DOI: 10.23746/2018-10-03

Uladzimir Krautsou, PhD in Engineering Science, Associate Professor, Head of the laboratory, Institute BelNIIS RUE (Minsk, Belarus)

COMPARATIVE ANALYSIS OF EUROPEAN AND BELARUSIAN STANDARDS FOR GEOTECHNICAL DESIGN OF PILE FOUNDATIONS IN THE CONTEXT OF THE REPUBLIC OF BELARUS

ABSTRACT

The article presents results of the geotechnical studies and verification of design approaches and methods for calculating the bearing capacity of pile foundations in the ground conditions of the Belarusian region carried out by the Institute BelNIIS RUE under agreement with the Ministry of Architecture and Construction (MAiS) of the Republic of Belarus for the clarification of the parameters of National Annexes to Eurocode 7. Examples of comparative geotechnical calculations according to Belarusian and European standards are provided, and their analysis is given.

Generalization of the results of comparative calculations according to Belarusian (hereinafter – "TKP RB [1-4]") and European (hereinafter – "TKP EN [5-8]") frameworks of national standards (TNPA) allowed us to identify some patterns:

1 – when calculating the bearing capacity (the first group of limit states), according to the TKP RB and TKP EN using the data of static pile load testing of soils, the main role in its determination is played by the following factors:

– the size of the pile cross section. The greater the cross section of the pile, the greater the difference in the results of calculations for the two TNPA frameworks. The greatest coincidence of results is established for piles with a diameter or a larger side of (200–500) mm;

– the number of tests performed and the variation of their results, since the safety factors in TKP EN are constant, and in TKP RB their value is determined based on the number of tested piles using the probabilistic-statistical method;

– method of determining the bearing capacity of piles, the value of which according to TKP EN is set depending on the settlement taken at 10 % of the diameter or the larger side of the pile, and according to TAP RB it is set depending on the share of the average (maximum) foundation settlement allowed for the designed structure.

2 – when calculating the bearing capacity of natural foundations of piles using physical and mechanical characteristics (theoretical method) according to the two national TNPA frameworks, the discrepancies between their results when reaching the limit state are 10–20 % (when compared with DA1...DA2) and up to 50 % or more (with DA3). The smallest discrepancy between the TNPA frameworks is observed when using the Eurocode 7 DA2 design approach, which is recommended as the main approach for National Annex in pile calculations.

Keywords: Belarusian and European standards, Eurocode 7, comparative calculations, design approaches, foundation, piles, bearing capacity, partial safety factors.

For citation: Krautsou U. Comparative analysis of European and Belarusian standards for geotechnical design of pile foundations in the context of the Republic of Belarus. Contemporary Issues of Concrete and Reinforced Concrete: Collected Research Papers. Minsk. Institute BelNIIS. Vol. 10. 2018. Pp. 36–57. https://doi.org/10.23746/2018-10-03

Кравцов Владимир Николаевич, канд. техн. наук, доцент, заведующий лабораторией, РУП «Институт БелНИИС» (г. Минск, Беларусь)

СРАВНИТЕЛЬНЫЙ АНАЛИЗ ЕВРОПЕЙСКИХ И БЕЛОРУССКИХ НОРМ ПО ГЕОТЕХНИЧЕСКОМУ ПРОЕКТИРОВАНИЮ СВАЙНЫХ ФУНДАМЕНТОВ В УСЛОВИЯХ РЕСПУБЛИКИ БЕЛАРУСЬ

АННОТАЦИЯ

В статье даны результаты выполненных в РУП «Институт БелНИИС» по договору с Министерством архитектуры и строительства (МАиС) Республики Беларусь геотехнических исследований и верификации проектных подходов и методов расчета *несущей способности оснований свайных фундаментов в грунтовых условиях белорусского региона с целью уточнения параметров национальных приложений Еврокода 7. Приведены примеры сравнительных геотехнических расчетов по белорусским и европейским нормам и дан их анализ.*

Обобщение результатов сравнительных расчетов по белорусским (далее – ТКП РБ [1–4]) и европейским (далее – ТКП EN [5–8]) базам национальных норм (ТНПА) позволило выявить закономерности:

1 – при расчете несущей способности (первая группа предельных состояний), согласно ТКП РБ и ТКП EN с использованием данных статических испытаний грунтов сваями, основную роль при ее определении играют следующие факторы:

– размер поперечного сечения сваи. Чем больше поперечное сечение сваи, тем больше расхождение в результатах расчетов по двум базам ТНПА. Наибольшее совпадение результатов установлено для свай с диаметром или большей стороной (200–500) мм;

– количество выполненных испытаний и разброс их результатов, так как в ТКП EN коэффициенты безопасности постоянные, а в ТКП РБ их величина определяется исходя из количества испытанных свай вероятностно-статистическим методом;

– методика определения несущей способности свай, величина которой, согласно ТКП EN, устанавливается в зависимости от осадки, принимаемой равной 10 % доле диаметра или большей стороне сваи, а в ТКП РБ – от доли средней (максимальной) осадки основания, допускаемой для проектируемого сооружения.

2 – при расчете несущей способности грунтовых оснований свай с использованием физико-механических характеристик (теоретический метод) по двум базам норм национальных ТНПА расхождения между их результатами при достижении предельного состояния составляют 10–20 % (при сравнении с ПП1...ПП2/DA1...DA2) и до 50 % и более (при ПП3/DA3). Наименьшее расхождение между базами ТНПА наблюдается при использовании проектного принципа Еврокода 7 – ПП2 (DA2), который рекомендуется для его национального приложения при расчете свай в качестве основного.

Ключевые слова: белорусские и европейские нормы, Еврокод 7, сравнительные расчеты, проектные подходы, основание, сваи, несущая способность, частные коэффициенты безопасности.

