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SELECTION OF EQUIVALENT MATERIAL FOR SOIL TESTING USING PILES ON A SCALE MODEL TESTING APPARATUS

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ABSTRACT: This study addresses the problem of selecting an equivalent material for soil testing using piles on a large-scale experimental setup. The approach involved conducting model tests in a metallic tank with specific dimensions, allowing for a 1:25 scale. Fine and medium-grained sand was used as the equivalent soil material. The main criterion for sand selection was its similarity to medium-sized sand (0.25-0.50 mm). To ensure test reproducibility, only one sand fraction corresponding to the medium size was used. The results revealed that the chosen sand composition (Type 1) exhibited optimal homogeneity and particle size distribution. For modeling equivalent clay, Type 4 fine sand with 4% oil content was found to be the most suitable, demonstrating increased shear strength. The study concludes that the methods used effectively evaluate the load-bearing capacity of foundation piles, providing insights for optimizing designs for enhanced stability in diverse soil conditions. This approach paves the way for developing sustainable and ecologically efficient engineering structures in varying soil environments.

Keywords: Equivalent material, Section pile, Pile foundations, Piles, Equivalent soil

1. INTRODUCTION

The design and analysis of pile foundations are crucial for ensuring the stability and safety of structures in geotechnical engineering. Realistic and precise testing of pile behavior is fundamental for understanding the interaction between piles and the surrounding soil [1]. However, conducting full-scale tests on actual structures can be expensive, labor-intensive, and logistically complex. Therefore, as an alternative, testing on scaled models can be employed, providing an economically efficient and controlled environment to study the interaction of piles with the soil [2, 3].

In this regard, selecting a suitable equivalent material that mimics the behavior of natural soils is a key aspect of conducting reliable tests on a scaled model. The equivalent material must accurately replicate the mechanical properties and behavior of real soil, enabling a true understanding of pile-soil interaction. The objective is to create a scaled-down yet representative environment in which the pile's response to various loading conditions can be studied in a controlled and precise manner [4].

This article is dedicated to the methodology and considerations associated with choosing an equivalent material for scaled pile testing on an experimental setup. The study explores the use of sands of varying granularities and specific treatments to replicate the behavior of different soil types. Careful selection of samples, testing, and analysis is conducted to ensure that the chosen equivalent materials precisely match the granulometric characteristics of natural soils. The ultimate goal is to establish a reliable and reproducible testing environment, providing valuable insights into pile behavior under various conditions and enhancing understanding and best practices in geotechnical engineering design [5, 6].

The selection of an appropriate equivalent material that accurately represents natural soils is a crucial aspect of conducting reliable scaled model tests. By thoroughly examining and comparing different types of sand, this research guides the selection process, ensuring that the chosen material closely replicates the mechanical properties and behavior of real soil. This meticulous selection enhances the accuracy and reliability of the experiments, leading to more meaningful and applicable findings[7, 8].

The article discusses research findings aimed at selecting the ideal soil composition to replicate sandy and clayey soil conditions (termed as equivalent soil). This equivalent soil, whether comprising sand or clay, will be employed to evaluate the performance of a novel pile design on a reduced scale. The primary advantage of this innovative pile design lies in its ability to enhance load-bearing capacity compared to traditional piles [9]. Achieving increased load-bearing capacity involves inducing sectional displacement of the pile at various rotation angles relative to its axis of symmetry. This manipulation alters the pile-soil interaction, creating additional zones of resistance and thereby amplifying the frontal resistance area [10, 11].

As a consequence, a substantial economic benefit is expected, associated with reduced costs during the initial construction phase: enhancing the load-bearing capacity of individual foundations will lead to a reduction in their overall quantity. Essentially, the effectiveness is directly proportional to the load-bearing capacity of the piles and inversely proportional to their quantity.
While the article does not present the results of direct load tests (only the selection of equivalent soil), Figure 1 illustrates various technological solutions for comprehending the proposed pile construction. Subsequent research endeavors will evaluate their performance in equivalent soils [12, 13].

