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DESIGN

PREDICTION OF BEARING CAPACITY OF DRIVEN PILES IN SEMI-ROCKY SOILS

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The article discusses the prediction of the bearing capacity of driven piles on argillite-like clays and sandstones of the Permian age. The methodology was developed and field tests of piles were performed; the aspects of the formation of the bearing capacity of piles are revealed; and recommendations are formulated for the design of foundations on bases composed of of argillite-like clays and sandstones. The results can serve as a reference for the preliminary assessment of the bearing capacity of driven piles embedded in semi-rocky soils without conducting expensive and time-consuming field trials.

Introduction

Bearing capacity is one of the most important factors to consider in constructing foundations. Despite the numerous experimental and theoretical studies of the operation of piles on weathered rocky soils [1-16], an accurate assessment of the bearing capacities of such piles is yet to be realized, due to the need to consider many factors such as the shape, size, and depth of the foundation and the variability of the base soil characteristics. The existing approach to determining the bearing capacity of the solid mass as a homogeneous isotropic continuous medium with a linear damage rule does not reflect the real properties of the weathered rock base [7-9]. For a fractured and weathered rock mass, loads from the foundation can lead to not only the elastic deformation but also the plastic deformations of the base [13, 17]. The lack of reliable methods for calculating the bearing capacity of piles on weathered argillite-like clays and sandstones leads to the need for expensive tests of production piles and stamps.

In this work, a method for calculating the bearing capacity of a driven pile resting on weathered argillite-like clay and sandstones of the Permian age was developed, and comprehensive experimental studies were performed. The results were analyzed, and equations were obtained for calculating the bearing capacity of a driven pile resting on weathered semi-rocky soils. Moreover, recommendations were formulated to predict the bearing capacity of driven piles on argillite-like clays and sandstones of the Permian age.

Experimental Research Method

The experimental studies included the field testing of argillite-like clays and sandstones using a driven pile (with static and dynamic loads and a method using the principles of the wave theory of impact). All experimental studies were performed at sites in Perm (Russia). The geological and lithological structures of the test sites were represented by bulk soils, loams from a low-plastic to very soft

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TABLE 1

Characteristics	Argillite-like clay	Sandstone
Density, g/cm^3	2.02	2.07
Natural moisture content	0.19	0.16
Index of plasticity	0.16	-
Liquidity index	<0	-
Porosity factor	0.61	0.56
Degree of water saturation	0.84	0.83
Weathering coefficient	0.76	0.76

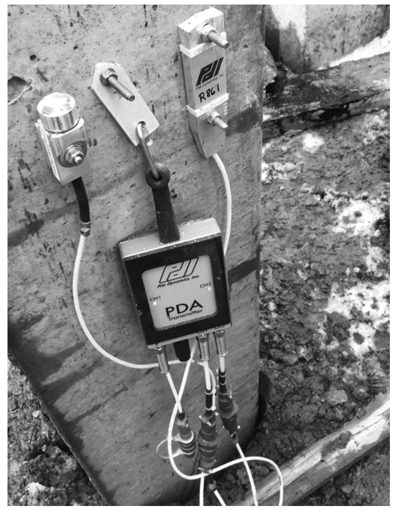

Fig. 1. A driven pile with sensors installed for testing by the wave theory of impact.

consistency, fine and gravelly sands, clayey gravel-cobble soils, weathered argillite-like clays, and sandstones. Table 1 presents the characteristics of argillite-like clays and sandstones of the Permian age.

At the experimental sites, soils with a static pressing load were tested for four driven piles on mud argillite-like clays and five piles on sandstones. For the investigated sites, dynamic load tests of piles were also performed (three tests of piles on argillite-like clay and three tests on sandstones). In addition, at one of the experimental sites, two tests were performed using the principles of the wave theory of impact (Fig. 1).

The cross sections of all tested driven piles were 0.3×0.3 m, and the pile material was concrete of class B25. The piles were embedded into argillite-like clays and sandstones in the experimental sites at depths of 0.1-2.5 m. The driven piles were 8.0-11.0 m long. Tests using the method of the wave theory of impact were performed for driven piles 11.0 m long embedded at a depth of 0.2 m in sandstones. All tests were performed following the requirements in [18]. The field tests of piles on argillite-like clays and sandstones enabled identifying the features of the distribution of the bearing capacity of piles along the tip and lateral surface and determining the bearing capacity of piles at design loads. In addition to field studies, the load-bearing capacity of piles was calculated according to the method in Ref. [19], and the results were compared with those of numerical calculations in Plaxis 3D presented in earlier works.

Results and Analysis

Figure 2 presents the load-settlement plots obtained during field tests with the static loads of driven piles on argillite-like clays and sandstones.