Для цитирования: Кравцов, В. Н. Сравнительный анализ европейских и белорусских норм по геотехническому проектированию свайных фундаментов в условиях Республики Беларусь / В. Н. Кравцов // Проблемы современного бетона и железобетона : сб. науч. тр. / Ин-т БелНИИС; редкол.: О. Н. Лешкевич [и др.]. – Минск, 2018. – Вып. 10. – С. 36–57. https://doi.org/10.23746/2018-10-03

INTRODUCTION

Since 01.01.2010, the national set of technical regulations in the field of architecture and construction (TNPA) of the Republic of Belarus currently includes two regulatory frameworks: Belarusian (hereinafter – "TKP RB", "SNB RB", "STB RB") and European (hereinafter – "TKP EN: Eurocode", "STB EN"). According to the order No. 340 of 10.12.2014 "On the transition to Eurocodes", since 1 July 2015, design of a number of structures (monolithic reinforced concrete and steel, aluminium) buildings and structures should be carried out only according to TKP EN 1992 (Eurocode 2), and TKP EN (1990, 1991, 1993 and 1999), developed on the basis of European standards (Eurocodes).

As a result, in the practical use of Eurocodes that are not listed in the order No. 340 of 10.12.2014, specialists have a lot of questions related to the use of approved documents, their status, procedure and priority in relation to the Belarusian TKP RB including to calculation methods.

Partially, these questions are covered by the letter [9] of the Ministry of Architecture and Construction of the Republic of Belarus, which states that the European standards approved and put into effect in the Republic of Belarus do not cancel the effect of the set of Belarusian TNPAs, except for those mentioned above. They are allowed to be used for internal design and construction along with Eurocodes.

According to [9], the decision on the application of certain standards (TKP RB, TKP EN) in the design is made by the customer and the design organization with the indication of this condition in the design contract (agreement), and design assignment.

In addition, general integration of Belarusian and European standards in the Republic of Belarus is carried out on the basis of the Technical Regulation (TR) "Buildings and structures, building materials and products. Safety" [10] approved by the Resolution of the Council of Ministers No. 1748 of 31.12.2010. The Technical Regulation are developed on the basis of European Union Directives 89/106/EEC and 2002/91/EC and defines requirements for buildings, structures, building materials and products, the rules for confirming compliance with the requirements of the Technical Regulation, and rules for conformity marking. However, these documents [9, 10] lack data (measures) on updating and implementing Eurocodes for design and effective application of methods for calculating various designs, including foundations and their bases.

The Programme of Building Eurocodes related to the design of foundations includes the following standards:

EN 1997, Eurocode 7: Geotechnical design. Part 1, Part 2.

EN 1998, Eurocode 8: Design of structures for earthquake resistance.

Eurocode 7, Part 1 adopted with the National Annex.

Eurocode 7, adopted (introduced) in the Republic of Belarus (TKP EN /3, 4/) is a version of translation from English of the German standards DIN EN 1997 – 1:2005-10 and is intended for designing foundations of all types of structures, including retaining structures. It provides means for calculations of geotechnical effects on the structure, and the stability of the ground exposed to the structure. The document contains all requirements and rules for the implementation of the geotechnical part of the construction project.

Eurocode 7 consists of two parts: TKP EN 1997-1 "Geotechnical design. Part 1. General rules" [7]; EN 1997-2 "Geotechnical design. Part 2. Ground investigation and testing" [8]. They should be used in conjunction with EN 1990 "Eurocode 0: Basis of structural design" (CEN, 2002) [5] and Eurocode 1: Actions on structures [6].

Part 1 of the Eurocode 7 "General rules" is a general document setting out only the principles of geotechnical design as part of the method of limit state design (LSD). In particular, it provides a general calculation of the geotechnical actions of the ground mass on the structural elements of the structure, such as: supports, foundations, piles, underground parts of buildings, etc., and also deformations and stresses arising in the ground from external actions. Some detailed design information or design schemes and principles (exact formulas, graphs, etc.) are given in "informative" (recommended) annexes and one regulatory (mandatory) Annex A, which shows "partial" (particular) factors, correlation coefficients for critical ultimate limit states and their recommended values, clarified at the national level or assumed by default.

In this regard, the loads on the elements of structures and their permissible displacements upon contact with the ground must be previously determined.

Verification of ultimate limit states (ULS) established by Part 1 of Eurocode 7 should be carried out in accordance with Eurocode 0 "Basis of structural design" [5].

Currently, the parameters defined in Eurocode 7 at the national level are assumed by default or without proper justification, which prevents from reliably taking into account geographical, geological and climatic conditions, and the degree of safety acceptable for specific conditions of the Republic of Belarus. This leads to a decrease in the effectiveness of the application of Eurocode 7 [7] in the Belarusian region. In addition, it includes no or not fully updated STB EN for ground testing, and survey organizations are not equipped with appropriate equipment that comply with STB EN. It should also be noted that:

1 – For the building design, and calculation of strength and stability of supporting structures, the European Commission recommends that participating countries implementing the EC introduce guidelines on the application of Eurocodes, in particular, in higher education, retraining courses and advanced training of engineering and technical staff. Currently there are no such guidelines in the Republic of Belarus.

2 – Among the specialists–developers of the Eurocode 7 there are also significant disagreement on the STR and GEO formats of checking the limit states. Some insist on double check (uncertainty of external load and ground stability), while others prefer to use only one format of combinations of actions [11 and others].

In this regard, Eurocode 7 recommends three different approaches for geotechnical design: Design Approaches (1, 2, 3) DA1, DA2, DA3). According to [5, 7, 11, etc.], the DA should be selected at the level of each individual country and be fixed in the National Annex to Eurocode 7. This approach is used for all types of geotechnical structures (natural foundations, pile, retaining structures, slopes, overall stability). Currently, DA1 is adopted in England and another 6 European countries for pile calculation; DA2 – in about 9 countries; DA3 – in 3 countries (Figure 1).