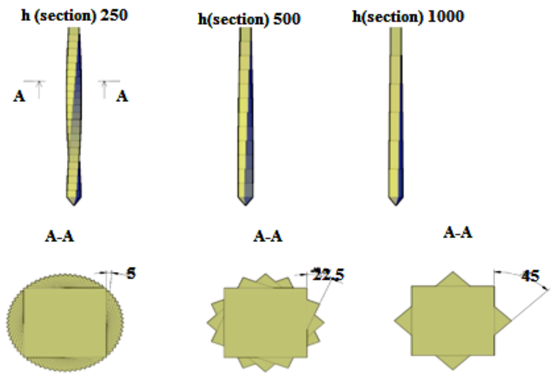


Fig. 1 Potential variability in structural design

In general, the variability in structural solutions is related to different angles of displacement and the magnitude (length) of the section.

2. RESEARCH SIGNIFICANCE

The significance of this research lies in its contributions to the field of geotechnical engineering and the design of pile foundations. Pile foundations are critical structural elements that provide stability and support to various types of constructions. Understanding the behavior and interaction of piles with the surrounding soil is paramount for ensuring the safety, durability, and efficiency of these foundations.

The research addresses the challenges associated with conducting full-scale experiments on real structures, which are often costly, time-consuming, and logistically demanding. By proposing and investigating scaled model testing with an equivalent material, this study offers a practical and cost-effective alternative. This approach allows for controlled experimentation, providing valuable insights into pile-soil interaction without the complexities of full-scale testing.

Overall, this research contributes to advancing the field by presenting a well-defined methodology and considerations for selecting an equivalent material for scaled pile testing. By promoting accuracy, cost-efficiency, and reproducibility in testing, the study ultimately supports the creation of safer, more stable, and more effectively designed pile foundations, which is of immense significance for the construction and infrastructure industries.

3. METHODS

Modeling tests were conducted in a testing setup represented by a metallic container with dimensions in plan of 0.8x1.5 m and a height of 1.0 m. The dimensions of the container allowed for tests to be conducted at a 1:25 scale. In this case, the dimensions of a standard pile with a length of L=10 m and a cross-section of A=30x30 cm in actual scale would be scaled down to L=40 cm and A=1.2x1.2 cm. The adopted model pile dimensions permitted the use of this container without its boundary conditions affecting the stress-strain state of the soil. Thus, during pile testing, the stresses on the boundaries of the container should be zero, and the container dimensions should only allow for the displacement of the pile due to the resistance of the soil along its lateral surface and under its bottom end. Nevertheless, to eliminate the potential influence of boundary conditions on the test results, the walls of the container were treated with anti-friction lubricant to reduce friction between the equivalent soil material and the container surface.

Fine and medium-fraction sand were utilized as the equivalent soil material. Since the research tasks did not involve assessing the pile's performance in specific sands, there was no need to model a particular type of sand at a reduced scale for the pile. The evaluation of the proposed pile type was performed by comparing it with a traditional pile. Therefore, the key criterion for the qualitative assessment was the reproducibility of identical ground conditions for each test. Consequently, there was no need to employ the law of dynamic similarity for the selection of the equivalent material composition, unless the inverse task was to define the ground to which the selected composition of the equivalent material could correspond. The fraction composition available in the market (referred to as quarry sand) was a characteristic indicator for selecting the equivalent sand. The primary criterion for the equivalent sand was its correspondence to sand of medium coarseness in the range of 0.25-0.50 mm. To ensure the reproducibility of the tests, a decision was made to use only one fraction of sand (corresponding to the medium coarseness) from the condition of its maximum percentage content in quarry sand. This would guarantee the uniformity of the equivalent ground when used repeatedly. To model clayey ground, a decision was made to use fine-fraction sand (range 0.25-0.05 mm) with the addition of oil. The inclusion of oil in the equivalent material contributes to an increase in cohesion (C>1 kPa), characteristic of clayey ground [14]. A decision was made to use only one fraction corresponding to fine sand, similarly to the case of sand selection. In both cases, the choice of raw materials was based on the maximum percentage content of the sand particles of the required fraction in the quarry samples. The selection of the equivalent ground material included the following tasks:

