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RESEARCH ARTICLE

DESIGN OF A SLAB FOUNDATION WITH VERTICALLY REINFORCING ELEMENTS

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Abstract. *This article addresses the construction of high-rise buildings on loess collapsible soils stabilized with reinforcing elements. The primary objective of this study is the scientific and methodological justification of the effectiveness of reinforcing the base of a slab foundation for a multi-story building with vertical elements. The novelty of this research lies in the enhancement of the subgrade reaction coefficient through the design of the reinforcement grid parameters and the reinforcement length within the soil mass to ensure load-bearing capacity and reduce the settlement of the slab foundation. The design methodology is based on the requirements of Eurocode 7. Numerical simulations were performed using the finite element method (FEM) in the PLAXIS 3 software, employing the Hardening Soil model to simulate soil strengthening. As a result of increasing the subgrade reaction coefficient by incorporating rigid vertical reinforcing elements, the load-bearing capacity of the foundation was doubled. The findings substantiate the efficiency and reliability of the vertical reinforcement method for creating artificial foundations, significantly reducing both construction time and costs.*

Keywords: *slab foundation, vertical reinforcement, loess collapsible soils, finite element method (FEM), PLAXIS 3, subgrade reaction coefficient, Eurocode 7*

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ҒЫЛЫМИ МАҚАЛА

ТІК КҮРДЕЛІ ЭЛЕМЕНТТЕРМЕН КҮШЕЙТІЛГЕН ПЛИТАЛЫ НЕГІЗДІ ЖОСПАРЛАУ

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Аңдатпа. *Бұл мақала арматуралық элементтермен бекітілген лессалық шөгінді топырақтарда биік ғимараттарды салу мәселесін қарастырады. Зерттеудің басты мақсаты – тік элементтерді пайдалана отырып, көпқабатты ғимараттардың плиталы іргетасының негізін күшейтудің ғылыми-әдістемелік негіздемесін жасау. Жұмыстың жаңалығы арматуралық тор параметрлерін және топырақ массасындағы арматуралық элементтердің ұзындығын жобалау арқылы негіздің серпімділік коэффициентін арттыруда жатыр. Бұл әдіс іргетастың жүк көтеру қабілетін қамтамасыз етіп, оның шөгуін азайтуға бағытталған. Жобалау әдістемесі Eurocode 7 талаптарына негізделген. PLAXIS 3 бағдарламалық жасақтамасында ақырлы элементтер әдісі (FEM) қолданылып, Hardening Soil моделі бойынша топырақты нығайту процесі модельденді. Тік қатты арматуралық элементтерді енгізу арқылы іргетастың жүк көтеру қабілеті екі есеге артты. Алынған нәтижелер жасанды негіздерді жасау үшін тік арматуралау әдісінің тиімділігі мен сенімділігін дәлелдейді, сонымен қатар құрылыс уақыты мен шығындарын едәуір азайтады.*

Түйін сөздер: *плиталы іргетас, тік арматуралау, лессалық шөгінді топырақтар, ақырлы элементтер әдісі (FEM), PLAXIS 3, негіздің серпімділік коэффициенті, Eurocode 7.*

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НАУЧНАЯ СТАТЬЯ

ПРОЕКТИРОВАНИЕ ПЛИТНОГО ФУНДАМЕНТА С ВЕРТИКАЛЬНО АРМИРУЮЩИМИ ЭЛЕМЕНТАМИ

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Аннотация. *В данной статье рассматривается строительство высотных зданий на лессовых просадочных грунтах, укрепленных арматурными элементами. Основной целью исследования является научное и методологическое обоснование эффективности армирования основания плитного фундамента многоэтажного здания вертикальными элементами. Новизна работы заключается в повышении коэффициента постели за счет проектирования параметров арматурной сетки и длины армирования в массиве грунта, что способствует увеличению несущей способности и снижению осадки плитного фундамента. Методика проектирования основана на требованиях Eurocode 7. Численные расчеты выполнены методом конечных элементов (FEM) в программе PLAXIS 3, используя модель упрочняющегося грунта (Hardening Soil). В результате увеличения коэффициента постели путем включения жестких вертикальных арматурных элементов несущая способность фундамента возросла в два раза. Полученные результаты подтверждают эффективность и надежность метода вертикального армирования при создании искусственных оснований, что значительно сокращает время строительства и затраты.*

Ключевые слова:. *плитный фундамент, вертикальное армирование, лессовые просадочные грунты, метод конечных элементов (FEM), PLAXIS 3, коэффициент постели, Eurocode 7.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым Зерттеу жеке қаржыландыру көздері есебінен жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ / ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось Министерством науки и высшего образования Республики Казахстан за счет частных источников финансирования научных исследований.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

The In civil engineering, an increasing number of high-rise buildings are being constructed on previously undesirable sites, such as loess collapsible soils and reclaimed land. The construction of such structures poses complex geotechnical challenges related to the stress-strain state of superstructures interacting with the soil foundation. One of the alternative solutions for constructing high-rise buildings on loess collapsible soils is the vertical reinforcement of the foundation soil **(Usmanov, 2014)**, which aims to enhance load-bearing capacity and reduce foundation settlement **(Popov, 2015)**.

The regulatory document NTP RK 07-01.3-2011 on the design and implementation of foundation reinforcement with vertical reinforcing elements, adapted to Eurocodes **(SP RK EN 1997-2:2007)**, recommends the use of vertically deployed reinforcing elements to improve the engineering properties of foundation soils **(NTP RK 07-01.3-2011)**. An important advantage of improving the physical and mechanical characteristics of the foundation soil with reinforcing elements is the increase in compressive and tensile stresses within the foundation or geomass. Such reinforced soil can withstand differential deformations of buildings and structures under complex geotechnical conditions. Additionally, this method reduces the labor intensity associated with soil compaction or replacement, enhances structural safety, and shortens construction timelines **(Simões, 2020)**.

A distinctive feature of vertical bar reinforcement, compared to conventional pile foundations, is the load transfer mechanism: loads from the superstructure are transmitted through the soil cushion onto the vertical reinforcement elements and the surrounding soil via frictional forces. In this case, the performance of the reinforcing element within the soil is ensured through lateral confinement and frictional resistance. The reinforcement element absorbs the load through its upper part at the contact surface with the soil or foundation and transfers it to the underlying layers via its lower section and lateral friction forces.

Experimental and theoretical studies have demonstrated that the stress-strain state of a slab foundation reinforced with vertical elements depends on the adopted soil model **(Marinichev, 2016)**, the structural configuration of the reinforced foundation **(Makovetsky, 2021)**, and various other influencing factors.

