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GEOTECHNICAL AND PROBABILISTIC EVALUATION OF THE EFFICIENCY OF A MODEL FOR STRENGTHENING THE BASE OF A RAFT FOUNDATION USING RIGID REINFORCEMENT ELEMENTS

ҚАТТЫ ДОМАЛАТЫЛҒАН АРМАТУРАЛАУ ЭЛЕМЕНТТЕРІМЕН ТАҚТАЛЫ ІРГЕТАС НЕГІЗІН КҮШЕЙТУ МОДЕЛІНІҢ ТИІМДІЛІГІН ГЕОТЕХНИКАЛЫҚ ЖӘНЕ ЫҚТИМАЛДЫҚ БАҒАЛАУ

ГЕОТЕХНИЧЕСКАЯ И ВЕРОЯТНОСТНАЯ ОЦЕНКА ЭФФЕКТИВНОСТИ МОДЕЛИ АРМИРОВАНИЯ ОСНОВАНИЯ ПЛИТНОГО ФУНДАМЕНТА ЖЕСТКИМИ РАСКАТНЫМИ ЭЛЕМЕНТАМИ

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Keywords:

soil reinforcement; raft foundation; foundation settlement; rigid inclusion; concrete reinforcing element; reinforcement efficiency; reliability index.

ABSTRACT

Construction in densely built urban areas, especially on artificial fill and highly compressible soils, requires effective methods for improving foundation performance. One of the most promising solutions is soil reinforcement using rigid inclusions; however, unified design and construction approaches remain insufficiently developed. This study proposes a model for reinforcing raft foundation bases with vertical rigid displacement elements by integrating geotechnical, structural, and probabilistic methods. The proposed model allows prediction and control of foundation settlement through the equivalent deformation modulus of the reinforced soil and the stiffness of the improved base, determined by the spacing and number of reinforcing elements. The reliability of the system was assessed using Monte Carlo, FORM, and SORM methods, which enabled determination of the reliability index and the most probable failure point. The results demonstrate that the proposed reinforcement technology can reduce foundation settlement, improve reliability, lower construction costs, and shorten construction time compared with conventional soil improvement techniques. The developed approach may serve as a basis for the design and reliability assessment of reinforced foundation systems in civil engineering.



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Түйінді сөздер:

топырақты армирлеу,
тақталы іргетас, негіздің
шөгуі, қатты қосынды,
бетонды армирлеуші
элемент, армирлеу
тиімділігі, сенімділік
индексі, ықтимал бұзылу,
технологиялық тиімділік.

ТҮЙІНДЕМЕ

Тығыз қалалық құрылыс жағдайында, әсіресе үйінді және күшті сығымдалатын топырақтарда құрылыс жүргізу іргетас негіздерінің сенімділігін арттыруға бағытталған тиімді шешімдерді талап етеді. Осындай әдістердің бірі – топырақты қатты қосындылармен армирлеу, алайда оларды жобалау мен орнатудың бірыңғай тәсілі әлі толық қалыптаспаған. Зерттеуде геотехникалық, конструктивтік және ықтималдық тәсілдерді біріктіруге негізделген тақталы іргетас негізін тік қатты жаймалау элементтерімен армирлеу моделі ұсынылған. Ұсынылған модель армирлеу дәрежесіне, сондай-ақ армирлеуші элементтердің саны мен орналасу қадамына байланысты топырақтың эквивалентті деформация модулі мен күшейтілген негіздің қаттылығын ескере отырып, іргетас шөгуін болжауға және басқаруға мүмкіндік береді. Жүйенің сенімділігі Monte Carlo, FORM және SORM әдістері арқылы бағаланып, сенімділік индексі мен ең ықтимал бұзылу нүктесі анықталды. Зерттеу нәтижелері ұсынылған технологияның іргетас шөгуін азайтып, негіздің сенімділігін арттыратынын, құрылыс құнын төмендетіп, құрылыс мерзімін қысқартатынын көрсетті. Алынған нәтижелер азаматтық құрылыста армирленген негіздерді жобалау мен олардың сенімділігін бағалау үшін пайдаланылуы мүмкін.