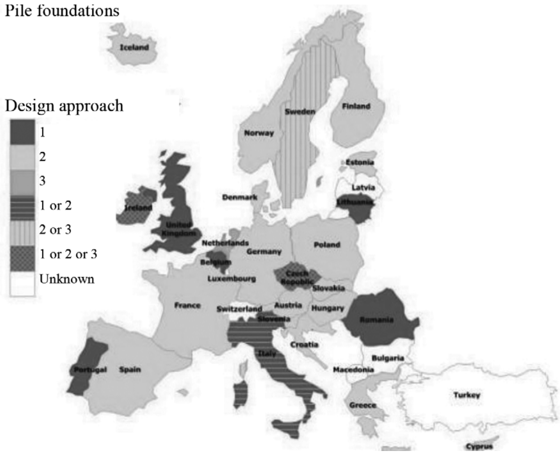

Figure 1. Design approaches according to Eurocode 7 adopted in the EU countries for designing pile foundations

Based on the above, effective implementation of Eurocode 7 in the Republic of Belarus requires the following:

1. In accordance with EU Directive 89/109, develop a guideline (recommendations) on the use of TKP EN for the conditions of the Republic of Belarus.

2. Determine the most effective design approach (from DA1-DA3) and clarify the partial and correction factors to ensure maximum efficiency of the chosen approach for design and construction of foundations from the condition: “Reliability – economic and technical efficiency – consumer protection” [5, 7, 11].

To solve the tasks on updating the Eurocodes set by the Ministry of Construction and Architecture of the Republic of Belarus, the Institute BelNIIS RUE conducted a set of geotechnical studies of design methods for Belarusian TKP RB [1-4] and European TKP EN 1997 1 2009: Eurocode 7, Part 1 [7] standards in order to clarify the parameters of National Annexes and its effective implementation in the conditions of the Belarusian region.

This article provides a part of the content of the work performed, concerning the comparative analysis of results of the calculation of the pile foundations according to two regulatory frameworks of the national TNPA of the Republic of Belarus.

METHOD OF COMPARATIVE ANALYSIS OF TWO TNPA FRAMEWORKS IN THE CALCULATION OF PILE FOUNDATIONS

Methods of comparative calculations of the piles listed in the two regulatory national TNPA frameworks: Belarusian TKP RB [1–4, etc.] and European TKP EN [5–8], are based on:

- taking into account particular properties of the ground of the Belarusian region, according to Annex A [1], test calculations of the pile foundations most common in the Republic of Belarus;
- analysis of literature sources on the use of Eurocode 7 for geotechnical design, in particular, the following foreign authors: R. Frank, A. Bond, A. Harris, P. Arnold, G. A. Fenton, M. A. Hicks, T. Schweckendiek, B. Simpson, L. L. Trevor, E. R. Farrel, R. Driscoll, P. Scott, J. Powell, Trevor Orr [11–21, etc.].

The purpose of the calculation methods used in the 2 national TNPA RB frameworks is to check the two groups of limit states for the material and ground (Table 1).

The article provides the results of comparative calculations according to the two TNPA frameworks for the limit state only on the bearing capacity of the pile foundations with the pressed axial load, taking into account the ground conditions of the Belarusian region.

Table 1

Comparison of limit states used in national TNPAs for calculation of pile foundations

Limit states in compared national TNPA frameworks	
European (TKP EN)	**Belarusian (TKP RB)**
In bearing capacity: - Loss of overall stability; - Loss of compressive strength for pile foundations; - Pulling or insufficient tensile strength of the pile foundation; - Failure of the foundation by the action of the transverse load on the pile foundation; - Failure of pile structures by compression, stress, bending, loss of longitudinal stability or shear; - Combined failure of the base and pile foundation; - Combined failure in ground and structure; In deformation and dynamics: - Excessive settlements; - Excessive heave; - Excessive transverse displacement; - Unacceptable vibrations	The first group (bearing capacity): - Strength testing of materials of pile and pile caps; - Bearing capacity testing of the pile foundation ground; - Verification of the bearing capacity of the base of pile foundations at high horizontal loads The second group (deformations): - Testing of vertical and horizontal displacements of the piles; - Testing of the formation of cracks in the structures

According to [22, etc.], layered bases from Quaternary deposits of the second category of complexity are the most typical for construction sites of the Belarusian region and are described by calculation model II in Annex A [1], which is accepted as the basis (Figure 2). Quaternary deposits of sands and clays, with characteristics for the TKP [4] (table values), that are most commonly found on the territory of the Belarusian region are taken as the basis for the calculation model in Figure 2.

The work performed and the test calculations considered the following types of precast (prefabricated) and cast-in-place piles and their technology most commonly used in mass construction:

- Traditional precast factory-made piles, sunk by driving (hereinafter – “driven pile”);
- Traditional bore piles in drilled wells;
- Cast-in-place in drilled wells with enlarged base and shaft (rammed, stamped, including injection and rolling);
- Screw metal piles;
- Jet grouting piles, etc.

N_{sv} is standard load on the pile; L_{sv} is pile length; DL is grade elevation

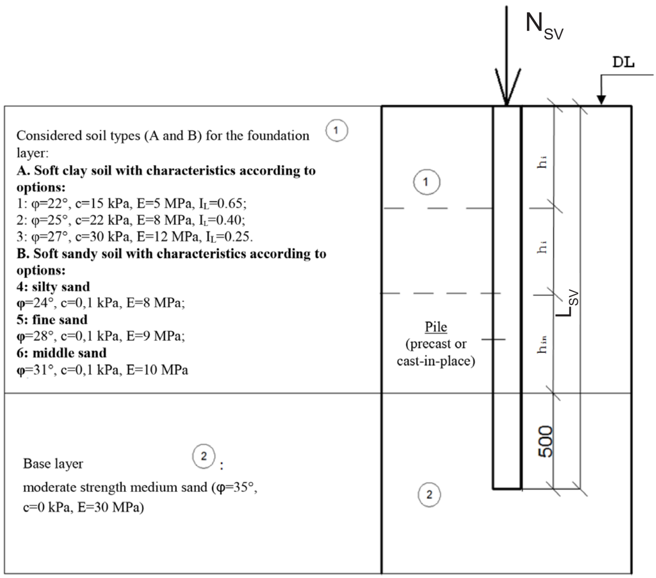

Figure 2. Calculation models for comparative calculations of pile foundations according to the results of their static tests and the theoretical method using data from the physical and mechanical characteristics of soils

Up to 70 % of all piles used in mass industrial and civil engineering are precast reinforced concrete square prismatic piles with a cross section (β×η: 300×300, 350×350, 400×400) mm and a length of up to (6-10) m and round bored piles with a diameter of (300–800) mm, and in some cases (for high-altitude and highly-loaded structures) with a diameter of (1 000–2 000) mm and a length of up to 30 m.