2 LITERATURE REVIEW

Computational and experimental studies on geotechnical structures are commonly conducted using two well-established elastoplastic models: the Mohr-Coulomb model **(Popov, 2015)** and the Hardening Soil model **(Semet, 2023)**. Numerical simulations using PLAXIS have allowed for a comparative assessment of these models, guiding design objectives and recommendations **(Arjun, 2017)**. The Hardening Soil model is preferred for analyzing the stress-strain state of geotechnical structures under construction **(Lina, 2018)**, while the Mohr-Coulomb model is typically used for evaluating ultimate stress states **(Amjad, 2019)**.

Modern software packages enable the consideration of nonlinear soil properties when solving geotechnical problems **(Golubev, 2010)**. Advanced computational tools such as MIDAS GTX, Plaxis 3D, and others facilitate comprehensive analysis of slab foundations in complex geological conditions **(Samorodov, 2016)**. These tools not only account for foundation deformations but also assess the overall stress-strain behavior of the entire structural system supported by the slab foundation. Additionally **(Gilemhanov, 2016).)**, they provide solutions for spatial interaction between superstructures and three-dimensional soil mass models **(Botalov, 2019)**.

Despite the availability of regulatory guidelines for designing reinforced foundations, numerous challenges persist in engineering practice. These include accounting for soil heterogeneity over time, determining the stress-strain state of reinforcing elements and the spaces between them, optimizing the quantity and dimensions of reinforcing elements, assessing their optimal placement, predicting load-bearing capacity and deformability, and selecting cost-effective **(Ter-Martirosyan,2010)**, reliable, and environmentally sustainable construction methods **(Mirsayapov, 2005)**.

The objective of this study is to provide a scientific and methodological justification for the effectiveness of reinforcing slab foundation bases of high-rise buildings with vertical elements, using a real-world construction project as a case study.

3 MATERIALS AND METHODS

The reinforced geomass as a whole represents a composite system, which is characterized by the equivalent properties of the geomass—namely, the deformation modulus (E_2) and the design resistance (R_2). In this model, the load from the building is redistributed across the entire stabilized soil mass, thereby preventing the formation of localized stress concentration zones.

A key advantage of this method lies in the fact that the engineer essentially designs the foundation, creating the required physical and mechanical properties tailored to address specific practical challenges.

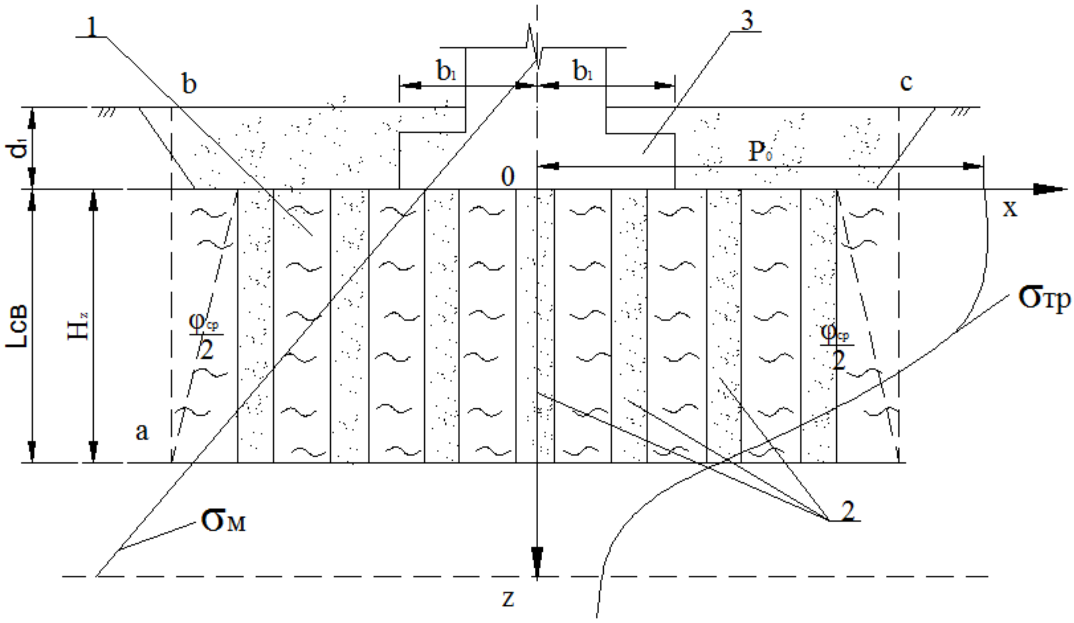

Figure 1 – Diagram for the calculation of a foundation reinforced with vertical elements.

Design standards recommend considering the reinforced foundation as a transversely isotropic medium and performing calculations based on ultimate limit states, including both critical failure conditions and serviceability criteria. In this approach, foundation calculations are conducted by assessing whether the ultimate state is reached due to failure or excessive deformations (GEO) under the given conditions.

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

$$S_{ap} \geq S_u \quad (2)$$

where

$\alpha = V_{ar}/V_{gr}$ — coefficient characterizing the proportion of reinforcing elements within the volume of the stabilized soil (V_{ar} — volume of reinforcing elements, V_{gr} — volume of soil);

R_1 — design resistance of the unreinforced soil beneath the foundation base, kPa;

R_2 — design resistance of the reinforcing material, assuming the replacement of natural soil with reinforcement, kPa;

P — average pressure beneath the foundation base, kPa;

S_{ar} — settlement of the reinforced foundation section;

S_u — ultimate allowable deformation of the foundation-structure system.

The settlement of the reinforced foundation section (S_{ar}) is calculated using the layered summation method according to the following formula:

$$S_{ap} = \sum_{i=1}^{n} \frac{\sigma_{zp,i} h_i}{E_3} \quad (3)$$

where

h_i — calculated thickness of the i-th soil layer within the compression zone of the reinforced foundation, determined by the condition 0.2i h = b (b — foundation width), m;

n — number of layers into which the compressible thickness of the reinforced soil is divided;

$\sigma_{zp,i}$— average additional vertical stress in the i-th reinforced layer, equal to the arithmetic mean of the stresses at the upper (Z_{i-1}) and lower (Z_i) boundaries of the layer along the vertical axis passing through the center of the foundation base, kPa;

E_3 — deformation modulus of the reinforced soil in the direction perpendicular to the soil surface, kPa.

The deformation characteristics (E, E_3) should be determined experimentally, and in the absence of test data, they can be estimated using approximate formulas:

$$Nd / n = Fd / \gamma d \quad (4)$$

where

N_d — design load, kN;

n — number of reinforcing elements (vertical reinforcing elements);

γ_d — safety factor for soil;

F_d — load-bearing capacity of the reinforcing elements (vertical reinforcing elements) based on soil (material), kN.

3.1 PROBLEM STATEMENT

The analysis considers the interaction between the foundation, the slab, and the superstructure under the assumption that the building and the foundation undergo identical displacements only in the vertical direction. The slab thickness is considered constant, and friction forces between the slab and the foundation are neglected. The soil foundation beneath the slab is characterized by a stiffness coefficient.

