Improved design for settlement of helical pile in clay

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Abstract. A method is being developed for calculating the settlement of a single two-bladed helical pile in clay. It is proposed to use the results of laboratory direct shear tests to determine the pile settlement, caused by shear deformation around the pile. The method takes into account the real behavior of the soil during shear deformation, which theoretically allows one to obtain a non-linear dependence of the pile settlement on the external applied load, observed in the experiments. This solution is based on the use of a patented design solution of a two-bladed helical pile. Using the example of comparison with the results for soils with semi-solid consistency, it is shown that the method allows increasing the reliability of settlement forecast in clay.

1. Introduction
In the construction of industrial and agricultural complexes, modern technologies are becoming increasingly popular, allowing the construction of rapidly erected temporary buildings that transfer small loads to the ground base (about 100-150 kN, 80-140 kN/m). Examples of rapidly erected buildings are warehouses, cabins, greenhouses, tents, summer pavilions and other structures, which are often classified as temporary, because their service life is usually short (to 20-30 years). The use of two-bladed helical piles with a length of 1,5 to 3,0 and a blade diameter of 0,3-0,4 m reduces the cost of foundation.

To increase the bearing capacity of metal helical piles, it is usually decided to increase their length, diameter of shaft and / or blade. At the same time, their material consumption increases. As the length of the helical piles increases, the question occurs about the possibility of screwing them into a given depth. Therefore, a more promising approach to increase the bearing capacity of helical piles up to 3,0 m long is to place not one, but two blades on its shaft. The design solution of two-bladed helical piles has been tested and successfully used in the construction of rapidly erected buildings [1-4].

The authors carried out experimental, numerical and analytical studies of the work of two-bladed helical piles with a length of 1,5-3,0 m in clay. It was found that the clayey soil, confined between the blades of the two-bladed helical pile acquires during loading the shape of a "soil cylinder" and starts to act together with the shaft as a single whole element. Based on the data of the studies, a design scheme is proposed for determining the final settlement of a single helical pile S (Figure 1) [1]. It was found that the scheme of the interaction of two-bladed helical piles with the clayey soil of the base does not differ much from that of friction piles with interblade distance L ≤ 2,0 D, so that the well-known theoretical tenets can be used to improve the settlement calculating method. According to [1], when an external load N is applied to a two-bladed helical pile, two characteristic areas can be identified on the graph of its settlement S (Figure 2). The first stage of loading is characterized by uniform (linear)

growth of the settlement S and is completed at some settlement S_1, above which the soil on the lateral surface of the "soil cylinder" becomes 'detached'.

When the pile's vertical displacement corresponding to the value of the settlement S_1 is reached, the second stage of loading of the two-bladed helical pile begins, on which the work of the lower blade in the soil is fully detected. In this case, the graph $S = f(N)$ has a nonlinear dependence.

2. The approach to solving the problem

The final settlement of the two-bladed helical pile S at a given load N ($N_1 < N < N_2$) is the sum of the settlements S_1 and ΔS:

$$S = S_1 + \Delta S = S_1 + S_1 \xi, \tag{1}$$

where S_1 − shear settlement accumulated at the first stage of loading, m; ΔS-increment of settlement at the second stage of loading, m (Figure 2);

The ξ parameter has the form:

$$\xi = \frac{\Delta N (N_n - N_R) - (\Delta N - N_R) N_R}{N_R (N_n - \Delta N)}, \tag{1a}$$

where all designations are given in [1]. The parameter ξ in the presented form was first published by the authors in [1]. It was obtained on the basis of the results of research by M. V. Malyshev and N.S. Nikitina, who proposed the settlement calculation method of individual foundations with a nonlinear relationship between stresses and strains in soils (1982) [5].

Analysis of formula (1) shows that the accuracy of the final settlement S of a single pile depends on the accuracy determination of settlement S1, at which the resistance forces on the lateral surface of the "soil cylinder" of the pile are fully realized.

The work [1] proposes the formula for estimating the settlement S_1 of a two-bladed helical pile, which is based on the solution of Randolph M. F. and Wroth C. P. [6]. Taking into account the results of the studies [4,7] the considered formula of the settlement S_1 of two-bladed helical pile is improved and has the form:

$$S_1 = \frac{mN_f}{\pi LG} \tag{2}$$

where m is the dimensionless coefficient equal to: $m = 0,203$, $m = 0,35$, $m = 0,46$ for clayey soils of high-plastic, plastic and semi-solid consistency, respectively; L is the interblade distance, m; G- soil shear modulus, kPa, N_f is the part of the external load transferred to the near-pile soil massif by the lateral surface of the "soil cylinder", kN.

