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Justification of the Load-Bearing Capacity of the Existing (Old) Pile Foundation of the Bridge under Modern Loads

Abstract:

The operation of a significant number of road bridges constructed in the second half of the twentieth century is currently affected by increased traffic loads and updated regulatory requirements, which necessitates reassessment of their structural reliability. In particular, pile foundations designed according to outdated standards often become a critical limiting factor in bridge reconstruction projects. The key problem addressed in this study is the insufficient load-bearing capacity of existing pile foundations when modern normative traffic load classes are applied, as well as the engineering feasibility of strengthening such foundations instead of replacing them entirely. This problem is especially relevant in the context of cost-effective and sustainable infrastructure rehabilitation. The scientific novelty of the study lies in the integrated justification of the load-bearing capacity of existing pile foundations under modern loads through a combination of normative analytical calculations and detailed numerical modelling, followed by the verification of a rational strengthening solution. The subject of the study is the engineering assessment and verification of the load-bearing capacity of pile foundations under increased regulatory traffic loads. The object of the study is the pile foundation system of a road bridge support structure designed according to earlier regulatory standards. The study aims to substantiate the feasibility of using and strengthening an existing pile foundation to ensure compliance with current normative traffic loads. The research methods include analytical calculations based on regulatory documents and numerical modelling using the LIRA-SAPR structural analysis software package. The study considers the interaction between structural elements of the bridge, pile foundations, and foundation soils, as well as the redistribution of internal forces within the pile group under multiple load combinations. The essence of the research consists in determining the actual load-bearing capacity of existing piles with respect to soil, identifying non-compliance with modern regulatory requirements, and developing a technically justified strengthening solution based on additional driven piles and a monolithic reinforced-concrete pile cap. The results of the study demonstrate that the existing pile foundations do not satisfy normative requirements under increased traffic loads, while the proposed strengthening solution ensures regulatory reliability of the structure. The findings confirm that rational strengthening of pile foundations can effectively extend the service life of existing bridges and may be applied in the reconstruction of similar bridge structures.

Keywords: pile foundation, loads and actions, load-bearing capacity, strengthening.

Introduction

A significant proportion of road bridges currently in operation were designed and constructed in the second half of the twentieth century, under traffic conditions and regulatory requirements that differ substantially from those in force today. Over recent decades, the steady

growth in traffic intensity, axle loads, and vehicle mass has led to a systematic increase in the load effects acting on bridge structures. As a result, many existing bridges are now subjected to operational demands that exceed or approach the limits assumed in their original design, raising concerns regarding structural safety, serviceability, and long-term reliability.

In this context, the reconstruction and upgrading of existing bridges have become a critical engineering task. Full replacement of bridge structures or foundations is often economically impractical and may cause significant disruption to transport networks. Consequently, modern bridge engineering increasingly focuses on assessing the residual capacity of existing structural elements and developing technically justified solutions for their strengthening. Particular attention is paid to foundations, as their condition and load-bearing capacity largely determine the overall reliability of the bridge system and the feasibility of further structural interventions.

Pile foundations, widely used in bridge construction during the twentieth century, present a specific challenge in reconstruction projects. Changes in load classes and design philosophies require a reassessment of their load-bearing capacity with respect to soil, taking into account both current regulatory requirements and the actual geotechnical conditions. The relevance of systematic engineering verification of existing pile foundations, combined with the development of rational strengthening solutions, is therefore evident in the context of sustainable infrastructure management and cost-effective bridge rehabilitation.

The scientific novelty of the study lies in the integrated approach to evaluating and upgrading existing pile foundations under increased regulatory traffic loads. Unlike conventional reconstruction strategies that primarily focus on replacing deficient foundation systems, the present research emphasises the analytical and numerical justification of the load-bearing capacity of existing piles, followed by targeted strengthening measures where necessary. A distinctive feature of the study is the combined use of analytical calculation methods and detailed numerical modelling to assess the behaviour of pile foundations under modern load combinations. This approach allows for a more accurate representation of load distribution among piles, soil–structure interaction, and the effects of increased traffic loads on existing foundations. The methodology is applied specifically to foundations designed according to outdated load standards, which remain common in current bridge stock. Furthermore, the study provides a substantiated engineering solution for strengthening pile foundations by integrating additional driven piles into the existing pile group through a monolithic reinforced-concrete pile cap. The effectiveness of this solution is verified through a comprehensive set of load combinations, demonstrating its applicability as a practical alternative to full foundation replacement in bridge reconstruction projects.

The subject of the study is the engineering assessment and verification process of the load-bearing capacity of existing pile foundations of road bridges under increased design traffic loads, including the analytical and numerical evaluation of structural response and the development of strengthening solutions.

The object of the study is the pile foundation system of a road bridge support structure, designed according to earlier regulatory standards, and subjected to reassessment under modern normative load classes.

The study aims to justify the feasibility of using and strengthening an existing pile foundation to ensure compliance with current regulatory traffic loads.

To achieve the stated aim, the following objectives were defined:

- analyse the existing design assumptions and loading conditions of the pile foundation;
- determine the load-bearing capacity of existing piles with respect to soil under increased traffic loads;

- assess the compliance of the existing foundation with current regulatory requirements;
- develop a technically justified solution for strengthening the pile foundation;
- verify the effectiveness of the proposed strengthening solution using numerical modelling and load combination analysis.

The results of this study are intended for structural and geotechnical engineers involved in the design, assessment, and reconstruction of bridge foundations. The proposed methodology and findings are particularly relevant for specialists dealing with the upgrading of existing bridges constructed under outdated design standards and operating under increased traffic demands.

In addition, the research may be of interest to researchers in the fields of bridge engineering, foundation engineering, and soil–structure interaction, as well as to technical experts and decision-makers responsible for infrastructure maintenance, rehabilitation planning, and the development of regulatory guidelines for bridge reconstruction.

Methods

The methodological framework of this research is based on an integrated engineering approach combining general scientific methods with specialised analytical and numerical techniques used in bridge engineering and geotechnics. The study addresses the problem of assessing the load-bearing capacity of an existing pile foundation designed according to outdated regulatory standards and operating under increased modern traffic loads. In this context, the methodology is structured to ensure consistency between regulatory requirements, analytical calculations, numerical modelling, and engineering decision-making.

The research methodology follows the logic of applied structural and geotechnical analysis, where the assessment of existing structures precedes the development and verification of strengthening solutions. The methods used in the study are selected to allow both qualitative interpretation of the structural condition and quantitative verification of load-bearing capacity under a wide range of load combinations. Particular emphasis is placed on compliance with current normative documents governing loads, actions, and limit state verification.

The analytical method constitutes the foundational component of the research methodology. It is applied to systematise the initial data on the bridge structure, loading conditions, and geotechnical characteristics of the foundation soil. Analytical reasoning is used to identify the governing load cases, determine the critical structural elements, and establish the logical sequence of verification procedures. Within the analytical framework, the study evaluates the feasibility of reusing the existing pile foundation under increased traffic loads. This includes analysing the implications of changing load classes, assessing the compatibility of original design assumptions with current regulatory requirements, and determining the necessity of strengthening measures. The analytical method provides a conceptual basis for subsequent numerical modelling and ensures that all calculations are grounded in engineering logic and нормативная consistency.

A key methodological component of the study is the normative method, which involves the systematic application of current regulatory documents governing bridge design, loads, and foundations. Loads and actions are defined in accordance with the relevant standards, including the classification of permanent, variable, and environmental actions, as well as the use of load reliability factors, combination factors, and dynamic amplification coefficients. The normative method ensures that all calculations are performed within the framework of legally binding and technically accepted rules. It plays a critical role in verifying compliance with the first and second groups of limit states, which correspond to ultimate and serviceability performance criteria. By

strictly adhering to regulatory prescriptions, the study guarantees the practical applicability of its results in real-world bridge reconstruction projects.