In connection with the above, the following types of piles, most used in the mass construction of Belarus, and their characteristic foundations are considered for the test calculations in the performed studies:

- Standard precast (driven) square piles (calculation model according to Figure 2 corresponds to the category of complexity II of foundations according to Annex A of the TKP [1]):
  I – ($b \times h \times L_{sv}$=300×300×4000) mm; **II** – (350×350×5000) mm;
  III – (400×400×6000) mm;
- Typical bore piles, installed in drilled wells (foundations per Figure 2):
  IV – ($\varnothing \times L_{sv}$=300×4 000) мм, **V** – (600×7 000) mm,
  VI – (800×9 000) mm; **VII** – (1 200×15 000) mm.

In [1–3, 7] the following recommended methods are given for calculating the pile foundations by bearing capacity:

a – according to the results of static load pile testing of soils;

b – according to static or dynamic probing data;

in – according to the physical and mechanical characteristics of the soil, established by testing or according to the tables.

This article analyses the results of calculations using methods **a** and **c**.

Comparative methods for piles calculation according to the first group of limit states according to TKP RB [1–3] require calculation of the allowable load on the pile F_u, and according to TKP EN [7], the estimated design value of the soil resistance of the pile foundation $R_{c;d}$, based on:

- TKP RB [1–3]:

$$N \le F_u, \qquad (1)$$

where N is the maximum calculated pressed axial load on the pile in the most unfavorable combination, in kN; F_u is the permissible load (limit) on the pile according to the strength of the soil foundation, in kN;

– EN TAP [7]:

$$F_{c;d} \leq R_{c;d}, \qquad (2)$$

where $F_{c;d}$ is the most unfavorable design pressed axial load on the pile, in kN; $R_{c;d}$ is the design value of the resistance of the soil foundation to the pressure of the pile in the limit state, in kN.

Parameters F_u and $R_{c;d}$ are taken as criteria for the comparative analysis of the calculation methods by bearing capacity and selection of the design approach for the conditions of the Republic of Belarus. In accordance with [5-7], the design load on the pile, in turn, depends on the percentage of temporary and permanent loads relative to its total value. Therefore, the calculation is performed taking into account the following load ratios: 30 %/70 %; 40 %/60 %; 50 %/50 % (the numerator is the percentage of the **temporary** load of its total value; the denominator is the **permanent** load).

Due to a disagreement among the specialists from different European countries on the approaches and principles for the calculation of foundations (see Figure 1), there is no one specific design approach specified in the TKP EN, comparative calculations are performed according to all three approaches.

COMPARATIVE STUDIES OF GEOTECHNICAL METHODS OF CALCULATION OF FOUNDATIONS ACCORDING TO TWO TNPA FRAMEWORKS. RESULTS AND ANALYSIS

Comparative calculations based on the results of pile load testing of soils. Methods for determining the permissible (limit) load on the pile regulated by the TKP RB and the design (limit) resistance of the pile foundation TKP EN using static load pile testing of soils for pressed axial loads are similar. Graphs of pile settlement in relation to the load $s = f(p)$ are plotted based on the static load test data. Then, for the allowable settlement, taking into account the number of pile tests, according to the TKP RB [1-3], the excess resistance of its foundation F_u (allowable pile-bearing load) is checked, and according to the EN [7] TAP, the limit state by foundation failure is checked (GEO), based on the three design approaches (DA1...DA3), using sets of partial factors in combinations (A1, A2 for representative actions of F_{rep}, M_1, M_2 for characteristic parameters of $X_{k,}$ R_1...R_4 for resistances).

The fundamental differences between the methods for determining the maximum load of pile foundation (the first group of limit states) in the TKP RB [1–3] and the TKP EN [7] are as follows:

- the settlement, at which this characteristic is determined, depends on the proportion of the average settlement of the building $s = \xi \bullet Su.mt$, which takes into account its construction design, level of responsibility, class of complexity of the foundation, number of tests carried out, and is within (80–400 mm), where ξ is the coefficient of transition from the building settlement to the pile settlement, equal to 0.2–0.5. TKP EN 1997-1 specifies Rc;d at the a settlement equal to 10% of the diameter or the transverse size of the pile (see 7.6.1.1. (3) [7]). As a result, with a pile diameter of 1200 mm, the amount of settlement, at which the ultimate resistance of its foundation is determined, is almost 2–4 times greater in TKP EN than in TKP RB, which greatly overestimates Rc;d according to the test results.
- when determining the allowable (ultimate) load on the pile foundation according to TKP RB and the calculated (design) value of the soil resistance to the pressing of the piles according to TKP EN, various partial and correction factors are used for actions, resistances, and characteristics of materials.

Below are examples of the comparative determination of the permissible load on the pile foundation F_u according to TKP RB and the design (calculated) value of the foundation resistance to the pressing of the pile $R_{c;d}$ according to TKP EN.

Example 1 of comparative calculations of the bearing capacity of the pile foundations according to the results of their static load tests.

4 bore piles ∅1200 mm were tested on the construction site of a building with a reinforced concrete frame of the II level of responsibility. Soil foundation of piles of II category of complexity. Design (calculated) pile-bearing load N = Fc;d = 1.0 MN. Distribution of temporary and permanent load in its total volume is 40%/60%. Graphs (Figure 3) of the dependence of their settlement on the load s=f(p) were obtained.