To determine N_f in formula (2), we use the expression [1]:

$$N_f = 2\pi r_0 L \tau_{max}, \tag{3}$$

where τ – is the limiting value of tangential stresses, kPa; r_0 is the radius of the "soil cylinder".

The maximum tangential stresses τmax are determined from the Coulomb-Mohr strength condition:

$$\tau = \tau_{max} = \sigma \varphi_1 + c_1 \tag{3a}$$

where σ - is the normal stress acting on the lateral surface of the "soil cylinder" (the horizontal component of the stress from the soil's own weight), kPa, φ_1 and c_1 are respectively the calculated values of the angle of internal friction and the specific adhesion of the soil at the site of its contact with the lateral surface of the "soil cylinder".

Formula (2) also includes the initial soil shear modulus G, which depends on the shear stresses $\tau 0$ distributed along the lateral surface of the "soil cylinder". The method [1] assumes the initial shear modulus to be determined from the relations of the elasticity theory:

$$G = E_0 \left(2\left(1 + \mu\right)\right)^{-1} \qquad (4)$$

where E_0 – the deformation modulus of the soil, established in the linear range of the dependence graph $S=f(p)$; μ - the Poisson's ratio of soil.

In the process of deformation of clayey soil around the "soil cylinder" of a two-bladed helical pile, its resistance to shear decreases with increasing external load. The introduction of the initial shear modulus G into the formula (2) theoretically increases the resistance of clay, which leads to a decrease in the settlement of the piles, especially for clay of solid and low-plastic consistency.

To date, various nonlinear dependences for the estimation of the shear modulus are proposed, for example, dependency of A. I. Botkin, R. L. Kondner and Zelasko J. S., J. M. Duncan, and others. [8] However, these dependences include additional parameters (e.g., R_f), that are taken from table values which reduces the accuracy of their determination.

To increase the reliability of the final settlement, in accordance with the design scheme of the pile it is proposed to determine the shear settlement S_1 due to shear deformations of the soil around the lateral surface of the "soil cylinder" by processing the results of direct shear tests of previously compacted samples.
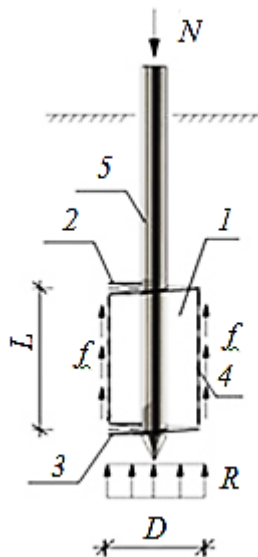

Figure 1. Diagram of the interaction of a two-bladed helical pile with clayey soil: 1 - clayey soil; 2,3 – top and bottom, respectively, blade of a two-bladed helical pile; 4 - lateral surface of "soil cylinder" (outer contour); 5 – shaft of helical pile; L – interblade distance; N - load on the pile; f - resistance (friction) of the soil along the lateral surface of the "soil cylinder"; R - resistance of the soil under the bottom blade; D - diameter of the blade.

Direct shear test is carried out on a given cut plane, which should correspond to the conditions of its operation on the outer contour of the "soil cylinder". Shear test results are presented in a graph "τ-γ", where τ - shear stress, kPa; γ - shear strain.

Figure 3 shows typical "τ-γ" dependences for clay soils of a solid and high-plastic consistencies [9]. Dependence 1 is typical for the overconsolidated clay soils of solid conformation. During the tests, the sample is compacted with a pressure $p = K\sigma_z$, where $K = 1{,}2(1-\sin\varphi)$ for overconsolidated soils based on the results of [7], then a shearing force is applied to it. The characteristic point in the graph 1 of Figure 3 is the peak of strength corresponding to the maximum values of τ_{max}. For this value, γ is set.

For clayey soils of high-plastic consistency, the presence of peak strength is not typical [8]. In the absence of peak strength, for the criterion of the onset of the limiting state, we take the value of τ_{max}, at which there is a decrease in the stiffness of the soil by shear (graph. 2 of Figure 3). In this case, the values of the shear deformation will be greater, compared with the soils of a solid and semi-solid consistency.

