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RESEARCH ARTICLE

# RELIABILITY OF RAFT FOUNDATIONS FOR WIND POWER PLANTS ON REINFORCED SOIL

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**Abstract.** *The reliability assessment of wind power plants founded on raft foundations is highly relevant due to the rapid growth of wind energy projects. The aim of this study is to develop a scientifically substantiated methodology for the geotechnical and probabilistic reliability assessment of wind power plants (WPPs) on raft foundations, considering the interaction within the "soil-foundation slab-wind turbine tower" system, the variability of soil physical and mechanical properties, and the stochastic nature of wind loads. The results of geotechnical analyses performed using the finite element method in MIDAS GTS NX confirm that the gravity-type monolithic foundation satisfies the deformation and bearing capacity criteria. Probabilistic modelling methods enabled the quantitative evaluation of the reliability index β and probability of failure Pf of the raft foundation, considering the actual variability of soil properties, and allowed the safety margins in terms of structural strength and stability to be assessed. The scientific novelty of the study lies in the development of an integrated probabilistic-geotechnical approach for assessing the reliability of wind power plants on raft foundations while accounting for the stochastic variability of soil physical and mechanical properties, distinguishing the proposed methodology from conventional deterministic design approaches. The practical significance of the study lies in the direct applicability of the developed methodology to the design, construction, and operation of wind power plants, thereby improving the safety, economic efficiency, and durability of wind energy infrastructure.*

**Keywords:** *wind power plants; reliability; soil-foundation-tower interaction; reliability index; probability of failure; safety; durability.*

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ҒЫЛЫМИ МАҚАЛА

# ЖЕЛ ЭЛЕКТР СТАНЦИЯЛАРЫНЫҢ КҮШЕЙТІЛГЕН ТОПЫРАҚТАҒЫ ТАҚТАЛЫ ІРГЕТАСЫНЫҢ СЕНІМДІЛІГІ

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**Аңдатпа.** *Жел энергетикасы жобаларының қарқынды дамуына байланысты тақталы іргетастардағы жел электр станцияларының сенімділігін зерттеу өзекті болып табылады. Зерттеудің мақсаты - «топырақ негізі - іргетас тақтасы - жел қондырғысының мұнарасы» жүйесінің өзара әрекеттесуін, топырақтардың физика-механикалық сипаттамаларының өзгергіштігін және жел жүктемелерінің кездейсоқ сипатын ескере отырып, тақталы іргетастардағы жел электр станцияларының (ЖЭС) сенімділігін геотехникалық және ықтималдық бағалаудың ғылыми негізделген әдістемесін әзірлеу. MIDAS GTS NX бағдарламалық кешенінде ақырлы элементтер әдісімен орындалған геотехникалық есептеулердің нәтижелері гравитациялық монолитті іргетастың деформациялар мен негіздің көтергіш қабілеті бойынша критерийлерге сәйкестігін растады. Ықтималдық модельдеу әдістері топырақ сипаттамаларының нақты өзгергіштігін ескере отырып, тақталы іргетастың сенімділік индексін β және істен шығу ықтималдығын Pf сандық бағалауға, сондай-ақ құрылымның беріктігі мен орнықтылық қорын анықтауға мүмкіндік берді. Жұмыстың ғылыми жаңалығы топырақтың физика-механикалық сипаттамаларының стохастикалық өзгергіштігін ескере отырып, тақталы іргетастардағы жел электр станцияларының сенімділігін бағалаудың кешенді ықтималдық-геотехникалық тәсілін әзірлеуде жатыр. Бұл тәсіл дәстүрлі детерминистік жобалау әдістерінен ерекшеленеді. Зерттеудің практикалық маңыздылығы әзірленген әдістемелерді жел электр станцияларын жобалау, салу және пайдалану кезінде тікелей қолдану мүмкіндігінде жатыр, бұл жел энергетикасы нысандарының қауіпсіздігін, экономикалық тиімділігін және ұзақ мерзімділігін арттыруға мүмкіндік береді.*

**Түйінді сөздер:** *жел электр станциялары; сенімділік; топырақ-іргетас-мұнара жүйесі; сенімділік индексі; істен шығу ықтималдығы; қауіпсіздік; ұзақ мерзімділік.*