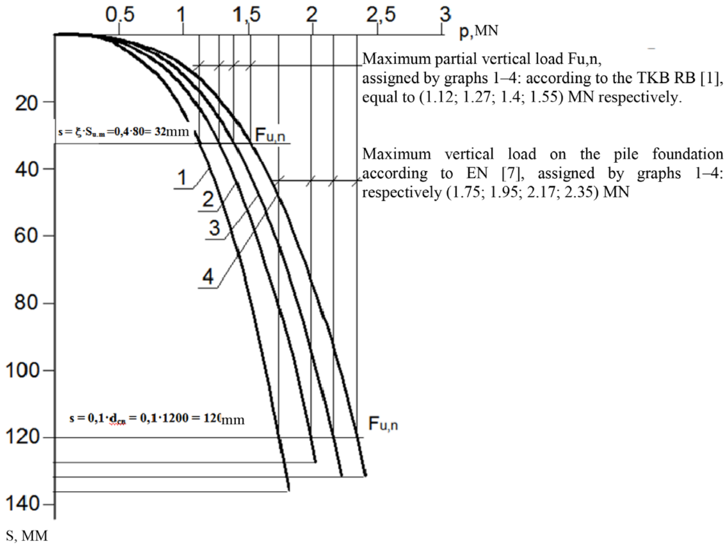

Figure 3. Dependence graphs of the settlement of bored piles with a diameter of 1 200 mm from the load s = *f*(p)

Calculation according to TKP RB. According to the results of static load tests (see Figure 3), the indices of partial values of 4 identical piles tested on the same site during the settlement, according to [1], $s = \xi \cdot S_{u.mt} = 0.4 \cdot 80 = 32$ mm were $F_{u,n} = (1.12, 1.27, 1.40, 1.55)$ MH.

Since the number of pile tests is less than 6, the bearing capacity, according to [1], is assigned to the lower of all partial values using the formula

$$F_d = \gamma_c \bullet F_{u.n} / \gamma_g = 1.0 \bullet 1.12 / 1.0 = 1.12 \text{ MN},$$

where γ_c is the coefficient of working conditions; γg is the reliability coefficient for the soil, taken in accordance with 5.2.16.1 [1], equal to 1.0, since the number of tests was less than 6.

Then the allowable pile-bearing load will be:

$$F = \frac{F_d}{\gamma_k} = \frac{1.12}{1.2} = 0{,}93 \text{ MN}; \cong N = 1{,}0 \text{ MN},$$

where γ_k is the reliability coefficient of the method for determining the bearing capacity of a pile on the soil, equal to 1.2 according to Table 5.6 [1].

Calculation according to TKP EN. According to the results of static tests (see Figure 3), the indices of the ultimate specific characteristic values of soil resistance to the pressing of 4 identical piles on one site with a settlement, according to [7], equal to 10 % of its diameter, s = 1 200 x 0.1 = 120 mm, were respectively: $R_{c;k}$ = (1.75; 1.95; 2.17; 2.35) MN. According to [7], the characteristic value $R_{c;k}$ of soil resistance to the pile pressing according to test results, if their number n > 1, is assigned based on two values: minimum $R_{m,min}$ = 1.75 MN and average $R_{m,mean}$ = 2.06 MN of the values of the indices of ultimate loads on pile foundations, (see Figure 3) according to the formula (3)

$$R_{c;k} = \min (R_{m,\ mean} / \xi_1; R_{m,\ min} / \xi_2), \qquad (3)$$

where ξ_1, ξ_2 are correction factors that take into account the number of tested piles. For the four tests in Table A9 [7]: ξ_1=1.10; ξ_2=1.0.

Then $R_{c;k}$ = min{2.06/1.1=1.87; 1.75/1.0=1.75}, taken as $R_{c;k}$ = 1.75 MN.

The design (calculated) resistance of the foundation to the pile pressing $R_{c,d}$ depends on the chosen design approach. Taking into account that [7] provides 3 design approaches (DA1-DA3) and the National Annex gives none of them priority, $R_{c,d}$ is calculated using all three approaches.

The design resistance of foundation $R_{c,d}$, when using approach **DA1** and the corresponding 2 combinations of a set of partial resistance factors γ_t, defined in Table A.7, γ_t = 1.1 (combination 1) and γ_t = 1.0 (combination 2), will be:

- for combination 1: $R_{c,d} = R_{c,k} / \gamma_t$ = 1.75 / 1.1 = 1.59 > $F_{c.d}$ = 1.0 MN;

- for combination 2: $R_{c,d} = R_{c,k} / \gamma_t$ = 1.75 / 1.0 = 1.75 MN > $F_{c.d}$ > 1.0 MN.

Similarly, when using design approaches **DA2** and **DA3**, the design (calculated) resistances of the pile foundation to the pressing, in their corresponding combinations of sets of partial coefficients for resistances R_2 (in DA2), γ_t = 1.1, and R_3 (in DA3), γ_t = 1.0, will be:

- when using **DA2**: $R_{c,d} = R_{c,k} / \gamma_t$ = 1.75 / 1.1 = 1.59 MN > $F_{c.d}$ = 1.0 MN, which corresponds to the combination 1 according to **DA1**;

- when using **DA3**: $R_{c,d} = R_{c,k} / \gamma_t$ = 1.75 / 1.0 = 1.75 MN > 1.0 MN, which corresponds to combination 2 according to **DA1**.

Examples of comparative calculations of pile bearing capacity by analytical method using data of physical and mechanical properties of the soil. One of the variants of comparative calculations using the above methods for research of two geotechnical frameworks of national TNPA on the design of pile foundations is considered.

Baseline. Calculation of a traditional precast (driven) prismatic pile of standard size I (see Methods) with a square cross section with sides (0.3×0.3) m and length 4 m, immersed in a layered foundation with soil characteristics determined by specific tests on one well (see Option A in Figure 3) is performed: for the 1st and 2nd soil layers h1 and h2: γ '= 20 kN/m3, c'u = 15 kPa, for the 3rd layer h3: γ' = 18 kN/m3, c'u = 0, 01 kPa. The standard (representative) axial pile-bearing load is Nn (Frep) = 250 kN. Distribution of temporary and permanent load in its total volume is 40 %/60 % (numerator/denominator). According to the test results for 3 piles Fun.min (Rm.min) = 364 kN, the standard (representative) bearing capacity of their foundation is: the minimum average of three is Rm.min = 396 kN. The calculation model for a pile of standard size I (see Methods) with the characteristics of the properties of its foundation is shown in Figure 3.