When designing a reinforced foundation, it is necessary to determine the required length of the reinforcing elements to ensure the load-bearing capacity of the deformable geomass. Another important aspect is defining the optimal spacing between reinforcing elements to minimize slab foundation deformations, as well as assessing the influence of the reinforcement percentage on the foundation stiffness coefficient.

Engineering practice suggests that a gravel cushion (buffer layer) with a thickness of 50 cm, compacted in layers, is commonly used to ensure an even distribution of loads on the reinforced soil foundation. The installation of vertically reinforcing elements is recommended using the borehole rolling technology, as it is considered a more efficient and practical method for improving foundation stability.

The settlement calculation of the reinforced foundation is performed using the PLAXIS 2D software package, which is based on the finite element method and employs the traditional Mohr-Coulomb soil model.

As the computational model, a nine-story residential building with a monolithic structure is used. The building has a rectangular shape in plan with overall dimensions of 29.6 m × 16.4 m, as shown in Figure 2.

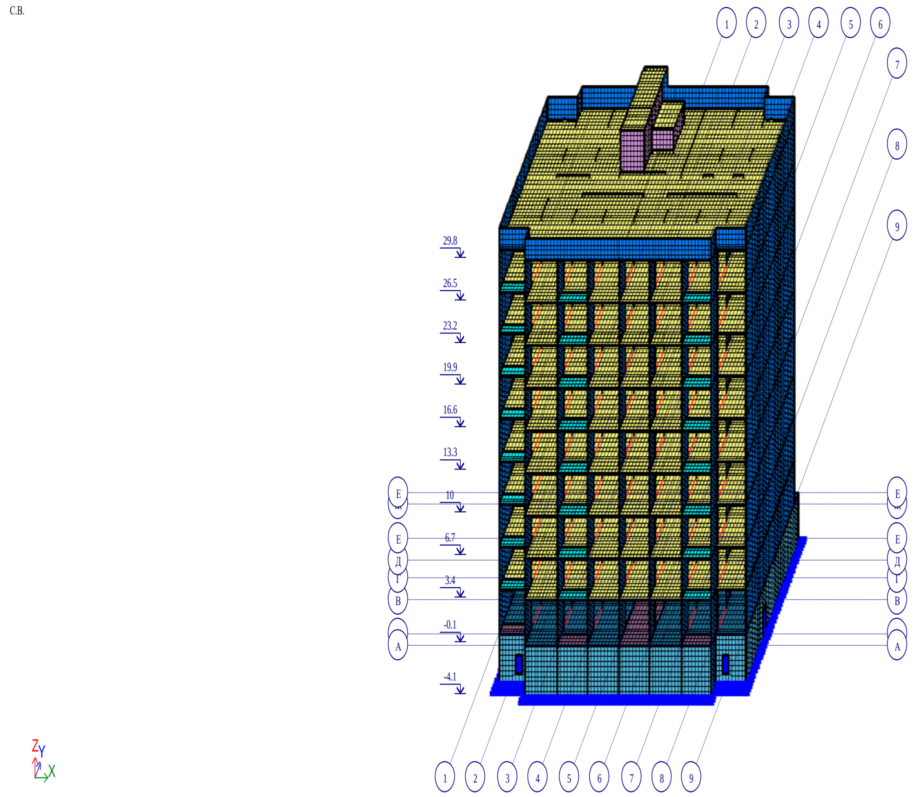

Figure 2 – Structural Scheme of the Residential Building.

The foundation is a monolithic slab with a thickness of 80 cm, resting on a 50 cm thick gravel cushion.

The primary output parameters of the calculation, based on the finite element method, include displacements and internal forces at the nodal points of the foundation and the slab foundation.

The soil characteristics according to engineering-geological elements (EGE) are presented in table 1.

Table 1

Physical and Mechanical Properties of Soils

Soil Type	Main Soil Characteristics	Additional Parameters for the HSS Model
EGE-1 Silty sandy loam, gray, with plant remains and sand interlayers, fluid consistency	γ = 18.8 kN/m³, ν = 0.35, c = 7 kPa, ϕ = 21°, E = 5400 kPa	E50 = 5400 kPa, EoedE_{oed}Eoed = 5400 kPa, EurE_{ur}Eur = 16200 kPa, K0K_0K0 = 0.642
EGE-2 Silty clay loam, gray, faintly layered, with plant remains, fluid consistency	γ = 18.9 kN/m³, ν = 0.35, c = 4 kPa, ϕ = 17°, E = 5000 kPa	E50 = 5000 kPa, EoedE_{oed}Eoed = 5000 kPa, EurE_{ur}Eur = 15000 kPa, K0K_0K0 = 0.708
EGE-3 Silty sandy loam, gray, with gravel, pebbles, and clay loam interlayers, plastic consistency	γ = 21.4 kN/m³, ν = 0.35, c = 20 kPa, ϕ = 21°, E = 12000 kPa	E50 = 12000 kPa, EoedE_{oed}Eoed = 12000 kPa, EurE_{ur}Eur = 36000 kPa, K0K_0K0 = 0.642
EGE-4 Silty sandy loam, gray, with gravel, boulders, and clay loam interlayers, stiff consistency	γ = 21.8 kN/m³, ν = 0.35, c = 21 kPa, ϕ = 30°, E = 16000 kPa	E50 = 16000 kPa, EoedE_{oed}Eoed = 16000 kPa, EurE_{ur}Eur = 48000 kPa, K0K_0K0 = 0.5