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НАУЧНАЯ СТАТЬЯ

# НАДЕЖНОСТЬ ПЛИТНОГО ФУНДАМЕНТА ВЕТРОВЫХ ЭЛЕКТРОСТАНЦИЙ НА АРМИРОВАННОМ ГРУНТЕ

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**Аннотация.** *Исследование надежности ветровых электростанций на плитном фундаменте является актуальным в связи с ростом ветроэнергетических проектов. Целью исследования является разработка научно обоснованной методики геотехнической и вероятностной оценки надежности ветровых электростанций (ВЭС) на плитных фундаментах с учетом взаимодействия системы «грунтовое основание - фундаментная плита - башня ветроустановки», изменчивости физико-механических характеристик грунтов и случайного характера ветровых нагрузок. Результаты геотехнических расчетов, выполненных методом конечных элементов в ПК MIDAS GTS NX, подтверждает соответствие гравитационного монолитного фундамента критерием по деформациям и несущей способности основания. Применение вероятностных методов моделирования позволило количественно оценить индекс надежности β и вероятность отказа Pf плитного фундамента с учетом реальной изменчивости характеристик грунтов, а также определить запасы прочности и устойчивости сооружения. Научная новизна работы заключается в разработке комплексного вероятностно-геотехнического подхода к оценке надежности ветровых электростанций (ВЭС) на плитных фундаментах с учетом стохастической изменчивости физико-механических характеристик грунта, что отличает его от традиционного детерминированного проектирования. Практическая значимость исследования заключается в возможности непосредственного применения разработанных методик при проектировании, строительстве и эксплуатации ветровых электростанций (ВЭС), что обеспечивает повышение безопасности, экономической эффективности и долговечности объектов ветроэнергетики.*

**Ключевые слова:** *ветровые электрические станции; надежность; грунт-фундамент-башня; индекс надежности; вероятность отказа; безопасность; долговечность.*

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## 1 INTRODUCTION

The development of wind energy is a strategic priority of the energy policies of many countries, including Kazakhstan. In the context of the transition to a low-carbon economy, the reliability of wind power plants (WPPs) is becoming increasingly important, particularly given the complex engineering-geological and climatic conditions of several regions of the country, including high-wind areas, weak soils, and seismicity [1].

Modern wind turbines generate significant dynamic loads, resulting in a substantial increase in the forces transmitted to the foundation and supporting soil. In such conditions, raft foundations are among the most commonly used solutions for WPPs, particularly on medium-strength and weak soils. However, their reliability depends not only on the strength of concrete but also on the performance of the entire “soil-foundation-tower” system. Gravett and Markou presented full-scale 3D modeling of the “soil-foundation-tower” system using modal analysis and nonlinear material models. Their results demonstrated the sensitivity of dynamic characteristics to soil conditions and provided a basis for optimizing reinforced concrete raft foundations [2,3].

Numerous studies have demonstrated that conventional deterministic approaches are insufficient for assessing the reliability of WPP foundations, particularly with increasing turbine dimensions and load variability. Probabilistic methods provide a more adequate assessment of failure risks by accounting for uncertainties in soil properties and external actions [4].

A recent review published in 2025 discusses the structural behavior of shallow foundations for onshore wind turbines considering soil-structure interaction (SSI). Particular attention is given to deformation modeling, the influence of soil parameters and dynamic loading, and the optimization of structural solutions for large wind turbines [5].

A review of reliability methods for wind turbine structures presents probabilistic approaches for assessing structural component failures under random actions, including wind and cyclic loading [6]. The study covers first- and second-order reliability methods as well as Monte Carlo simulation techniques applicable to the reliability assessment of structures and their components.

Recent studies indicate that the spatial variability of soil properties and correlated environmental loads should be considered when assessing foundation reliability, since neglecting these factors may lead to inaccurate estimates of the probability of failure [7].

A 2024 study analyzed the behavior of monolithic foundations under lateral loading using a probabilistic approach combined with finite element modeling, including the evaluation of the reliability index and parameter sensitivity [8,9].

Recent reviews emphasize that soil-structure interaction (SSI) and cyclic foundation loading have a significant influence on foundation durability, deformation behavior, and long-term stability, requiring integrated numerical modeling and reliability analysis. The response of a wind turbine foundation is strongly dependent on the stiffness and strength characteristics of the supporting soil, foundation geometry, and magnitude and cyclic nature of the applied loads. At the same time, the structural analysis of bored pile foundations plays an important role in WPP foundation design, particularly under unfavorable geotechnical conditions. However, comprehensive methodological guidelines that integrate soil-foundation interaction, deformation criteria, and probabilistic reliability assessment remain limited for practicing engineers [10-12].

