the SLS (service limit state), it is allowed to count the minimum discretization step for finite elements or the discretization step that is applied in the calculation of ultimate limit states.

2.The research shows the possibility of iterative recalculation neglection during foundational plate design leading to the overstimulation of the load perceived by the foundation, exceeding its integrity [8].

c. The Assessment of the Reliability and Validity of Scientific Results and Conclusions

The results of reinforcing foundation structures were obtained using verified and established research methods for foundation design, widely accepted in practice.

d. The Significance of the Obtained Results for Practice

The results of this work have practical importance for selecting the optimal structural solution for the foundation based on specific engineering-geological conditions of construction. The obtained results and dependencies can be applied for further research in the field of structural solutions and the economic benefit of the real-estate developer [9].

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Methods

The computation is carried out using the SCAD Office design and computing system [10]. This system facilitates the modeling of both static and dynamic structural designs through finite element analysis. It conducts stability checks, identifies critical combinations of loads, assesses the load-bearing capacity of steel structures, and aids in selecting appropriate reinforcement for reinforced concrete structures.

A method of finite elements using displacements and rotations of nodes as primary unknowns in the structuraldesign is the basis for the calculation performed. The scheme is represented by a system of finite elements, thus the structure is idealized. The step for diving into finite elements is chosen to be 0.4 mm.

The transition to stresses along the specified direction for the places was carried out according to the following scheme: for vertical plates – along the Z axis of the common coordinate system, for horizontal plates – along the X axis of the common coordinate system.

The type of a finite element is characterized by its geometric shape, the physical laws governing the relationship between internal forces and displacements, and a set of parameters defining its stiffness. Additionally, the finite element is associated with rules governing its interaction with nodal displacements.

In structural design, a node is conceptualized as an infinitely rigid body with negligible dimensions. Each node possesses six degrees of freedom, comprising three linear displacements and three rotational angles. The node's position during system deformation is determined by the coordinates of its center and the rotational angles of three axes rigidly connected to it.

The primary displacement method involves imposing constraints at each node that restrict any possible nodal displacement. These constraints, representing equilibrium resolving equations, have zero force conditions, while the displacements associated with them are the primary unknowns of the displacement method.

In spatial structures, nodes typically exhibit all six displacements:

1. Linear displacement along the X-axis

2. Linear displacement along the Y-axis

3. Linear displacement along the Z-axis

4. Rotation angle around the X-axis

5. Rotation angle around the Y-axis

6. Rotation angle around the Z-axis

The displacement field within the element (excluding rod-type elements) is generally represented by simplified dependencies. The error in stress and strain determination is typically proportional to $(h/L)k$, where h represents the maximum mesh step size, and L denotes the characteristic size of the domain. The convergence rate, indicating the decrease in error of the approximate result, is determined by the exponent k, which varies for displacements and different components of internal forces (stresses).

a. Characteristics of the Computational Model

1. Residential Unit

Number of stories – 12 stories (ground stories)

The fire-resistance rating of the building – I.

The structure fire hazard class of the building – C0.

The building responsibility's level – II – normal, with a service life of not less than 50 years.

The reference mark of 0.000 m is taken as the level of the first-story finish floor that corresponds to the absolute mark of +11.10.

The height of the building from the soil surface

a. 43.3 m up to the top of the parapet;

b. 0.17 m from the mark of surrounding areas to the first story floor (0.000 m). The dimensions of the building in axes are 14.62 x 22.88 m.

The basement is reserved for communication constructions. The clear height of the basement is 2.3 m. The basement is equipped with 2 emergency exits and two areaways with a window whose dimensions are 1.0 x 1.3 (*h*).

The dwelling units are to be constructed from the first to the twelfth story.

The height of a story is 3.0 m. The finished dwelling unit height is 2.73 m.

Due to the increased number of stories, every section of the building is constructed with the first type of pressurized staircase with passage through the exterior air zone and separate exit to the street, as well as smoke extraction from the floor corridor on each residential story.

Access to the first type pressurized staircase is guaranteed through the elevator lobby.

Every section of the building is equipped with 2 residents serving elevators. The elevator route is planned to cover the stories from the first to the twelfth included.

The building's structural design is cross-cast with the rigid connection of walls, wall columns, and floor slabs.

The outside walls of the building are non-bearing.

The load-bearing walls and pillars are built using monolithic construction. In the basement, the wall thickness measures 250 mm and 200 mm, while on other stories, it is 200 mm thick. The maximum span of each bay is 6.3 m. Additionally, the building features pillars with a sectional view of 1400x200 mm. The outer wall of the basement, also constructed monolithically, has a thickness of 300 mm. B25 W4 concrete is used for the vertical bearing constructions, and B25 W8 F150 for the constructions touching the soil and outdoor air.

The floor slabs are constructed of monolith and are 200 mm thick. B25 W4 F150 concrete is used in the construction of the floor slabs.

The parting walls are designed to be constructed of PK-160 walling stone, 160 mm thick and with 20 mm plaster on two sides with a total thickness of 200 mm. In the rooms with wet-mix processes waterproof parting walls constructed of concrete and partition stones of SKTS 2R-19 type of

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concrete are designed. The walls are 80 mm thick with a plaster coat of 10 mm on every side, with a total thickness of 100 mm.

The stair flights are constructed using reinforced concrete, while the staircases' landings are made of monolithic reinforced concrete. These stair flights are supported by the landings, which, in turn, are supported by the walls enclosing the stairs. The staircases themselves are also constructed using B25-class concrete.

The elevator wells are constructed of monolithic reinforced concrete 160 mm thick. The elevator wells are included in the bearing carcass of the building.

The roof is flat, integrated, and non-exploitable.