Ключевые слова:

армирование грунта,
фундаментная плита,
осадка основания,
жесткое включение,
бетонный армирующий
элемент, эффективность
армирования, индекс
надежности, вероятный
отказ, технологическая
эффективность.

АННОТАЦИЯ

Строительство в условиях плотной городской застройки, особенно на насыпных и сильносжимаемых грунтах, требует эффективных решений по улучшению оснований фундаментов. Одним из перспективных методов является армирование грунтов жёсткими включениями, однако единые подходы к их проектированию и устройству до настоящего времени отсутствуют. В работе предложена модель армирования основания плитного фундамента вертикальными жёсткими раскатными элементами, основанная на интеграции геотехнических, конструктивных и вероятностных методов анализа. Модель позволяет прогнозировать и регулировать осадки фундамента за счёт изменения эквивалентного модуля деформации грунта и жёсткости армированного основания в зависимости от количества и шага армирующих элементов. Надёжность системы оценена с использованием методов Монте-Карло, FORM и SORM, что позволило определить индекс надёжности и наиболее вероятную точку отказа. Результаты показали, что применение предложенной технологии снижает осадки, повышает надёжность основания, сокращает сроки строительства и уменьшает затраты по сравнению с традиционными методами улучшения грунтов. Полученные результаты могут быть использованы при проектировании и оценке надёжности армированных оснований в гражданском строительстве.

INTRODUCTION

Under conditions of rapid urbanization, construction is increasingly performed on collapsible, technogenic, and highly compressible soils characterized by non-uniform deformation and a high risk of differential settlement. Traditional methods of ground improvement, including soil replacement and stabilization with lime, cement, geopolymers, synthetic zeolites, and other additives, can effectively improve soil properties but are often labor-intensive and costly (Eyo et al., 2020; Sabri et al., 2022).

To reduce settlement and increase bearing capacity, modern geotechnical practice increasingly employs rigid inclusions such as soil, stone, polymer, and composite columns. Since their introduction in the late 1970s, rigid inclusions have become one of the most effective solutions for soft soil improvement (Bohlooli et al., 2026a; Swift & Pearlman, 2024). Their effectiveness has been confirmed through analytical studies, laboratory investigations, and field tests (Hamidi & Racinais, 2025; Rebolledo et al., 2022).

Advances in numerical modeling have improved the understanding of load-transfer mechanisms between foundations and rigid inclusions. Numerical and experimental studies demonstrate that loads are redistributed through load-transfer platforms, ensuring efficient interaction between the foundation and reinforcing elements (Lu et al., 2019). In addition, the use of cement- or lime-treated platforms reinforced with geogrids has been shown to further enhance system stiffness and performance (Niu et al., 2018).

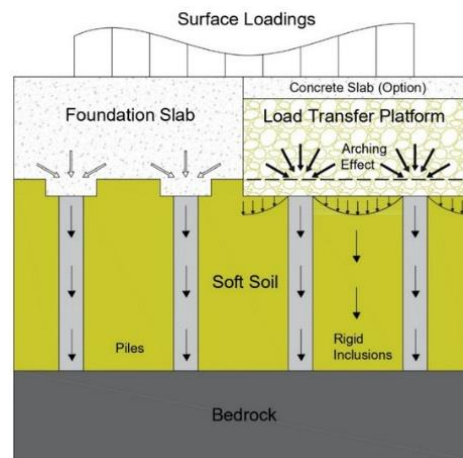


Figure 1. Load transfer in the soil–rigid element–soil platform–foundation system

The performance of rigid reinforcing elements depends on their material properties, geometric characteristics, and arrangement within the foundation system (Larisch, 2025). Numerous studies have evaluated the interaction between foundations and rigid inclusions through numerical simulations, laboratory investigations, and field tests, considering parameters such as element length, diameter, spacing, and load-transfer layer thickness (Acar & Mollamahmutoğlu, 2023; Alenov et al., 2025). These approaches have improved the understanding of load-transfer mechanisms and enabled the development of effective reinforcement models for soft soils (Mannah et al., 2024; Melese, 2022).