Calculation according to TKP RB (Example 2). According to [1, 2], the bearing capacity of the pile foundation Fd is determined by the analytical method as the sum of the resistance of the soil to the pressing of the lower end and the shaft. For this, first, the pile foundation is divided into 3 layers h1 = 2 m, h2 = 1.5 m and h3 = 0.5 m, according to Tables 6.1 and 6.2 [2], for which the calculated values of soil resistance are determined at the level of its lower end, equal in this case: R = 4400 kPa and Rfi = (7.5; 14; 60) kPa.

$F_d = \gamma_c \cdot (\gamma_{cr} \cdot RA + \gamma_{cf} \cdot u_i \cdot \Sigma R_{fi} \cdot h_i) =$

$= 1\,(1 \cdot 4\,400 \cdot 0.09 + 1 \cdot 1.2 \cdot (7.5 \cdot 2 + 14 \cdot 1.5 + \cdot 60 \cdot 0.5)) =$

$= 396 + 79.2 = 475.20$ kN,

where γ_c, $\gamma_{cr,}$ γ_{cf} are the coefficients of the working conditions of the pile in the soil, equal to 1; A is the cross-sectional area of the pile, 0.09 m^2; u_i is the average perimeter of the transverse shaft of the pile in the i-th layer of the soil, 1.2 m; h_i is the thickness up to 2 meters of the i-th layer of soil in contact with the side surface of the pile, which the pile foundation is divided into, m;

Permissible (ultimate) pile-bearing load, according to the TKP RB, based on the results of:

– calculations

$$F_{cal} = \frac{F_{d.cal}}{\gamma_k} = \frac{475,20}{1.4} = 339,43 : N > N = \gamma_n \cdot N_n = 1,2 \cdot 250 = 300 \text{ kN};$$

– tests

$$F_m = \frac{F_{dm}}{i_k} = \frac{364}{1.2} = 303.33 \text{ MN}; > N = \gamma_n \cdot N_n = 1,2 \cdot 250 = 300 \text{ kN}.$$

where γk is the coefficient of reliability of the method for determining the bearing capacity of the pile, according to [1], equal to: γk = 1.4 for the analytical method γk = 1.2 according to the results of pile tests.

Calculation according to TKP EN (Example 3). The ultimate characteristic resistance of the soil to pile pressing, in the analytical method using the physical and mechanical characteristics of the soil, and in the method based on the results of static load pile testing, are determined by the formula similar to (3), where the indices "m" ("measured") replaced by "cal" ("calculated"), and the values ξ1, ξ2 are replaced by ξ3, ξ4, given in Annex A [7].

The characteristic values of $(R_{c.cal})_{mean} = (R_{b.cal} + R_{s.cal})_{mean}$ and $(R_{c.cal})_{min} = (R_{b.cal} + R_{s.cal})_{min}$ (see formula (3)) may be determined by any of the analytical theories confirmed by experimental data using correction and partial factors to assign the design (calculated) resistance of the pile $R_{c;d}$.

The characteristic resistance of the foundation (bearing capacity according to terminology in [1]) to pile pressing Rc;k = (Rb.k + Rs.k) according to the above baseline, is defined as the sum of the resistance to pressing of its lower end Rb.k and the shear resistance of its shaft Rs.k, with the use of correction and partial factors ξ4 and analytical formulas of the theory of elasticity, recommended by [7].

$R_{b;k} = R_{b.cal} / \xi_4 = R_b \bullet (c' \bullet N_c \bullet s_c + q' \bullet N_q \bullet s_q + 0.5 \bullet \gamma' \bullet B \bullet$
$\bullet N_\gamma \bullet s_\gamma) / \xi_4 = 0.3 \bullet 0.3 \bullet (1 \bullet 61.30 \bullet 1.63 + 72 \bullet 48.89 \bullet 1.69 +$
$+ 0.5 \bullet 18 \bullet 0.3 \bullet 74.83 \bullet 0.7) / 1.4 =$ **382.11** kN,

where $s_q = 1 + \sin\phi' = 1 + 0.616 = 1.62$; $s_c = (s_q \bullet N_q - 1)/(N_q - 1) =$
$= (1.616\text{-}48.89 - 1) / (48.89 - 1) = 1.63$; $s\gamma = 0.7$.

$$N_q = e^{\pi \cdot \mathrm{tg}\varphi'} \mathrm{tg}^2\left(45^\circ + \frac{\varphi'}{2}\right) = 48,89;$$

$N_c = (N_q - 1) \bullet \mathrm{ctg}\phi' = 61.30;$

$N_\gamma = 2 \bullet (N_q - 1) \bullet \mathrm{tg}\phi' = 74.83;$

$q' = \gamma' \bullet d = 18 \bullet 4 = 72$ kPa.
$R_{s.k} = \sum R_{s.cal} / \xi_4 = (R_{s\,h1.cal} + R_{s\,h2.cal}) / \xi_4 = 25.56 / 1.4 = 18.26$ kN,
here $R_{s\,h1.cal} = A_{s1} \bullet \alpha \bullet c_u = 4 \bullet 0.3 \bullet 3.5 \bullet 0.4 \bullet 15 = 25.2$ kN,
$R_{s\,h2.cal} = A_{s2} \cdot \alpha \cdot c_u = 4 \cdot 0.3 \cdot 0.5 \cdot 0.6 \cdot 1 = 0.36$ kN.