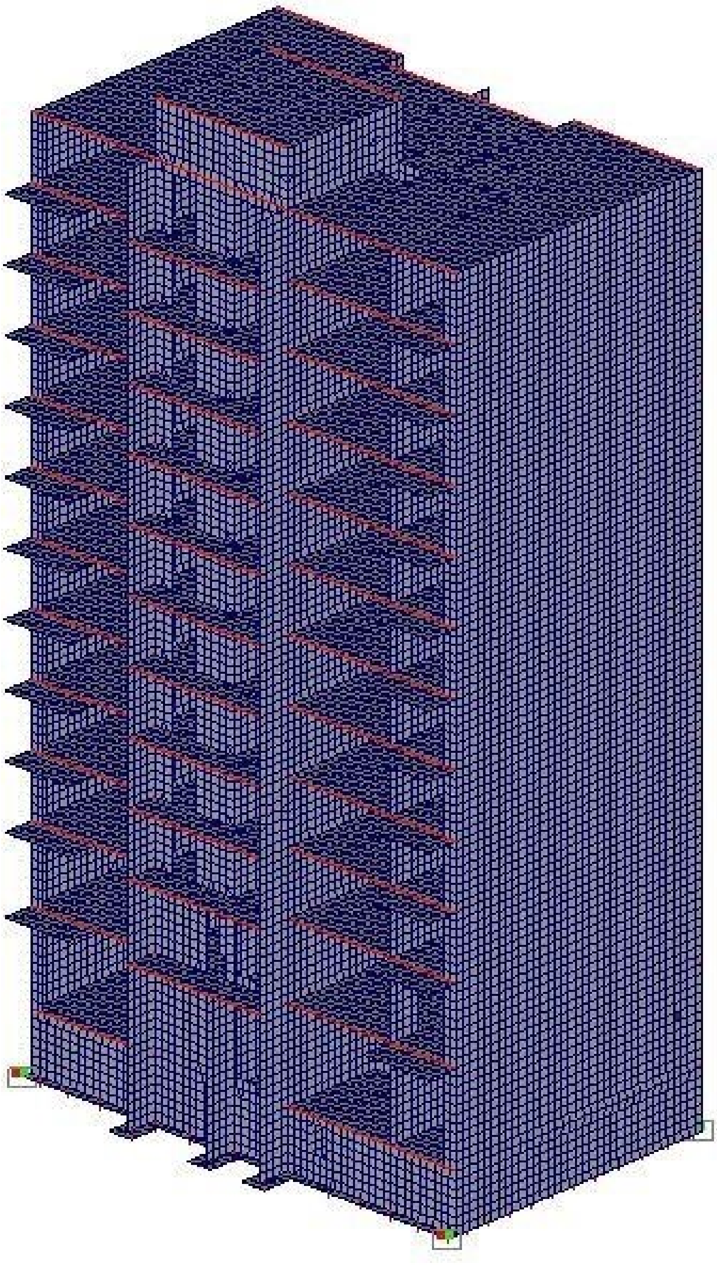

Figure 1. ***Structural Design***

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Results and Discussion

A. Structural Design Coordinate Systems

The global right-handed coordinate system XYZ is used to describe the structural design of the building (Figure 1), as well as local right-handed coordinate systems associated with each finite element.

The structural design is categorized as a general system type. Deformations and their primary unknowns are depicted through linear displacements of nodal points along the X, Y, and Z axes, as well as rotations around these axes. The static analysis of the system is conducted within a linear framework.

Boundary conditions possible displacements of junction points in the finite element structural design are constrained by external restraints, prohibiting some of these displacements.

The boundary conditions are specified as follows:

Constraints are applied in X and Y directions at four nodes along the edges of the slab (Figure 2).

1. linear displacement along the X-axis;

2. linear displacement along the Y-axis.

