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ASSESSMENT OF THE BEARING CAPACITY OF VARIABLE PROFILE PILES IN SOIL USING STATIC LOAD MODEL TESTS ON A TESTING APPARATUS

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The paper presents the results of the study of the proposed type of variable profile piles. The proposed type of piles is reinforced concrete driven piles segmented in length. Each subsequent section has a radial displacement along the axis of symmetry relative to the previous section. The positive effect of the performance of the proposed pile is to change the nature of the lateral contact of the pile with the soil, and to increase the drag of the soil. The conducted research is aimed at solving the problem related to the relatively low bearing capacity of traditional square section piles. The research was carried out by the method of model tests of piles on a test bench (tray) at a scale of 1:10. The tests were performed for variant pile types in comparison with a standard square section prismatic pile. The adopted dimensions of the pile model allow the use of this tray without the influence of its boundary conditions on the stress-strain state of the soil. A total of 42 tests were performed, 3 tests for each type of piles compared. Evaluation of pile bearing capacity was performed by static loading of pile models with vertical indentation load until failure. According to the results of the investigations, the resistance values of the compared pile types in the soil were obtained, as well as the dependence of bearing capacity changes on the section dimensions and on the rotation angle. According to the results, the optimal pile solution was selected. The bearing capacity of the proposed optimal pile solution exceeds the bearing capacity of the standard driven pile by 22 %. The results obtained allow us to conclude about the influence of the technological solution of the proposed pile type on its serviceability in soil conditions

Keywords: model tests, variable profile piles, driving piles, static load test, bearing capacity

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1. Introduction

Modern construction imposes specific demands on engineers and designers, leading to the adoption of new, economically and ecologically efficient energy-saving technologies in place of established traditional solutions [1]. In this context, the issue of updating technological and technical solutions has extended to the field of foundation construction, particularly in the realm of deep foundation technology, commonly known as pile foundations [2, 3].

Pile foundations are among the most sought-after types of foundations on construction sites. The rationale for their use lies in the necessity to ensure a high load-bearing capacity for buildings and structures, including tall structures. This has prompted the emergence of new technologies and equipment for pile foundation construction, which offer direct advantages over the established technologies prevalent in the construction market [4]. Therefore, research devoted to the development of a new type of piles with increased bearing capacity (with commensurate material intensity with the traditional driven pile) becomes relevant and in demand in the construction industry.

2. Literature review and problem statement

To date, the dominant solution of driven piles at construction sites is a prismatic pile of square cross-section [5]. Undoubtedly, this technological solution has an advantage in its simplicity of production, but it has a significant disadvantage associated with relatively low indicators of their bearing capacity. The latter is especially noticeable when they are used in weak soils [6]. The low resistance on the shaft and tip of driven piles is primarily due to their limited size [7]. In contrast to bored piles, the decision to use driven piles has a bearing capacity limit in the soil [8].

Certainly, there are many technological solutions to increase the bearing capacity of the pile related to modifying the cross-sections (increasing the lateral contact area), such as hypocycloid, herringbone, triangle and others [9]. These solutions are mainly aimed at reducing material consumption, whereas the proposed solution implies an increase in bearing capacity with the same material intensity as the traditional prismatic pile. There are a number of other inventions related to increasing the bearing capacity, where the main solution is the use of the principle of sectional buildup of the pile [10]. These technological solutions, as a rule, are labor-intensive in execution, have limited engineering and geological features (it is impossible to use them in sands) [11]. The foregoing indicates the feasibility of the research, the purpose of which is to increase the specific bearing capacity of piles at the same material intensity as the traditional prismatic pile.

In this research work, it is supposed to study a reinforced concrete pile by model testing method, which is constructed by traditional driving method, but has a number of fundamental differences from the driven reinforced concrete piles available on the market today. The main advantages of the proposed pile are the increased bearing capacity (relative to the traditional one). The technological effect of increasing the bearing capacity on the soil is achieved by sectional displacement of the pile at different angles of rotation relative to the axis of symmetry of the pile. In general, the effect is achieved by changing the nature of the lateral contact of the pile with the soil, due to which additional resistance areas appear. Considering the relevance of the use of driven piles (due to their relative cheapness and installation time), the proposed alternative to the driven pile may be a sought-after product in the construction market.