Loess and collapsible soils, as well as soils characterized by relatively low deformation moduli and considerable spatial variability of mechanical properties, are widespread in several regions of Kazakhstan, particularly in the southern and western parts of the country. Such ground conditions may result in excessive total and differential settlements, redistribution of stresses beneath the foundation, and a gradual reduction in the operational reliability of WPP structures. These effects become particularly important for modern wind turbines because their foundations are subjected to combinations of vertical loads, horizontal forces, overturning moments, and cyclic wind-induced actions. Therefore, the reliability assessment of wind power plants supported by raft foundations is particularly relevant due to the probabilistic risk of premature loss of serviceability and the potentially high economic consequences associated with foundation failure or excessive deformation [13-15].



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In this context, there is a need for an integrated approach that combines conventional geotechnical calculations with probabilistic reliability assessment and explicitly accounts for uncertainties in soil properties and external loading. Such an approach can provide a more realistic representation of foundation performance than purely deterministic calculations and can identify the parameters that have the greatest influence on structural safety and serviceability.

The aim of this study is to develop a scientifically substantiated methodology for the geotechnical and probabilistic reliability assessment of wind power plants (WPPs) supported by raft foundations, considering the interaction within the "soil-foundation slab-wind turbine tower" system, the variability of the physical and mechanical properties of soils, and the stochastic nature of wind loads. The proposed approach is intended to quantify the reliability level of the foundation system and provide a basis for more rational and reliable design decisions under uncertain geotechnical and loading conditions.

## 2 MATERIALS AND METHODS

The research methodology is based on an integrated combination of theoretical, computational, probabilistic, and experimental-analytical methods, taking into account the specific behavior of wind power plants (WPPs) supported by raft foundations.

The "soil-raft foundation-WPP tower" system is considered as a spatial nonlinear system accounting for contact interaction and stress redistribution. The methodology is based on the limit state theory for soils and foundations, with bearing capacity and allowable settlement adopted as the principal performance criteria.

The probabilistic model is based on reliability theory, where variations in the soil deformation modulus $E_s$ and soil strength characteristics are treated as random variables. Probabilistic analysis and reliability assessment are performed using the reliability index $\beta$ method and by establishing the relationship between the probability of failure $P_f$, load level, and foundation parameters.

Numerical modeling is performed using the finite element method (FEM) to simulate the nonlinear interaction between the raft foundation and the supporting soil. Statistical processing and sensitivity analysis are carried out by evaluating the influence of each parameter on the reliability index and identifying the variables that have the greatest effect on the probability of system failure.

The calculation and input data for the applied part of the study were obtained from a wind power plant (WPP) project located in the Zhambyl Region of the Republic of Kazakhstan.

The foundation was designed as a monolithic circular reinforced concrete foundation made of C32/40 (B40) concrete, with a diameter of 24.0 m and an overall height of 3.8 m. It includes a tower-base pedestal with a height of 2.6 m and a diameter of 7.0 m. The foundation embedment depth is 3.5 m (Figure 1).

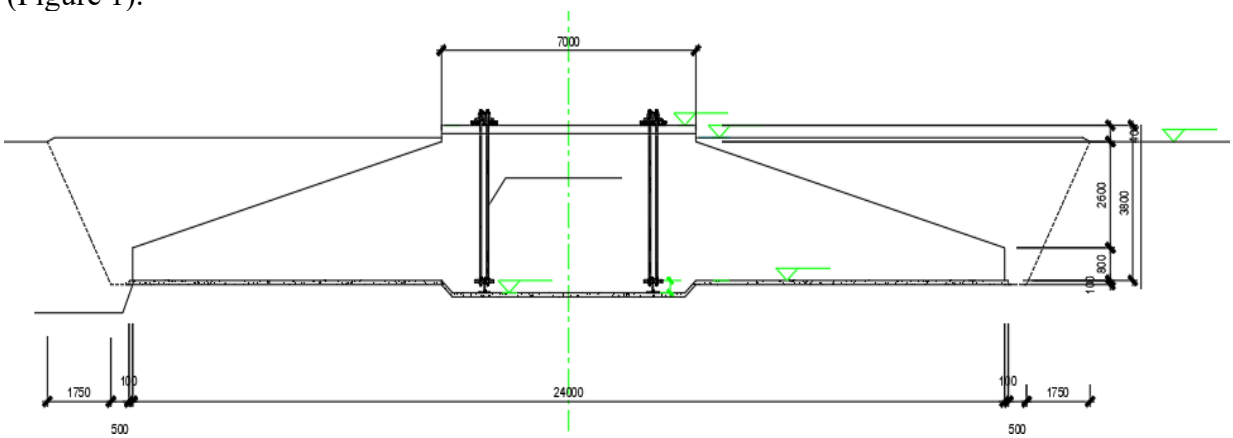


**Figure 1 -** Foundation Cross-Section.



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The engineering-geological conditions are represented by a multilayer soil profile comprising several engineering-geological elements (EGEs): clayey gravel with sand, loam with gravel, weathered sandstone, and shale/argillite. The design parameters of the soil layers include the deformation modulus $E$, effective internal friction angle $\varphi'$, cohesion $c'/C_u$, and Poisson's ratio $\mu$. The site is classified as seismically active, with design ground accelerations of $a_{gh} = 0.19g$and $a_{gV} = 0.133g$, and the soil category is classified as IB.