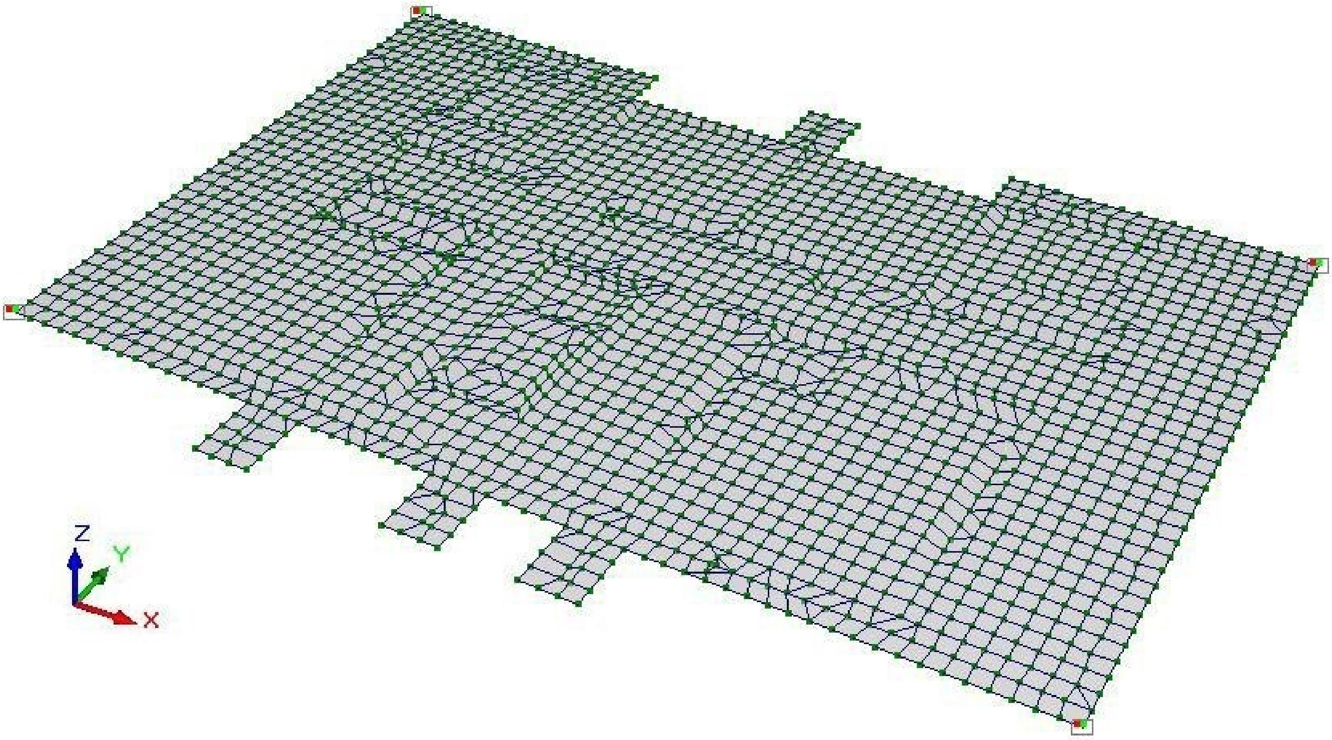

Figure 2. ***Installation of Connections for the Slab Foundation***

a. Slab foundation

Constraints are applied in the X and Y directions at four nodes along the edges of the slab plate

(Figure 3).

1. linear displacement along the X-axis;

2. linear displacement along the Y-axis.

b. Piled Foundation

Piles are modeled using special finite elements (finite stiffness links, type 51). The building is supported by piles.

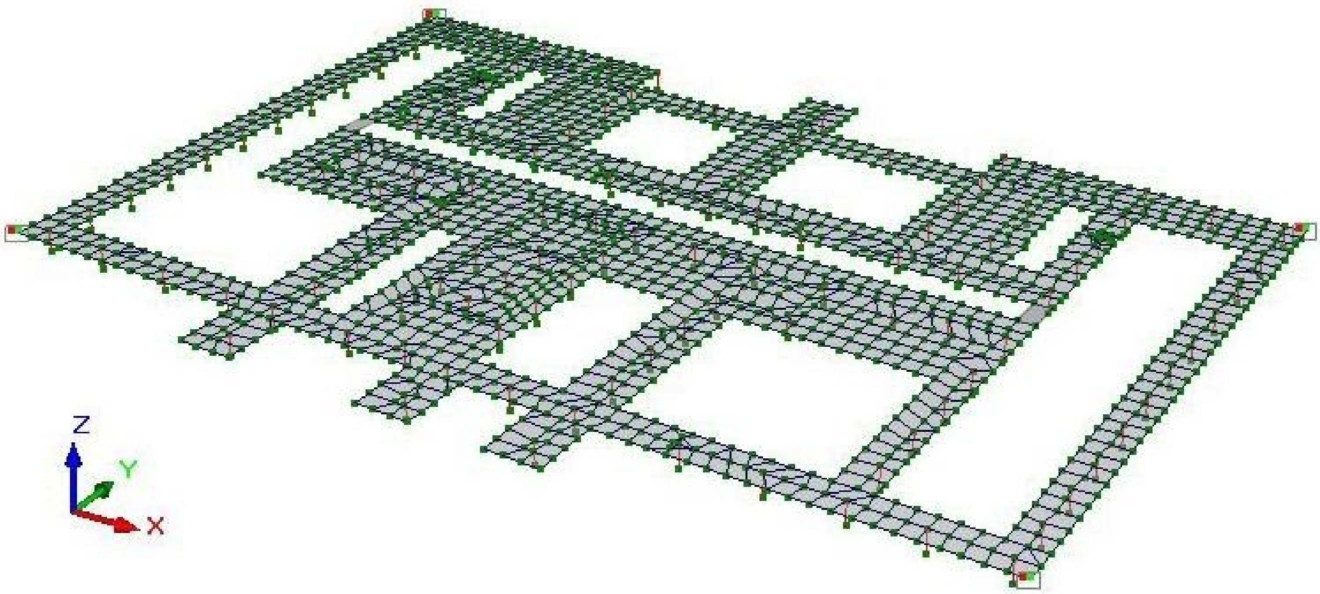

Figure 3. ***The Installation of Connections for the Piled Foundation***

B. Characteristic of the Used Types of Finite Elements

The structural design incorporates various types of finite elements, each with distinct characteristics:

The structural design incorporates finite elements of the following types:

1. Pivotal finite elements: These elements operate based on conventional rules of material integrity theory. The stress state is related to a local coordinate system, where X1 aligns along the pivot, and Y1 and Z1 axes align along the principal axes of section inertia. Some pivots connect to nodes through rigid inserts, considering node attachment eccentricities. In such cases, the X1 axis aligns along the elastic part of the pivot, with Y1 and Z1 axes along the principal axes of section inertia of the elastic part of the pivot's cross-section.

2. Shell finite elements: These elements have a flat geometric shape over a small section. Displacements within the element are approximately represented by simplified dependencies. The stress state is associated with a local coordinate system, where X1 and Y1 axes lie in the element's plane, with X1 directed from the first node to the second, and Z1 orthogonal to the element's surface.

3. Triangular element (Type 42): This element models normal displacements inside with a 4th-

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degree polynomial and tangential displacements with a 1st-degree polynomial. It can be positioned arbitrarily in space and is not compatible.

4. Quadrilateral element (Type 44): This element, with four junction points, models normal displacement inside with a 3rd-degree polynomial and tangential displacements with an incomplete 2nd-degree polynomial. Like the triangular element, it can be positioned arbitrarily in space and is not compatible.

a. Loads and Actions

The collection of loads was carried outby State standard (All-Union State Standard) «Reliability of constructions and foundations. Principal rules of the calculations [11].