1. Selection of medium-coarseness sandy ground samples from three sources (quarries) for modeling the equivalent sand.
2. Selection of fine-fraction sandy ground samples from three sources (quarries) for modeling the equivalent clay.
3. Conducting studies to assess the particle size distribution of the selected samples.
4. Data analysis to choose the most suitable quarry for selecting the equivalent sand and clay.
5. Conducting tests on direct shear of the equivalent clay with varying oil content: 1, 2, 3, 4, 5% by weight.
6. Determination of the compositions of the equivalent grounds. The tests to assess the granulometric composition were conducted following the procedures stipulated by GOST 12536-2014 "Soils. Laboratory methods for determining particle size distribution and micro-aggregate composition."

The evaluations of the strength characteristics of the clay were performed in accordance with the methodology outlined in GOST 12248.1-2020 "Soils. Determination of strength characteristics using the uniaxial compression method."Particle size distribution tests of the sand were conducted using sieves and a vibratory drive. Sieves of sizes 0.63, 0.50, 0.315, 0.25 mm were used to evaluate the medium-coarseness sand composition. Sieves of sizes 0.315, 0.25, 0.125, 0.05 mm were employed to evaluate the composition of the fine-fraction sand [15].

Since the testing involves an equivalent material comprised of dry particles of fine sand with a specific oil content (to simulate friction), the soil tests with a single-plane section were conducted using an unconsolidated, undrained (without water access) method on Controls equipment. The tests were performed at specified stresses in a kinematic mode (with a constant deformation rate of the sample). Before applying the horizontal load, the specimens were subjected to normal pressure for 10 minutes. The normal pressure P during the preliminary compaction of the specimens (in both cases) was set at 0.10, 0.15, and 0.20 MPa. The pressure increments were set as follows: starting from 0.025 MPa until reaching values of 0.05 MPa, then the increments continued at 0.05 MPa (according to GOST12248).

To comprehend the objectives pursued by the current research, Figure 2 illustrates an experimental test pit and models of compared types of deep foundation