The verification of structural performance using the limit state method represents one of the core specialised methods employed in the research. The study applies calculations for both the first group of limit states, addressing strength, stability, and fatigue, and the second group of limit states, focusing on stiffness and crack resistance. This method allows for a differentiated assessment of structural behaviour under various loading scenarios and provides a clear framework for identifying whether the existing pile foundation satisfies safety and serviceability requirements. The use of limit state verification is essential for determining the admissibility of continued operation of the foundation and for justifying the need for strengthening measures.

A specialised geotechnical method used in the study is the analytical calculation of the load-bearing capacity of driven piles with respect to soil. The method is based on normative formulas that account for resistance under the pile toe and along the pile shaft, incorporating coefficients of working conditions and soil resistance parameters. This calculation enables the determination of the design bearing capacity of individual piles and provides a basis for comparing the calculated resistance with the design axial forces acting in the piles. The method is crucial for identifying deficiencies in the existing pile foundation and for quantifying the extent to which the piles fail to meet regulatory requirements under increased loads.

The determination of soil resistance parameters constitutes an important supporting method within the geotechnical analysis. The study uses design values of soil resistance beneath the pile toe, obtained from geotechnical data and interpolated for specific depths corresponding to the actual embedment of piles. This method ensures that the interaction between piles and soil is represented realistically and that variations in soil stratification are properly taken into account. Accurate determination of soil resistance parameters is essential for reliable assessment of pile performance and for avoiding both unsafe underestimation and overly conservative overestimation of bearing capacity.

Numerical modelling represents a central methodological element of the study. The structural behaviour of the bridge and its foundations is analysed using the finite element-based structural analysis software package LIRA-SAPR. Numerical modelling allows for the simulation of complex load combinations, load redistribution among piles, and the interaction between superstructure, substructure, and foundation. Through numerical analysis, internal forces in piles are determined for a large number of load combinations, providing a detailed picture of the stress state of the foundation system. This method significantly enhances the accuracy of the assessment compared to purely analytical approaches and enables the identification of critical load scenarios governing the design.

The method of load combination analysis is applied to account for the probabilistic nature of simultaneous load occurrence. The study considers a comprehensive set of 104 design load combinations, incorporating permanent, variable, and environmental actions with appropriate combination factors. This method ensures that the most unfavourable combinations of loads are identified and that the verification of load-bearing capacity is based on realistic worst-case scenarios. Load combination analysis is particularly important in bridge engineering, where multiple traffic and environmental actions may act concurrently and significantly influence structural response.

An important methodological aspect of the research is the modelling of soil–structure interaction through the assignment of stiffness parameters representing the foundation soil. Settlement effects and subgrade stiffness are incorporated into the numerical model, allowing for a more realistic representation of foundation behaviour. This method enables the assessment

of both vertical and horizontal stiffness of piles and contributes to the accurate prediction of displacements and internal forces. Modelling soil–structure interaction is essential for understanding the overall performance of the bridge foundation system under increased loads.

The comparative analysis method is employed to evaluate alternative reconstruction strategies for the bridge foundation. Specifically, the study compares an option involving the construction of new pile caps without strengthening the existing pile group with an option that includes additional driven piles and a new monolithic pile cap. This method allows for an objective assessment of the effectiveness and feasibility of each option, based on quantitative performance criteria rather than purely qualitative considerations. Comparative analysis supports informed engineering decision-making and contributes to the selection of the most rational reconstruction solution.

The engineering method of foundation strengthening constitutes a practical and applied component of the research methodology. It involves the integration of additional driven piles into the existing pile group and their rigid connection through a monolithic reinforced-concrete pile cap. This method is designed to redistribute loads more evenly among piles, increase the overall bearing capacity of the foundation, and ensure compliance with regulatory requirements. Its effectiveness is verified through analytical calculations and numerical modelling, demonstrating its suitability for bridge reconstruction projects.

A verification method based on comparative evaluation of structural performance before and after strengthening is applied in the study. This method involves comparing design axial forces in piles with their calculated load-bearing capacity both in the original configuration and after the introduction of strengthening measures. Such verification provides clear quantitative evidence of the effectiveness of the proposed solution and ensures that the strengthened foundation meets safety and serviceability criteria. It also allows for transparent demonstration of compliance with regulatory standards.

The interpretation and validation method is used to analyse the results obtained from analytical calculations and numerical modelling. This method involves critical assessment of calculated values, identification of governing load cases, and validation of conclusions through consistency checks between different calculation approaches. Interpretation of results plays a crucial role in translating numerical data into engineering conclusions and recommendations. It ensures that the final decisions are based on a comprehensive understanding of structural behaviour rather than on isolated calculation outcomes.

The reliability of the applied methodology is ensured through the combined use of established analytical formulas, normative procedures, and advanced numerical modelling tools. The integration of these methods reduces uncertainty and enhances the robustness of the results. At the same time, the methodology acknowledges inherent limitations related to assumptions in soil modelling, idealisation of structural behaviour, and the availability of geotechnical data. These limitations are considered acceptable within the scope of engineering practice and do not compromise the validity of the conclusions.

The methodological approach adopted in this study provides a comprehensive and reliable framework for assessing and strengthening existing pile foundations of road bridges under increased traffic loads. By combining general scientific methods with specialised analytical, numerical, and normative techniques, the research ensures both scientific validity and practical applicability of its results.

The applied methods allow for accurate identification of deficiencies in existing foundations, objective evaluation of reconstruction options, and substantiation of effective strengthening solutions. As a result, the proposed methodology can be recommended for use in

the assessment and rehabilitation of similar bridge structures designed according to outdated standards and operating under modern load conditions.

Literature Review

The assessment and strengthening of bridge foundations under changing traffic loads represent a well-established but continuously evolving field of research within bridge engineering and geotechnics. The present study builds upon a body of normative documents and scientific publications addressing load assessment, soil–structure interaction, numerical modelling, and reconstruction strategies for bridge foundations.

A fundamental regulatory basis for the present research is provided by the national standard *Bases and foundations of buildings and structures. General provisions (DBN V.2.1–10:2018)*. This document defines the general principles for the design, assessment, and verification of foundations, including pile foundations, with respect to soil bearing capacity and limit state requirements. In the context of the present study, this standard forms the methodological foundation for evaluating the bearing capacity of piles and for ensuring that the adopted calculation procedures comply with current regulatory expectations for safety and reliability (*DBN V.2.1–10:2018*).

Closely related to the regulatory framework of bridge foundations are the standards governing transport structures, particularly bridges and culverts. The document *Transport structures. Bridges and culverts. Basic design requirements (DBN V.2.3–22:2009)* establishes the general performance criteria for bridge structures, including durability, serviceability, and structural safety. This standard provides the conceptual background for assessing whether an existing bridge structure, including its foundations, can continue to operate safely under revised loading conditions.

The rules for detailed structural verification are further specified in *Transport structures. Bridges and culverts. Design rules (DBN V.2.3–14:2006)*. This document is particularly relevant to the present research in defining calculation procedures, safety factors, and verification principles for bridge components. In this study, it is used to ensure that both analytical and numerical calculations of pile foundations are carried out in accordance with accepted engineering practice, especially when evaluating stability-related limit states.