The proposed design solution seems to be promising, since any increase in the resistance area (in this case, as a result of the rotation of the section) can potentially lead to an increase in the frontal resistance of the soil, hence an increase in the bearing capacity of the pile. The proposed type of pile can be applied in practice, the maximum advantage of the pile can be achieved when it is used in conditions of weakly bearing soils (clays, loams, saturated soils, etc.). It should be noted that the proposed design solution leads to a reduction in the cross-sectional area of the classical prismatic pile, which may lead to a decrease in the material bearing capacity. However, the material bearing capacity of the pile is predominantly higher in relation to the pile bearing capacity. Moreover, in the set of the present study, the use of a modified admixture is proposed to improve the concrete strength performance of the proposed pile type. However, this study is not discussed in this paper [1]. As for the pile reinforcement, quantitatively the pile reinforcement does not differ from the prismatic pile of classical design, except for the constructive displacement of longitudinal reinforcement bars to the center of the pile.

As a result of pile modernization, we can obtain an economic effect related to the reduction of zero-cycle construction costs: an increase in the bearing capacity of an individual foundation will lead to a reduction in their total number. That is, efficiency is directly proportional to the bearing capacity of piles and inversely proportional to their number. Nevertheless, determining the optimal, and therefore the most acceptable, technological solution requires more in-depth study, calculation and data analysis, for example: estimation of the increase in pile bearing capacity from the displacement of the pile section, optimization of the displacement with respect to ground conditions, estimation of the increase in the cost of manufacturing from the same displacement, estimation of the driving resistance for different technological solutions, etc.

Thus, the proposed pile model is aimed at solving the existing problems of driven piles, primarily related to the relatively low bearing capacity in the soil and the limited use of piles under heavy loads.

3. The aim and objectives of the study

The aim of the study is to evaluate the performance of the proposed type of driven pile in comparison with the conventional square section prismatic pile.

To achieve this aim, the following objectives are accomplished:

– to obtain private load-displacement relationships, 3 relationships for each of the compared pile types;

– to compare the obtained dependencies of all pile types according to control criteria, with average values of pile displacements from the applied load;

– to obtain summary data of comparative analysis of all types of piles with determination of the most optimal technological solution.

4. Materials and methods

The object of the study is a driven reinforced concrete pile of variable profile with pivoting sections. The main hypothesis of the study is that the proposed design solution will lead to an increase in its bearing capacity on the soil, as a result of an increase in the lateral resistance of the soil.

The method of pile serviceability assessment is model tests of piles by static vertical indentation loads in the ground on a reduced scale. To realize the set aim, the selection of equivalent materials of soil and piles was performed, the program of static loading tests was developed, variant model tests were carried out, analysis of the obtained data was performed, results were obtained and conclusions were drawn.

When conducting model tests, there is no need to select an equivalent soil material since the goal of this task is not to model specific engineering-geological conditions. The objective here is to compare the load-bearing capacities of different pile types under identical, partially idealized conditions. Based on the grain size distribution of medium-coarse sand, a quarry was selected, and the composition of equivalent sand was chosen. For model pile testing in sand, the optimal fraction is sand with a particle size between 0.63 and 0.5 mm. This choice was determined based on the condition of maximizing the content of particles within one fraction in the composition of quarry sand (an average of 58.87 %) and its uniformity. To model the equivalent clay, fine fraction sand with an average content of 57.98 % was selected. The optimal solution for the oil content in the equivalent clay (to increase the cohesion) was 4 %. At this ratio, there was an increase in cohesion (an increase of 72 % compared to 1 % oil content) with a relatively minor decrease in the angle of internal friction (a decrease of 5 % compared to 1 % oil content). Further increasing the percentage of oil content leads to a sharp decrease in the angle of internal friction (a decrease of 9 % compared to 1 % oil content) while showing a slight increase in cohesion (an increase of 8 % compared to 4 % oil content). According to the laboratory test results of the physical and mechanical characteristics of the equivalent soil, the internal friction angle of the optimal composition of the equivalent soil is 28° and the cohesion is 4.33 kPa.