The engineering-geological conditions of the site are characterized by diverse geomorphological and geological features formed by complex tectonic and erosional processes. The terrain includes plains, foothills, and mountain ranges and is classified into denudation-tectonic, denudation, and accumulative landforms. Arid-denudation plains and erosion-formed plateaus represent transitional zones between mountainous areas and regions of sediment accumulation.

The seismicity of the site is determined by its location in the Zhambyl Region within a seismically active zone according to SP RK 2.03-30-2017. According to the OSZ-2475 seismic zoning maps, the expected seismic intensity is 7 points on the MSK scale, with a 10% probability of exceedance in 50 years. According to the OSZ-22475 maps, the expected seismic intensity is 8 points on the MSK scale, with a 2% probability of exceedance in 50 years.

The design parameters required for foundation design at different relative densities of the soils encountered during the site investigation are presented in Table 1.

**Table 1 -** Design Parameters of the Soil beneath the Foundation Slab

| Soil Layer / Parameter | Depth, m | Unit Weight, kN/m³ | E, MPa | φ′, ° | c′, kN/m² | $C_u$, kN/m² | μ |
|---|---|---|---|---|---|---|---|
| EGE-1: Clayey gravel with sand | 1.0-3.20 (for all boreholes except BH-20, where it extends to 10.0 m, and BH-18, where it extends to 7.0 m) | 18 | 22.30 | 32 | 0 | - | 0.3 |
| EGE-2: Loam with gravel | 0.50-2.60 | 19 | 6.0 | 20 | 30 | 40 | 0.35 |
| EGE-3: Weathered sandstone (bedrock) | From 1.0-3.0 m to the end of borehole (EOB) in BH-6, BH-7, BH-13, and BH-14 | 23 | 600 | 33 | 200 | - | 0.25 |
| EGE-4: Shale/argillite (bedrock) | From 1.0-3.0 m to the end of borehole (EOB) in all boreholes except BH-6, BH-7, BH-13, BH-14, BH-18, and BH-20 | 23 | 300 | 30 | 180 | - | 0.25 |

*Note: $c'$- drained cohesion; $C_u$- undrained cohesion; μ- Poisson's ratio.*

The geotechnical reliability assessment of wind power plants (WPPs) on raft foundations was performed by evaluating foundation displacements, settlements, and the stress state of both the foundation and the supporting soil using the finite element method in MIDAS GTS NX. The analysis was carried out using a deformed soil-foundation interaction model. GTS NX is specialized software developed for finite element modeling of the interaction between structures and their supporting ground. It enables staged numerical analysis of excavations, embankments, structural construction, loading, and other effects that directly influence design and construction processes. The numerical model of the circular foundation used in the analysis is presented in Figure 2.



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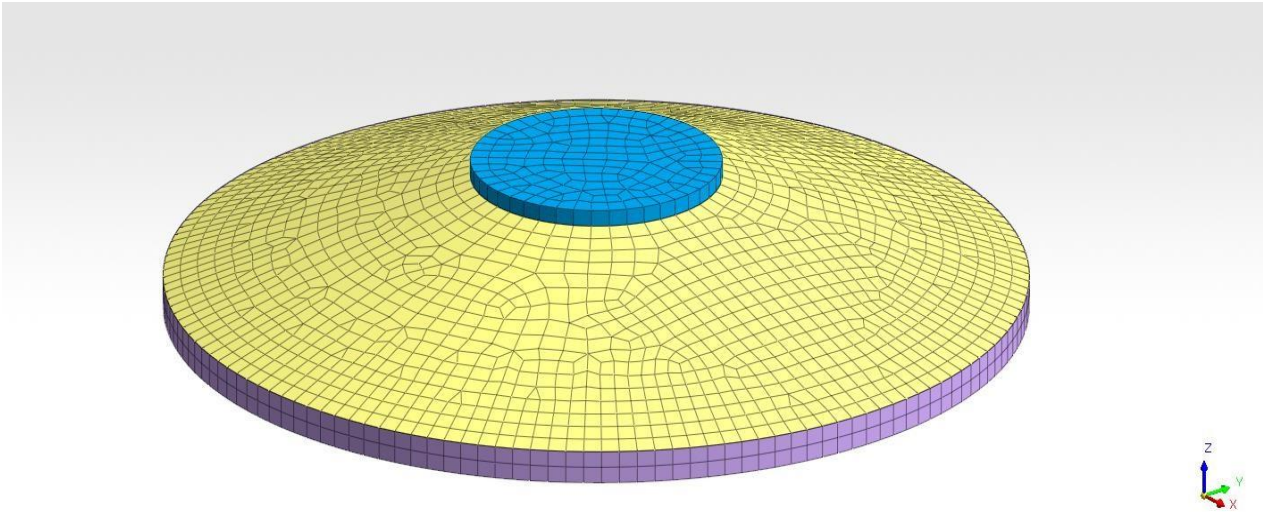