The determination of traffic loads and their combinations is governed by *Transport structures. Bridges and culverts. Loads and actions (DBN V.1.2–15:2009)*. This standard plays a central role in the present research, as it defines load classes, load models, combination factors, and dynamic coefficients applicable to road bridges. The adoption of modern load classes A15 and NK100, as well as the formation of multiple load combinations, is directly based on this document. Its provisions ensure that the reassessment of the existing pile foundation reflects realistic and regulatory-compliant loading scenarios (*DBN V.1.2–15:2009*).

In addition to regulatory sources, the present study builds upon applied research addressing bridge reconstruction under changing load conditions. The work by Miroshnyk et al. (2025) investigates the justification of capital repair of a highway bridge when traffic loads are increased. This study demonstrates the importance of reassessing existing structures rather than relying solely on original design assumptions. It provides a methodological precedent for analysing the consequences of load class changes and supports the relevance of the present research, which focuses specifically on pile foundations as a critical component of bridge systems (*Miroshnyk et al., 2025*).

The problem of strengthening bridge supports during reconstruction is addressed in the study by Kvasha and Saliichuk (2013). Their work examines various strengthening techniques

for bridge supports and highlights the role of structural intervention in extending the service life of existing bridges. Although their research is not limited to pile foundations, it provides important insights into reconstruction strategies and reinforces the practical relevance of strengthening approaches adopted in the present study (*Kvasha & Saliichuk, 2013*).

A significant contribution to the understanding of soil–structure interaction and numerical modelling of pile-supported bridge structures is provided by Kelesoglu and Springman (*2011*). Their research presents analytical and three-dimensional numerical modelling of bridge abutments on pile foundations in soft soils. This study demonstrates the advantages of numerical analysis in capturing complex interactions between piles, soil, and superstructure. The methodological principles outlined in their work support the use of finite element modelling in the present research and justify the application of numerical analysis for evaluating pile forces under multiple load combinations (*Kelesoglu & Springman, 2011*).

The importance of numerical methods in bridge foundation analysis is further confirmed by the study of Wu et al. (*2020*), which focuses on analytical and numerical analysis of additional stresses in the foundations of bridge approach embankments. Their work highlights how changes in loading conditions can significantly affect stress distribution within foundation systems. The findings of this study are relevant to the present research, as they emphasise the necessity of detailed numerical modelling when assessing existing foundations under altered load regimes (*Wu et al., 2020*).

Recent research by Tiutkin et al. (*2025*) explores numerical and modal analysis of railway bridge piers. Although focused on railway infrastructure, this study demonstrates the effectiveness of advanced numerical techniques in evaluating the structural behaviour of bridge substructures. The methodological approaches employed in their work support the use of numerical analysis tools, such as finite element modelling, for assessing internal forces and dynamic characteristics of bridge foundations, which is consistent with the methodology adopted in the present study (*Tiutkin et al., 2025*).

The issue of strengthening highway bridge foundations under critical infrastructure conditions is addressed by Tiutkin and Ostapenko (*2020*). Their research analyses strengthening strategies in the context of deteriorating transport infrastructure and increasing эксплуатационные demands. This work provides a conceptual link between infrastructure condition assessment and foundation strengthening, reinforcing the practical motivation for the present study and supporting the relevance of strengthening existing pile foundations rather than replacing them entirely (*Tiutkin & Ostapenko, 2020*).

Taken together, the reviewed literature demonstrates that the reassessment and strengthening of existing bridge foundations under increased loads are well-recognised challenges in modern bridge engineering. Regulatory documents provide a robust framework for load assessment and limit state verification, while scientific studies highlight the importance of numerical modelling, soil–structure interaction analysis, and rational strengthening solutions. However, despite the availability of general methodologies, there remains a need for applied studies focusing specifically on existing pile foundations designed according to outdated standards and subjected to modern traffic loads.

The study contributes to this body of knowledge by integrating normative calculation methods with detailed numerical modelling and by providing a practically verified strengthening solution for an existing pile foundation. In doing so, it bridges the gap between regulatory requirements, scientific research, and engineering practice, offering a methodological approach that can be applied to the reconstruction of similar bridge structures.

Results

General Part

The road bridge is located at kilometre 15+822 of the Category III public road of national significance T-12-05 Kropyvnytskyi–Nova Praha–Oleksandriia. The structure is a simply supported beam bridge made of precast reinforced concrete. The total length of the existing bridge is 57 m, with a span arrangement of 5×11.36 m. The carriageway width corresponds to gauge G-7+2×1.0 m.

According to the technical inspection report of the bridge structures prepared in October 2020 by specialists of the limited liability company “Scientific and Production Enterprise Ukrtransakad”, the bridge was constructed in 1970 for the design load classes N30 and NK80. At the time of inspection, according to DSTU-N B V.2.3–23:2012, the bridge was classified as being in the 5th (unserviceable) operational condition. The operational condition of each main structural element is presented separately in the Appendix (*Table 1*).

Considering the identified defects and the need to redesign the bridge to accommodate modern traffic loads, two alternative configurations of the load-bearing structural system were adopted for analysis, namely:

- Construction of new high monolithic reinforced-concrete pile caps on the existing pile group, followed by the installation of new superstructure spans and pier structures. The layout of this option is shown in the Appendix (*Figure 1*) (new bridge elements are indicated in green, existing piles in red);
- Strengthening of the existing foundations by installing additional driven prismatic piles with a cross-section of 35×35 cm in the number required by calculation, together with the construction of new monolithic reinforced-concrete pile caps to replace the defective ones for the end piers No. 0 and No. 5, and new pier structures on low monolithic reinforced-concrete pile caps for the intermediate piers No. 1–No. 4, followed by the installation of new superstructure elements.

A detailed description of the second bridge option is provided in the Results.

Loads and Actions

The loads and actions adopted in the present analysis ensure the verification of the bridge structures and their elements in accordance with DBN V.1.2-15:2009 (2009):

- for strength, stability and fatigue under the first group of limit states;
 - for stiffness and crack resistance under the second group of limit states.
- The following loads and actions were taken into account in the calculations.
- Permanent loads:
- self-weight of structural elements –1;
 - earth pressure of the embankment fill –3;
 - effect of foundation settlement (*specified as subgrade stiffness) –6.
- Variable loads from traffic and pedestrians:
- vertical loads –7;
 - [1] horizontal transverse impact from moving vehicles –10;
 - [1] horizontal longitudinal load due to braking or traction forces –11.
- Other actions:
- [1] ice loads –13;
 - temperature and climatic loads –15;
 - friction in bearings (*specified as stiffness for bearing devices) –18.

Notes:

[1] – loads (actions) that are not considered in combination with the given load (action).

Calculations for the second group of limit states were performed only for combinations of loads and actions 1, 3, 6 and 15. In addition, when checking the crack resistance of reinforced-concrete bridge structures, load 11 was also considered, while loads 10 and 13 were considered when analysing horizontal displacements at the top of the piers.

The combination factor η , which accounts for the probability of simultaneous occurrence of design loads in combinations of variable loads, is given in the Appendix (*Table 2*).

When analysing bridge structures for the first and second groups of responsibility, a reliability factor with respect to responsibility γ_n was applied to the design load effects. This factor was used as a multiplier for the action effects (deflections, internal forces, stresses), except in cases where the effect is unloading. The values of the factor are:

- for the first group of limit states $\gamma_n = 1.100$;
- for the second group of limit states $\gamma_n = 0.975$.

When forming design load combinations in the LIRA-SAPR structural analysis software, this factor can be applied automatically as a multiplier to all involved loads.

The loads and actions used for structural verification under all groups of limit states were adopted with load reliability factors γ_f and dynamic amplification factors $(1 + \mu)$ according to Table 5.3 of DBN V.1.2-15:2009 (*2009*).