In order to understand the proposed pile type, Fig. 1 shows the variation in the technological design of the variable profile pile that will be tested with static loads in this study.

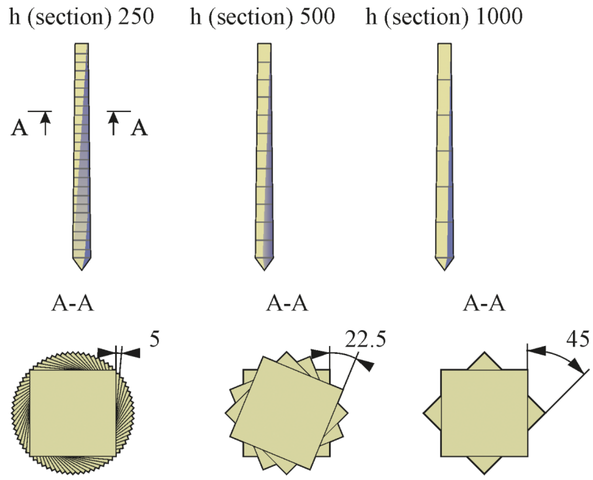


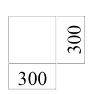
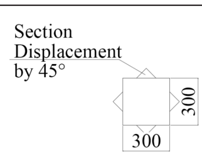
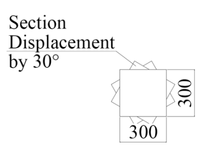
Fig. 1. Potential variability in structural design

The pile testing was conducted on a test stand (tank) at a scale of 1:10 (Fig. 2). The test stand comprises a metallic container with plan dimensions of 0.8×1.5 m and a height of 1.0 m. The dimensions of the tank allow for testing at a 1:10 scale. In this case, the dimensions of a standard pile with a length L=6 m and a cross-section A=30×30 cm, in scale, become L=60 cm and A=3.0×3.0 cm. The adopted dimensions of the pile model enable the use of this tank without the influence of its boundary conditions on the stress-strain state of the soil. This means that during pile testing, the stresses at the boundaries of the tank should be equal to 0, and the dimensions of the tank should facilitate pile displacement solely due to the soil's resistance along its lateral surface and beneath its lower end. In any case, to exclude potential boundary conditions' impact on the test results, the tank walls were treated with anti-friction lubricant to reduce friction between the equivalent soil material and the tank's surface.

As a first approximation (with the aim of approaching maximum load-bearing capacity), structural solutions presented in Table 1 will be utilized.

Table 1

Structural solutions for sectional displacement of piles

Type	Description	Visualization
Type 1	Classic Reinforced Concrete Pile: A traditional square-section reinforced concrete pile with no section displacement	 300 300
Type 2	Reinforced Concrete Pile with 45° Section Displacement: A square-section reinforced concrete pile with each section displaced by 45° relative to the previous one	 Section Displacement by 45° 300 300
Type 3	Reinforced Concrete Pile with 30° Section Displacement: A square-section reinforced concrete pile with each section displaced by 30° relative to the previous one	 Section Displacement by 30° 300 300

Technical variability encompasses both section displacement variability and section length variability. In this regard, the first approximation will be made based on section length variability with a specified displacement of 450, and the second approximation will be made for variable section displacement with the best results from the first approximation, given a specific section length. In other words, we initially determine the optimal section length and then the optimal section displacement. The highest load-bearing capacity corresponds to the optimal solution [12].

Based on the information provided, the sequence of model tests is as follows:

Type 1: Static loading of a classic square-section reinforced concrete pile with a constant section of 30×30 cm (3×3 cm in scale) and a length of 6 m.

Type 2a: Static loading of a pile with a 450 displacement of each section, with each section having a length of 33.3 cm (3.33 cm in scale), and a total length of 6 m.

Type 2b: Static loading of a pile with a 300 displacement of each section, with each section having a length of 33.3 cm (3.33 cm in scale), and a total length of 6 m.

