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Bearing capacity equations of piles in weathered claystone and sandstone

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Abstract. The article proposes models of nonlinear estimation of the bearing capacity of piles on weathered claystone and sandstone. These soils are often used as the foundation for deep foundations for critical structures such as bridges, transport structures, dams. Often, laboratory tests of such soils give underestimated values of the characteristics. As a result, the bearing capacity of the designed pile foundations is much more than necessary. The main goal of this study is to develop equations that allow us to evaluate the bearing capacity of the pile foundation in these soils by a non-destructive method. The authors propose semi-empirical equations based on analytical solutions and empirical data, obtained from plate-bearing tests. These equations can be used for an estimation of the bearing capacity of piles of various diameters without conducting expensive field tests. Assessment of the obtained equations reliability showed that the determination coefficient is 0.90 for claystone, and 0.96 for sandstone. This allows us to characterize the obtained approximating functions as theoretical models of good quality. Proposed equations was compared with other methods and static load test results.

1. Introduction

Pile bearing capacity is one of the most important factor in deep foundations design. Over the years, the bearing capacity of the deep foundation in a weathered and fissured rock base has been the subject of many studies in the field of geotechnics [1−22]. As a result, the researchers proposed a number of theoretical and experimental solutions for predicting the bearing capacity of piles. However, an accurate estimation of the pile bearing capacity and a reliable interpretation of the mechanism of load transfer from the pile to the ground are still far from perfect due to the complexity of the problem. In addition, many factors must be taken into account: the shape and size of the foundation, the laying depth, the load, and the characteristics of the weathered rocky soil.

The calculation methods given in the Russian Federation standards are developed primary for quaternary sandy-clay soils of sedimentary origin and rocky unripe soils and do not always allow obtaining the correct values of the bearing capacity of End-bearing pile in argillite-like clays and sandstones. Weathered argillite-like clays and sandstones of Permian age cannot be classified as low-compressible rocky soils [23, 25], since they have a deformation modulus much less than 50 MPa. Due to the lack of reliable methods for calculating the bearing capacity of piles on weathered claystone and sandstone, it is often necessary to use expensive and time-consuming static tests and plate-bearing tests. Calculation methods implemented in world design practice [2, 13−17, 25−29] require the use of additional soil parameters that are not always determined in practice of engineering and geological surveys. In addition, the proposed theoretical models require correlation by comparing the results of calculations with the field tests data.

As follows from the foregoing, the goal of this work is the development of a methodology for calculating the bearing capacity of piles in weathered claystone and sandstone of Permian age. To achieve this goal, the following issues were solved:

1. An analysis of the existing calculation methods for determining the bearing capacity of piles.

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2. Soil resistance under the pile toe was determined from the plate-bearing tests results. The technique of experimental studies is described. The results of field tests are analyzed.

3. Equations for calculating the bearing capacity of cast-in-place piles in weathered claystone and sandstones of Permian age have been developed.

It has been proven that rock masses have fracture, anisotropy, nonlinearity of properties, etc. Therefore, a simple theoretical approach to determining the bearing capacity for the case of a homogeneous isotropic continuous medium with a linear fracture law does not reflect the real properties of the rock mass at the base of the foundation [4, 6, 7, 11, 13, 26, 30]. In the case when the rock mass is highly weathered and fractured, loads from the foundation can lead to the appearance of both elastic and plastic deformations. The most widely used methods for determining the bearing capacity of foundations can be divided into four groups: analytical methods, numerical methods, semi-empirical methods and field tests of piles. Numerical methods, such as the finite element method (FEM) and the limit equilibrium method (LEM), predict the pile bearing capacity using geometry and the soil properties of the foundation as input. [17, 31, 33]. Semi-empirical methods are based on a correlation between the bearing capacity and soil properties based on empirical observations and the results of experimental tests [4, 11, 28, 33−41].

The existing semi-empirical equations (1, 2) for calculating the bearing capacity of piles use data from laboratory soil tests.

$$F_d = \gamma_c \frac{R_{c,m,n}}{\gamma_g}\left(1+0.4\frac{l_d}{d_f}\right)A \quad (1)$$

where γ_c is coefficient of pile working conditions in the soil, taken equal to 1; $R_{c,m,n}$ is the value of the uniaxial compression strength of rocky soil in a water-saturated state in the field; γ_g is the soil reliability coefficient equal to 1.4; A is the cross section area of the pile toe, m^2; l_d is the calculated depth of embedment of the pile into claystone, m; d_f is the outer diameter of the pile, m.

$$Q_p = A_p \cdot q_p = A_p \cdot (c' N_c + q' N_q) \quad (2)$$

where A_p is the cross section area of the pile toe, m^2; q_p is the soil resistance characteristic under the tip of the pile; c' is the cohesion of the soil surrounding the pile; qp is the soil resistance under the tip of the pile; q' is the effective vertical stress at the depth of the tip of the pile; Nc, Nq is the coefficients taken according to Eurocode tables.