Possible deviations of loads toward unfavorable (larger or smaller) values from their normative values are taken into account by load reliability coefficients. The values of these coefficients may vary for different limit states and different situations.

Let us consider the action of wind loading on the building. The wind loading is determined with the help of the WeST program. The wind area is identified by V, and the terrain type is by B. Forces are applied to beams of fictitious stiffness at the level of floor and floor slabs. The values of the forces applied are presented in Table 1.

№	Name	Type	Р n кН/м 2	γ f	Р n кН/м 2
1	A dead load of bearing construction	Constant	SCAD*	1,1	SCAD*
2	Running load	Short duration	SCAD*	1,4	SCAD*
3	A dead load of floors	Constant	0,18	1,1	0,20
4	A dead load of enclosure structures	Constant	0,91	1,1	1,00
5	A dead load of parting walls	Time-depended and sustained	0,07	1,1	0,08
6	Snow loading	Short duration	0,18	1,2	0,22
7	A dead load of stairs	Constant	1,24	1,2	1,49
8	Wind loading	Short duration	normal value	1,4	normal value

Table 1. ***Load Summary***

Note: SCAD - the load is determined automatically by the software application. Pn is the normative value of the load; T/m ^{2} (unless specified); γf – load dependability coefficient; P – calculation value of the load, T/m ^{2} .*

C. Reinforced Concrete Building Based on Slab Foundation

1. Converge Analysis of the Finite Element Method for the Slab Foundation on a « Bilinear » Basis

Nowadays, with the development of computing technics, joint calculations of buildings and foundations compile the basics of construction design. However, it is to be noted that the actual accuracy of foundation deformation calculations is significantly lower than the requirements that are to be met during structural calculations. In project practice, a lenient approach to the choice of calculation models, programs, and the interpretation of calculation results is often applied.

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Historically, structural calculations were developed separately for foundation slabs that are meaning to calculate without including their action and relations with the above-ground part.

The foundation simplification was carried out in two directions:

a. By substituting the foundation with spring isotropic medium.

b. By introducing the so-called bedding coefficients that are convenient for numeral calculations.

The design analysis of any structure begins with determining the significant factors and those factors that can not be neglected. A particularly serious issue is the structuring of the system into finite elements. Excessive structuring into smaller units leads to increased computation time and requires large computer memory resources for data storage and processing. Instabilities in the calculation process may occur, as well. However, large-scale structuring can result in a loss of accuracy in the results.

A bilinear model is an elastoplastic model represented by a layer supported by a significantly rigid semi-space. The model also takes into account the soil's structural integrity.

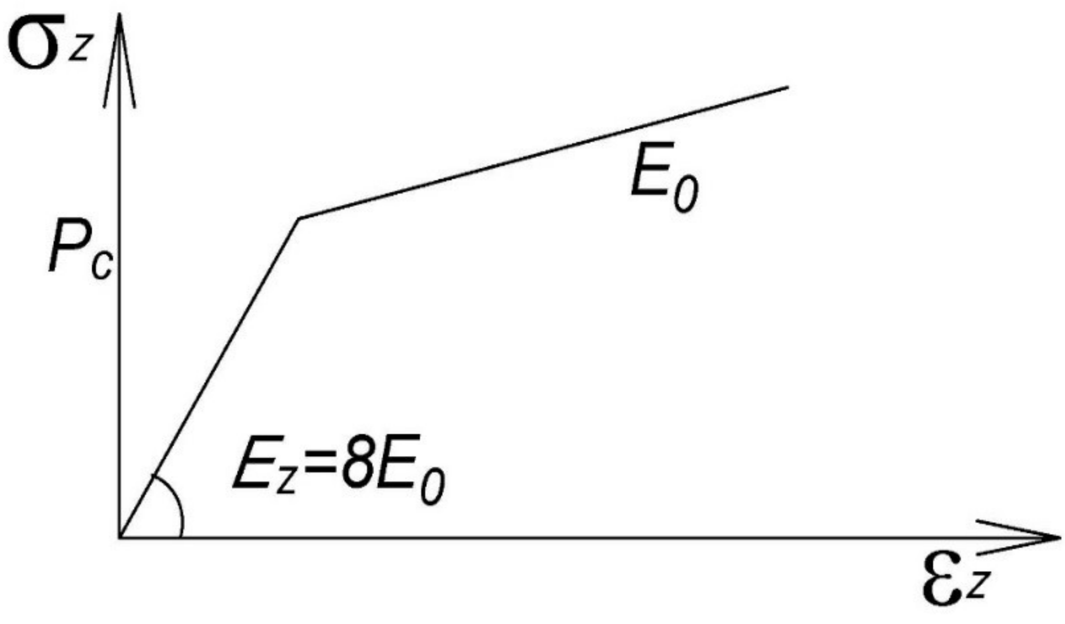

Figure 4. ***Soil's Bilinear Model***

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Essentially, the expression for ε_z reflects the soil's nonlinear properties, for which various moduli of soil deformation are adopted, determined through compression tests of soil with structural integrity for the identification of which loadings are applied in small increments of σ_z (Figure 4).

The modulus of soil deformation is a key element of the model since the modulus is the element that links the foundation model with soil models.

In the SCAD Office, a linear problem is solved. Foundation structures and above-foundation structures are to be considered linear-elastic. The consideration of inelastic deformations of concrete and reinforcement, as well as the presence of cracks is taken into account by an iterative process of solving linear problems. According to CRR (Construction Rules and Regulations) 2.03.01-84* «Concrete and reinforced concrete structures», the forces in a hyperstatic structure are allowed to be determined under the assumption of their linear elasticity.

The model under consideration (Figure 5) represents a slab foundation with plan dimensions of 18x12m and a thickness of 600 mm. Concrete of B25, W6, and F100 classes are used for the model.

The engineering-geological conditions of Atyrau are specified by 3 boreholes.