Due to the inherent variability of soil properties and loading conditions, the reliability of reinforced geotechnical systems remains an important research topic. Reliability-based approaches have been widely applied to foundations, retaining structures, and embankments under static and seismic actions (Zhang et al., 2011). Probabilistic methods enable the assessment of settlement behavior and reliability levels by accounting for uncertainties in geotechnical parameters (Li et al., 2020).

Various installation technologies for rigid inclusions have been developed, including displacement, vibro-replacement, and drilling methods (Chwała et al., 2023; Varaksin, 2020). Among them, the CMC Menard technique has demonstrated high efficiency due to the significant increase in stiffness of the reinforced zone (Bessimbayev et al., 2024; Romanov & Racinais, 2018). Design standards also recommend displacement drilling technologies, which improve soil compaction around the borehole and enhance the mechanical properties of the surrounding ground (Briançon et al., 2015; Z. Abu, 2025).



Despite extensive research and practical applications, the implementation of rigid inclusions remains constrained by the absence of unified design and assessment methodologies suitable for routine engineering practice.

MATERIALS AND METHODS

The research methods include theoretical analysis, numerical modeling using the finite element method implemented in PLAXIS 2D, interpretation of the obtained results, and reliability assessment of the building foundation using probabilistic approaches that account for statistical heterogeneity and random actions.

The design standards of Kazakhstan recommend considering the improved foundation as a transversely isotropic medium and performing calculations according to two groups of limit states: ultimate limit states and serviceability limit states (Bohlooli et al., 2026b).

The ultimate limit state corresponding to failure or excessive deformations of a structural element or the foundation (STR and GEO) should be verified according to Equation (1).

$$E_d \leq R_d, \quad (1)$$

where: E_d — the design effects of actions, which are determined according to the following expressions.

$$E_d = E \left[\gamma_F F_{rep}; \frac{X_k}{\gamma_M}; a_d \right], \quad (2)$$

Partial factors are applied either to the actions or to the resulting effects of these actions E in accordance with the National Annexes to Eurocode 7.

R_d — the design resistances, which are determined according to the following expressions.

$$R_d = R \left[\gamma_F F_{rep}; \frac{X_k}{\gamma_M}; a_d \right], \quad (3)$$

Partial factors may be applied either to the soil parameters X or to the resistances R .

The calculation of foundations reinforced with rigid reinforcing elements is performed based on the achievement of the ultimate limit state for failure (GEO) according to the following condition:

$$\alpha R_2 + (1 - \alpha) R_1 \geq P, \quad (4)$$

where $\alpha = V_{ar}/V_{gr}$ is the coefficient characterizing the proportion of reinforcing elements within the volume of the improved soil; V_{ar} is the volume of reinforcing elements, and V_{gr} is the volume of soil.

R_1 — the design resistance of the unreinforced soil beneath the foundation base, kPa;
 R_2 — the design resistance of the reinforcing element material assuming the replacement of natural soil by the reinforcing element, kPa; P — the average pressure beneath the foundation base, kPa.

or excessive deformations of the foundation (GEO) according to the following condition:

$$S_{ap} \leq S_u, \quad (5)$$

where S_{ar} is the settlement of the reinforced part of the foundation base, and S_u is the limiting value of the combined deformation of the foundation and the structure.

The settlement of the reinforced part of the foundation base (S_{ar}) is calculated using the layer-by-layer summation method according to the following expression:

$$S_{ap} = \sum_{i=1}^n \frac{\sigma_{zp,i} \cdot h_i}{E_3}, \quad (6)$$

where h_i is the calculated thickness of the i -th soil layer within the compression zone of the reinforced foundation base, taken from the condition $0.2 i h_b$, where b is the foundation width, m;

General properties								
V_{unsat}	kN/m^3	19,60	16,90	18,00	18,10	19,30	19,80	19,60
V_{sat}	kN/m^3	19,70	17,10	18,00	18,30	19,40	19,90	19,60
Strength								
c_{ref}	kN/m^2	12,00	9,000	15,00	39,00	34,00	23,00	25,00
φ (phi)	°	26,00	21,00	16,20	12,00	14,00	19,00	19,00
ψ (psi)	°	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Velocities								
V_s	m/s	60,43	53,07	14,21	22,40	24,54	38,79	60,89
V_p	m/s	125,8	110,5	29,58	46,63	51,09	80,75	126,8

Figure 2. Soil characteristics in the PLAXIS software environment

To construct the geological model of the building foundation in PLAXIS, a soil mass with dimensions of 60×140 m was adopted.