Determination of the tensile strength of weathered claystone and sandstones under laboratory conditions often shows underestimated results in relation to field tests [13]. As a result, the application of the uniaxial compression strength results obtained in laboratory conditions gives underestimated values of the bearing capacity of the end-bearing pile. In addition, for calculations it is often necessary to use special coefficients that take into account the fracture of weathered rocky soils. However, in the standard engineering and geological surveys, this coefficient is not determined.

The calculation of the bearing capacity of piles on hard clay, presented in [19], showed that the bearing capacity of piles is significantly underestimated in comparison with the results of piles field tests. Often, instead of plate-bearing tests, cone penetration test and pile with static and dynamic load tests are used. However, cone penetration test has limited application in dense claystone and sandstone with cementation bonds and static load testing can be quite expensive especially for heavily loaded cast-in-place piles. High strain dynamic pile testing may be a good solution, but most standards require a large safety factor for the results of these tests. A description of existing methods for calculating the bearing capacity of piles and some issues encountered in their application can be found in [10, 14−18, 28, 31, 34, 35, 37, 39, 40]. When drilling piles are used in soft soils, the bearing capacity is mainly limited by the stability of the piles [40, 41]. But for pile less than 40 m in length capacity is still majorly limited by soil resistance.

Based on the results of the analysis, it can be concluded that it is necessary to adjust existing solutions in the field of calculating the bearing capacity of piles on weathered claystone and sandstone. The development of analytical and semi-empirical solutions that can be used to calculate the foundations at the pre-design stages is of particular interest.

2. Methods

In this study, the results of plate-bearing tests of the early Permian age claystone and sandstone are analyzed. The geological and lithological structure of the plate-bearing test sites is represented by fill-up soils, loam from a hard-plastic to a fluid-plastic consistency, gravel-pebble soils with clay aggregate, which overlap claystone below (Fig. 1a) and Permian sandstone (Fig. 1b).

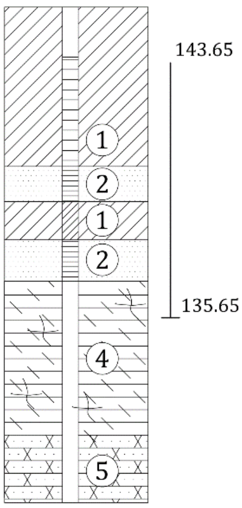
a) Claystone b) Sandstone

Figure 1. Claystone (a) and Sandstone (b) samples.

The claystone is dark brown. It consists of clay material (60−70 %), silt material (10−20 %), admixture of carbonates (10−15 %) and iron oxides. The sandstone is greenish-gray and grayish-brown, fine and fine-grained (rarely medium-grained), layered (from thin-layered to unclear-layered), polymictic, with carbonate-clay, clay-carbonate and carbonate cement. The content of clastic material in sandstones is 50−90 %, cement is 12−30 %. The values of the physical and mechanical properties of claystone and sandstone are given in Table 1. The properties were determined according to Russian State Standard GOST 12248-2010.

Cohesion and friction angle were defined from the direct shear test. In most cases modules are defined from oedometer soil test. The RQD parameter was not determined. Usually, during geological surveys it is impossible to take cores of the considered soil with a height of more than 10 cm.

Table 1. Average values of physical characteristics of claystone and sandstone.

Typical borehole	Physical and mechanical properties	Claystone (4)	Sandstone (5)
	Bulk density, g / cm^3	2.02	2.07
	Humidity	0.19	0.16
	Liquid limit	0.33	-
	Plasticity Limit	0.23	-
	Plasticity Index	0.16	-
	Liquidity Index	<0	-
	Saturation	0.84	0.83
	Coefficient of weathering	0.76	0.76
	Elastic modulus, MPa	11.6	12.8
	Coefficient of cohesion, kPa	30	11
	Friction angle	26	33

The plate-bearing was conducted in the well. A type III plate with a sole area of 600 cm^2 was used. Drilling the test well was carried out with casing. The embossing of plate in claystone ranged from 1.0 to 11.0 m, in sandstone – from 0.5 to 6.0 m. A hydraulic jack DU100P150 with a manual hydraulic station NRG 7036 was used as a loading device (Fig. 2).

Figure 2. Plate-bearing test.