Permanent Loads and Actions

The load reliability factors γ_f for permanent loads and actions were adopted according to Table 6.2 of DBN V.1.2-15:2009 (*2009*). For all areas where the same load is applied, the factor γ_f was taken as uniform, except for stability analyses, in which the value of γ_f was adopted according to DBN V.2.3-14:2006 (*2006*).

The characteristic vertical load was determined from the self-weight of all bridge elements, both load-bearing and auxiliary.

The self-weight of all reinforced-concrete bridge structures was automatically taken into account by the software based on the geometric properties of the cross-sections predefined in the stiffness table.

The loads acting on the reinforced-concrete temperature-continuous deck slab are presented in the Appendix (*Table 3*; *Table 4*).

Variable Loads and Actions

The characteristic temporary vertical load from road traffic was adopted using two load models:

- Model 1, representing traffic loading according to the AK load scheme;
- Model 2, representing a single wheel load according to the NK scheme.

Traffic loads in the form of AK load lanes were applied in combination with other moving loads specified in DBN V.1.2-15:2009 (*2009*).

As the bridge is located on a Category III road, a load class of $K = 15$ was adopted for the calculations. The traffic load applied to each load lane was taken as a uniformly distributed load with an intensity of $v = 0.98K \text{ kN/m}$ and a tandem axle load with an axle force of $P = 9.81K \text{ kN}$, i.e., $v = 0.98 \times 15 = 14.7 \text{ kN/m}$ and $P = 9.81 \times 15 = 147.15 \text{ kN}$.

Two transverse arrangements of the A15 traffic load were considered in the analysis:

- Case 1 is operational condition;

- Case 2 is maintenance condition.

Under the operational condition, the axis of the first load lane was located at a distance of $P + 0.55 + 1.9/2 = 2.50 \text{ m}$ from the edge of the kerb, while the axis of the second load lane was located 3.0 m from the first lane. Under the maintenance condition, the axis of the first load lane was placed at the minimum permissible distance of 1.50 m from the kerb edge.

When analysing the bridge structures for the second group of limit states, only the first (operational) arrangement of the moving load was considered.

The transverse arrangement of temporary vehicular loads and pedestrian crowd loads on the sidewalks is shown in the Appendix (*Figure 2*).

Model 2 is represented by a single NK load, corresponding to a four-axle wheeled vehicle, in accordance with DBN V.1.2-15:2009 (2009). For a Category III road, the NK-100 load was adopted:

- NK-100, with an axle load of $P = 245 \text{ kN}$ (25 tf).

Loading by the single NK-100 vehicle was considered in the absence of other moving loads on the bridge, according to DBN V.1.2-15:2009 (2009). The vehicle was positioned at a single location along the direction of traffic, within the carriageway clearance. The vehicle axis was located at a distance of 1.75 m from the safety strip of width $P = 1.0 \text{ m}$, i.e., at $P + 1.75 = 2.75 \text{ m}$.

The NK load was not considered simultaneously in fatigue calculations or in analyses for the second group of limit states.

The longitudinal arrangements of vehicular loads along the bridge are presented in the Appendix (*Figure 3*).

The characteristic temporary load acting on the sidewalks was adopted as a vertically uniformly distributed load:

- 1.96 kPa (200 kgf/m²) when traffic load AK is present;
- 3.92 kPa (400 kgf/m²) in the absence of other moving loads.

The design values of moving vertical loads are given in the Appendix (*Table 5*).

The characteristic horizontal transverse load from vehicle impact, regardless of the number of AK load lanes on the bridge, was taken as either a uniformly distributed load equal to 0.39K kN/m (0.04K tf/m) or a concentrated force equal to 5.9K kN (0.6K tf), applied at the level of the roadway surface, according to DBN V.1.2-15:2009 (2009).

The characteristic horizontal longitudinal load due to braking or traction forces of moving vehicles was taken as 50% of the uniformly distributed component of the AK lane load (excluding the weight of tandem axles), but not less than 7.8K kN (0.8K tf) and not greater than 24.5K kN (2.5K tf), according to DBN V.1.2-15:2009 (2009).

Verification of the Load-Bearing Capacity of the Existing Pile Foundation (Option 1)

One of the considered options involves the construction of new pile caps on top of the heads of the existing pile group. This option assumes an increase in the traffic load class on the bridge to A15 and NK100, as well as the replacement of the existing beams with new ones and the installation of a temperature-continuous reinforced-concrete deck slab above them.

Under these conditions, the loads acting on the foundations increase significantly compared to the original design loads adopted in 1970 (N30 and NK80). Therefore, as a first step, the load-bearing capacity of the piles of each pier with respect to the soil was determined, in order to allow subsequent comparison with the design axial load N (kN).

Based on the adopted design formula

$$N \leq \frac{F_d}{\gamma_k}$$

the value of the right-hand side term was determined using the reliability factor γ_k , which is equal to 1.65 for the end piers and intermediate piers No. 2 and No. 3 with seven piles in the foundation, and 1.55 for intermediate piers No. 1 and No. 4 with fourteen piles in the foundation.

The load-bearing capacity F_d , κH , of a hanging driven pile, installed without soil removal and subjected to compressive loading, was determined using the following formula:

$$F_d = \gamma_c (\gamma_{cR} RA + u \sum \gamma_{cf} \cdot f_i \cdot h_i)$$

where

$\gamma_c = 1,0$ is coefficient of working conditions;

$A = 0,3 \cdot 0,35 = 0,105 \text{ m}^2$ is pile base area in contact with the soil;

$u = 2(0,3 + 0,35) = 1,30 \text{ m}$ is external perimeter of the pile.

The design soil resistance R beneath the pile toe (IGE-7) is given in the Appendix ([Table 6](#)). The pile toes are embedded within the zone of soil layer 8 or 9 of IGE-7, as shown in the Appendix ([Figure 4](#)).

The soil working condition factors adopted in the calculation of the load-bearing capacity for the driving of solid and hollow piles with a closed toe using mechanical (suspended), steam-air, and diesel hammers were taken as follows:

- beneath the pile toe: $\gamma_{cR} = 1$;
- along the pile shaft: $\gamma_{cf} = 1$.

For the determination of the remaining parameters, the soil profile beneath each foundation was analysed separately.

The calculated data were also used to determine the pile stiffness in the horizontal and vertical directions, to verify the foundation with respect to deformations, and to model the behaviour of the entire bridge structure considering the stiffness of the soil foundation.

The load-bearing capacity of the pile foundations with respect to soil for piers No. 0, 1, 2, 3, 4, and 5 is not satisfied; therefore, the design condition is not fulfilled:

$$N = 870,0 \text{ } \kappa\text{H} > 411,3 \text{ } \kappa\text{H} \text{ for pier } \text{№}0$$

$$N = 639,6 \text{ } \kappa\text{H} > 389,2 \text{ } \kappa\text{H} \text{ for pier } \text{№}1$$

$$N = 1132,6 \text{ } \kappa\text{H} > 342,1 \text{ } \kappa\text{H} \text{ for pier } \text{№}2$$

$$N = 1141,3 \text{ } \kappa\text{H} > 398,6 \text{ } \kappa\text{H} \text{ for pier } \text{№}3$$

$$N = 646,7 \text{ } \kappa\text{H} > 438,5 \text{ } \kappa\text{H} \text{ for pier } \text{№}4$$

$$N = 869,0 \text{ } \kappa\text{H} > 390,5 \text{ } \kappa\text{H} \text{ for pier } \text{№}5$$

The calculation of the load-bearing capacity of the pile foundation of pier No. 0 is presented in the Appendix ([Figure 5](#)).