Type 3a: Static loading of a pile with a 450 displacement of each section, with each section having a length of 50 cm (5 cm in scale), and a total length of 6 m.

Type 3b: Static loading of a pile with a 300 displacement of each section, with each section having a length of 50 cm (5 cm in scale), and a total length of 6 m.

Type 4a: Static loading of a pile with a 450 displacement of each section, with each section having a length of 100 cm (10 cm in scale), and a total length of 6 m.

Type 4b: Static loading of a pile with a 300 displacement of each section, with each section having a length of 100 cm (10 cm in scale), and a total length of 6 m.

The segment length for Types 1 and 2 was chosen based on the condition of having 3 segments per 1 meter of pile length.

The pile tests were conducted using a staged application of static compressive loads until failure (40 mm settlement), following the procedure described in reference [1]. Each load increment was maintained until achieving a conditional stabilization of 0.1 mm over a 15-minute observation period. Before the eighth stage, the load increment was 100 N per stage, and 50 N after the eighth stage. Clock-type indicators with a measurement accuracy of 0.01 mm were used to record displacements. The testing process is illustrated in Fig. 2.

A total of 42 tests were conducted, with 3 tests for each pile type. The analysis of pile load-bearing capacity will be performed based on the criteria of allowable settlements. The control values for maximum pile settlements are 24 mm, 30 mm, and 40 mm.

The first value of 24 mm was adopted based on the allowable settlement of 12 cm for buildings and structures using a reinforced concrete frame, which translates to 120 mm×0.2=24 mm when transitioning to static tests under pile stabilization conditions. The second value of 30 mm was adopted from the allowable settlements of 15 cm for buildings and structures made of steel. The third value of 40 mm represents the ultimate pile failure under static loads. In practice, the pile load-bearing capacity is selected based on the value corresponding to complete soil stabilization (i.e. the preceding stage). However, for analysis purposes, all values will be determined by interpolation since each stage (including 40 mm) was maintained until stabilization (meaning the dependency has limits). While the first case involves selecting the pile load-bearing capacity based on the condition of guaranteed safe pile operation, the second case characterizes the point resistance of the pile (in this context, corresponding to a specific displacement value) from the obtained dependency, necessary for a quality comparative analysis.

a *b* *c* *d*

Fig. 2. Scale testing of piles in the flume: *a* – general view; *b* – piles models; *c* – soil model; *d* – loading

5. Results of the pile model test

5. 1. Individual load-settlement relationships

The test results are presented in Fig. 3–5:

– Fig. 3 shows the test results for Type 1 piles;

– Fig. 4 displays the test results for Type 2a and 2b piles;

– Fig. 5, 6 depict the results for Type 3a, 3b, 4a, and 4b piles, respectively.

Table 2 provides values corresponding to the previously determined criteria for allowable pile settlements: 24 mm, 30 mm, and 40 mm.

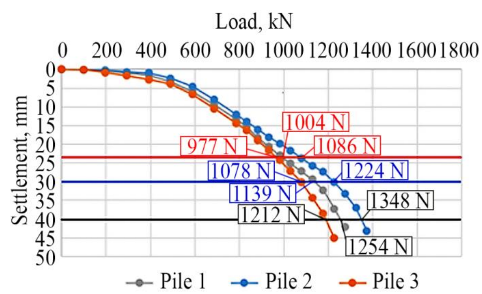
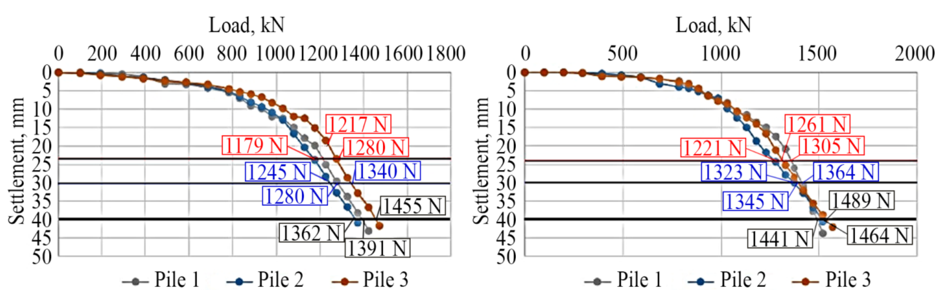
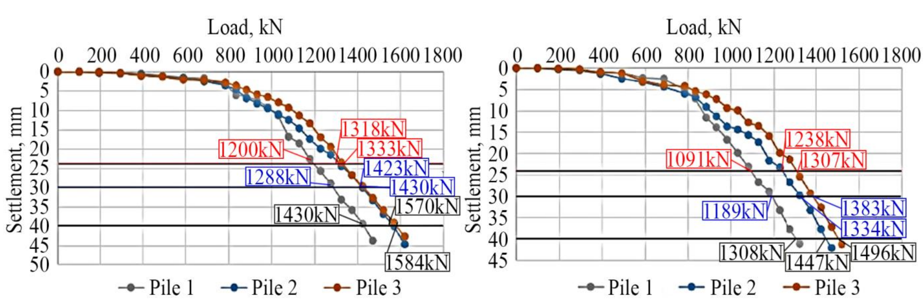