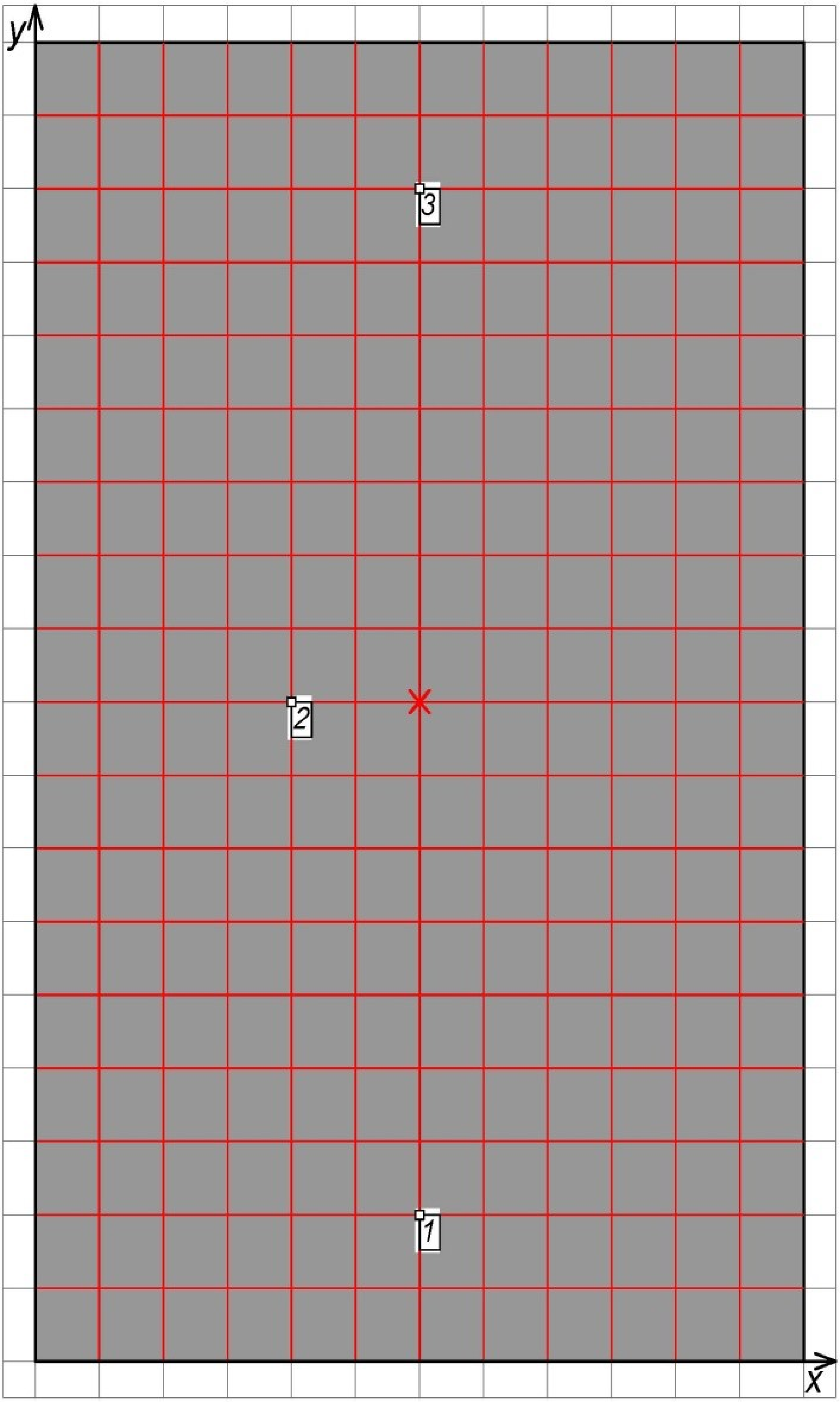
y
x
3
2
1

Figure 5. ***A Model of Slab Foundation***

During the construction of an elastic base model, an iterative calculation was performed. The calculation allowed to bring the base model and foundation model together. Six consecutive iterations were conducted. The base settlements are determined assuming the bilinear type of the model.

As a result of the calculation, representations of settlement contours are obtained in two forms, one of them being the raw settlement type, calculated at the level of the foundation base, and the other being the bedding coefficient that is the «reduced» settlement (settling divided by the load). The average settlement of the building is 0.16 mm. The maximum settlement of the building is 0.19 mm.

Thus, for practical foundation calculations according to the service limit state, the use of a minimum subinterval (size of a finite element – 2 m) is possible.

Diagrams of the maximum and minimum rates of the bedding coefficient C1 from the 1^{st} to the 6^{th} iteration change based on calculation results were constructed. Further use of the Cross program is impractical, as the distribution of coefficient rates has stabilized [12].

2. Description of the Analysis Model

The slab is made of reinforced concrete (concrete is of B25, W4, and F100 classes) and is designed to be 1000 mm, and has undergone a crushed-stone base course to preserve the slab from the capillary water, The crushed-stone base course is used as a drain line.

The waterproofing of the slab’s lateral surface consists of two layers of bonding compound on sealing compound.

The basement story walls are constructed of monolithic reinforced concrete (concrete of B25, W4, and F100 classes is used) with the exterior walls 300 mm, and interior walls – 250 mm and 200 mm thick.

The walls of the stories from the 1^{st} to the 12^{th} included are constructed of monolithic reinforced concrete (concrete of B25 class is used) with a thickness of 200 mm.