The pressure in the system was controlled using a trusted pressure gauge with a division price of 1 kgf/cm^2. Reactive efforts were perceived by a custom manufacturing anchor system. The design of the stand was previously designed for a load of 1.5 times the required load during the test. The set was recorded using 6PAO deflection meters, the temperature deformations of the steel wire were taken into account using the compensation deflection meter. The plate was loaded in steps of 0.2 MPa. Each pressure stage was maintained until the plate was conditionally stabilized. It was believed that the plate was stabilized if the stamp settling speed did not exceed 0.1 mm per 0.5 hours. The final value of pressure p_n was determined as follows: if, at pressure p_i, the pressure increment is twice as large as for the previous pressure step p_{i-1}, and at the next pressure step p_{i+1}, the pressure increment will be equal to or greater than the pressure increment at p_i, for the final value p_n should take p_{i-1}. In the absence of a criterion for achieving pressure p_n, the test was terminated when the ultimate load bearing capacity of the stand was reached. In total, in this study, 11 stamp tests of claystone and 5 stamp tests of sandstone were considered.

3. Results and Discussion

In order to identify the probabilistic relationships between the uniaxial compression strength in the field ($R_{c,m,n}$) and the plate embedment depth (l_d), an analytical function was searched that best describes the dependence of $R_{c,m,n}$ on ld. The results of plate-bearing test presented in diagrams of the characteristics $R_{c,m,n}$ and l_d for claystone and sandstone in Fig. 3 and Fig. 4, respectively.

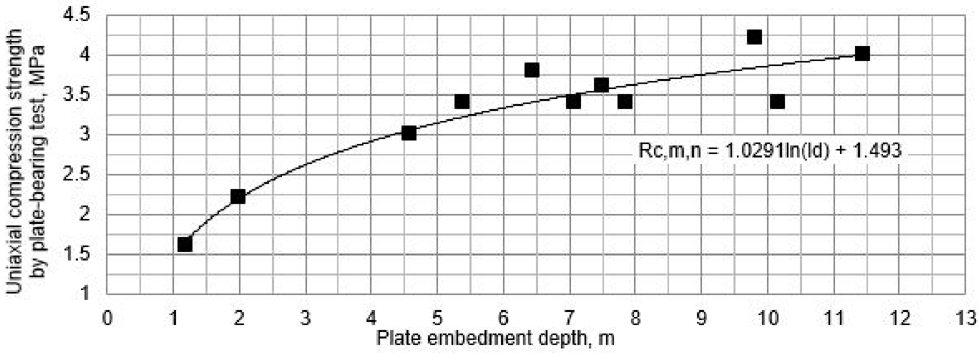


Figure 3. The relationship between the tensile strength of uniaxial compression plate in the field (Rc, m, n) from the depth of the punch (ld) for argillite-like clay.

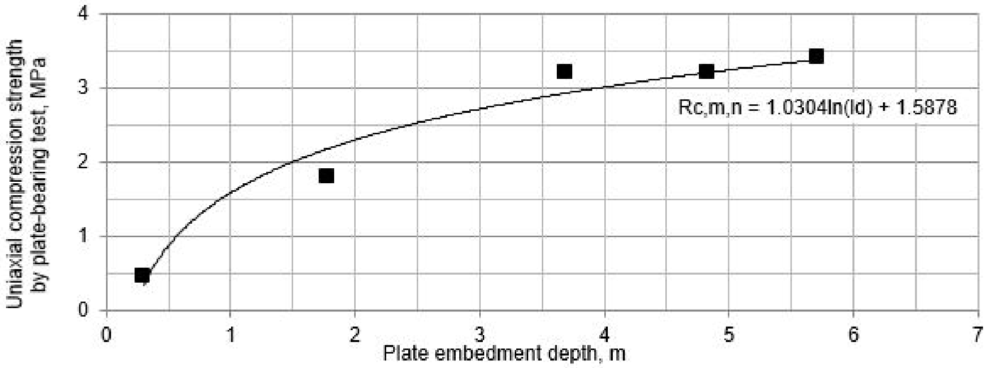


Figure 4. The relationship between the tensile strength of uniaxial compression stamp in the field (Rc, m, n) from the depth of the punch (ld) for sandstone.

Figs. 3 and 4 show that with an increase in the immersion depth of the test plate in claystone and sandstone, the ultimate bearing capacity of soil also increases.

To approximate the experimental data, logarithmic functions were chosen. Assessment of the reliability of the approximation of the obtained equations showed that the determination coefficient is 0.90 for claystone and 0.96 for sandstone. Therefore, it can be said that the obtained approximating equation describes well the relationship between the depth of embedment of the slab and the resulting soil rotation.