Fig. 3. Loading results of Type 1 pile models



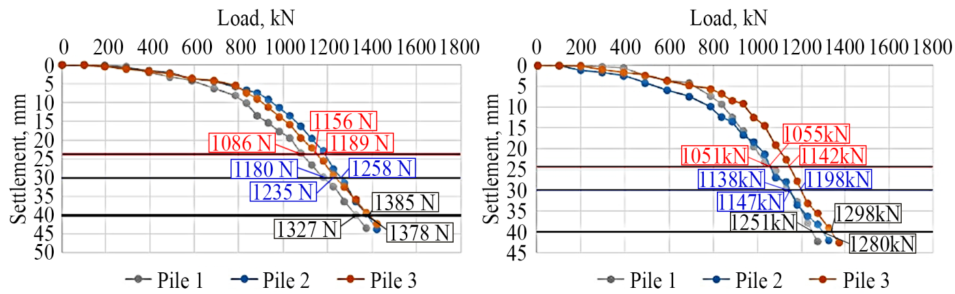
a *b*

Fig. 4. Loading results of Type 2 pile models: *a* – Type 2a; *b* – Type 2b



a *b*

Fig. 5. Loading results of Type 3 pile models: *a* – Type 3a; *b* – Type 3b



a *b*

Fig. 6. Loading results of Type 4 pile models: *a* – Type 4a; *b* – Type 4b

Table 2

Pile load-bearing capacity indicators

Acceptable draft criterion	Bearing capacity, N						
	Type 1	Type 2a	Type 2b	Type 3a	Type 3b	Type 4a	Type 4b
24 mm	1,004	1,217	1,305	1,200	1,091	1,086	1,051
	1,086	1,280	1,221	1,318	1,238	1,156	1,055
	977	1,179	1,261	1,333	1,307	1,189	1,142
30 mm	1,139	1,280	1,364	1,288	1,189	1,180	1,138
	1,224	1,340	1,323	1,423	1,334	1,235	1,147
	1,078	1,245	1,345	1,430	1,383	1,258	1,198
40 mm	1,254	1,391	1,441	1,430	1,308	1,327	1,251
	1,348	1,455	1,464	1,570	1,447	1,385	1,298
	1,212	1,362	1,489	1,584	1,496	1,378	1,280

All modernized piles (Type 2–4) demonstrated higher load-bearing capacities than the traditional Type 1 piles. The highest load-bearing capacities were found in Type 3 piles, with section lengths of 50 mm.

5. 2. Comparison of dependencies of all types of piles

Fig. 7 illustrates a comparative chart of various pile types based on control criteria, with average pile displacement values corresponding to the applied load.