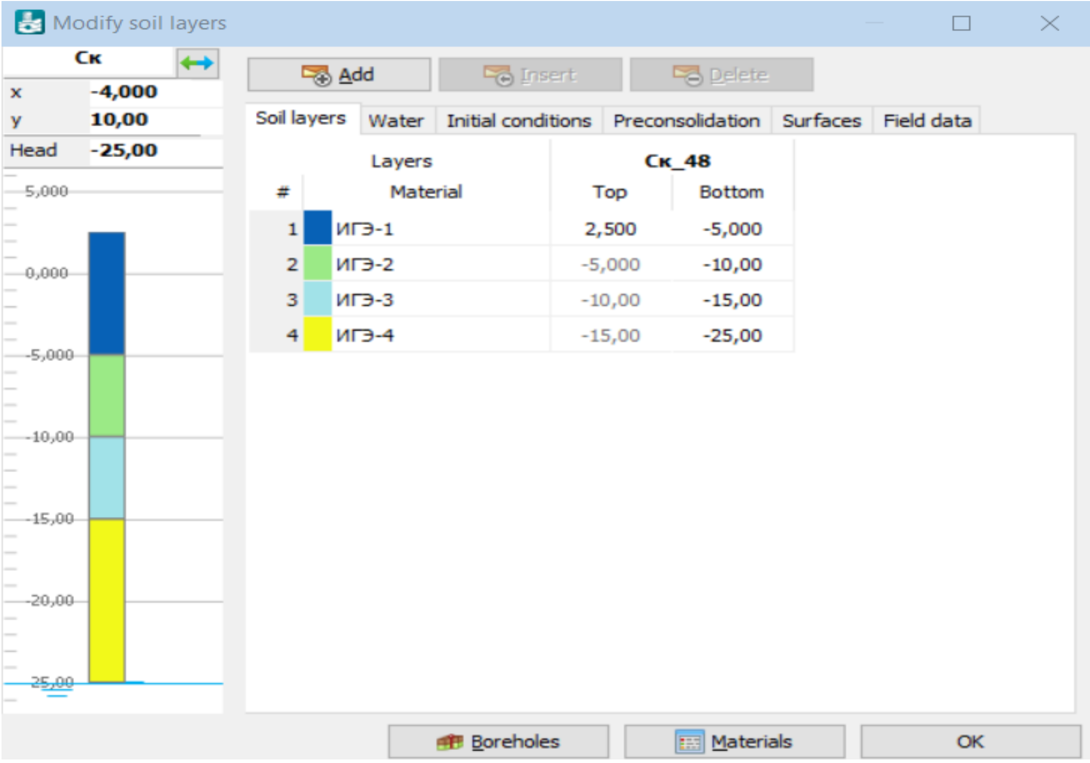

Figure 3 – Geological model in PLAXIS software.

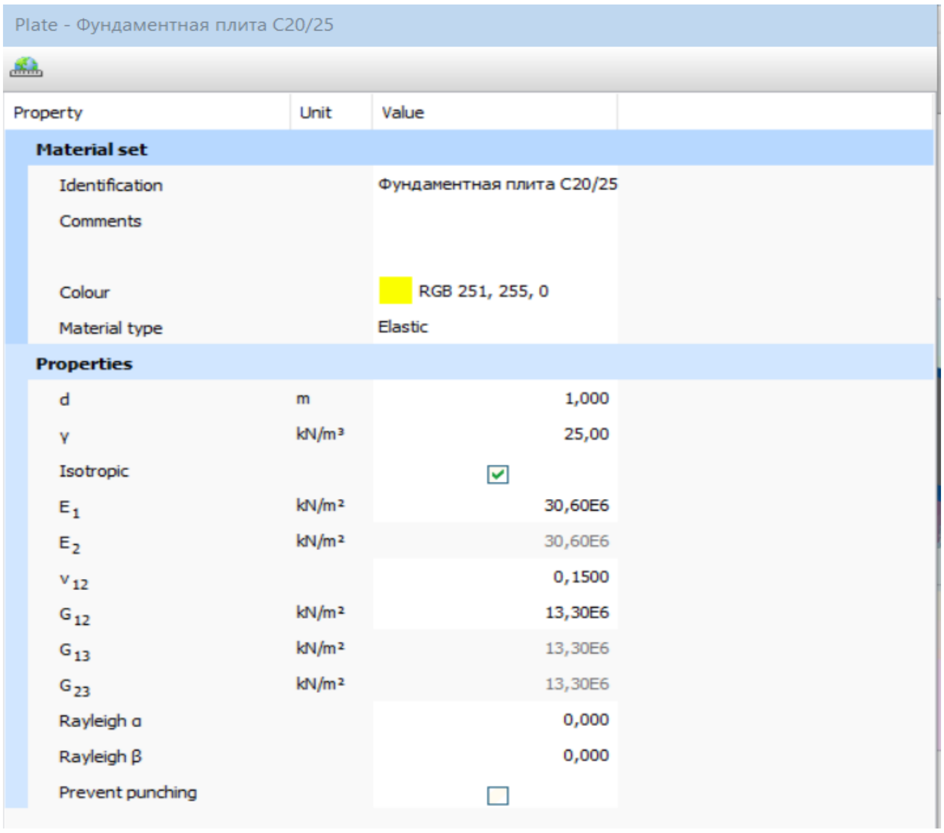

Figure 4 – Foundation slab with a thickness of 1.0 m (Concrete B25).

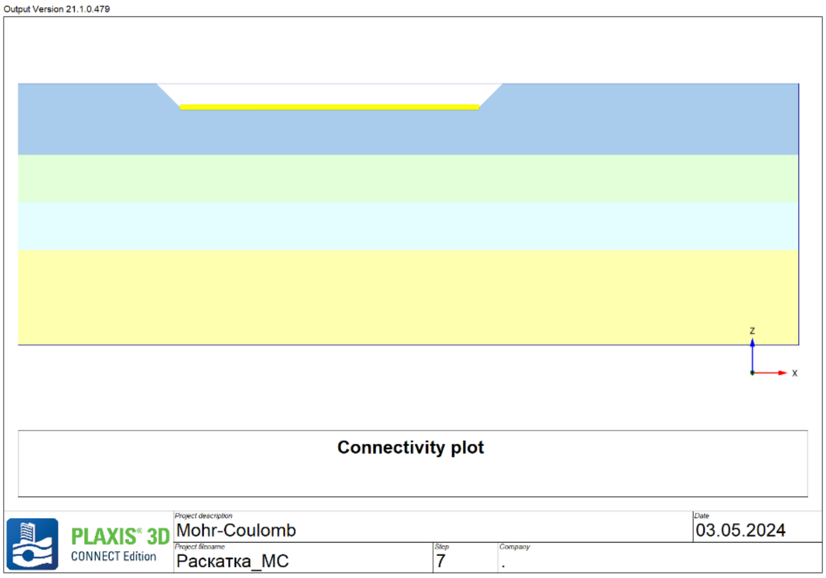

Figure 5 – Foundation cross-section.

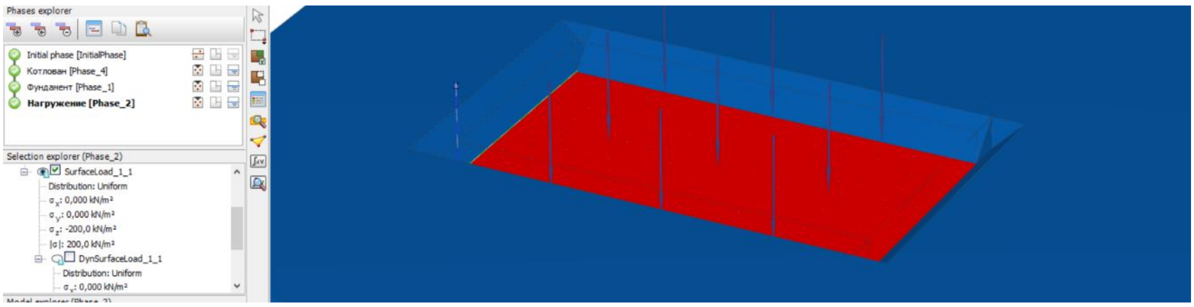

Figure 6 – Average pressure of 20.0 t/m².