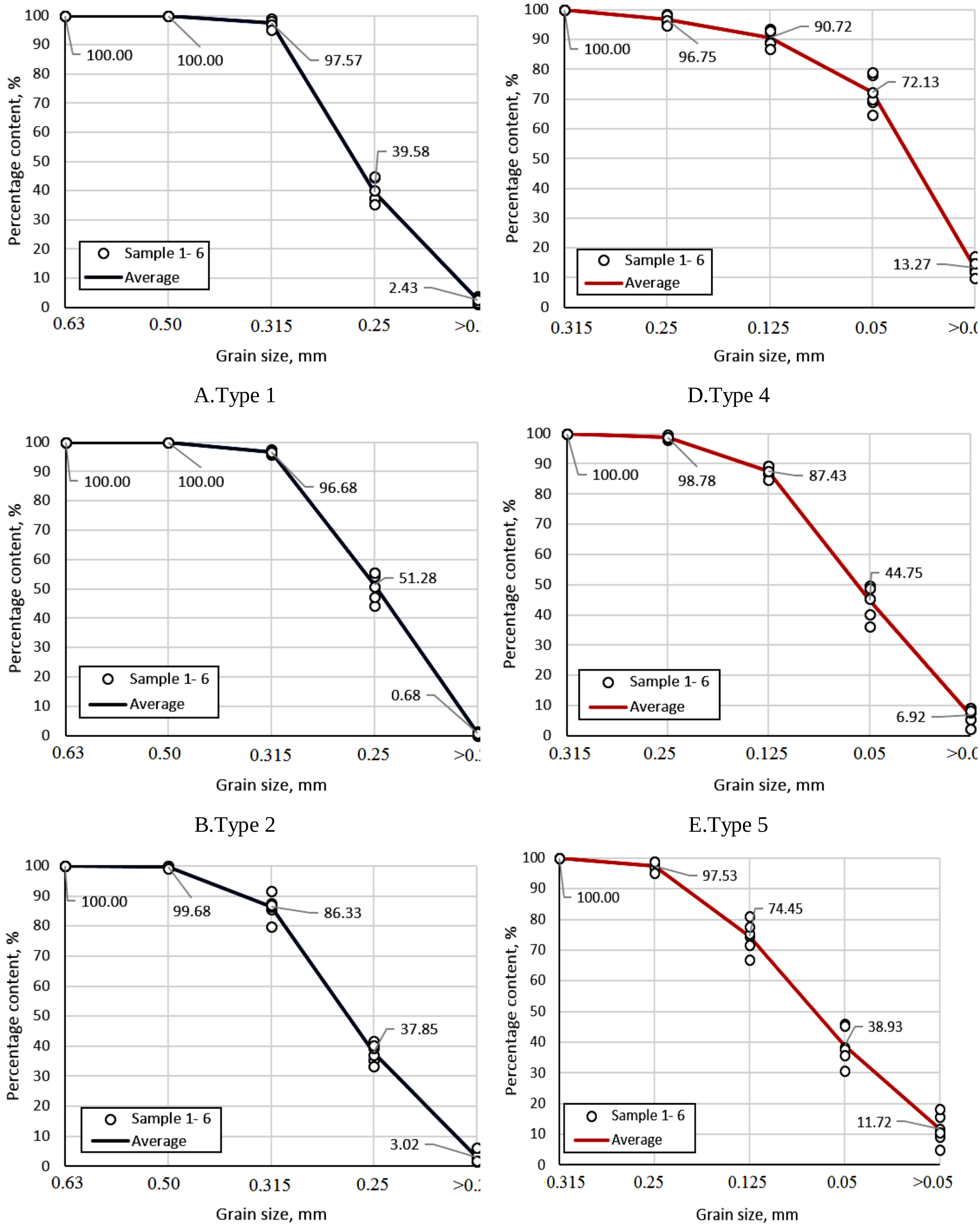
a) Test pit

b) Models of compared types of deep foundation

Fig. 2 a) Test pit, b) Models of compared types of deep foundation.

4. RESULTS AND DISCUSSION

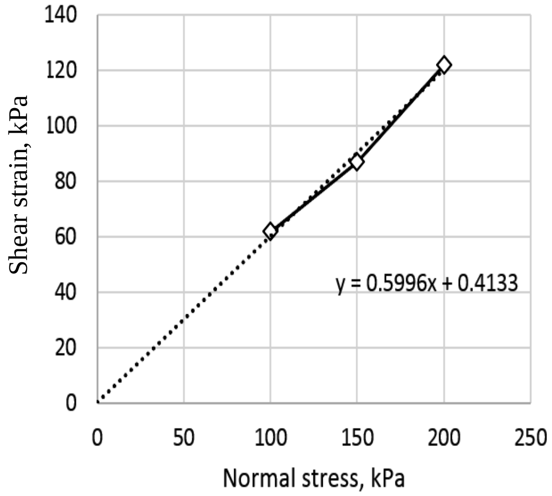
Figure 3 presents the diagrams of the particle size distribution of quarry sands. Figure 3A displays the percentage distribution of grain sizes for medium-coarse sand type 1, Figure 3B shows the size distribution for sand type 2, and Figure 3C represents sand type 3. Figures 3D, 3E, and 3F present the same information for fine-fraction sand for types 4, 5, and 6, respectively.



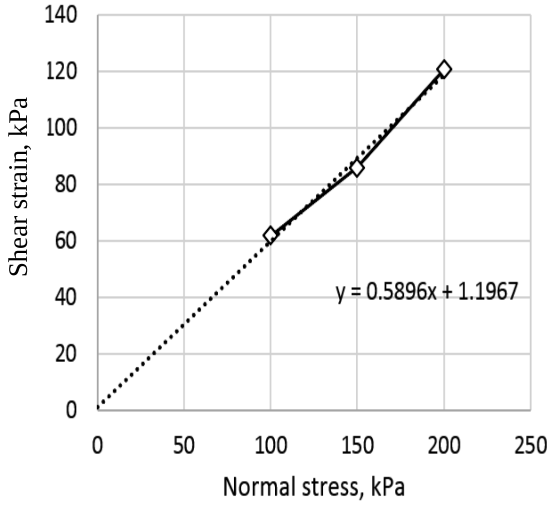
A.Type 1
D.Type 4
B.Type 2
E.Type 5
C.Type 3
F.Type 6