The results of the static tests of piles revealed that with an increase in the piling depth, the bearing capacity at design loads tended to increase. The tests of piles with design loads showed that

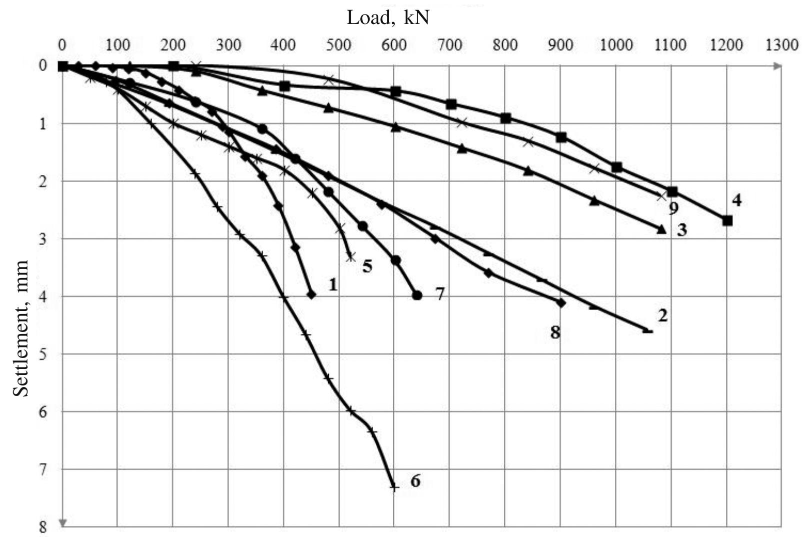

Fig. 2. Graphs of the settlements of production piles on argillite-like clays (no. 1-4) and sandstones (No. 5-9) according to the results of static load tests.

TABLE 2

Method for determining the bearing capacity of piles	Bearing capacity, kN	
	Argillite-like clay	Sandstone
Static load (up to design loads)	450-1200	520-1100
Dynamic load	735-980	895-1060
Method of the wave theory of impact	–	1947-2050
Calculation according to [19]	831-1199	794-979
Calculation according to this study	450-1248	465-1060

the bearing capacity of the soils at the base of the piles was not exhausted, but the tensile strength of the pile material was reached; the bearing capacity referred to here is that at the design loads on the pile and not the maximum load on the foundation soil, since the static tests of piles on argillite-like clays and sandstones did not provide the maximum bearing capacity of the foundation soil because the piles and the foundation frames were destroyed during the tests. An analysis of the experimental data showed the relationship between the pile bearing capacity and the pile embedment depth. Based on these data, Eq. (1) is proposed to calculate the bearing capacity at design loads F_d (kN) of a driven pile resting on weathered argillite-like clays, while Eq. (2) is proposed to calculate that of a pile resting on sandstones.

$$F_d = 315.98\ln(l_d) + 958.4; \quad (1)$$

$$F_d = 184.78\ln(l_d) + 890.48, \quad (2)$$

where l_d is the estimated depth of the pile into the argillite-like clay or sandstone.

The bearing capacities at design loads on a driven pile with a cross section of 0.3×0.3 m and embedment depth of 0.1-2.5 m in argillite-like clay and sandstone were calculated using Eqs. (1) and (2), respectively. The determination coefficient of the equations obtained for argillite-like clay was found as 0.95, and that for sandstone was 0.96. This characterizes the obtained approximating functions as high-accuracy theoretical models.

The field measurement results of the bearing capacity agree well with the calculation result based on the method in [19] and that based on the equations obtained in the study (Table 2). For one of the piles, the bearing capacity calculated according to [19] was 1.8 times higher than that obtained by the static load tests.

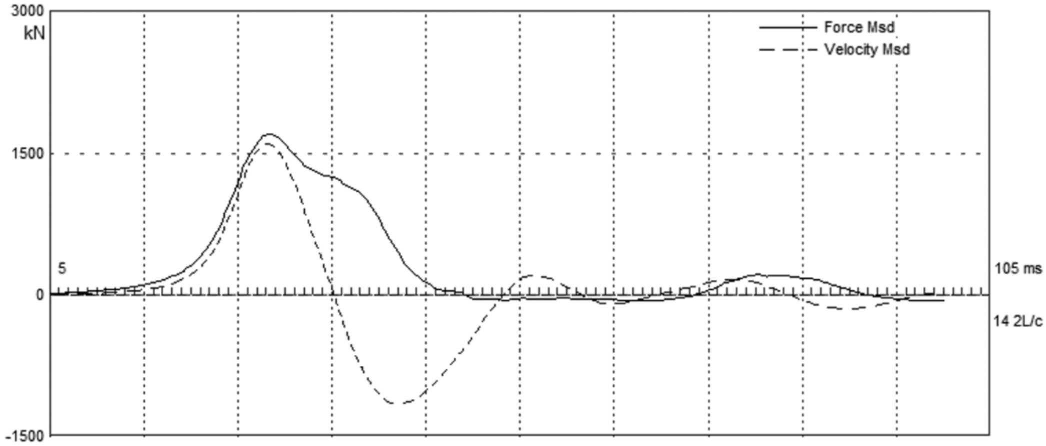

Fig. 3. Oscillogram obtained by the test results of the wave theory of impact.