4 RESULTS AND DISCUSSION

During the step-by-step loading process of the foundation with the weight of the foundation slab and the superstructure, the deformation pattern of the geomass was obtained (Fig. 7) along with the settlement diagram (Fig. 8), indicating a settlement of 97.8 mm.

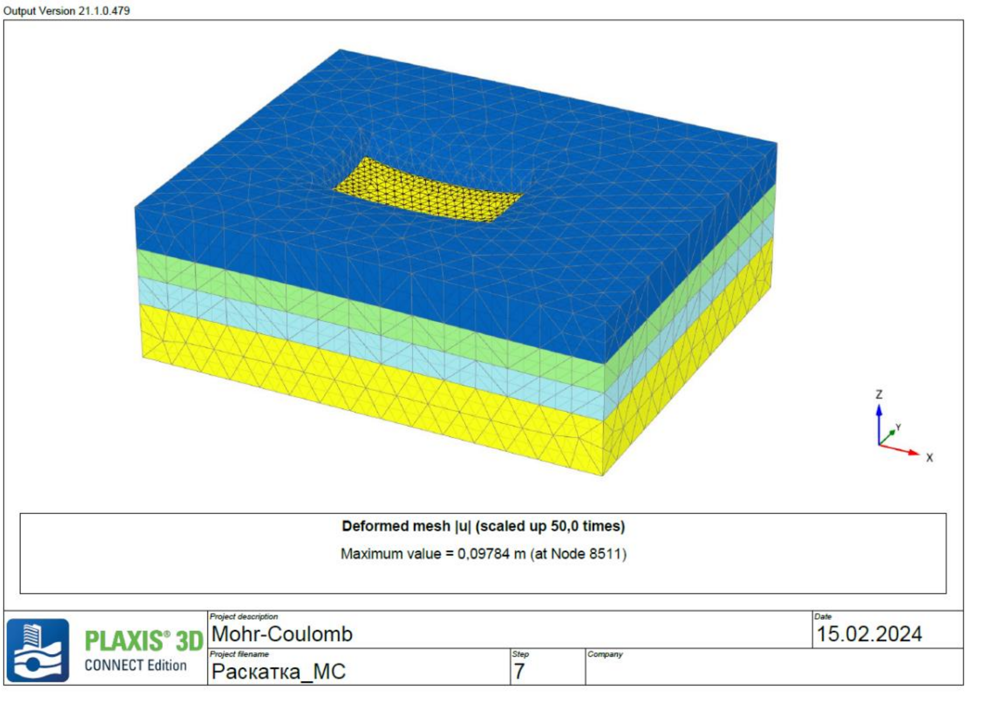

Figure 7 – Deformation pattern (Mohr-Coulomb model).

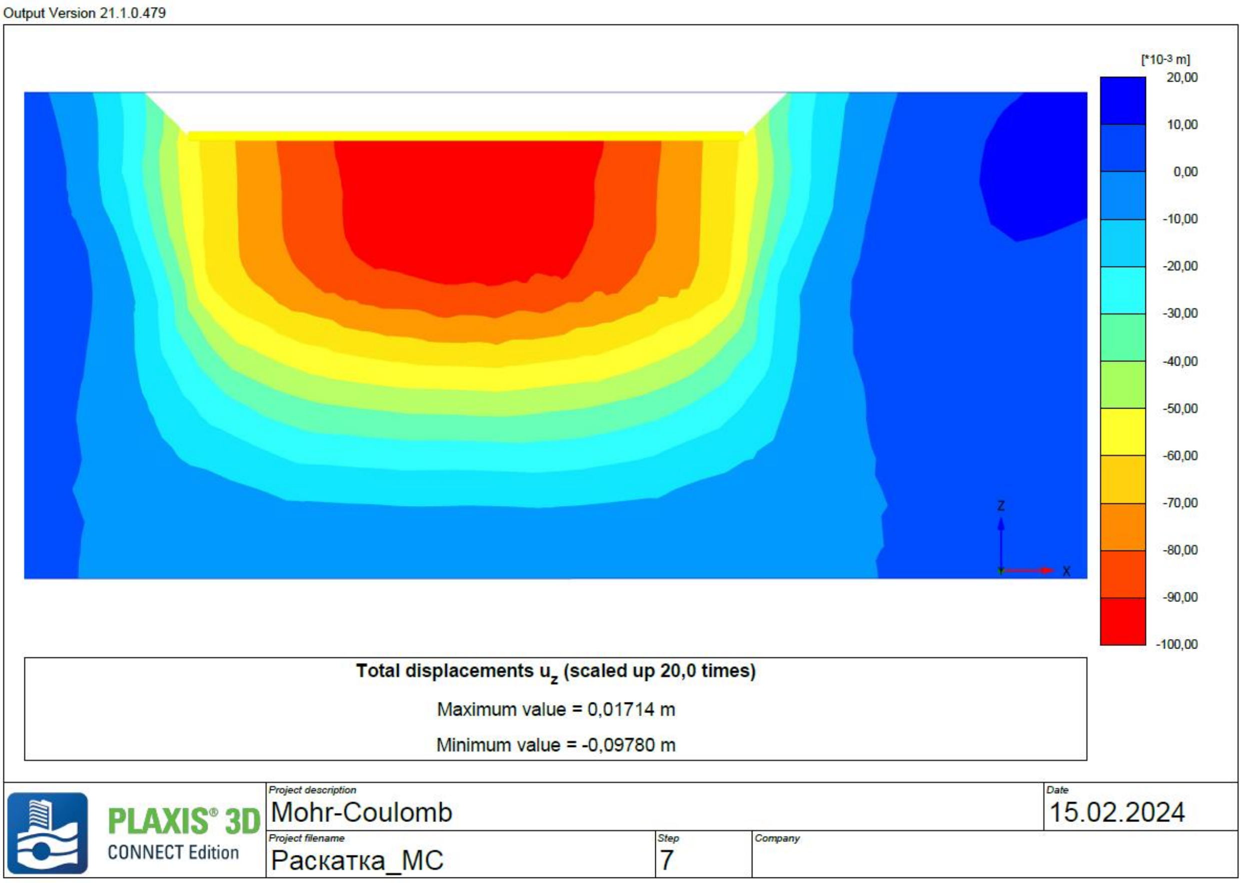

Figure 8 – Settlement according to the Mohr-Coulomb model without foundation reinforcement (max 97.7 mm).

In this case, the subgrade reaction coefficient (sometimes denoted as C), determined using Equation (1), is 205 t/m³.

$$K = P/s\ , \tag{5}$$

where:

P — pressure applied to the soil surface;

s — settlement at the point of pressure application;

K — subgrade reaction coefficient (sometimes denoted as C).