The design (calculated) resistance to pile pressing is determined according to the research methods, for all 3 design approaches DA1...DA3:

– according to **DA1**, the calculation is performed for two combinations, where for the set of coefficients in the combination A1+M1+R1 only the partial factors of the actions of the set A1 are not equal to one: $\gamma_G = 1.35$ and $\gamma_Q = 1.5$; and in combination 2: A2+M1+R4, coefficients of the effects of the set A2: $\gamma_G = 1.0$, $\gamma_Q = 1.3$, and set R4: $\gamma_t = 1.3$. Consequently:

– for combination 1:

$$\mathbf{F_{c;d} = \gamma_G \cdot \left(0{,}6 \cdot F^{G}_{rep}\right) + \gamma_Q\left(0{,}4 \cdot F^{Q}_{rep}\right) = 1{,}41 \cdot F_{rep} = 1{,}41 \cdot 250 = 352{,}50\ kN}$$

$\leq R_{c.dcal} = (R_{b.k} + R_{s.k}) / \gamma_t = (382.11 + 18.26) / 1 =$ **400.37** kN (deviation from the calculation results according to TKP RB, Example 1, towards of overestimation ("+") is: $i_{cal} = (+)18$ % relative to the experimental data $R_{c;dm} = R_{m.min} / \gamma_t = 364 / 1 = 364$ kN – $i_m = (+)10$ %).

– for combination 2:

$F_{c.d} = 1{,}12 \bullet F_{rep} = 1{,}12 \bullet 250 =$ **280** кН $< R_{c.dcal} = R_{c.k} / \gamma_t = 400.37 / 1.3 =$ **307.98** kN (deviation towards underestimation ("–") from TKP RB: $i_{cal} = (–)10$ %, from the test results: $(364 / 1.3 = 280)$ – $i_m = (+)10$ %).

– according to **DA2**, in the combination A1+M1+R2, factors not equal to one are, respectively, for A1: $\gamma_G = 1.35$ and $\gamma_Q = 1.5$ and for R2: $\gamma_t = 1.1$, then:

$F_{c.d} = 1.41 \bullet 250 =$ **352.50** kN $< R_{c.dcal} = 400.37 / 1.1 =$ **363.97 kN** ($i_{cal} = (+)7$ %; $i_m = (–)9$ % ($R_{c.dm} = 330.91$ kN).

– according to **DA3**, in combination A1+M2+R3, factors equal to more than one are, for sets A1: $\gamma_G = 1.35$ and $\gamma_Q = 1.5$; in M2: $\gamma\phi_{,} = 1.25$; $\gamma_{cu} = 1.4$. Then:

$\phi›_d = \tan^{-1} (\tan 38° / 1.25) = 30.4$; $N_q = 19.27$; $N_c = 31.78$; $N\gamma = 21.44$;

$c'_{u1} = c'_{u1} / 1.4 = 15 / 1.4 = 10.7$ kPa; $c'_{u2} = 1 / 1.4 = 0.71$ kPa:

$R_{b;k}$ = 0.3 • 0.3 (0.71 • 31.78 • 1.63 + 72 • 10.27 • 1.62 + 0.5 • 18 • 0.3 • 21.44 • 0.7) / 1.4 = 149.46 kN;

$R_{s.k}$ = (4 • 0.3 • 3.5 • 0.4 • 10.7 + 4 • 0.3 • 0.5 • 0.6 • 0.71) / 1.4 = 13.03 kN;

$R_{c.k}$ = 149.46 + 13.03 = 162.49 kN.

$F_{c.d}$ = 1.41 • 250 = **352.50** kN > $R_{c.d}$ = 162.49 = **162.49** kN (i_{cal} = (–)52 %,

i_m = (–)52 % ($R_{c.dm}$ = 364 kN)). The condition $F_{c.d} \leq R_{c.d}$ is not satisfied, i.e. according to DA3, the pile must be buried deeper into the foundation for another 1 meter.

Analysis of the results. The analysis of generalized results of research carried out by the Institute BelNIIS RUE throughout the whole range of studies (different types of piles, soils, etc., see the above Methods) showed that despite the same fundamental approaches to the pile calculations (for the 2 groups of limit states) the design techniques used in the Belarusian and European regulatory frameworks (TNPA) – as a result of the established historical traditions in the field of application of computational (theoretical) models – have significant differences, in particular:

1 – when assessing the bearing capacity of pile foundations F_d, according to TKP EN [7], based on the data of static pile **testing** of soils, the main role is played by:

– the number of tests and the variation of their results, since the safety factors in TKP EN are constant, and in TKP RB their value depends on the number of tested piles calculated using the probabilistic-statistical method;

– the size of the pile cross section (the greater the cross section of the pile, the greater the difference in the results of calculations for the two TNPA frameworks [1, 5 and 7]), since according to TKP EN, F_d is assigned depending on the settlement, assumed to be 10 % of the diameter or the larger side of the pile, and in TKP RB it depends on the share of the average (maximum) foundation settlement allowed for the designed structure. As a result, F_d values may differ by 2 or more times. The greatest coincidence of results is established for piles with a diameter or a larger side of (200–500) mm.

2 – when assessing the bearing capacity of pile foundation F_d using the physical and mechanical characteristics (analytical method) according to the two TNPA frameworks [1] and [7], the discrepancies

between their results (limit state condition) are 10–20 % for DA1, DA2 and up to 50 % or more for DA3. Based on the fact that the minimal discrepancies between the TNPA frameworks [1] and [7] are observed when using the design approach DA2 of Eurocode 7, it is recommended to be established in the National Annex to Eurocode 7 as the main approach for pile calculations.

CONCLUSION

1. On the basis of the developed research methods, comparative geotechnical calculations of the bearing capacity of the pile foundations according to the Belarusian and European national TNPA frameworks and verification of European standards (Eurocode 7 [7]) were applied in the context of the Republic of Belarus.
2. Comparative analytical calculations of the bearing capacity of natural pile foundations of the Belarusian region by the physical and mechanical characteristics of the soils using the methods of Belarusian and European national TNPA frameworks, showed that the difference between their results in the context of the Republic of Belarus, when reaching the limit state, is 10–20 % for DA1, DA2 and up to 50 % or more for DA3 (see Examples 1–3). The minimum discrepancy between the results of the compared calculation methods according to [1] and [7] is provided by the design approach DA2, which is recommended to be established as the main approach in the National Annex to TKP EN 1997-1-2009: Eurocode 7 Part 1.
3. To update TAP EN 1997-1-2009: Eurocode 7, for it to be actively used in the design practice of the Republic of Belarus, it is necessary to fully translate from English and put into operation STB EN for soil testing, and fit testing laboratories with appropriate equipment.
4. The results of generalization of comparative calculations of pile foundations for two groups of limit states also serve as starting material for the development of guidelines (manual), explaining with practical examples an algorithm for effective application of the principles of European standards in the Republic of Belarus for the purposes of retraining and advanced training of various

categories of technical specialists. Without these measures (including items 2 and 3), the effective use of Eurocode 7 is impossible.