According to the obtained results, the maximum load-bearing capacities were identified for Type 3a piles with section sizes of 5.00 cm (50 cm at full scale) and a 450-degree rotation of each section. The lowest values were observed for traditional prismatic piles. The increase in load-bearing capacity was 1.25 times for allowable concrete buildings, 1.20 times for steel buildings, and 1.20 times for the ultimate value. Significant increases in load-bearing capacity were also observed for Type 2b piles with section sizes of 3.33 cm (333 cm at full scale) and a 300-degree rotation. The differences in load-bearing capacity were 1.23 for concrete buildings, 1.17 for steel buildings, and 1.15 for the ultimate value. The smallest changes in load-bearing capacity were found for Type 4b piles with section sizes of 10.0 cm (100 cm at full scale) and a 300-degree rotation of sections. The increase in load-bearing capacity was 1.06 for concrete buildings, 1.01 for steel buildings, and 1.01 for the ultimate value. The increase in load-bearing capacity for Type 2a piles, with similar section lengths and a 450-degree rotation, was 1.12 for concrete buildings, 1.07 for steel buildings, and 1.07 for the ultimate value. Intermediate but relatively high increases in load-bearing capacity were observed for Type 2a and 3b piles. The increase in load-bearing capacity for Type 2a piles, with section lengths of 3.33 cm and a 450-degree rotation, was 1.19 for concrete buildings, 1.12 for steel buildings, and 1.10 for the ultimate value. The increase in load-bearing capacity for Type 3b piles, with section lengths of 5.00 cm and a 300-degree rotation, was 1.18 for concrete buildings, 1.13 for steel buildings, and 1.11 for the ultimate value.

The dependency of load-bearing capacity changes on section sizes is shown in Fig. 8, *a*, and the dependency of load-bearing capacity changes on the rotation angle is shown in Fig. 8, *b*.

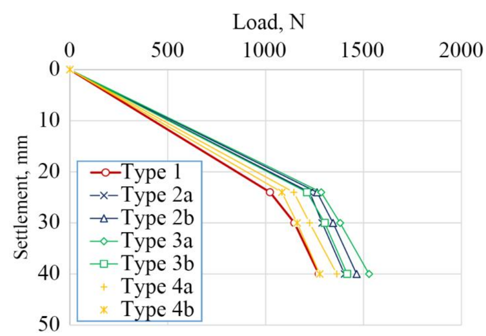
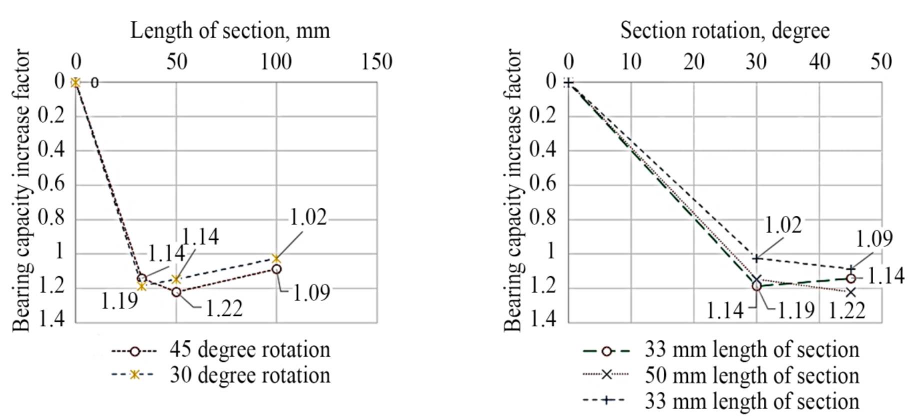


Fig. 7. Comparative load-settlement diagrams



a *b*

Fig. 8. Load-bearing capacity changes: *a* – based on section sizes; *b* – based on rotation angle

For visualization purposes, the diagrams display average values for all three criteria of allowable pile settlements (in terms of section displacements to assess the impact of length and in terms of section lengths to assess the influence of displacements). The last assumptions represent the average change in load-bearing capacity, sufficient for visualization of the dynamics.

5. 3. Summary of comparative data

The results of the research are summarized in Table 3.