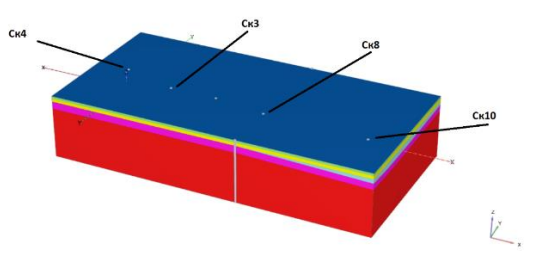


Figure 3. Soil characteristics based on the engineering–geological cross-section in PLAXIS

The geological cross-section of the soil mass based on borehole data shows (Fig. 4) that the building foundations are located within fill soils (IGE-3, IGE-5, IGE-6).

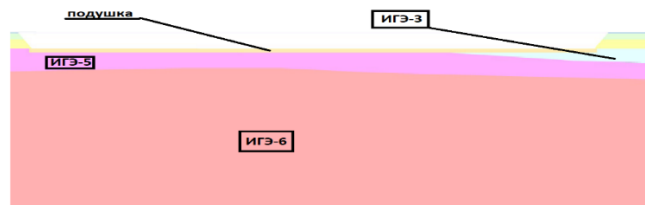


Figure 4. Section IV–IV in the PLAXIS software environment

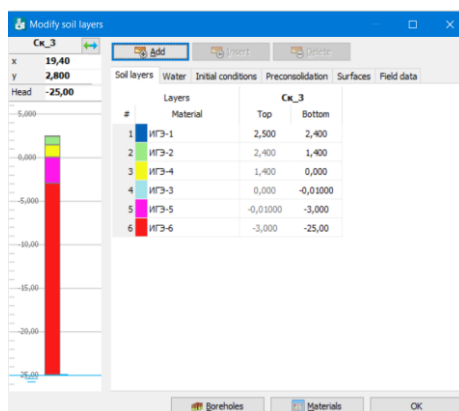


Figure 5. Numerical model in the PLAXIS software environment for Borehole 3.

Plate - Фундаментная плита C20/25			
			
Property	Unit	Value	
Material set			
Identification		Фундаментная плита C20/25	
Comments			
Colour			RGB 251, 255, 0
Material type		Elastic	
Properties			
d	m		1,000
γ	kN/m³		25,00
Isotropic		☒	
E ₁	kN/m²		30,60E6
E ₂	kN/m²		30,60E6
ν ₁₂			0,1500
G ₁₂	kN/m²		13,30E6
G ₁₃	kN/m²		13,30E6
G ₂₃	kN/m²		13,30E6
Rayleigh α			0,000
Rayleigh β			0,000
Prevent punching		☐	

Figure 6. Properties of the 1.0 m thick raft foundation (B25 concrete) in the graphical interface of the PLAXIS software

RESULTS AND DISCUSSION

Geotechnical Assessment Based on Numerical Modeling

The simulation of the loading process of the raft foundation up to the design load, presented in the deformed scheme of the foundation base, illustrates the nature and magnitude of changes in the finite element mesh, where soil deformation occurs under the load of the building or structure, as well as the distribution of stresses within the foundation soil mass.

The calculation results obtained using the Hardening Soil model indicate that the maximum deformation value of 259.1 mm is observed in the central part of the raft foundation (Fig. 7).