**Figure 2 -** Numerical Model of the Foundation.

The calculation results show that the maximum foundation settlement is 2.32 cm, which is below the allowable limit of 10 cm specified by the client and adopted in accordance with SP RK 5.01-102-2013. The distribution of total deformations of the supporting soil and foundation is presented in Figure 3, with maximum values of 2.38 cm for the soil and 2.32 cm for the foundation.

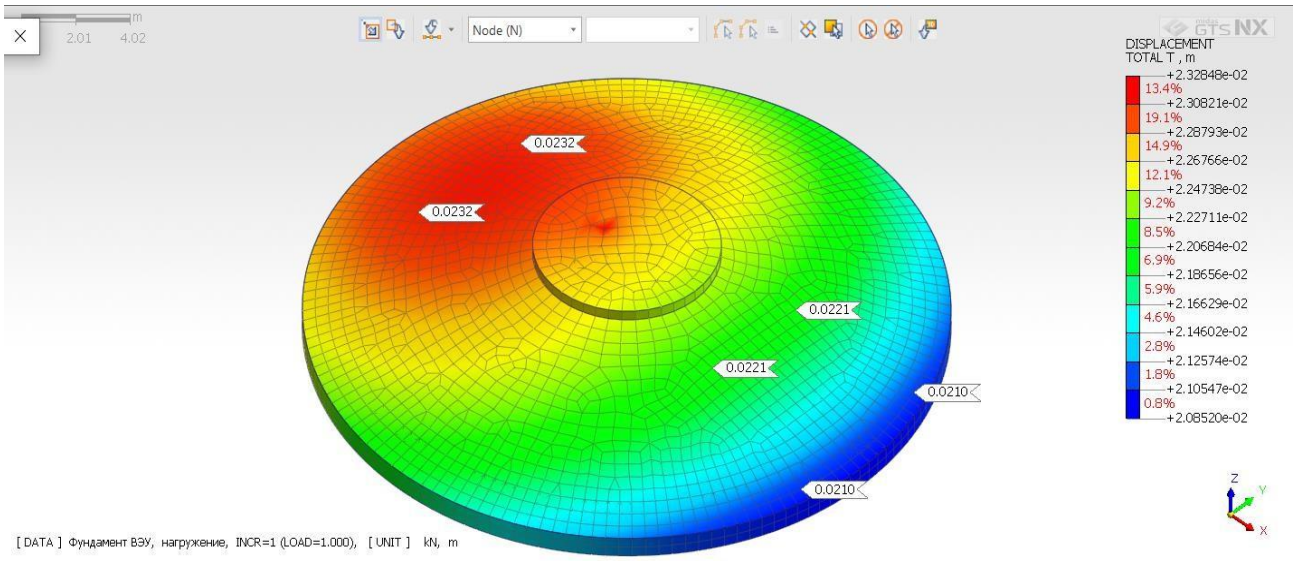


**Figure 3 -** Total Foundation Deformations (max. 2.32 cm; min. 2.08 cm).

The relative differential settlement was verified using the following expression:

$$\frac{S_1 - S_2}{L} = \frac{23{,}2 - 20{,}0}{24000} = 0{,}0001 < 0{,}005, \quad (1)$$

which satisfies the specified criterion. The graphical representation of the relative differential settlement is presented in Figure 4.