Table 3

Summary results of the research

Type of pile	Type 1	Type 2a	Type 2b	Type 3a	Type 3b	Type 4a	Type 4b
Description	Reference (standard pile)	Section 33.3 cm, rotation 45 degrees	Section 33.3 cm, rotation 30 degrees	Section 50.0 cm, rotation 45 degrees	Section 50.0 cm, rotation 30 degrees	Section 100.0 cm, rotation 45 degrees	Section 100.0 cm, rotation 30 degrees
Bearing capacity increase factor	1.00	1.14	1.18	1.22	1.14	1.08	1.02
Increased frontal area, %	0	34.31	30.94	22.88	20.63	11.44	10.31

According to the test results, the best option for the pile with rotating sections was the Type 3a pile: a pile with a section length of 5 cm (0.5 m in real life) and a rotation angle of each section of 45° relative to each other.

6. Discussion of experimental results of the pile model test

The proposed type of piles has a feature (the presence of rotating sections) that distinguishes them from those available in the construction market. There are inventions of driven reinforced concrete piles: KZ A426088, E02D 5/30, E02D 5/34, E02D 27/35; KZ A430809, E02D 5/00, E02D 5/22; KZ A431061, E02D 5/00, E02D 5/22; KZ A29424, E02D 5/30, E02 D 27/35; KZ A27763, E02D 5/22; KZ A429424, E02D 5/30, E02 D 27/35, etc. All inventions are aimed at increasing the efficiency of pile work in the ground; however, they have a different design solution from the proposed one, but do not have the ability to increase. Mostly these solutions are aimed at reducing material consumption, while the proposed solution implies an increase in load-bearing capacity with the same material intensity as the traditional prismatic pile. Moreover, the proposed technological solution is fundamentally different from the above.

In the studies [13–15], similar pile tests are presented in the test box, however, in these works, other types of piles (driven) were studied, and the purpose of the study was to assess the impact of the manufacturing process on the load-bearing capacity. In general, the approach to testing in these works is similar, equivalent materials were used to model piles and soil, selected based on the law of dynamic similarity.

The obtained results of pile loading (Fig. 3–5 and Table 2) showed the elastic-plastic behavior of the soil foundation. The character of the load-settlement curve generally corresponds to the pile performance in loamy soil (modeled soil). The individual pile bearing capacity results confirm the effect of increasing the tip resistance of the pile on increasing the bearing capacity. Thus, piles of Type 1, with relatively smallest tip area showed the lowest value of bearing capacity, while piles of other types with increasing tip area showed higher bearing capacity values.

Comparisons of pile bearing capacity from section length and rotation angle (Fig. 5) allowed us to evaluate the dynamics of bearing capacity increase from the variant pile modifications introduced. The obtained dependencies made it possible to determine the most effective variants of technological solutions of piles, which have the greatest increase in bearing capacity in the conditions of the modeled equivalent soil.

At the same time, there is a different influence of the pile rotation length depending on the section length: for Type 2 the best technological solution for the section rotation was 30 degrees, and for Type 3 – 50 degrees. The latter can be explained by the peculiarity of the rheological properties of the equivalent material.

According to the obtained load capacity increase coefficients (Table 3), the following assumptions can be made: The insignificant increase in the bearing capacity of Type 4 piles can be explained by the small number of pivoting sections, hence the relatively small increment in additional resistance area (Table 3). The difference in the increase in bearing capacity between Type 4a piles (8 % increase in bearing capacity) and Type 4b piles (2 %) can also be explained by the difference in the areas (of the frontal resistance sections). For the most part, a logical trend of the influence of area on pile resistance was observed: all piles of Type 4a and 3a showed higher bearing capacity than piles of Type 4b and 3b (4 % to 8 %). However, a contradictory result regarding the influence of area was shown by type 2 piles. The increase in area of Type 2a piles is 34.31 % relative to the frontal area of the standard pile (900 cm^2) and Type 3a piles is 22.88 %, but the bearing capacity of all Type 2a piles is less than Type 3a piles by 8 % on average. As discussed above, the latter can be explained by the rheological peculiarities of the equivalent soil, i.e. under constant loading, the soil in the protrusions of the pivot sections does not have time to recover, due to the short length of Type 2 sections relative to Type 3 and 4 piles.