Fig.3 Particle Size Distribution of Sands

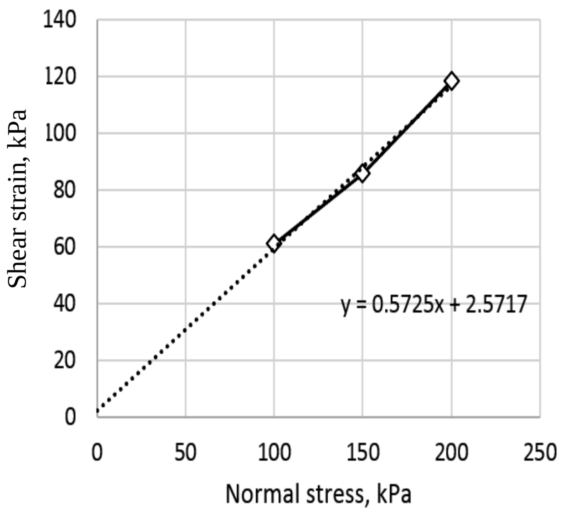
Based on the sand uniformity indicator, it can be concluded that type 2 sands have the highest uniformity coefficient U=1.58, while type 1 sands have the lowest U=2.52, and type 3 sands have U=2.0. In our case, the latter is not an evaluative criterion but merely characterizes granular material with particle sizes closest to each other within the range of fractions related to the medium coarseness criterion. However, considering the dimensional particles within the variability range, type 1 sands have the highest percentage