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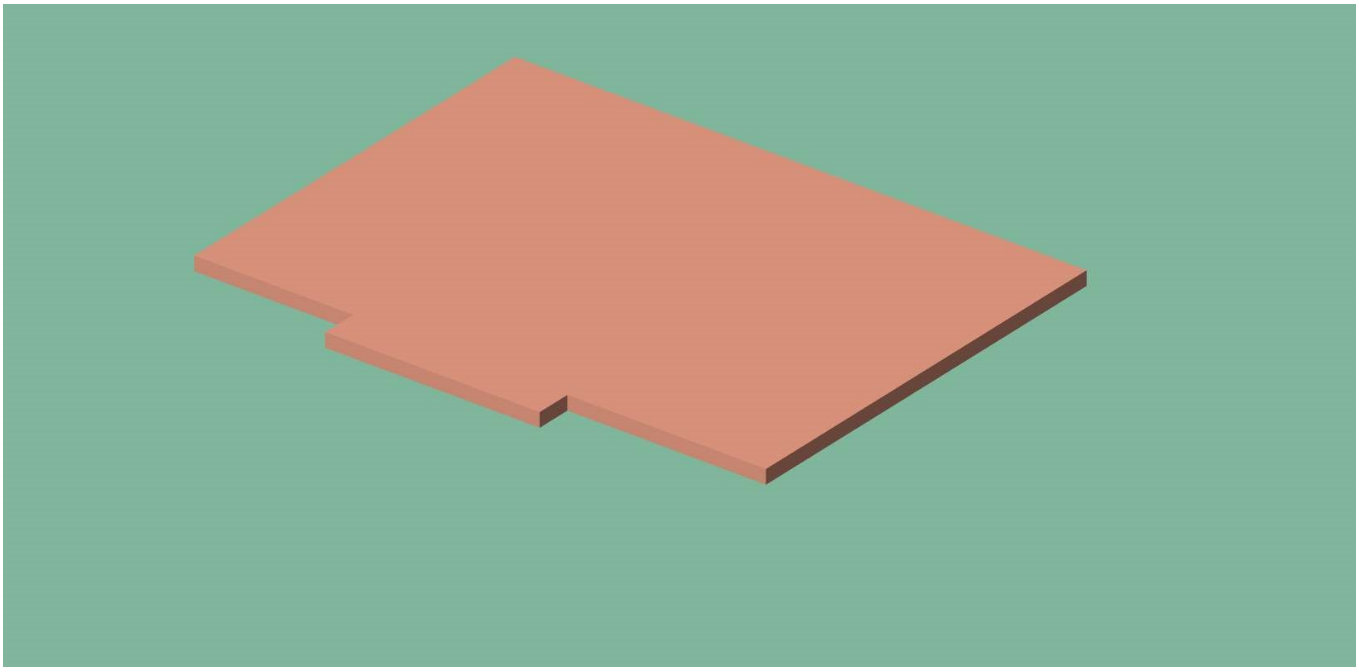

Figure 6. ***Slab Foundation***

3. Calculation and Reinforcement of Slab Foundation

The calculation of the foundation for deformations is necessary to determine and limit the absolute displacement of the slab foundation and the structure standing on it. Among all types of deformations, let us consider soil settings that occur due to soil compaction under the influence of external forces. Deformations can also occur due to the changes in humidity rate or freezing and thawing of water in the soil pores. A more complex calculation is associated with determining and limiting horizontal displacements.

4. Reinforcement of Slab Foundation

Calculations in the SCAD Office for the reinforcement of the multi-story monolithic residential building foundation selected as a research model have been carried out.

The reinforcement of the structural elements is performed by the calculated combinations of forces. The determination of forces in the elements of the structural system is carried out considering the action of calculated permanent, long-term, and short-term loads, as well as for the calculated combination. The determination of vertical displacements (deflections) of the slab is performed considering the action of normative permanent and long-term vertical loads [13].

The calculation was performed using the finite elements method, considering the ultimate load-carrying capacity (for integrity and stability) and the serviceability (for crack resistance and deformations).

To carry out the reinforcement calculation, it is initially to be determined the surfaces where reinforcement is applied (the junction points between walls and the slab foundation). Reinforcement is performed using *Ø14* bars. The results of the reinforcement calculation are presented in Table 2.

Element undergoing reinforcement	Number of bars per 1 meter

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The lower zone of the slab	5Ø12
The upper zone of the slab	5Ø12

Table 2. ***Reinforcement of Slab Foundation***

D. Reinforced Concrete Building on a Piled Foundation

1. Description of the Analysis Model

A piled foundation is used in cases of an anti-washout layer of soil located so deep that the use of different foundation types is impossible, as in the case of the soils in the city of Atyrau.

The construction of such a foundation type consists of a combination of a strip foundation and a piled foundation (see Figure 7). Deeply driven piles possess a reinforced frame, which is in turn connected to the reinforcement of the strip frame. The poured concrete makes the entire structure a single integral foundation [14].