The relationship between the shear deformation and displacement is established by the known geometric relations (Cauchy's equations):

$$\gamma = \frac{du}{dz} + \frac{d\omega}{dr} \tag{4a}$$

where $\frac{du}{dz}$ are partial derivatives of horizontal displacements in depth, $\frac{d\omega}{dr}$ is a partial derivative of vertical displacements in the radial direction.
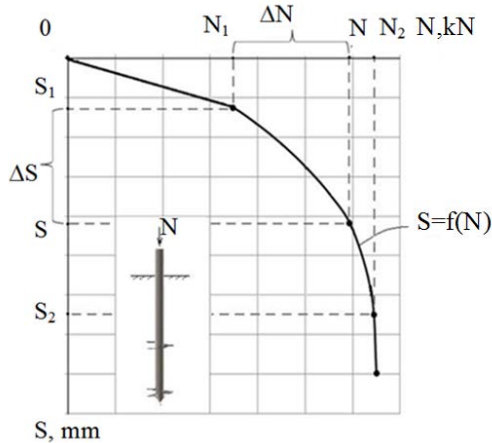

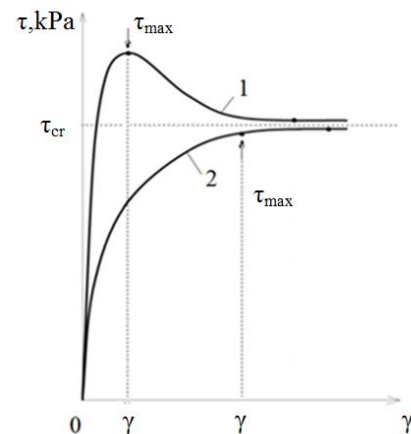**Figure 2.** Behavior of two-bladed helical pile in clay.

Figure 3. Dependence of the shear resistance for various soils: 1 - overconsolidated soil; 2 - normally consolidated soil.

Based on the research carried out by V.A. Barvashov (1968), vertical movements of soil around the pile practically do not vary in depth, this is due to the fact that the change in horizontal displacement of soil along the depth around the pile is not significant (no more than 2-5%) [10].

On the basis of this provision, we write down:

$$\gamma = \frac{du}{dz} + \frac{dw}{dr} \approx \frac{dw}{dr} \tag{4b}$$

where w is the vertical displacement (pile settling), m;

The vertical displacement w is:

$$w = \gamma r_m \tag{4c}$$

where r_m - radius of influence, m;

The authors of this paper propose the following empirical formula for determining the distance r_m in a clayey soil from low-plastic to semi-solid consistency:

$$r_m = kr_0 \tag{5}$$

where k is the dimensionless coefficient equal to $k = 1,5$ and $k = 1,75$ for clayey soils of high-plastic and solid consistency, respectively.

The coefficient k from formula (5) is established from the results of laboratory experimental studies of deformations of clayey soil in the base of models of two-bladed helical piles [11]. It follows from expression (5) that the radius of influence of r_m is much less (approximately 3-4 times) in comparison with the data of M.F. Randolph and others (1978) [6]. The decrease in the radius of influence r_m in the formula (5) takes into account the geometric parameters of the two-bladed helical piles of short length (up to 3 m long) and the features of their interaction with the clayey soil of the base.

Substituting expression (4c) into formula (4b) and taking $w = S_1$, we obtain an expression for determining the settlement S_1 of a two-bladed helical pile at the first stage of its loading:

$$S_1 = k\gamma r_0 \qquad (6)$$

where γ is the shear deformation; r_0 is the radius of the "soil cylinder", m.

The external load N_1 corresponding to the achievement of the shear settlement S_1 is determined by the formula:

$$N_1 = N_f + N_R \qquad (7)$$

where N_R is the portion of the external load that is transmitted to the base soil by the bottom blade of two-bladed helical pile at the end of the linear dependence in the settlement plot $S = f(N)$ (at the moment of full realization of the soil resistance along the lateral surface of the "soil cylinder"), kN .

The load N_f is determined by the formula (3), with the maximum value of the tangential stresses τ_{max} obtained in the single-plane cutting device, and the load N_R in accordance with the method described in [1].

Thus, formulas were obtained for calculating the settlement S_1 and the external load N_f of a two-bladed helical pile in the first stage of its loading.The advantage of the proposed formula (6) over the formula (2) is that the shear settlement is established directly from the shear deformation obtained during the soil tests in the single-plane cutting, while taking into account the actual deformation of the soil under load. The accuracy of formula (2) largely depends on the initial shear modulus G, which is assigned from the relations of the theory of elasticity.

To determine the total settlement S by the formula (1), it is necessary to determine the parameter ξ, which is set by the formula (1A) [1]. The decision takes a nonlinear dependence of the pile settlement on the applied external load. The nonlinear dependence is due to the fact that the initial shear modulus G in the calculation scheme is taken as a fractional-linear function of the shear deformation.

3. The research results analysis

Calculations of the settlement S_1 of a two-bladed helical pile using the proposed method (6) were carried out for semi-solid clay. Physical characteristics of soil is presented in tables. 1. Geometric parameters of the two-bladed helical pile: the shaft diameter d of the helical pile was equal to d = 0,108 m; diameter of the blades D = 0,35 m; the interblade distance was L = 0,7 m; depth of immersion of the pile in the soil z = 2,9 m. Fig. 4 shows a graph obtained according to results of direct shear test of soil.