The foundation settlement results under the applied load, as shown in Fig. 7, indicate that the deformation of the foundation slab is at the limit of allowable values (65–100 mm). In design practice, an increase in the subgrade reaction coefficient is considered in such cases by utilizing the characteristics of a reinforced geomass, strengthened with Deep Soil Mixing (DSM) concrete reinforcing elements made of B12.5 concrete.

The preliminary spacing of the reinforcing elements is assigned within a range of 7 to 11d, where d is the diameter of the reinforcing element. This spacing is determined based on the deformation modulus of the surrounding soil or the requirement for ensuring the composite behavior of the reinforced soil mass, as well as achieving the necessary load-bearing capacity of the compacted foundation.

In this case, the spacing between the centers of the boreholes is determined using the following formula:

$$i_{ck} = 0{,}95d\sqrt{\frac{\rho_{dc}}{(\rho_{dc}-\rho_d)}} \qquad (6)$$

where:

p_d — dry density of the natural soil, t/m³;

p_{ds} — average dry density of the compacted soil mass, t/m³.

During the borehole drilling process using a rolling compactor, the soil surrounding the borehole is compacted to a certain diameter.

For preliminary calculations, the diameter of the compacted zone (d_s), which can be achieved after the rolling process, is determined using the following formula:

$$d_s = \gamma_c d\sqrt{\frac{\rho_{dc}}{(\rho_{dc}-\rho_d)}} \qquad (7)$$

where:

d — diameter of the rolling compactor (RC), m;

ρ_{ds} — dry density of the compacted soil, t/m³;

ρ_d — dry density of the natural soil, t/m³;

γ_c — soil working condition coefficient, assumed to be greater than 1.

The reinforcement of the geomass with DSM concrete column elements is simulated using Plaxis 3D software. According to structural calculations, the diameter of the vertically reinforcing element is Ø100 mm, with a length of L = 9.5 m and a grid spacing of 3 × 3 m between axes.

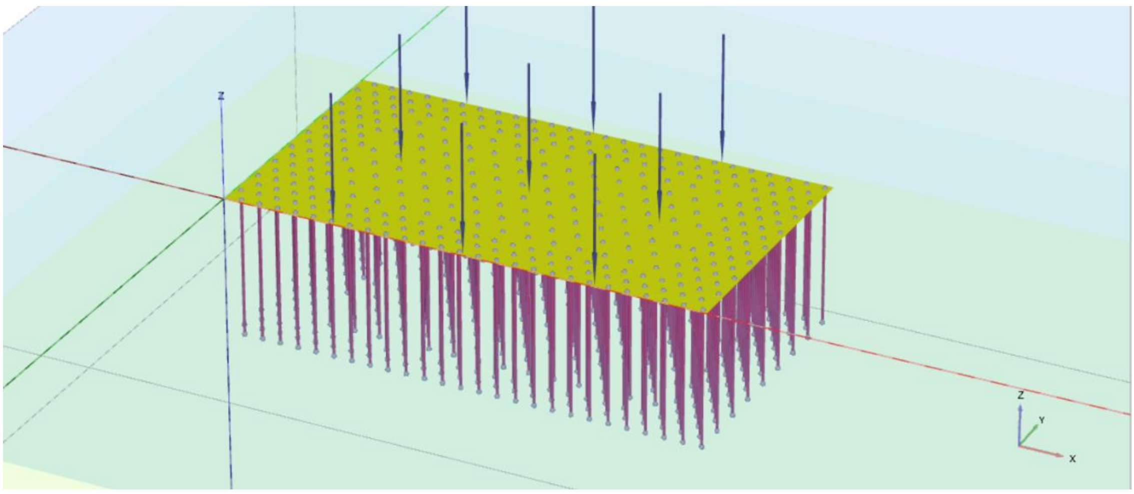

Figure 9 – Spatial model of the reinforced geomass.

In this case, when reinforcement is applied beneath the slab foundation, the load from the superstructure is transferred to the soil mass through the reinforcing elements via frictional forces. In the presented computational model (Fig. 8), the performance of the reinforcing element within the soil is ensured by lateral confinement and frictional forces. The reinforcing element, through its contact surface with the soil or the slab foundation, absorbs the load at its upper section and transfers it to the underlying layers through its lower section. Here, the vertical concrete reinforcing elements serve to withstand compressive stresses (Fig. 9).