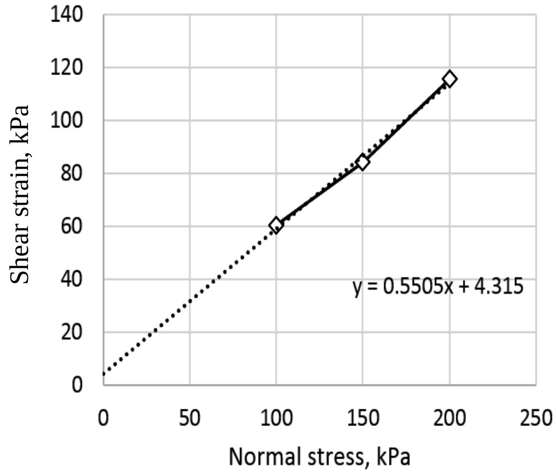
A.Type 1



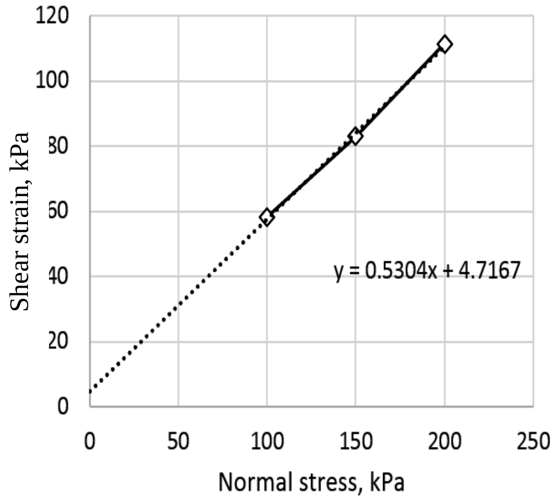
B.Type 2



C.Type 3



D.Type 4



E.Type 5

Fig.4 Results of Direct Shear Tests

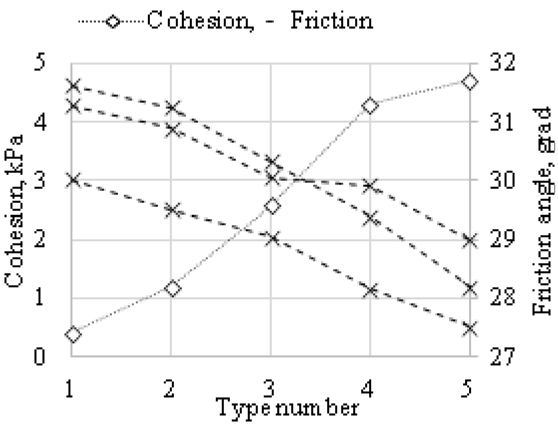
distribution of particles of a single size, corresponding to the specified selection criterion, averaging 58.87%. For other types of sands, this indicator is lower: 42.68% for type 2 and 35.52% for type 3. Regarding the uniformity of the composition within the ranges (sieve sizes), it can be concluded that type 1 and type 2 sands have a more stable composition than type 3 sand: type 1 sand has a coefficient of variation ranging from 11.8 to 45.15; type 2 sand ranges from 11.7 to 49.9, and type 3 sand ranges from 18.5 to 55.2. Thus, from the grain size distribution diagrams of the medium sands, it is evident that type 1 is the most suitable for selecting equivalent sand.

The analysis of the particle size distribution of fine-fraction sands indicated that, in terms of the highest percentage distribution of particles of a single size, type 4 sand is the most suitable. The maximum percentage content of particles of a single size is: 57.98% for type 4 sands, 49.40% for type 5 sands, and 46.70% for type 6 sands. The uniformity coefficient for type 4 sands is U=2.00, while for type 5 and type 6 sands, it is U=2.52. The latter is not directly related to the choice of sand type for equivalent clay, but it does speak to the uniformity of the sand as a granulated product.

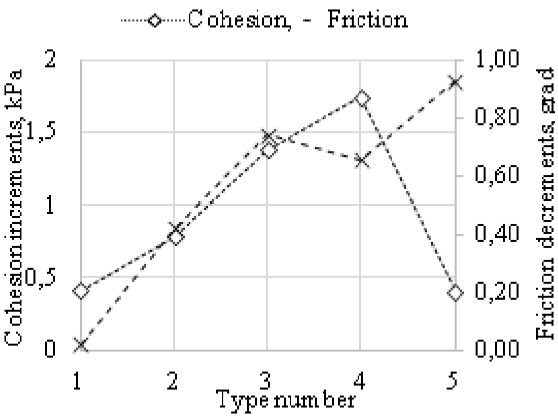
Regarding uniformity within the ranges, it can be concluded that type 4 sand has a more stable composition than type 5 and type 6 sands: type 4 sand has a coefficient of variation ranging from 6.42 to 58.91; type 5 sand ranges from 9.40 to 77.67, and type 6 sand ranges from 10.07 to 83.35. Thus, from the grain size distribution diagrams of the fine-fraction sands, it is evident that type 4 is the most suitable for selecting equivalent clay.

Table 1 Strength characteristics of the soil

Composition type	Specific adhesion, kPa	Internal friction angle, ^{0}
Type 1. 1%	0.33	34
Type 2. 2%	1.17	32
Type 3. 3%	2.92	31
Type 4. 4%	4.33	28
Type 5. 5%	4.53	23



A. Variation ***c*** and ***φ***



B. Increments IB and decrements ***φ***

Fig. 5 Changes in strength characteristics

The results of the direct shear tests are presented in Figure 4 and Table 1. Figures 4A, 4B, 4C, 4D, and 4E show the mean values of the tests for experimental specimens of types 1, 2, 3, 4, and 5, respectively. The equations of linear functions on the diagrams depict the variation of the shear strength depending on the percentage oil content. Upon adding 1% oil by weight, a slight increase in shear strength is observed, from 0 (sand samples without added oil) to 0.41 kPa.

In Figure 5, the variation in strength characteristics of the sand at different oil concentrations is presented. Figure 5A shows the changes in the values of the shear strength (**C**) and the internal friction angle (**φ**), while Figure 5B illustrates the increment of shear strength and the reduction of the internal friction angle.Figure 5B shows the increments of specific cohesion and decrements of the angle of internal friction.