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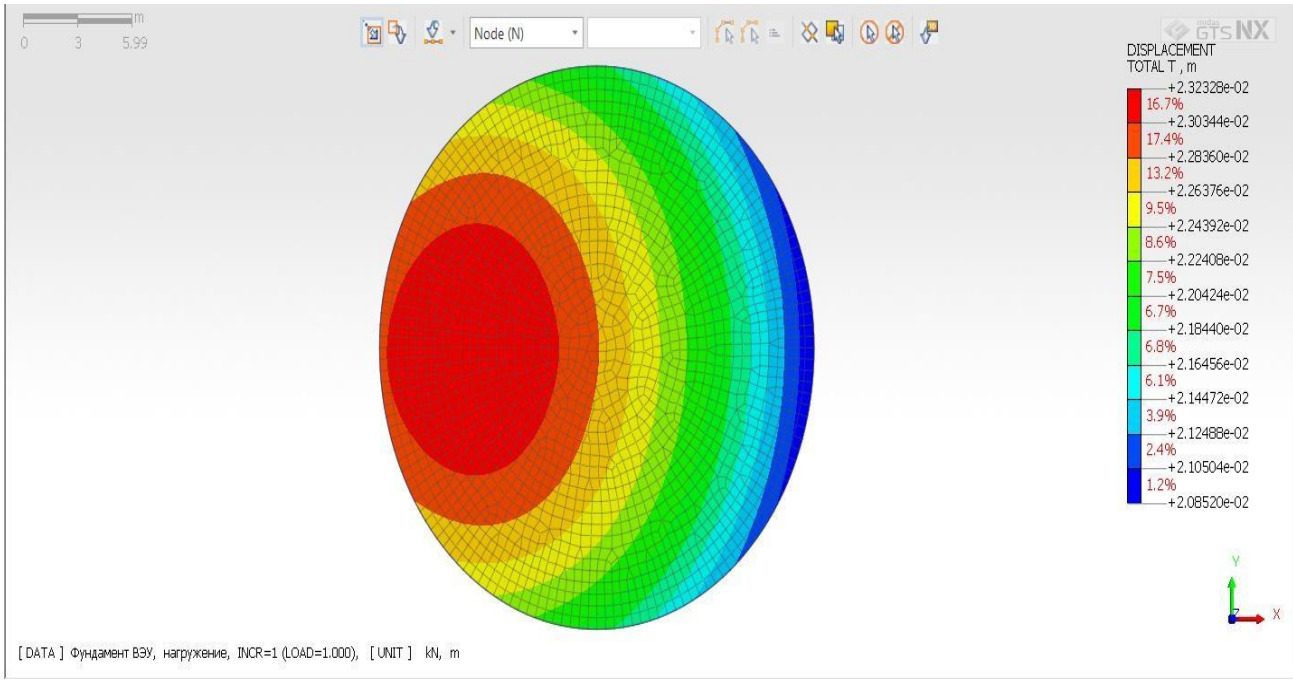


**Figure 4 -** Total Foundation Deformations (max. 2.32 cm; min. 2.08 cm).

The bearing capacity of the building foundation soil was calculated in accordance with SP RK 5.01-102-2013. In the foundation deformation analysis, the average pressure beneath the foundation base, P, should not exceed the design resistance of the foundation soil, R, determined by the following equation:
where $\gamma_{c1}$and $\gamma_{c2}$are the working condition coefficients adopted according to Table 2.

$$R=\gamma_{c1}\gamma_{c2}/k[M\gamma kzb\gamma II+Mqd1\gamma II'+(Mq-1)db\gamma II'+MccII] \quad (2)$$

where:

$k$ – is a coefficient taken as 1.0 when the soil strength parameters (φ and c) are determined by direct testing, and $k = 1.1$when they are adopted from the tables;

$M_\gamma$, $M_q$, and $M_c$ - are coefficients adopted according to Table 2;

$k_z$ – is a coefficient taken as 1.0 for $b < 10$m; $k_z = z_0/b + 0.2$for $b > 10$m, where $z_0 = 8$m;

b - is the width of the foundation base, m. When a concrete or crushed-stone preparation layer of thickness $h_p$is provided, bmay be increased by $2h_p$;

$\gamma_{II}$ - is the average design value of the unit weight of soils located below the foundation base, accounting for the buoyancy effect of groundwater where applicable, kN/m³;

$\gamma'_{II}$ - is the average design value of the unit weight of soils located above the foundation base, kN/m³;

$c_{II}$ - is the design value of the cohesion of the soil directly beneath the foundation base, kPa;

$d_1$ - is the foundation embedment depth, m, measured from the planning level for structures without basements, or the equivalent embedment depth of external and internal foundations measured from the basement floor. For raft foundations, $d_1$is taken as the minimum distance from the bottom of the raft to the planning level;

$d_b$ - is the basement depth, measured from the planning level to the basement floor, m. For structures with a basement depth greater than 2 m, $d_b$is taken as 2 m.



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## 3 RESULTS AND DISCUSSION

The calculated design resistance of the foundation soil is R = 676.68 kPa, confirming sufficient bearing capacity of the supporting soil under the applied foundation loads.