Strengthening of the Existing Foundation of the End Pier (Abutment) No. 0

As shown in [Figure 6](#) ([Appendix](#)), the strengthening of the existing foundation is achieved by introducing additional rows of prismatic driven piles with a cross-section of $35 \times 35 \text{ cm}$ and integrating them to act jointly with the existing piles by means of a new monolithic reinforced-concrete pile cap with a height of 60 cm. The connection between the piles and the pile cap is rigid.

The plan layouts of the pile arrangement are presented in the Appendix ([Figure 7](#)).

Verification of the load-bearing capacity of the pile foundation with respect to soil

The load-bearing capacity of the piles supporting the pier was determined in order to enable subsequent comparison with the design load N (kN).

Based on the inequality

$$N \leq \frac{F_d}{\gamma_k}$$

the value of the right-hand side was calculated using a reliability factor $\gamma_k = 1.55$ for abutment No. 0, which comprises 19 piles in the foundation.

The level of the pile toe for the new 35×35 cm piles was adopted to be the same as that of the existing 30×35 cm piles. Since the perimeter and cross-sectional area of the square piles differ, the corresponding parameters were recalculated (*Figure 8*):

$A_{35} = 0,35 \cdot 0,35 = 0,1225 \text{ m}^2$ is area of pile base bearing on the soil;

$u_{35} = 2(0,35 + 0,35) = 1,40 \text{ m}$ is external perimeter of the pile.

The design load N for pier No. 0 was determined based on the results of the bridge analysis considering 104 design load combinations in the LIRA-SAPR software.

The internal axial forces N in the piles of pier No. 0 are shown graphically in the Appendix (*Figure 9*).

Thus, the condition is satisfied, and the load-bearing capacity of the pile foundation of pier No. 0 with respect to soil is ensured:

- pile 300x350 mm: $N = 381,8 \text{ kH} < 437,9 \text{ kH}$;
- pile 350x350 mm: $N = 481,4 \text{ kH} \cong 480,8 \text{ kH}$.

Discussion

The results obtained in this study are of high practical and scientific relevance in the context of modern bridge engineering, where a significant portion of transport infrastructure operates beyond its originally assumed design conditions. The demonstrated increase in internal forces within pile foundations due to the transition from outdated load classes to modern regulatory traffic loads confirms the urgency of reassessing existing bridge foundations rather than relying on historical design assumptions. The findings highlight that the issue of load-bearing capacity of existing pile foundations is not limited to isolated cases but reflects a systemic challenge faced by bridge infrastructure constructed in the second half of the twentieth century. In this regard, the presented results provide a substantiated example of how regulatory changes in traffic loading directly affect the safety margins of foundation systems, thereby reinforcing the relevance of the adopted methodological approach. Moreover, the study contributes to the ongoing discourse on sustainable infrastructure management. By demonstrating the feasibility of strengthening existing pile foundations instead of complete replacement, the results align with contemporary engineering priorities focused on cost efficiency, minimisation of construction time, and reduction of environmental impact.

One of the key outcomes of the research is the identification of insufficient load-bearing capacity of existing piles with respect to soil under increased traffic loads for multiple bridge piers. This result confirms that foundations designed under earlier normative frameworks may no longer satisfy current safety requirements, even if they have remained operational for decades. The deficiency observed in the existing pile foundations should not be interpreted solely as a consequence of material degradation or construction defects. Instead, it reflects a fundamental mismatch between original design load assumptions and present-day operational demands. This distinction is crucial, as it shifts the focus of engineering assessment from condition-based deterioration to regulatory and load-related obsolescence. The results further indicate that the

inadequacy of pile capacity is unevenly distributed among piers, depending on the number of piles, their geometric characteristics, and local soil conditions. Such variability underscores the necessity of pier-specific assessment rather than adopting uniform reconstruction measures across the entire bridge.

The analysis of the reconstruction option involving new pile caps without strengthening the existing pile group demonstrates that such an approach does not ensure normative reliability of the structure. This finding is particularly significant, as the construction of new pile caps is often considered a relatively straightforward intervention in bridge rehabilitation projects. The results show that without increasing the effective bearing capacity of the pile foundation, redistribution of loads through new pile caps alone is insufficient to compensate for increased traffic loads. This insight highlights a critical limitation of partial reconstruction strategies that do not address the fundamental capacity constraints of foundation elements. From an engineering perspective, this outcome emphasises the importance of holistic foundation assessment. Reconstruction measures that focus exclusively on superstructure or substructure modifications may fail to achieve the desired safety level if the foundation system remains underdesigned with respect to modern loads.

The introduction of additional driven piles and their integration into the existing pile group through a monolithic reinforced-concrete pile cap proved to be an effective strengthening strategy. The results demonstrate that this approach ensures compliance with regulatory load-bearing capacity requirements with respect to soil. This strengthening method offers a rational balance between structural efficiency and constructability. By increasing the number of load-bearing elements and redistributing forces among both existing and new piles, the foundation system achieves the required performance without the need for complete replacement. The success of this approach also confirms the validity of combining analytical calculations with numerical modelling. The agreement between calculated bearing capacity and numerically obtained internal forces provides confidence in the reliability of the proposed solution.

Numerical modelling played a crucial role in interpreting the behaviour of the pile foundation under multiple load combinations. The use of a large number of load combinations allowed for the identification of governing scenarios that determine the maximum internal forces in piles. This aspect of the study demonstrates that simplified analytical approaches may be insufficient to capture the complexity of load redistribution in pile groups, particularly under combined traffic and environmental actions. Numerical analysis enables a more nuanced understanding of how forces are shared among piles and how strengthening measures influence overall system behaviour. The findings support the broader trend in bridge engineering towards integrating numerical modelling into standard assessment and reconstruction workflows, especially for existing structures with complex boundary conditions.

From a methodological standpoint, the study illustrates the importance of combining normative, analytical, and numerical approaches in the assessment of existing bridge foundations. Each method addresses a specific aspect of the problem: normative procedures ensure regulatory compliance, analytical calculations provide transparent verification of bearing capacity, and numerical modelling captures complex interactions within the structural system. The integration of these methods enhances the robustness of engineering conclusions and reduces the risk of overlooking critical load effects. This methodological synergy is particularly valuable in reconstruction projects, where uncertainties related to existing structures and soil conditions are inherently higher than in new construction.

The results of the study have broader implications beyond the specific bridge considered. They demonstrate a practical pathway for extending the service life of existing infrastructure

assets through targeted strengthening rather than full replacement. Such an approach is consistent with modern principles of asset management, which prioritise risk-based decision-making and optimisation of lifecycle costs. The ability to justify strengthening solutions through rigorous calculation and modelling supports informed investment decisions in transport infrastructure.

Despite the positive outcomes, the study also highlights several challenges inherent in the assessment and strengthening of existing pile foundations. One of the key challenges is the accurate representation of soil–structure interaction, particularly when geotechnical data are limited or based on historical investigations. Another challenge lies in the idealisation of existing structural elements in numerical models. Assumptions regarding pile stiffness, boundary conditions, and connection rigidity may influence calculated results and should be treated with caution. These challenges do not undermine the validity of the study but rather point to areas where further methodological refinement is desirable.

Based on the obtained results, several directions for further research can be identified. One promising area is the investigation of long-term behaviour of strengthened pile foundations, including creep effects, cyclic loading, and potential changes in soil properties over time. Further research may also focus on refining soil–structure interaction models, incorporating more advanced constitutive models for soil behaviour, and validating numerical results through field measurements or monitoring of strengthened foundations. In addition, comparative studies of alternative strengthening techniques, such as micropiles or soil improvement methods, could provide valuable insights into the relative efficiency and applicability of different reconstruction strategies.