REFERENCES

1. *Osnovaniya i fundamenty zdaniy i sooruzheniy. Osnovnye polozheniya. Stroitelnye normy proektirovaniya* [Footings and foundations of buildings and structures. The main provisions. Construction design standards] : TKP 45-5.01-254-2012. Vved. 05.01.2012. Minsk : MAiS RB : "Stroytehnorm", 2012. 164 p. (rus)
2. 2. *Osnovaniya i fundamenty zdaniy i sooruzheniy. Svai zabivnye*. *Pravila proektirovaniya* [Footings and foundations of buildings and structures. Drift piles. Design rules] : TKP 45-5.01-256-2012. Vved. 05.01.2012. Minsk : MAiS RB : "Stroytehnorm", 2013. 137 p. (rus)
3. *Proektirovaniye i ustroystvo buronabivnyh svay* [Design and installation of bored piles] *:* P13 k SNB 5.01.01-99. Vved. 01.01.2002. Minsk : MAiS RB : «Stroytehnorm», 2002. 43 p. (rus)
4. *Fundamenty plitnye. Pravila proektirovaniya* [Foundations slab. Design rules]: TKP 455.01672007. Vved. 05.09.2007. Minsk : MAiS RB : «Stroytehnorm», 2008. 36 p. (rus)
5. *Evrokod 0. Osnovy proektirovaniya stroitelnyh konstruktsyy* [Eurocode 0. Basics of the design of building structures] : TKP EN 1990-2011*. Vved. 15.11.2011. Minsk : MAiS RB : «Stroytehnorm», 2015. 86 p. (rus)
6. *Evrokod 1. Vozdeystviya na konstruktsyy. Chast 1-2…7. Obshie vozdeystviya* [Eurocode 1. Impacts on structures. Part 1-2 … 7. General effects] : TKP EN 1991-1-2…7-2009. Vved. 10.12.2009. Minsk : MAiS RB : "Stroytehnorm", 2010. (rus)
7. *Evrokod 7. Geotehnicheskoe proektirovaniye. Chast 1. Obshie pravila* [Eurocode 7. Geotechnical design. Part 1. General rules] : TKP EN 1997-1-2009. Vved. 10.12.2009. Minsk : MAiS RB : "Stroytehnorm", 2010. 121 p. (rus)
8. *Evrokod 7. Geotehnicheskoe proektirovaniye. Chast 2. Issledovaniya i ispytaniya grunta* [Eurocode 7. Geotechnical design. Part 2. Research and soil testing] : TKP EN 1997-2-2009.

Vved. 10.12.2009. Minsk : MAiS RB : «Stroytehnorm», 2010. 140 p. (rus)

9. *Pismo ministerstva arhitektury i stroitelstva Respubliki Belarus i Departamenta kontrolya i nadzora za stroitelstvom Gosudarstvennogo komiteta po standartizatsii Respubliki Belarus ot 3 marta 2010 goda № 06205/1345; ot 4 marta 2010 goda № 012/2/134 "O vvedenii v deystvie evropeyskih standartov i norm v oblasti proektirovaniya i stroitelstva"* [Letter of the Ministry of Architecture and Construction of the Republic of Belarus and the Department of Control and Supervision of the Construction of the State Committee for Standardization of the Republic of Belarus dated March 3, 2010 No. 06 2 05/1345; dated March 4, 2010 No. 01 2/2/134 On the implementation of European standards and norms in the field of design and construction] . Minsk : MAiS RB, 2010. 2 p. (rus)
10. *Zdanija i sooruzhenija, stroitel'nye materialy i izdelija. Bezopastnost'* [Buildings and structures, building materials and products. Security] : TR 2009/013/BY. Minsk : MAiS RB, 2009. 27 p. (rus)
11. Frank R. [and oth.] *Designers' Guide to EN 1997-1 Eurocode 7: Geotechnical Design – General Rules*. London : Thomas Telford LTD, 2004. 213 p.
12. Bond A., Harris A. *Decoding Eurocode 7*. London & New York : Taylor and Francis group, 2008. 507 p.
13. Arnold P. [and oth.] *Modern Geotechnical Design codes of practice. Implementation, application, and development*. Amsterdam : IOS press, 2013. 331 p.
14. Trevor L.L., Farrel E.R. *Geotechnical Design to Eurocode 7*. London : Springer, 1999. 165 p.
15. Driscoll P., Scott J., Powell R. *EC7 – Implications for UK practice.* Eurocode geotechnical design. London : CIRIA, 2008. 120 p.
16. Bond A [and oth.] *Eurocode 7: Geotechnical design. Worked examples*. Italy: European union, 2013. 160 p.
17. Orr T. Worked examples – design od piles foundations. *Geotechnical design with worked examples, Dublin, 13–14 June 2013.* European commission. Dublin, 2013. 37 p.
18. Burland JB. *"Shaft friction of piles in clay-a simple fundamental approach" Ground Engineering*. Vol. 6–3. 1973. Pp. 30–42.

19. Kerisel J. Vertical and horizontal bearing capacity of deep foundation in clay. *Proc. Symp. on Bearing Capacity of Settlement of Foundations.* 1965. Pp. 45–52.
20. Dennis N. D., Olsen R. E. *Axial capacity of steel pipe piles in clay*. Proc. Geotechnical Practice in Offshore Engineering. ASCE, 1983. Pp. 370–388.
21. Vijayvergiya V. N., Focht J. A. A new way to predict capacity of piles in clay. *Proc. Offshore technology Conf*. 1972. Pp. 865–871.
22. Kolpashnikov G. A. *Inzhenernaya geologiya* : Uchebnoe posobie [Engineering Geology: Educational Aid]. Minsk : "Tehnoprint", 2004. 134 p. (rus)

Received: 30.11.2018