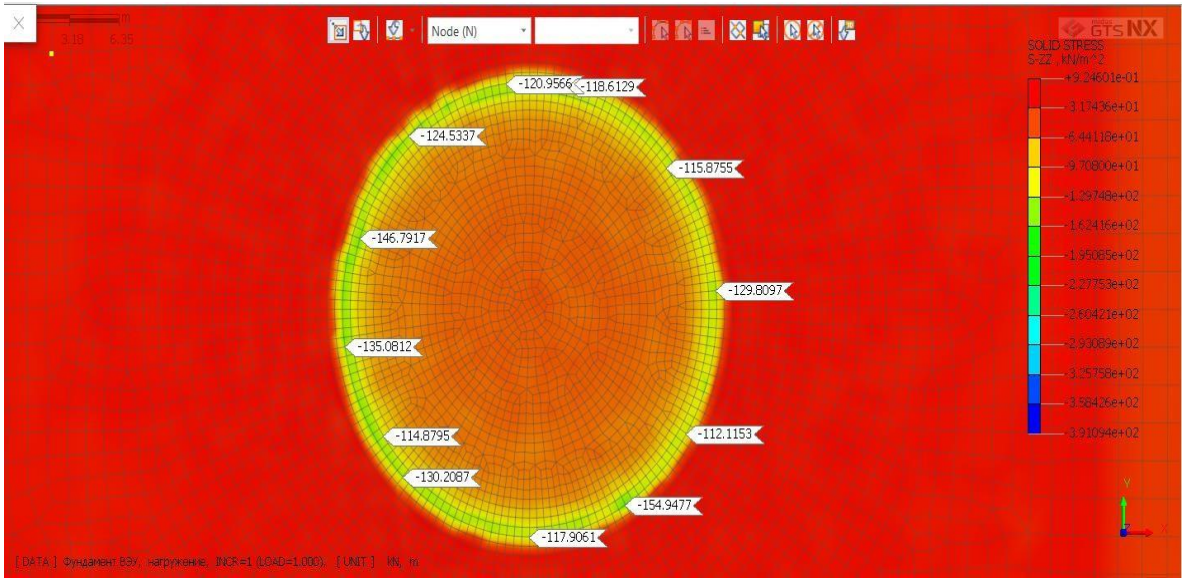


**Figure 5 -** Forces beneath the Foundation Base Obtained from MIDAS GTS NX Analysis.

The forces beneath the foundation base are approximately five times lower than the calculated design resistance of the foundation soil:

$$154.9 < 676.08 \text{ kPa} \tag{3}$$

Therefore, the bearing capacity criterion adopted in the MIDAS GTS NX analysis is satisfied.

The probabilistic reliability assessment of WPPs on raft foundations is based on the probability of satisfying the limit-state condition:

$$g = R - L > 0, \tag{4}$$

where Rand Lare random variables representing resistance and load, respectively.

For a normally distributed safety margin, the reliability index is defined as

$$\beta = \frac{\bar{g}}{S_g}, \tag{5}$$

and its relationship with the probability of failure is established through the Laplace function. In practice, stresses, deformations, and displacements are treated as random variables due to uncertainties in loads and material and soil properties. Therefore, probabilistic methods and statistical processing of the governing parameters are required.

To assess the reliability of the WPP foundation, a statistical approach based on the probability of foundation failure is adopted. The reliability coefficient with respect to bearing capacity is calculated as follows:

$$\gamma = \frac{R}{P} = \frac{676{,}68}{154{,}9} = 4{,}37 \tag{6}$$

The reliability coefficient with respect to settlement is calculated as follows:



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$$\gamma_s = \frac{s_{доп}}{s_{max}} = 4{,}31 \quad (7)$$

The overall probability of foundation failure is then determined as:

$$P_f = \Phi(-\beta) = \Phi\left(\frac{\ln \gamma}{\sigma_R}\right) = \Phi(\,1{,}45) \approx 0{,}07 \quad (8)$$

The probability of failure is calculated separately for each engineering-geological element (EGE) using the following equation:

$$R_i = c_i' + P\,tan(\varphi_i') \quad (9)$$

**Table 2 -** Comparison of Failure Probability Values for Individual Engineering-Geological Elements (EGEs).

| Layer | $\varphi',^0$ | $c'$, кPa | $R_i$, кPa | $\gamma$ | $P_f$, % |
|---|---|---|---|---|---|
| EGE-1: Clayey gravel with sand | 22,3 | 0 | 63,7 | 0,41 | 72 |
| EGE-2: Loam with gravel | 6 | 20 | 36,3 | 0,23 | 85 |
| EGE-3: Weathered sandstone (bedrock) | 23 | 600 | 665,6 | 4,29 | 2 |
| EGE-4: Shale/argillite (bedrock) | 30 | 180 | 269,4 | 1,74 | 20 |