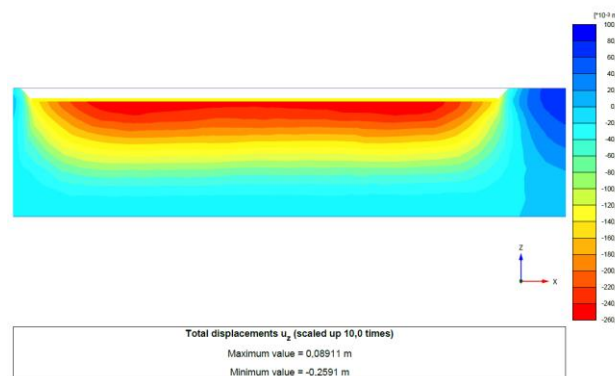


Figure 7. Settlement of the foundation base soil (max 259.1 mm).

The analysis showed that the ultimate limit state for excessive foundation deformation (STR and GEO) was not satisfied, indicating the need to improve the soil strength and deformation properties through reinforcement with vertical rigid concrete DSM elements.

Based on theoretical and experimental studies, the effectiveness of reinforcement depends on the diameter, spacing, and length of the elements, as well as the properties of the load-transfer layer. In this study, DSM elements with a diameter of 300 mm, length of 6.0 m, and spacing of 2.0 m were adopted. A 0.6 m thick sand cushion was provided beneath the raft foundation, and the average foundation pressure was 24.1 t/m².

The characteristics of the concrete reinforcing elements in the graphical interface of the PLAXIS software are presented in Fig. 8.

Property	Unit	Value
Material set		
Identification number		1
Identification		Раскатка
Comments		
Colour		RGB 199, 82, 143
Material type		Elastic
Properties		
E	kN/m ²	21,50E6
ν	kN/m ³	15,00
Beam type		Predefined
Predefined beam type		Massive circular beam
Diameter	m	0,3000
A	m ²	0,07069
I_2	m ⁴	0,3976E-3
I_3	m ⁴	0,3976E-3
Rayleigh α		0,000
Rayleigh β		0,000

Figure 8. Vertical reinforcing element with a length of 6 m and a diameter of 0.3 m (B12.5 concrete)

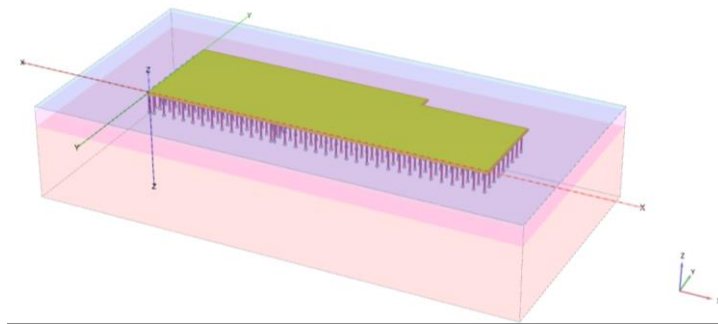


Figure 9. Spatial model with vertical reinforcing elements (element length – 6.0 m)

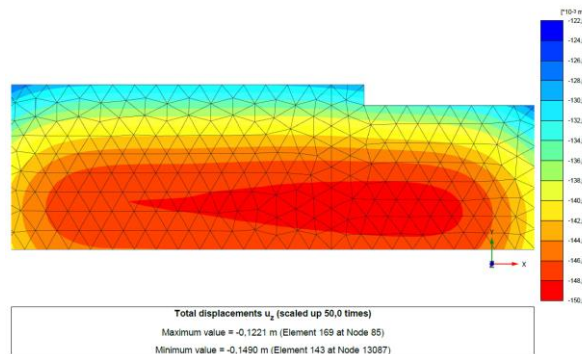


Figure 10. Vertical displacements of the foundation (max 149.0 mm)

The relative difference in settlements of the raft foundation in the longitudinal and transverse directions is as follows:

1. Settlement difference $(S_1 - S_2)/L = (149.0 - 122.0)/99000 = 0.00027 < 0.005$
2. Settlement difference $(S_3 - S_4)/L = (149.0 - 122.0)/24000 = 0.00112 < 0.005$

Accordingly, the absolute vertical displacement of the foundation considering the reinforced base is $z_{max} = 149.0\text{mm}$, which does not exceed the permissible limit value $z_{lim} = 225\text{mm}$. The relative difference in foundation settlements also does not exceed the allowable limit according to the regulatory document. As a result of introducing vertical reinforcement, a

uniform settlement of the building was achieved, which was confirmed by calculations performed in the PLAXIS software environment.