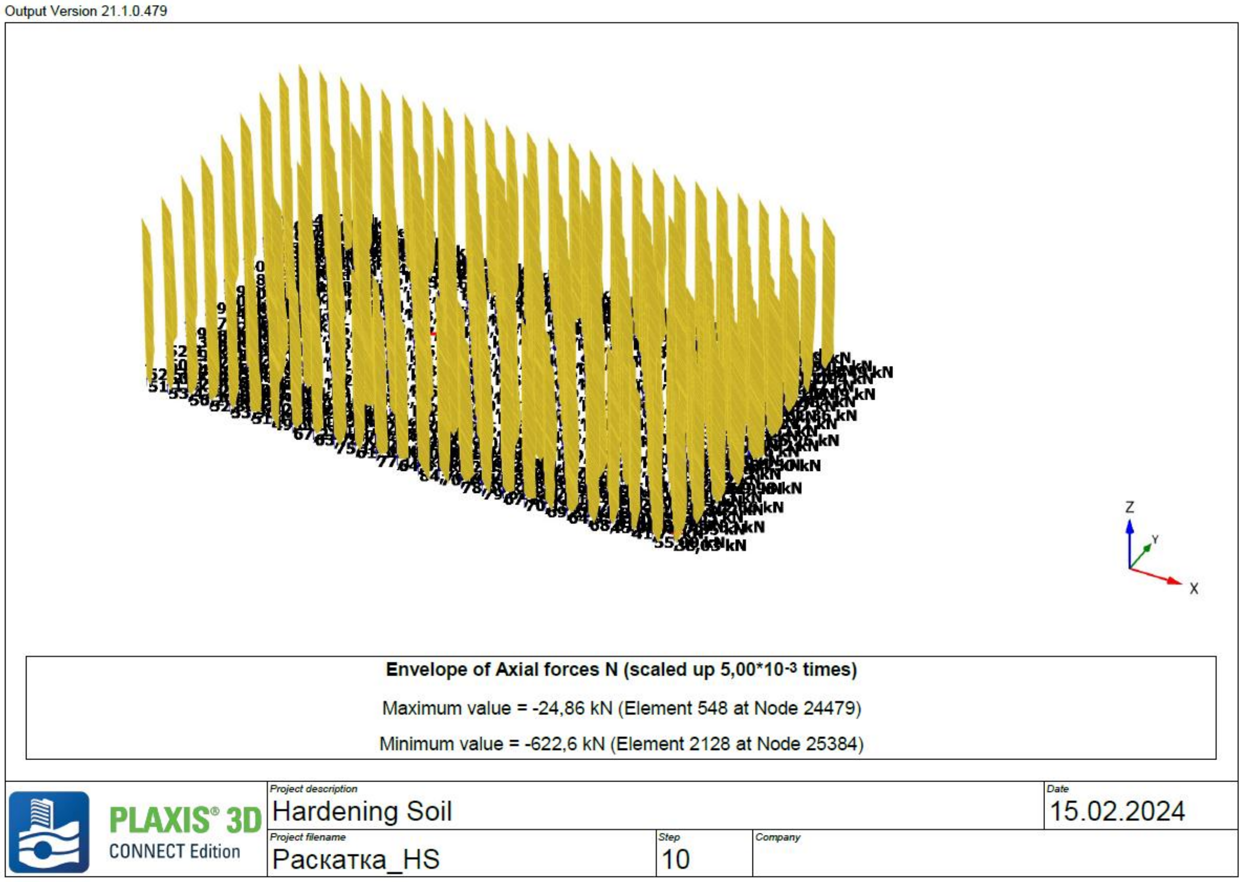

Figure 10 – Axial force N, Hardening Soil model (max 622.6 kN).

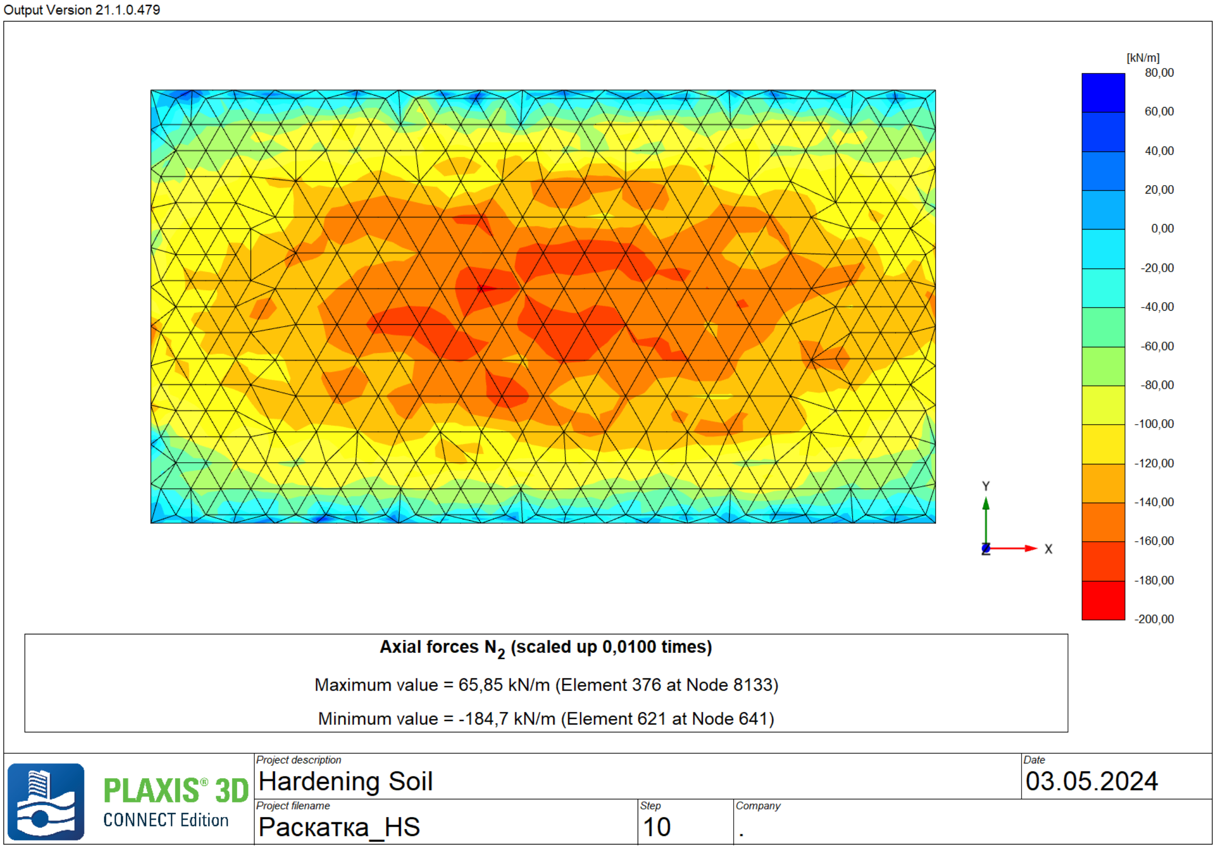

Figure 11 – Foundation. Axial force N, Hardening Soil model (max 184.7 kN/m).