In summary, the Discussion demonstrates that the present study contributes to bridge engineering practice by providing a validated approach for assessing and strengthening existing pile foundations under modern traffic loads. The results reinforce the necessity of revisiting foundation capacity in reconstruction projects and highlight the effectiveness of combining analytical and numerical methods. The study positions itself at the intersection of regulatory compliance, applied research, and practical engineering, offering insights that are directly transferable to similar bridge reconstruction scenarios. This positioning underscores the relevance of the research for both academic audiences and practising engineers.

Conclusion

This study addressed the problem of assessing the feasibility of using existing pile foundations of road bridges constructed under outdated regulatory frameworks when subjected to modern traffic loads. The conducted research confirms that changes in load classes and regulatory requirements represent a critical factor influencing the structural reliability of bridge foundations, even in the absence of significant physical deterioration.

An engineering analysis was performed to assess the feasibility of using the existing pile foundation of the bridge constructed in 1970 when upgrading it to comply with the current standard load classes A15 and NK100. It was established that the design load-bearing capacity of the piles with respect to the soil for piers No. 0–No. 5 does not satisfy the regulatory requirements when temporary loads are increased. The option involving the construction of new pile caps without strengthening the existing pile group does not ensure the normative reliability of the structure. A technically substantiated solution for foundation strengthening was developed, consisting in the installation of additional driven piles with a cross-section of 35×35 cm and a monolithic reinforced-concrete pile cap. The results of calculations performed using

the LIRA-SAPR software package (104 load combinations) confirmed that the load-bearing capacity of the strengthened foundations is ensured.

The analysis demonstrated that existing pile foundations, designed according to historical standards, may fail to satisfy current normative requirements with respect to load-bearing capacity under increased traffic actions. This finding underscores the necessity of systematic reassessment of foundation systems as an integral part of bridge reconstruction projects, rather than focusing exclusively on superstructure elements.

An important general conclusion of the study is that reconstruction strategies based solely on partial structural modifications, such as the construction of new pile caps without strengthening the pile group, are insufficient to ensure regulatory reliability. Foundation capacity must be explicitly addressed to achieve compliance with modern safety and serviceability criteria.

At the same time, the results confirm that technically justified strengthening solutions can effectively extend the service life of existing bridge foundations. The integration of additional driven piles combined with a monolithic reinforced-concrete pile cap provides a rational and economically viable alternative to full foundation replacement.

Overall, the study contributes to the broader field of bridge engineering by demonstrating a practical, calculation-based approach to foundation assessment and strengthening, aligned with contemporary principles of sustainable infrastructure management.

The aim of the study, defined as justifying the feasibility of using and strengthening an existing pile foundation to ensure compliance with current regulatory traffic loads, has been fully achieved. Through analytical calculations and numerical modelling, the study established the actual load-bearing capacity of existing piles and identified cases of non-compliance with modern load requirements. The proposed strengthening solution was subsequently verified and shown to restore compliance with regulatory standards. The confirmation of sufficient load-bearing capacity after strengthening demonstrates that existing pile foundations can be successfully adapted to modern load conditions without complete replacement, provided that appropriate engineering measures are implemented. Thus, the research purpose was achieved not only in a theoretical sense but also through practical verification, reinforcing the applicability of the proposed approach to real-world bridge reconstruction scenarios.

The first research objective, which involved analysing the existing design assumptions and loading conditions of the pile foundation, was accomplished through a comprehensive review of original load classes and their comparison with current regulatory traffic loads. This analysis established the context for further assessment and highlighted the extent of discrepancy between historical and modern design requirements.

The second objective, aimed at determining the load-bearing capacity of existing piles with respect to soil under increased traffic loads, was achieved using normative analytical calculations. These calculations quantified the bearing capacity of individual piles and enabled direct comparison with design axial forces obtained from numerical modelling.

The third objective, which focused on assessing the compliance of the existing foundation with current regulatory requirements, was fulfilled by evaluating the calculated pile capacities against the demands imposed by modern load combinations. This assessment clearly demonstrated that the existing pile foundation did not satisfy normative requirements for several bridge piers.

The fourth objective, concerning the development of a technically justified solution for strengthening the pile foundation, was addressed through the design of a strengthening scheme involving additional driven piles and a monolithic reinforced-concrete pile cap. This solution

was selected based on engineering feasibility, structural efficiency, and compatibility with the existing foundation system.

The fifth objective, which required verification of the effectiveness of the proposed strengthening solution, was achieved through numerical modelling and analysis of multiple load combinations. The results confirmed that the strengthened foundation satisfies load-bearing capacity requirements with respect to soil and ensures regulatory reliability of the structure.

In conclusion, the study provides a coherent and practically validated methodology for assessing and strengthening existing pile foundations of road bridges under modern traffic loads. The results support informed engineering decision-making in bridge reconstruction projects and demonstrate that rational strengthening measures can offer a sustainable alternative to full foundation replacement. The methodological approach and conclusions presented in this research may be applied to similar bridge structures designed according to outdated standards, thereby contributing to the efficient management and rehabilitation of transport infrastructure.

Conflict of Interest

The author declares that is no conflict of interest.

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Appendix

Table 1. Operational condition of bridge elements

Bridge Element	Operational Condition
Bridge deck	5 – unserviceable
Superstructure	5 – unserviceable
Pier crossbeams	4 – limited serviceability
Pier columns (piles)	4 – limited serviceability
Pier foundations	4 – limited serviceability
Approaches	4 – limited serviceability

Table 2. Combination factor η accounting for the probability of simultaneous occurrence of design loads in combinations of variable loads

Combination factor η for temporary loads and actions in load combinations					
Load numbers (actions) that produce the most unfavourable effect for the given analysis	No. 7	No. 10	No. 11	No. 13	No. 15
Load numbers (actions) acting simultaneously or separately to produce the most unfavourable effect		No.10, No.11, No.13, No.15	No.7, No.11, No.13, No.15	No.7, No.10, No.15	No.7, No.10, No.11, No.13
No. 7 – Temporary vertical loads	1.0	0.8	0.8	0.7	0.7
No. 10 – Transverse vehicle impact		1	0.8	0.7	0.7
No. 11 – Braking or traction forces		0.7	1	0.8	0.7
No. 13 – Ice loads			1	0.8	0.7
No. 15 – Temperature and climatic actions				1	0.8

Table 3. Loads acting on the reinforced-concrete temperature-continuous slab, $\kappa\text{N}/\text{m}^2$

Type of Load	Layer Thickness, cm	Characteristic Load, $\kappa\text{N}/\text{m}^2$	Load factor γ_f	Design Load, $\kappa\text{N}/\text{m}^2$
Asphalt concrete surfacing	11.0	$0.11 \times 23 = 2.53$	2.0	5.10
Waterproofing	0.5	$0.05 \times 20 = 1.00$	2.0	2.00
Total permanent design load per 1 m^2 of slab				7.10

Table 4. Loads acting on the reinforced-concrete temperature-continuous slab, $\kappa\text{N}/\text{m}^2$

Type of Load	Layer Thickness, cm	Characteristic Load, $\kappa\text{N}/\text{m}^2$	Load factor γ_f	Design Load, $\kappa\text{N}/\text{m}^2$
Asphalt concrete surfacing	11.0	$0.11 \times 23 = 2.53$	2.0	5.10
Waterproofing	0.5	$0.05 \times 20 = 1.00$	2.0	2.00
Total permanent design load per 1 m^2 of slab				7.10