Based on the performed theoretical and experimental studies, a technique for calculating the bearing capacity of piles on argillite-like clays and sandstones of Permian age is proposed. The equations presented below make it possible to calculate the bearing capacity of shell pile, filling and bored piles of any diameter with embedment from 1.0 to 11.0 m in claystone and from 0.5 to 6.0 m in sandstones. The pile bearing capacity in claystone can be calculated by the equation (3):

$$F_d = \gamma_c A \cdot (1.0291 \ln(l_d) + 1.493) \cdot (1 + 0.4 \frac{l_d}{d_f}) \quad (3)$$

where γ_c is the coefficient of pile working conditions in the soil, taken equal to 1; A is the cross section area of the pile toe, m^2; l_d is the calculated depth of embedment of the pile into claystone, m; d_f is the the outer diameter of the pile, m.

The pile bearing capacity in sandstone can be calculated by the equation (4):

$$F_d = \gamma_c A \cdot (1.0304 \ln(l_d) + 1.5878) \cdot (1 + 0.4 \frac{l_d}{d_f}) \quad (4)$$

Studies [2, 4−6, 9, 11, 14, 18, 20, 39] have repeatedly emphasized the need to take into account a large number of factors affecting the joint work of piles on weathered rocky soils. The equations presented in this study allow one to take into account a number of factors that have a significant impact on the bearing capacity of piles on weathered rocky soils: pile geometry, embedment depth, and soil strength near the pile end. The obtained solutions require additional verification in the case of application for other types of weathered rocky soils – shale, limestone, siltstone, granite, etc. It should be borne in mind that soils formed at different geological times and in different conditions can have different engineering properties.

For piles based on weathered rocky soils with compressive strength exceeding 2 MPa, soil resistance exceeds the strength of the pile material [18, 19, 41]. In such cases, pile set is more critical than bearing capacity. On weathered rocky soils that have rheological properties, great attention must be paid to the speed and degree of development of uneven foundation sets [41]. Uneven sets can lead to additional forces and brittle fracture in structural elements. Thus, the design of piles should be based on the assessment of set under design loads with the use of a safety factor. However, claystone and sandstone often have an uneven degree of weathering and uniaxial compression strength of less than 2.0 MPa. This leads to the need to take into account the bearing capacity of piles along with long-term settlement of piles.

For the soils under consideration, the RQD parameter is usually not determined, since it is usually not possible to drill a core with a height of 10 cm or more. In addition, these soils are highly weathered. According to the requirements of national standards, the load-bearing capacity of piles in highly weathered bases should be determined from static tests. The uniaxial compression strength is typically 1.15–2.15 MPa.

To compare proposed equations with other methods static load test of one cast-in-place pile was conducted. Pile has 22.52 meters in length and 600 mm in diameter. Bearing capacity was calculated according to SP 24.13330 method and finite element method. OCR parameter was obtained Initial stresses were generated using the K0 procedure using OCR = 1.8 coefficients for argillite-like clay to take into account the state of overconsolidation. Comparison of obtained results with static load test presented in Table 2.

Table 2. Comparison between proposed equations and standard equations.

Bearing capacity according to SP 24.13330 analytical method, kN	Proposed equations, kN	Finite element method (Plaxis)	Static load test, kN
3688	4975	4530	5400

As can be seen from the comparison results, the standard method significantly underestimates the bearing capacity of piles. The finite element method shows somewhat better convergence with SLT, however, the results are also lower. This may be due to incorrectly defined characteristics. All characteristics used in the calculations are determined in laboratory conditions. However, there is no guarantee that the sample does not lose strength at the time of sampling. Existing standards should be revised to ensure the design of piles on weathered claystone and sandstone using the correct equations and reliability factors to predict not only bearing capacity, but also long-term settlement.

4. Conclusion

1. This article addresses the issue of predicting the bearing capacity of piles on weathered rocky soils. The authors analyzed the results of determining the uniaxial compression strength of claystone and sandstone by plate-bearing test. Various relationships were revealed between the uniaxial compression tensile strength and the plate embedment depth for.

2. A semi-empirical technique is proposed for a preliminary assessment of the bearing capacity of a pile foundation, based on weathered claystone and sandstones of the early Permian age. The presented equations make it possible to calculate the bearing capacity of various types of piles of any diameter with embedment from 1.0 to 11.0 m in claystone and from 0.5 to 6.0 m in sandstones.

3. Assessment of the reliability of the obtained equations showed that the determination coefficient is 0.90 for claystone and 0.96 for sandstone. It should be noted that only claystone and sandstone of the early Permian age were considered in this paper. Soils, which are formed at a different geological time, and having a different loading history may have different engineering properties. Therefore, the resulting equations should be used with caution for other types of weathered rocky soils.

4. When designing pile foundations on weathered rocky soils, it is necessary to take into account both the bearing capacity of the pile and long-term set increase. This is because for piles based on soils with a compressive strength of more than 2 MPa, the bearing capacity of the soil exceeds the strength of the piles. Existing standards should be revised to ensure the design of piles on weathered claystone and sandstone using the correct equations and reliability factors to predict not only bearing capacity, but also long-term settlement.

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