The slight increase in load-bearing capacity for Type 4 piles can be explained by the small number of rotating sections, resulting in a relatively small increment in additional resistance area (Table 3). The fourfold difference in load-bearing capacity increase between Type 4a (9 % increase in load-bearing capacity) and Type 4b (2 %) can also be explained by the difference in areas (frontal resistance areas). In most cases, a logical trend of the influence of area on pile resistance can be observed: all Type 4a and 3a piles showed greater load-bearing capacity than Type 4b and 3b piles; all Type 2 piles showed greater load-bearing capacity than Type 3 piles, and Type 3 piles were larger than Type 4 piles. However, a contradictory result regarding the influence of area was observed for Type 2 piles. The increase in the area of Type 2a piles is 72 % relative to the frontal area of a standard pile (900 cm^2), while Type 2b piles have an increase of 43 %. Nevertheless, the load-bearing capacity of all Type 2a piles is lower than that of Type 3b piles by 5 %. This can be explained by the fact that under constant loading, the soil in the protrusions of rotating sections does not have enough time to recover due to the shorter length of Type 2 sections compared to Type 3 and 4 piles.

However, it should be realized that the obtained optimal solution (Type 3a) is the best only under test conditions. In order to determine the optimal technological solutions of piles for specific objects, modeling of actual engineering and geological conditions is necessary. In any case, the obtained results fully confirm the advantages of the proposed pile type in relation to the traditional square prismatic pile. Absolutely all the pile modifications showed greater bearing capacity than traditional piles to a greater or lesser extent. The latter makes the proposed pile model the most attractive, especially in a limited construction site with excessive bearing capacity requirements. Moreover, the specific increase in bearing capacity with the same material intensity becomes more efficient from an economic point of view.

Limitations of the study include the fact that soil condition modeling was carried out for a specific type of soil, hence the research results are only applicable to the type of soils used in the tests. The study of specific types of piles, as well as the scale of modeling (1:10), narrows the boundaries of the results of the present study in terms of their comparability with the research of other scientific works.

The disadvantages of the research can be attributed to the dimensionality of the tray equipment, which does not allow for testing on a smaller scale closer to the real size of the pile. A structural disadvantage of the study is also the lack of the ability to assess internal changes in the stress-strain state of the near-pile massif under load.

Further development of this research is reduced to conducting natural tests of real piles on static pushing and pulling loads, which will allow for correlation, assessing the error of the present research on a scale. It becomes necessary to further study the calculation situations of large-scale and natural tests by numerical modeling in calculation complexes using finite element methods.

7. Conclusions

1. Individual load-settlement relationships were obtained for the compared pile types in soil subjected to static loading. According to the results, the maximum load-bearing capacity was found for pile type 3a (see Methods), which showed an increase in load-bearing capacity of 22 % (on average) compared to the standard pile. The lowest values in the change in bearing capacity were found for the Type 4b pile, amounting to 2 % (on average). The latter is explained by a slight increase in the area (drag of the pile) of 10.31 % relative to the standard pile.

2. A comparison of the obtained dependencies of changes in bearing capacity on the section size and on the angle of rotation has been carried out. Comparison of the bearing capacity of Type 2 and Type 3 piles suggests that too small section length does not contribute to the increase in bearing capacity, despite the relatively significant increase in the drag area of the pile. The latter can be explained by the fact that with small section sizes, the soil between the sections is not able to fully recover, which affects the resistance.

3. According to the test results, the proposed design of the pile leads to an improvement in its performance in terms of increasing the non-bearing capacity in relation to the classical square prismatic pile (the proposed solution has the advantage of being identical in material intensity to the classical pile). All pile design variations showed higher bearing capacity values with respect to the classical prismatic pile, but the optimal (best) variant of the pile with rotating sections, under equivalent soil conditions, was the Type 2 pile: a pile with a section length of 5 cm (0.5 m in real life) and a rotation angle of each section of 450 with respect to each other. This technological solution is individual, inherent to the specific soil used in the tests. Nevertheless, the set objective of evaluating the influence of the pile modification on the bearing capacity was achieved. Further investigation of the proposed technological solution will require numerical modeling and field testing of the proposed pile type.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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