Table 1. Physical characteristics of soil.

Soil	Physical and mechanical characteristics					
	ρ_s (kNm^{-3})	ρ (kNm^{-3})	e	c (MPa)	φ (°)	E (MPa)
Semi-solid clay	2,72	1,85	0,84	0,051	14	18

To estimate the reliability of the calculation results according to the proposed method, their comparison with the results of static tests, as well as with the data established by the method proposed in [1], was carried out. Table. 2 shows the calculating results of settlement in various load ranges. The load preceding the pile failure was accepted for the maximum load Pu of a two-bladed helical pile on the ground. It was characterized by an intensive growth of the settlement, which was not damping in time at the last stage (Pu = 90 kN). It was found that the graph "settlement-load", built on the proposed method, is quite close to the experimental data (Figure 5), especially at the initial section in the range of up to 0.6 Pu – a discrepancy of less than 17%.

The greatest settlement discrepancy is observed at the initial stage in the determination by the method [1] (discrepancy up to 38%). Such a significant settlement discrepancy S1 is due to the use in

the calculations of the characteristics of the initial shear modulus G corresponding to the elastic behavior of the soil. This approach to the calculation overestimates the resistance of clayey soil to shear and leads to low values of final settlement S. The use of the dependence (6) allows to describe more correctly the work of the lateral surface of the "soil cylinder" of the two-bladed helical pile, increasing the reliability of the settlement forecast.
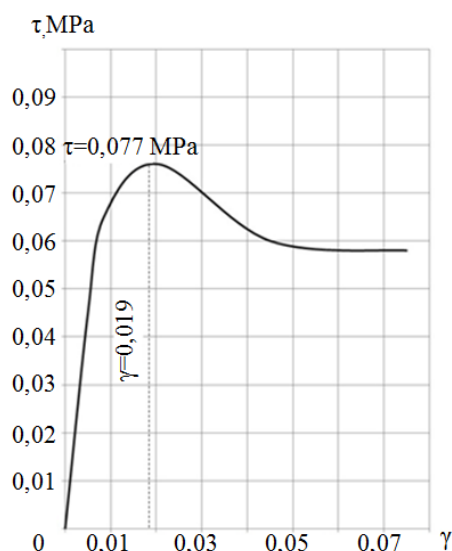

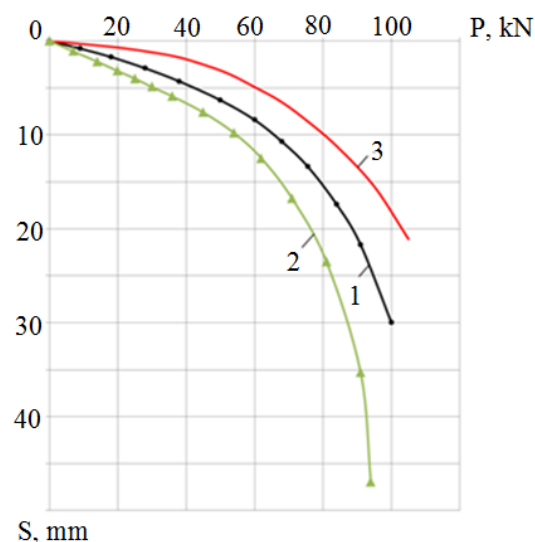**Figure 4.** Graph of dependence of clay resistance to shear (direct shear test).

Figure 5. Dependence "S - N" of the two-bladed helical pile: 1 - results of static tests, 2 - according to the proposed method; 3 - according to the method described in [1].

Table 2. Soil physical characteristics.

Settlement	S_1, mm	The value of the final settlement S, mm, depending on P, kN			
		0,6Pu	0,7Pu	0,8Pu	0,9Pu
Calculating by the method in [1], mm / discrepancy with experiment,%	2,6	3,9/ 38%	6,2/ 36%	7,3/ 34%	10,3/ 35%
Calculating by the proposed method, mm / discrepancy with experiment,%	7,2	7,6/ 17%	14,1/ 33%	17,4/ 32%	24,2/ 37%

4. Conclusions

Based on the results of experimental and theoretical studies, the method for calculating the settlement of a single metal two-bladed helical piles up to 3.0 m long in clay soils for the foundations of rapidly erected temporary buildings has been improved. The method is based on the use of a nonlinear relationship between the settlement S and the external applied load N and the results of single-plane cutting tests for clayey soil.

For reliability of the calculation results, they were compared with the results of full-scale static tests of metal two-bladed helical piles, as well as calculated data by the authors method published in [1] (2017). The comparison showed that the method proposed in this paper (2018) gives results comparable to experimental ones. At the same time, their similarity is closer in comparison with the results obtained in [1].

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