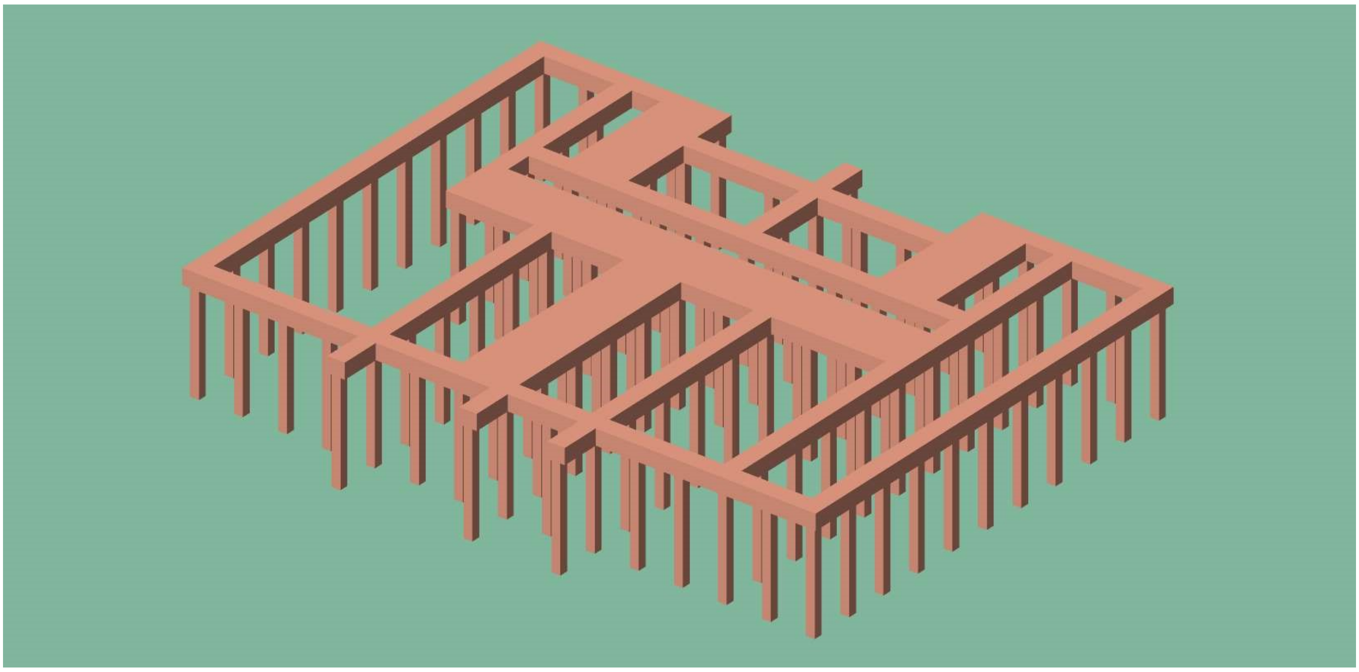

Figure 7. ***A Fragment of the K-2 Framework***

Piled foundation transfers the building load to the soil through two structural components, one of them being the foundation strip installed around the perimeter of the building and under bearing partitions, the other being piles that ensure the foundation’s integrity during seasonal soil movements.

To transfer the load from the building to the soil, piles of C 160-40-10 grade with a length of 16 meters combined with a monolithic grillage with a thickness of 1000 mm are used.

2. Assessment of the Pile ’s Bearing Capacity

In foundation construction practice, three methods are used to determine the bearing capacity of individual piles are used. The first method is the theoretical method; the dynamic method, based on the results of pile driving tests; the method of permanent static load that uses data obtained from

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loading piles with static loads or soil probing [15].

3. Reinforcement of the Piled Foundation

The determination of forces in the structural system elements is carried out under the action of calculated permanent, long-term, and short-term loads, as well as under the calculated combination. The determination of vertical displacements (deflections) of the slabs is carried out under the action of normative permanent and long-term vertical loads.

The calculation was performed using the finite element method, based on the ultimate limit state of two groups: for bearing capacity (for integrity and stability) and for operational suitability (for crack resistance and deformations). The results of the reinforcement calculation are summarized in Table 3.

Element undergoing reinforcement	Number of bars per 1 meter
The lower zone of the slab	5Ø12
The upper zone of the slab	5Ø12

Table 3. ***Reinforcement of Piled Foundation***

Thus, the pile grillage is reinforced with the K-2 framework. The spacing of the framework is 200 mm. A fragment of the framework per 1 meter is presented in Figure 8.

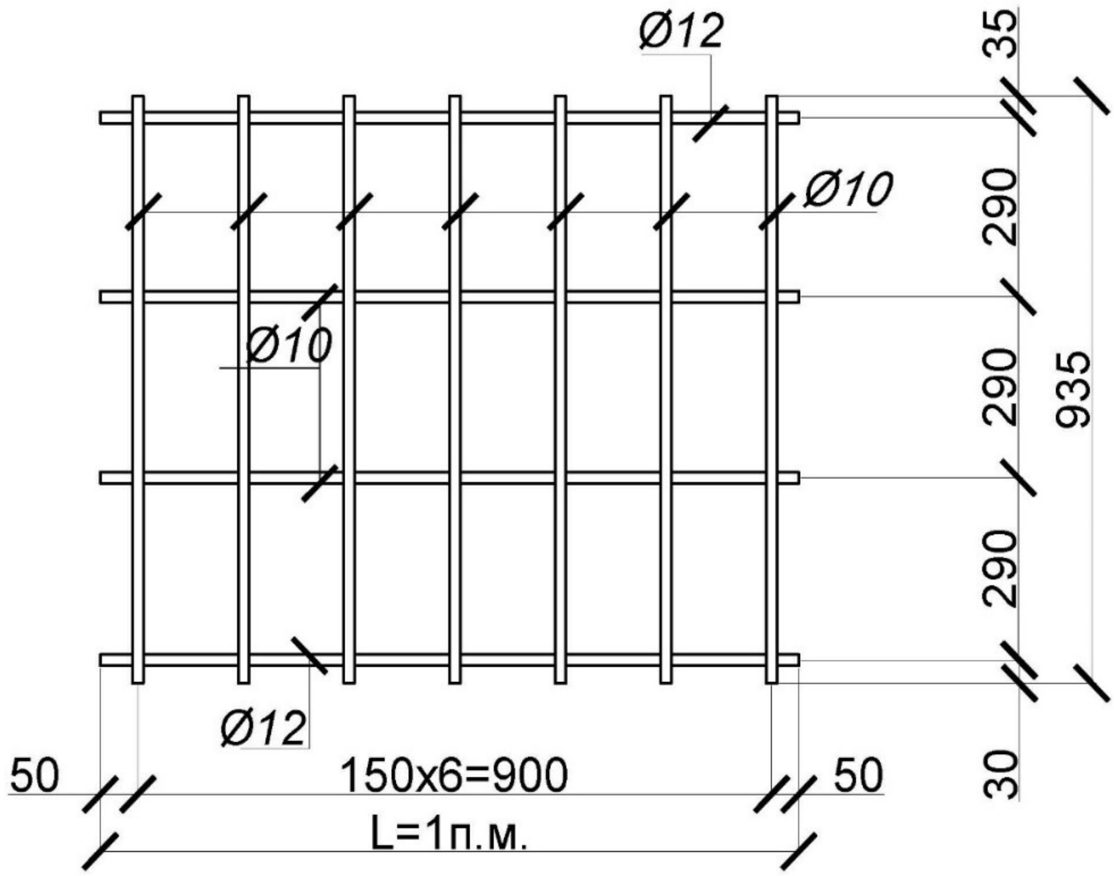

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Figure 8. ***A Fragment of the K-2 Framework***