To evaluate the influence of the geometric parameters of reinforcement on the strength and deformation characteristics of the reinforced base, several variants with increased spacing between the reinforcing elements were considered. As shown in **Table 1**, an increase in the distance between the elements leads to a decrease in the stiffness of the reinforced foundation base and, consequently, to an increase in foundation settlement.

Table 1. Comparison of foundation reinforcement parameters depending on the spacing between vertical elements

#	Title 2	Unit	Spacing between elements, m		
			2×2	3×3	5×5
1	Number of reinforcing elements	pcs	550	264	102
2	Volume of reinforcing elements	m ²	234	112	43
3	Reinforcement ratio	%	1.63	0.78	0.345
4	Stiffness of reinforced foundation base	t/m ²	1 610	1 212	1 025
5	Foundation settlement	mm	149	198	234

The results of modeling the foundation reinforcement indicate a significant dependence of the bending moments and deformation of the raft foundation on the spacing between the reinforcing elements (Table 2).

Table 2. Values of bending moments and deformation of the raft foundation depending on the spacing between reinforcing elements

Grid spacing between reinforcing elements, m	Bending moment, kN/m ²	Raft foundation deformation, mm
Without reinforcing elements	476,2	259
2 × 2	197,4	149
3 × 3	263,1	198
5 × 5	385,4	234

The results indicate that the stiffness of the reinforced foundation base increases with the reinforcement ratio, while larger spacing between reinforcing elements leads to greater foundation settlement and higher bending moments. Overall, the analysis confirms the effectiveness of rigid reinforcing elements in reducing raft foundation deformation and improving the performance of the reinforced foundation system.

Probabilistic assessment of the effectiveness of the raft foundation base reinforcement model

The probability of failure of the raft foundation is evaluated taking into account the variability of the geotechnical properties of the soil and seismic actions. The limit state is defined by the following expression:

$$g(X) = S_{\text{lim}} - S(E, c, \varphi, S_a), \quad (11)$$

Where $S_{lim}=225m$ is the code-based limiting settlement, and $S(E, c, \varphi, S_a)$ is the settlement calculated using a metamodel calibrated against the finite element analysis results obtained in PLAXIS 2D. The random variables are: E – soil deformation modulus, c – cohesion, φ – angle of internal friction, and $S_a(T_1)$ – spectral acceleration corresponding to the period of the first modal vibration.

The Monte Carlo method for estimating the probability of failure is expressed as follows:

$$P_f = P(g(X) < 0), \quad (12)$$

To reduce the variance of the estimates, the random parameters are generated using Latin Hypercube Sampling. To calculate the confidence interval of the probability of failure, the following expression is used:

$$CI = P_f \pm 1,96 \sqrt{\frac{P_f(1 - P_f)}{N}}, \quad (13)$$

where $N = 50,000$ is the number of realizations.

The response metamodel is defined by the following expression:

$$S = S_0 \left(\frac{E_0}{E}\right)^{0,6} \left(\frac{c_0}{c}\right)^{0,2} \left(\frac{\tan \varphi_0}{\tan \varphi}\right)^{0,1} (1 + 1,8 S_a) \quad (14)$$

where S_0 is the mean settlement. It is evaluated for three reinforcement cases.

Table 3. Statistical distributions and parameters of input random variables used in the reliability analysis

Variable	Distribution	Mean	Coefficient of variation
E	Normal	25 MPa	0,25
c	Normal	18 kPa	0,20
φ	Normal	28°	0,07
S_a	Lognormal	0.42 g	0,30

Figure 11 illustrates the distributions of the random input parameters used in the simulations.