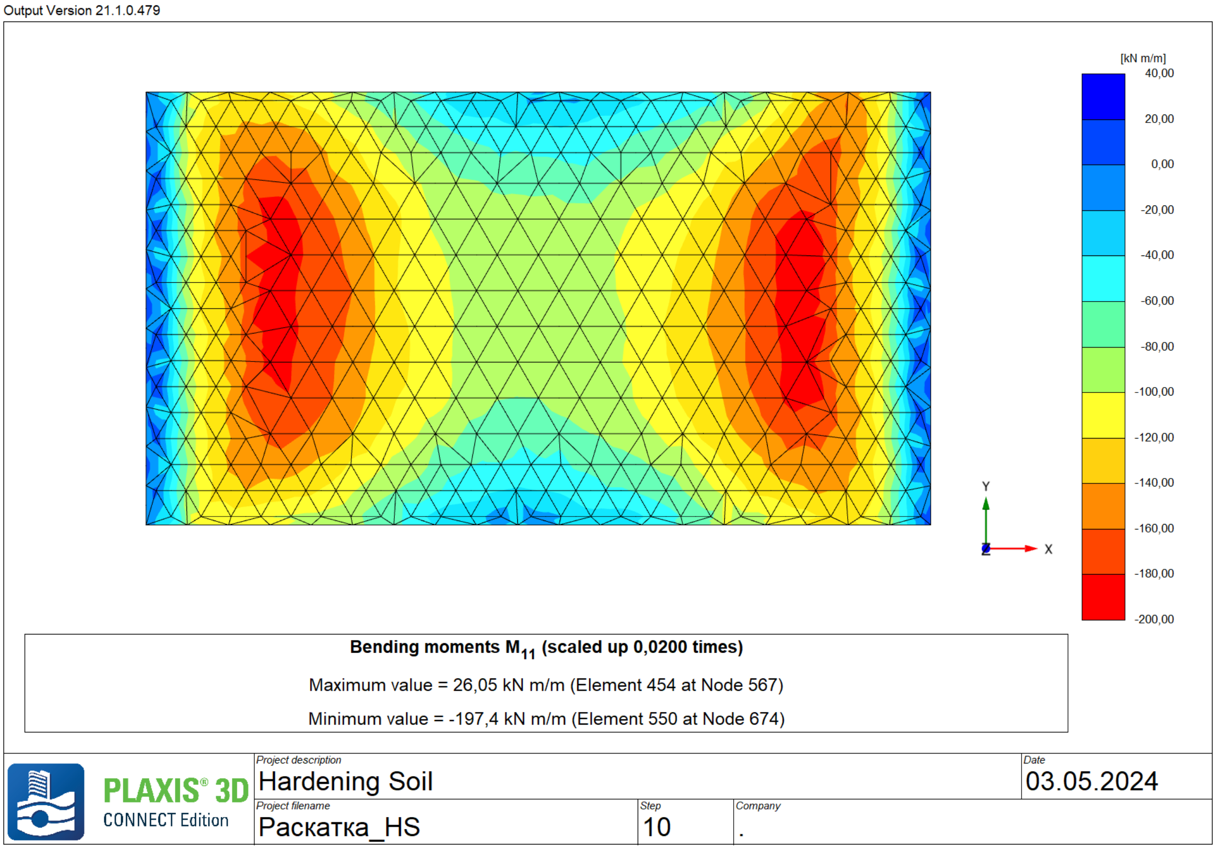

Figure 12 – Foundation. Bending moment M, Hardening Soil model (max 197.4 kN·m/m).

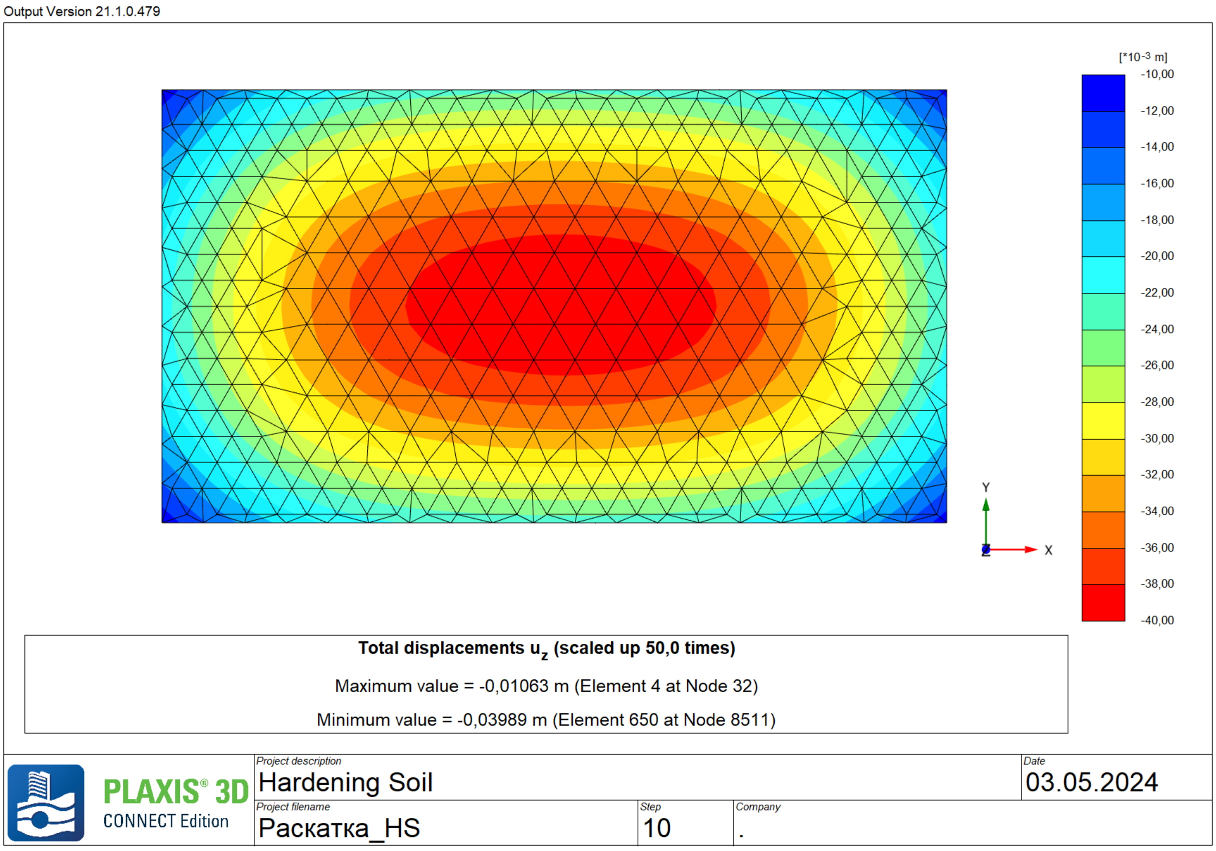

Figure 13 – Deformation of the foundation slab, Hardening Soil model (max 39.9 mm).

As a result, the structural solution for the vertically reinforced foundation of the slab foundation of a high-rise building includes reinforcing element spacing of 3 × 3 m, length of 9.5 m, diameter of 100 mm, and material—B12.5 concrete. Under these conditions, the maximum calculated settlement of the slab foundation is S = 3.99 cm. Consequently, the subgrade reaction coefficient has doubled, reaching K = 501 t/m³.

The increase in the load-bearing capacity of the foundation is also attributed to the borehole formation process, which involves drilling with a special rolling drill bit. This method ensures soil compaction around the borehole walls during drilling. A key factor is the doubling of soil density around the borehole wall, which significantly enhances pile shaft resistance due to lateral friction. Additionally, it is important to account for the elimination of the technological gap that may arise during the pile installation process.

5 CONCLUSIONS

1. Numerical modeling performed in PLAXIS 3 has demonstrated the effectiveness of reinforced foundations on highly compressible soils. The study confirmed that the implementation of rigid reinforcing elements with predefined geometric dimensions and physical-mechanical and deformation characteristics significantly enhances the foundation's load-bearing capacity. The numerical analysis allowed for an in-depth assessment of stress distribution, settlement reduction, and structural stability improvements in reinforced foundation systems.

2. The results indicate that the subgrade reaction coefficient is highly dependent on the structural configuration of the vertically reinforced foundation beneath the slab. Variations in reinforcement spacing, length, and material properties directly influence the stiffness and settlement behavior of the foundation. An optimized reinforcement design leads to a more uniform load distribution, reducing the risk of excessive differential settlements and enhancing the overall stability of the foundation system.

3. The length and spacing of vertical reinforcing elements were found to be critical parameters in improving the load-bearing capacity of the foundation. The optimized arrangement of reinforcement elements led to a threefold reduction in foundation deformability, significantly enhancing structural performance. This, in turn, results in substantial reductions in construction time and cost by minimizing the need for extensive soil stabilization measures and expediting the process of creating artificially reinforced foundations for high-rise buildings.

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