Within the framework of the master's thesis, the comparison based on technical indicators (structural scheme, material consumption, data on deformability and integrity), as well as on economic indicators (estimated cost, specific indicators) was conducted.

Based on the activity-dependent cost estimates for each of the foundation options, 2 estimates based on specific indicators were calculated.

Using estimates based on specific indicators, the estimated cost of the foundation per $1m^2$ of the total building was determined (Figure 9).

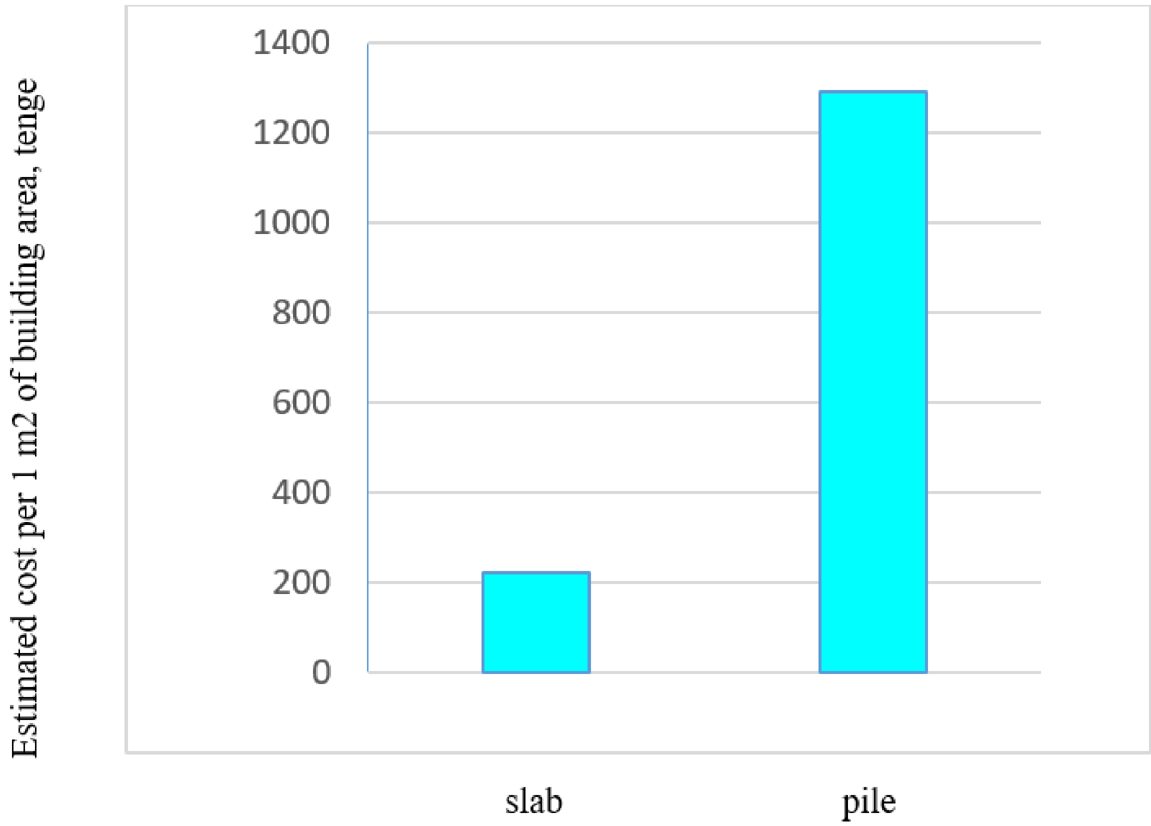

Figure 9. ***Estimated Cost of the Foundation per 1m ^{2} of the Total Building Area***

Through the calculation results it is identified that the most optimal variant by the estimated cost of the foundation per $1m^2$ of the total building area is the slab foundation.

Conclusion

1.Within the scope of the study, the optimal hsubinterval for discretization into finite elements has been determined. For calculations based on the ultimate limit state, it is generally recommended to count a finite element size of no less than b/10, where b is the smallest dimension of the slab (width and length).

2.For practical foundation calculations based on the service limit state, it is permissible to adopt either the minimum discretization subinterval or the subinterval used for calculations based on the ultimate limit state since the finite element size does not affect the average and maximum settling values or the distribution pattern of settlings.

3.It has been demonstrated that neglecting iterative recalculation in the slab foundation design can lead to an overestimation of the load perceived by the foundation, exceeding its integrity. Practical recommendations are provided for the joint calculation of building and soil foundations.

4.A technical and economic comparison of the two variants has been conducted. The economic requirements for a specific type of foundation aim to minimize the cost of structures and foundation construction. Based on the conducted technical and economic comparison of the two foundation variants, a reasoned decision has been made regarding the feasibility of applying one foundation variant over the other.

5.The results of this study have practical significance for selecting the optimal structural foundation solution based on specific engineering-geological conditions of construction. The obtained results and dependencies can be utilized for further research in the field of structural and economic benefits of a builder.

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