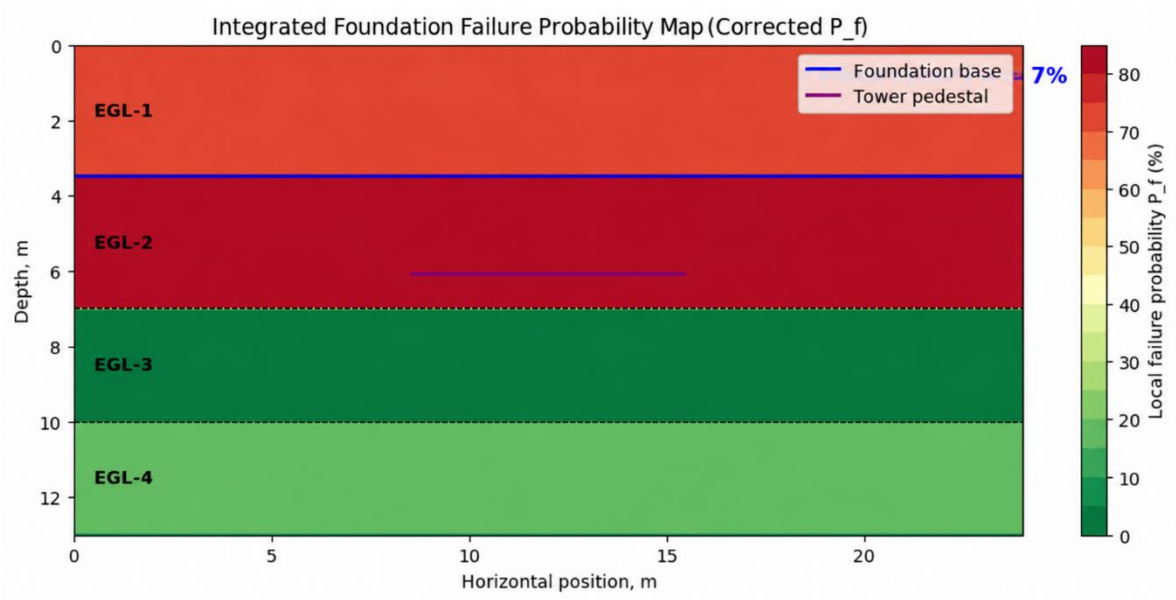


**Figure 6 -** Integrated Map of Foundation Failure Probability.

The obtained reliability coefficients indicate a sufficient safety margin of the foundation system. The overall probability of foundation failure is 7%. Among the engineering-geological elements, EGE-1 and EGE-2 are the least reliable, EGE-4 demonstrates a moderate level of reliability, while EGE-3 exhibits the highest strength and reliability.

## 4 CONCLUSIONS

1. The geotechnical analysis of the gravity-type monolithic foundation of the wind power plant (WPP), performed using the finite element method in MIDAS GTS NX, confirmed compliance with the deformation and bearing capacity criteria. The maximum settlement is approximately 2.32 cm, which is below the allowable limit of 10 cm. The relative differential settlement satisfies the specified limit, while the average pressure beneath the foundation base is significantly lower than the design soil resistance (154.9 kPa < 676.68 kPa). These results confirm the stability of the foundation according to the principal geotechnical criteria.



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2. The probabilistic modeling approach, accounting for the statistical variability of loads and soil resistance parameters, enabled the determination of reliability parameters and improved the accuracy of assessing the safety margins in terms of structural strength and stability. The developed probabilistic methodology allowed the quantitative evaluation of the reliability index β and probability of failure Pf of the raft foundation, considering the actual variability of soil properties, and provided a basis for optimizing the dimensions and reinforcement of the foundation slab.

3. The scientific novelty of the study lies in the development of an integrated probabilistic-geotechnical approach for assessing the reliability of wind power plants on raft foundations while accounting for the stochastic variability of the physical and mechanical properties of soils. This distinguishes the proposed methodology from conventional deterministic design approaches.

4. The practical significance of the study lies in the direct applicability of the developed methodology to the design, construction, and operation of wind power plants, thereby improving the safety, economic efficiency, and durability of wind energy infrastructure.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## ARTIFICIAL INTELLIGENCE STATEMENT

During the preparation of this manuscript, the authors used artificial intelligence tools solely for language editing, grammar checking, and text improvement. All scientific content, interpretations, analyses, and conclusions remain the responsibility of the authors.

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