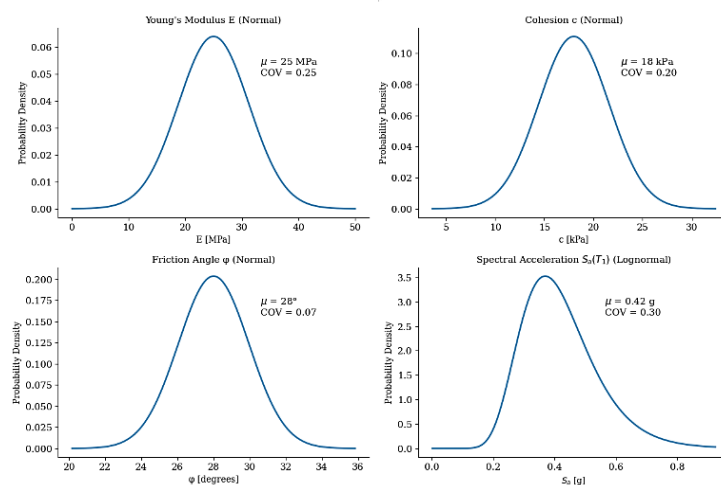


Figure 11. Distributions of random variables (E , c , φ , S_a)

The FORM method was applied to estimate the probability of failure by linearizing the limit-state function at the most probable point of failure (MPP), with the reliability index β defined as the distance from the origin to the MPP. Monte Carlo simulations showed that increasing the reinforcement ratio shifts the settlement distribution toward lower values and improves reliability. For reinforcement ratios of 0.345%, 0.78%, and 1.63%, the corresponding reliability indices were $\beta = -0.17, 2.70$, and 4.60 , respectively. The results indicate that a higher reinforcement ratio significantly reduces settlement and the probability of failure, while reinforcement ratios above approximately 1.3–1.4% satisfy the target reliability level specified by Eurocode 0 ($\beta = 3.8$).

For long-term assessment, the cumulative probability of failure over the design service life of the foundation is considered (Fig. 18). For an annual probability of failure $P_f^{annual} = 0.003$:

$$P_f^{50} = 1 - (1 - P_f^{annual})^{50} \approx 0.139 \quad (15)$$

The analysis of the cumulative probability of failure over a 50-year period indicates a significant reduction in risk when the reinforcement ratio exceeds 0.78%, while a reinforcement ratio of 0.345% does not ensure the required reliability level. To achieve the target reliability index of 3.8, a reinforcement ratio of 1.3–1.4% is recommended (Fig. 12).

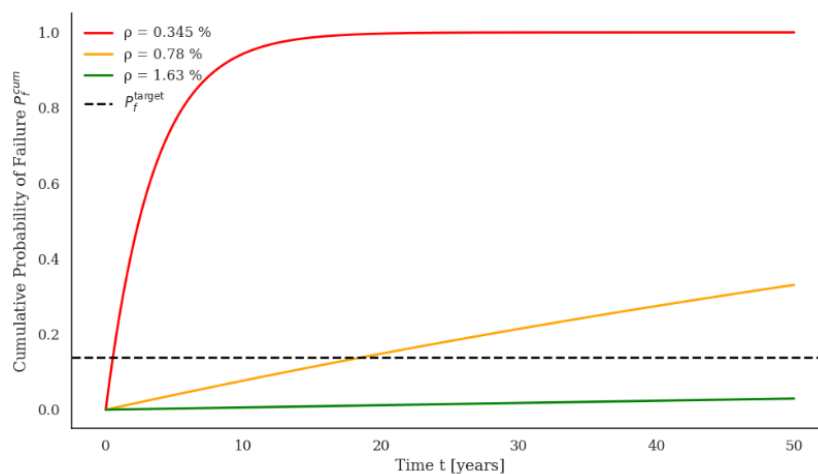


Figure 12. Cumulative probability of failure over a 50-year period

The failure direction coefficients α are determined in the standard normal space:

$$\alpha_i = \frac{\partial g / \partial u_i}{\sqrt{\sum_j (\partial g / \partial u_j)^2}} \quad (16)$$

where u_i are standardized random variables.

Figure 13 shows the influence of the deformation modulus, cohesion, angle of internal friction, and spectral acceleration on the reliability of the foundation. It is evident that the most significant contribution is made by the soil deformation modulus and the spectral acceleration of the first modal vibration.