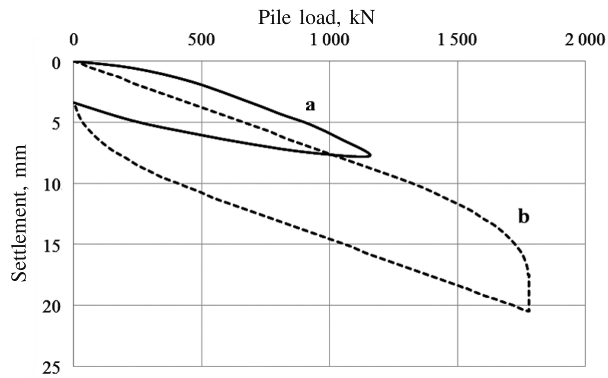

Fig. 4. The bearing capacity of piles according to the data of static tests and tests by the method of the wave theory of impact: a) static test, b) test by the method of the wave theory.

During analysis, the fact that the static load tests of piles were performed based on loads ranging from the design loads on the foundation to the maximum permissible loads on the test bench should be considered. In this range of pile loads, there was no sharp increase in pile settlement (pile breakdown). Thus, the real bearing capacity of the pile foundation soil during the static load tests was underestimated, which can provide a strength margin for the soil.

The test results of the piles obtained by the method of the wave theory of impact enabled obtaining the bearing capacity of sandstone at the base of the driven pile (Fig. 3). When using this method the bearing capacity is determined by comparing the theoretical graph of strength and velocity with the oscillogram obtained during the test.

Figure 4 compares the test results of piles obtained by the wave theory of impact with the result of static load tests of piles performed on one site.

The total bearing capacity obtained from the wave theory of impact test results exceeds the bearing capacity obtained from the static load test results. Tests using the wave theory method showed that the bearing capacity of piles on sandstones is determined by the bearing capacity along the edge of the piles, which significantly exceeds the strength of the pile material (Fig. 3).

Furthermore, a number of studies [14-17, 20] recommend that special attention be paid to calculating the unevenness of the foundation settlement on highly weathered rocky soils. This is because the uneven settlement of such bases can lead to additional strength and brittle fracture in structural elements. Sychkina et al. [20] performed numerical experiments for four piles on argillite-like clays; the bearing capacity obtained using the Plaxis 3D software package (Hardening Soil model) for the four piles turned out to be underestimated compared with the bearing capacity obtained at the design pile loads. Data obtained by Bartolomei et al. [16], showed that pile settlements on argillite-like clays obtained by numerical calculation turned out to be overestimated; it was up to six times higher than the predicted stabilized pile settlements. This can lead to errors in predicting long-term stabilized settlement of piles on argillite-like clays and sandstones, an emergency, and the destruction of structural elements. According to Sychkina et al. [20], for highly weathered argillite-like clays and sandstones of the Permian age, the soil models used for numerical calculations in the Plaxis 3D software package must be corrected.

Based on the findings of previous studies by the authors and other researchers [13-17, 20], the authors recommend designing piles on weathered argillite-like clays and sandstones of Perm using the proposed equations in two approaches:

1) For argillite-like clays and sandstones with a compressive strength of more than 2 MPa (according to plate-bearing tests), the operation of a driven pile should be predicted based on the assessment of long-term stabilized settlements at operational loads with the introduction of a safety factor. In this case, the bearing capacity is limited by the tensile strength of the pile material.

2) For highly weathered argillite-like clays and sandstones with tensile strength in uniaxial compression of less than 2.0 MPa, the bearing capacity of the driven pile should be calculated using the proposed equations, and the long-term stabilized settlement of the driven pile should be calculated with the introduction of safety factors. To implement this approach, the authors have developed a computer program SoftRockFoundation [21], which enables calculating the long-term stabilized settlement and the bearing capacity of a single pile at design loads on argillite-like clays and sandstones.

Conclusion

Comprehensive field studies of argillite-like clays and sandstones have shown consistent results.

Based on theoretical and experimental studies, the authors propose a semi-empirical technique for the preliminary assessment of bearing capacity under design loads of a driven pile of 0.3×0.3 m in cross section with embedment depths of 0.1-2.5 m in argillite-like clay and sandstone. An assessment of the reliability of the approximation by the obtained equations showed that for argillite-like clay and sandstone the determination coefficients were 0.95 and 0.96, respectively.

Driven piles on weathered semi-rocky soils should be designed according to two groups of extreme limit states, considering not only the bearing capacity but also the long-term stabilized settlement under operational loads with the introduction of a safety factor. For calculation, the SoftRock-Foundation computer program developed by the authors can be used.

The equations presented consider the embedment factor of the driven pile, which has a significant effect on the pile bearing capacity on weathered rocky soils. Moreover, equations derived from the proposed equations should be applied carefully for other varieties of weathered rocky soils, such as shales, limestones, siltstones, and conglomerates, formed at different geological times and under different engineering and geological conditions. In such cases, the use of these equations requires additional research.

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