The increase in shear strength values is not proportional to the increase in the percentage of oil content. The maximum increment of shear strength is observed at 4% oil content, which is 1.74 kPa, while the minimum is at 5% oil content, which is 0.40 kPa. The shear strength increment at 2% and 3% is 0.78 kPa and 1.35 kPa, respectively. Thus, it can be concluded that the optimal oil content contributing to an increase in shear strength is 4%. Evaluation of the values of the internal friction angles showed a decrease in shear stress with an increase in oil content. At 1% content, a slight reduction in the internal friction angle by 0.020 is observed, and the maximum reduction is observed at 5% concentration, which is 0.830. Since the reduction in friction at 4% content (0.260) is more than three times less than at 5%, it can be concluded that an oil content of more than 4% becomes impractical, as the increase in shear strength is proportional to a sharp reduction in friction.

For transition to real (full-scale) characteristics of soils through the obtained characteristics of the equivalent soil, we will use the general law of dynamic similarity taking into account gravitational influence and internal stress. Table 2 shows the characteristics of the matched equivalent soil and the corresponding real soil.

Table 2 Characteristics of equivalent and natural soil

№	Soil	Specific adhesion, kPa	Angle of internal friction,^{0}
2	Equivalent soil	4,33	28
1	Natural soil	40.72	26-30

According to the characteristics obtained, the natural soils correspond to loams or clays with moisture content at the rolling boundary between 12.5 and 15.4% and porosity up to 0.5.

The obtained results from assessing the particle size distribution of the sand provide an opportunity to optimize subsequent model tests of piles in the soil, as they reduce expenses and the preparation of equivalent material. The preparation of the latter requires substantial effort due to the small sample sizes relative to the large volume of the testing container. The obtained results from evaluating the strength characteristics allow for modeling clayey, loamy, and sandy loam soils.

The use of equivalent clay (instead of natural clay, loam, or sandy loam) eliminates the inconsistency in soil modeling that may arise during multiple tests using natural clay, loam, or sandy loam. This is because the preparation of the foundation during tests always necessitates a new layer-wise placement of soil and compaction to achieve the desired density. Therefore, utilizing the derived composition of equivalent material is deemed a better approach for modeling sands and clayey soils. When using natural soils, despite proper preparation, there is a higher likelihood of environmental heterogeneity, potentially distorting the results.

5. CONCLUSION

1. Studies of quarry sand were conducted to assess its suitability as an equivalent material for further testing of pile performance in sandy and clayey soils.
2. Tests of the particle size distribution of medium-coarse sand, intended for modeling the equivalent sand in model pile tests, were conducted. For the assessment of the equivalent clay for model pile tests, tests of the particle size distribution and direct shear of fine sand were conducted at different percentages of oil content, ranging from 1 to 5%.
3. According to the results of the particle size distribution of medium-coarse sand, a quarry and the composition of the equivalent sand were chosen. For model pile tests in sand, the optimal choice is Type 1 sand (see Methods), with a fraction from 0.63 to 0.5 mm. This was determined based on the condition of the maximum particle content of one fraction in the composition of quarry sand (58.87% on average) and its homogeneity.
4. To model the equivalent clay, fine sand Type 4 (see Methods) was chosen, as the results of the particle size distribution showed the highest percentage ratio of particles of one fraction (57.98% on average) compared to other types of sand. The optimal oil content in the composition of the equivalent clay (to increase shear strength) was 4%. At this ratio, an increase in shear strength was observed (an increase of 72% compared to 1% oil content) with a relatively small reduction in the internal friction angle (a reduction of 5% compared to 1% oil content). Further increase in the percentage of oil content leads to a sharp reduction in the internal friction angle (a reduction of 9% compared to 1% oil content), with a slight increase in shear strength (an increase of 8% compared to 4% oil content).
5. For further model studies evaluating the performance of the proposed pile structural solution with rotating sections in clayey and sandy soils, it is recommended to use an equivalent sand consisting of fractions within the range of 0.63-0.50 mm of medium-coarse sand equivalent to clay, composed of fine sand with a fraction of 0.125 mm and a 4% addition of oil.

6. ACKNOWLEDGMENTS

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