Table 5. Design values of moving vertical loads

Load	Characteristic value	γ_f	$(1 + \mu)$	Design value
Distributed load, $AK_s = 1.0 - v$, kN/m	14.7	1.50	1.0	22.1
Distributed load, $AK_s = 0.6 - v$, kN/m	14.7	1.50	1.0	13.3
AK tandem load – P, kN	147.15	1.50	1.3	287.0
NK vehicle load – P, kN	245.0	1.00	1.0	245.0
Crowd load (with AK) – p, kN/m ²	1.96	1.20	1.0	2.4
Crowd load (separately) – p, kN/m ²	3.92	1.40	1.0	5.5

Table 6. Design resistance R beneath the pile toe (IGE-7)

Pier	No. 0	No. 1	No. 2	No. 3	No. 4	No. 5
Depth of pile toe embedment, m	10.65	9.60	8.80	8.90	9.30	9.90
R – design resistance, kPa (interpolation)	1520	1480	1460	1460	1470	1490

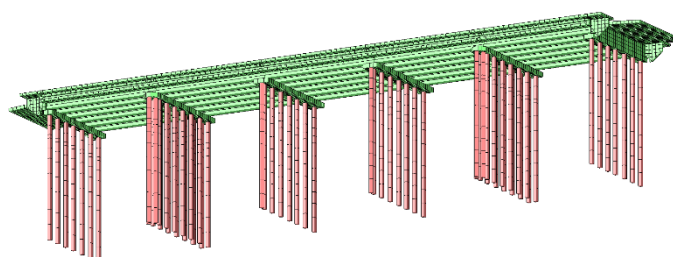


Figure 1. Bridge layout for Option No. 1 (new bridge elements are shown in green, existing piles are shown in red)

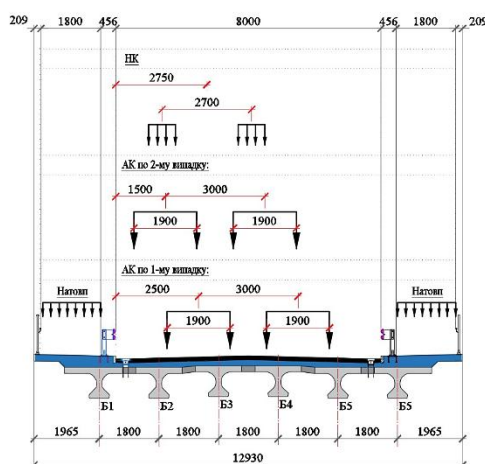


Figure 2. Layout of temporary vehicular loads and pedestrian crowd loads on the sidewalks across the bridge (In Ukr.)

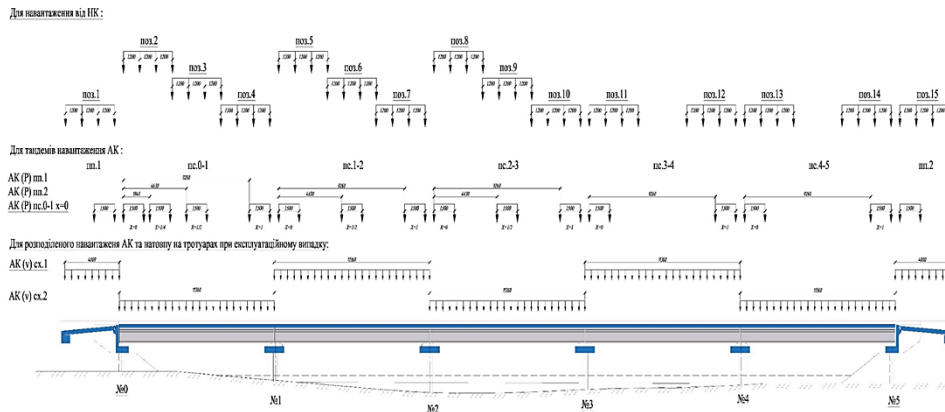


Figure 3. Variants of longitudinal arrangement of vehicular loads along the bridge

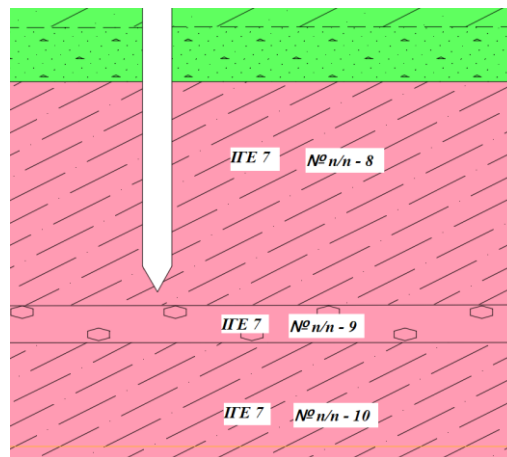
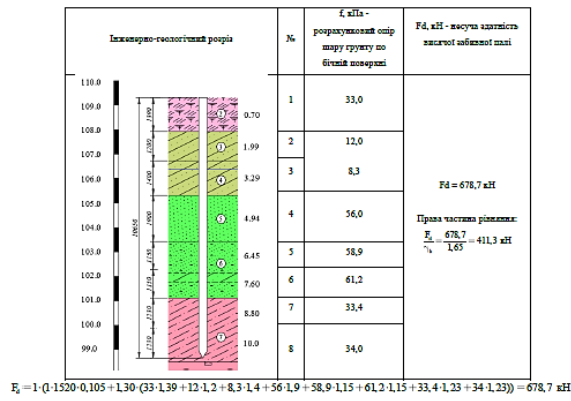
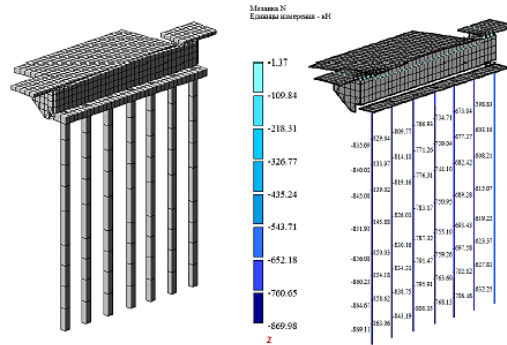


Figure 4. Schematic layout of the approximate position of the pile toe within the soil mass

Опора №0



$$F_n = 1 \cdot (1 \cdot 1520 \cdot 0,105 + 130 \cdot (33 \cdot 1,39 + 12 \cdot 1,2 + 8,3 \cdot 1,4 + 56 \cdot 1,9 + 58,9 \cdot 1,15 + 61,2 \cdot 1,15 + 33,4 \cdot 1,23 + 34 \cdot 1,23)) = 678,7 \text{ кН}$$



Отже умова не виконана, несуча здатність по ґрунту пальового фундаменту опори №0 не забезпечена:

$$N = 870 \text{ кН} \gg 411,3 \text{ кН}$$

Figure 5. Calculation of the load-bearing capacity of the pile foundation of Pier No. 0