The Monte Carlo, FORM, and SORM methods provide consistent results, confirming the adequacy of the selected model and the correctness of the probabilistic approach. The FORM method enables an efficient estimation of the reliability index and the identification of the most probable point of failure.

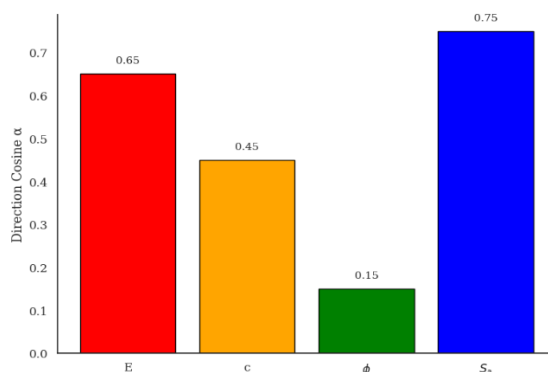


Figure 13. α -coefficients

The cumulative probability of failure over 50 years indicates a significant reduction in risk when the reinforcement ratio exceeds 0.78%. However, to ensure the required reliability level, a reinforcement ratio of 1.3–1.4% is recommended. The effective soil deformation modulus contributes most significantly to the probability of failure.

Technological efficiency of the raft foundation base reinforcement model

In addition to stability and reliability, geotechnical solutions must satisfy requirements of technological feasibility and economic efficiency. Modern displacement drilling technologies enable the installation of reinforcing elements with reduced construction time and cost under various soil conditions.

During displacement drilling, soil is compacted radially without excavation, resulting in increased density around the borehole and improved shaft resistance of the reinforcing elements. This technology is characterized by high productivity, with drilling rates reaching up to 1000 m and installation rates of 400–500 m per shift, significantly exceeding those of conventional bored piles.

Previous studies have demonstrated that reinforcement using vertical displacement elements is substantially more efficient than traditional ground improvement methods, requiring up to eight times less labor and approximately half the construction cost while maintaining the required geotechnical performance.

Table 3. Techno-economic assessment of foundation reinforcement alternatives

No.	Description of work	Unit	Quantity	Labor intensity, person-days	Cost of work, KZT
1	Soil replacement with layer-by-layer compaction	m ³	14 300	697	71 500 000
2	Soil compaction using heavy tampers	m ³	7 200	297	142 560 000
3	Foundation reinforcement with 6.0 m concrete elements (M12.5)	pcs	550	68	5 500 000

Foundation reinforcement using displacement drilling technology is characterized by high installation productivity, the absence of soil excavation, and the possibility of full mechanization, resulting in reduced construction time and costs. The proposed reinforcement model improves the technological, economic, and environmental efficiency of foundation construction while enhancing the reliability and durability of civil engineering structures.

CONCLUSION

The analysis of the reviewed literature made it possible to obtain a scientific and technical justification for the efficiency of the interaction between structural systems and a geotechnical soil mass reinforced with reinforcing elements. As a result, the main geometric parameters influencing the stability and the stress-strain state of the reinforced foundation were identified.

The conducted research substantiated the efficiency of the reinforcement system and established the dependence of raft foundation deformation on the thickness of the underlying layer, the diameter of the reinforcing element, and the spacing between the elements.

The regularities of soil foundation deformation depending on the reinforcement ratio and the stiffness of the reinforced base were identified.

The application of the probabilistic Monte Carlo method made it possible to determine the probability of limit states and the actual reliability coefficient of a foundation reinforced with rigid elements, taking into account real geotechnical conditions.

The technological efficiency and reliability of foundation reinforcement using rigid displacement elements were justified through a comparative analysis of labor intensity and installation duration indicators.

The use of rigid displacement elements for reinforcing the bases of raft foundations improves the structural performance of the system, enhances stress distribution, and reduces deformations under both service and ultimate loads. However, in practical engineering, there is still no unified methodology for evaluating the effectiveness of the mechanism, the quality of design, and the operational performance of such reinforcement systems in terms of durability, strength, and economic efficiency.

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