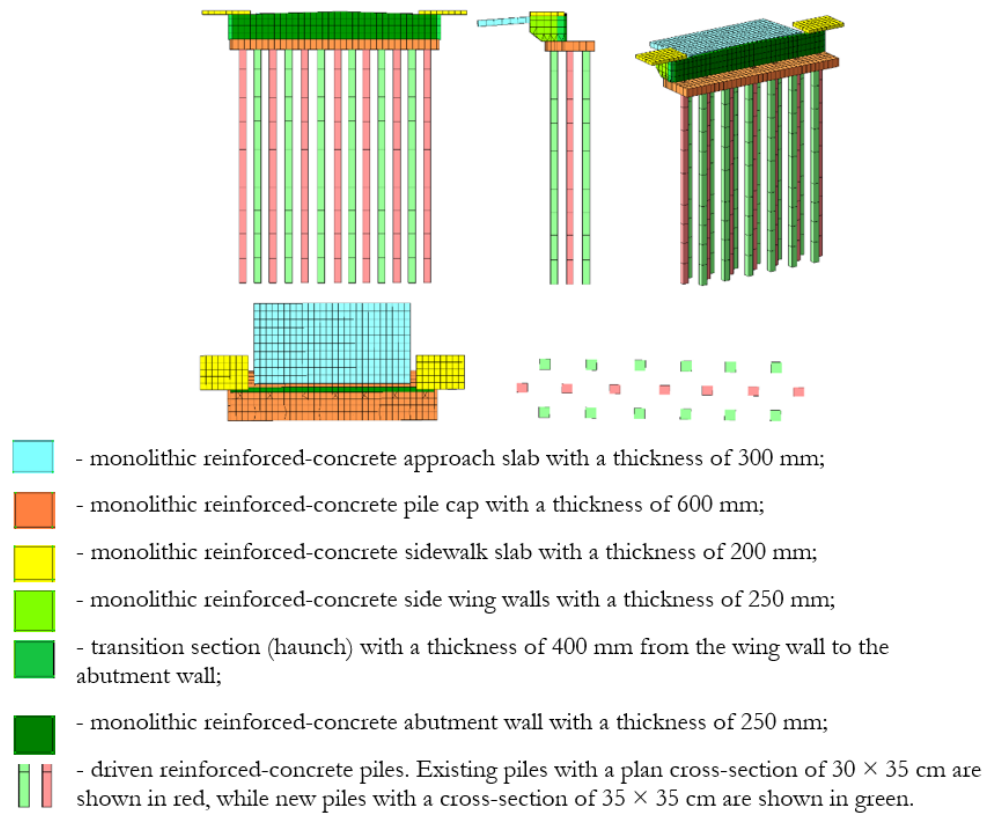


Figure 6. Visualisation of the computational model of the end pier

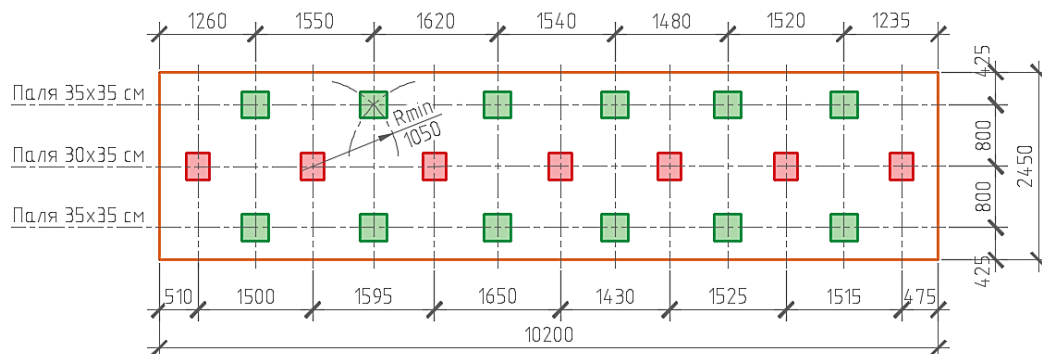
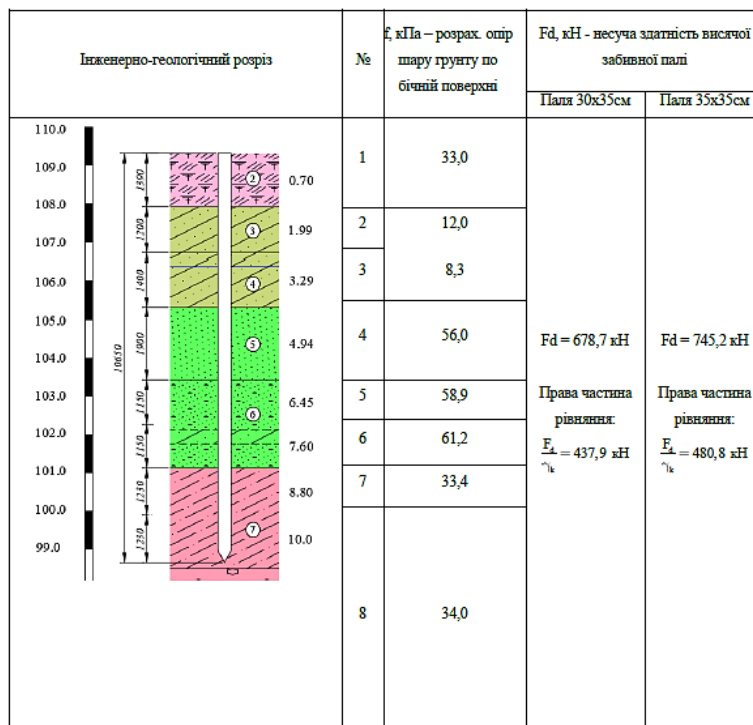


Figure 7. Layout of piles for end piers No. 0 and No. 5 (In Ukr.)

Опора №0



$$F_d = 1 \cdot (1 \cdot 1520 \cdot 0,105 + 1,30 \cdot (33 \cdot 1,39 + 12 \cdot 1,2 + 8,3 \cdot 1,4 + 56 \cdot 1,9 + 58,9 \cdot 1,15 + 61,2 \cdot 1,15 + 33,4 \cdot 1,23 + 34 \cdot 1,23)) = 678,7 \text{ кН}$$

$$F_d = 1 \cdot (1 \cdot 1520 \cdot 0,1225 + 1,40 \cdot (33 \cdot 1,39 + 12 \cdot 1,2 + 8,3 \cdot 1,4 + 56 \cdot 1,9 + 58,9 \cdot 1,15 + 61,2 \cdot 1,15 + 33,4 \cdot 1,23 + 34 \cdot 1,23)) = 745,2 \text{ кН}$$

Figure 8. Calculation of the load-bearing capacity of the new pile of Pier No. 0 (In Ukr.)

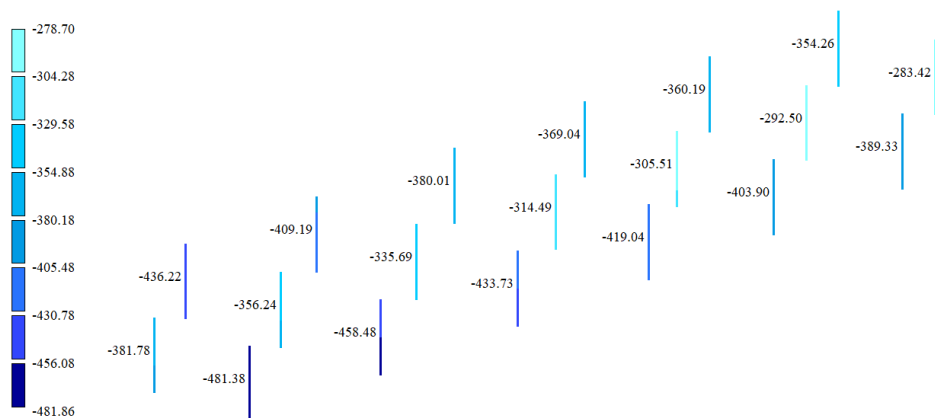


Figure 9. Internal forces N in the piles of Pier No. 0