Calculation method of single screw piles’ final settlement in the clay

A I Polishchuk¹, F A Maksimov¹ and N S Nikitina²

¹Kuban State Agrarian University named after I. Trubilin Kalinina st. 13, Krasnodar, 350004 Russia
²National research Moscow State University of Civil Engineering, Yaroslavskoye shosse, 26, Moscow, 129337, Russia
nsnikitina@mail.ru

Abstract. Numerical and analytical studies provided data on the interaction of screw metal piles of various constructive solutions (single-blade, double-blade) with clay soil foundation. The results of the research made it possible to develop a method for calculating the final settlement of single screw double-blade piles for foundations of lightly loaded prefabricated buildings. The method is based on patented design solution for a screw double-blade pile and takes into account the non-linear dependence of its settlement with the applied external load. The scope of the method application under consideration extends to screw double-blade piles up to 3.0 m in clay soils, mainly from soft to semi-solid consistency.

1. Introduction

In recent years, in the industrial, agro-industrial and Russian agricultural complex, the construction of lightly loaded prefabricated buildings and structures has increased significantly. Such structures are usually raised from a metal frame made of thin-walled lightweight structures. Constructive solutions of building elements’ junction points provide the possibility of dismantling buildings and reusing them. Examples of such construction are modular buildings for temporary camps, greenhouse and logistics complexes and other facilities. Due to the applied approach, the market of screw metal piles of small diameter (diameter of the blade up to 300 mm) has become noticeably more active, as their application at a length of up to 3.0 m contributes to a significant reduction in the cost of foundation construction. In the case of two or more blades placing on the trunk (with a reasonable distance between them), the efficiency of the screw piles usually increases, so, the distance (pitch) between the blades is an important parameter characterizing their operation.

The question of the blades’ pitch influence on the work of screw multi-blade piles was first published in [1-3]. According to the studies’ results of the multi-blade screw piles interaction with soil (clayey, sandy), the following was revealed [4, 5]. When the L / D parameter is nothing more than 2.0 (L, D are the distance between the blades and the mean value of their diameter, respectively), the clay soil enclosed between the blades is formed as a 'ground cylinder' and starts to work together with the cylindrical shear surface [1]. With the parameter L / D > 3.0 for clay soils [6] and L / D > 1.5 for sandy soils [7], the blades start to work independently of each other. The bearing capacity of the screw multi-blade pile in this case can be defined as the sum of the bearing capacity on the ground from each blade individually (individual plate method).
2. Research objective
The authors of this work carried out experimental, numerical and analytical studies of the screw metal piles work (single-bladed and double-blade) with a length of 3.0 m in a clayey soil [8]. It was found that the highest bearing capacity of screw piles can be achieved when the distance between the blades is (2.0 ... 2.5) D, where D is the diameter of the blade. It was revealed that clay soil, enclosed between pile blades, takes the form of a 'ground cylinder' and begins to work together with its bore (Figure 1).

![Figure 1. Scheme of a screw double-blade pile interaction with a clay soil: 1 — clay soil; 2, 3 — the upper and lower blades of the screw double-blade pile, respectively; 4 — the lateral surface of the 'ground cylinder' (outer contour); 5 — pile shaft of a screw pile; L — the distance between the blades; N — the external pressing load on the pile; f — resistance (friction) of the soil along the lateral surface of the 'ground cylinder'; R — resistance of soil under the lower blade; D — the diameter of the blade.]

The authors propose a design scheme for the interaction of screw double-blade piles up to 3.0 m in length with clay soil of the base under the external load action (Figure 2). According to [9], the external load N acting on the double-blade screw pile is perceived by the surrounding soil through the resistance f of the ground on contact with the side surface of the 'ground cylinder' and through the resistance R of the soil below the pile lower blade. Soil resistance f along the lateral surface of the metal (steel) smooth trunk of the screw pile (at the section of the trunk above the second blade) is not taken into account in the work according to the studies [10, 13]. The foregoing indicates that the scheme of screw double-blade piles interaction with clay soil of the foundation does not differ significantly from the scheme of the suspended piles interaction.

![Figure 2. Scheme of loading of a screw double-blade pile in clay soil.]

Two characteristic areas can be identified on the graph of its settlement S (Figure 2), increasing external load N is applied to a screw double-blade pile. The first section (the first stage of loading) is
characterized by a uniform (linear) increase in the settlement \( S \) and ends with a certain value of the settlement \( S_1 \), after reaching which, a "cut" of the soil along the lateral surface of the 'ground cylinder' occurs. The external load \( N_f \) corresponding to the end of the linear dependence on the settlement graph \( S = f(N) \) is

\[
N_f = N_f + N_{p_s},
\]

where \( N_f \) is the part of the external load transferred to the near-soil massif of the soil by the lateral surface of the 'ground cylinder', kN; \( N_{p_s} \) is the same, transferred to the ground of the base by the screw double-blade pile’s lower blade at the stage of the linear dependence end of the precipitation \( S = f(N) \) (at the full realization moment of soil resistance along the lateral surface of the 'ground cylinder'), kN.

When the vertical displacement of pile corresponding to the value of the settlement \( S_f \) is reached, the second stage of the screw double-blade pile loading begins, so, the work of the lower blade in the soil come in full force. In this case, the graph \( S = f(N) \) has a nonlinear dependence. The second stage of the screw double-blade pile loading (working) is completed when an external load \( N_2 \) is reached, which corresponds to the complete depletion of the pile's load capacity on the ground and unstable (sunk) settlement \( S_2 \). The peak load value of the screw pile on the ground is

\[
N_2 = N_f + N_{p_s},
\]

where \( N_2 \) is the external load corresponding to the complete depletion of the bearing capacity of the soil of foundation of the screw double-blade pile and unsterilized (failed) settlement, kN; \( N_f \), \( N_{p_s} \) are the same as in (1), kN; \( N_{p_s} \) is the part of the external load transferred to the ground by the lower blade and corresponding to the loss of its bearing capacity on the ground, kN.

The final settlement of the screw double-blade pile \( S \) for a given load \( N \ (N_f < N < N_2) \) is equal to the sum of settlements \( S_f \) and \( \Delta S \):

\[
S = S_f + \Delta S.
\]  

3. The results of the investigation

Shaft bearing (driven, built-in-place) pile settlement within the first line section shall be determined according to the M.F. Randolph and C.P. Wroth method [11]. The authors of the method [11] in deriving equation took into account only shear deformation. Authors conventionally accepted deformation of soil around piles in the form of concentric cylinders on sides, which are shear stresses \( \tau \), damped from piles in radial direction. The equation for determining the pile shaft settlement \( w \) of bearing pile due to the action of tangential stresses along its lateral surface has the form [11].

\[
w = \frac{\tau_0 r_0}{G} \ln \left( \frac{r_m}{r_0} \right),
\]

where \( r \) is the horizontal distance \( z \) from the vertical axis of the pile to any boundary within the linearly deformable region of the near-pile soil massif, m; \( r_m \) is the horizontal distance \( z \) from the vertical axis of the pile to the boundary where the vertical ground movements (radius of influence) are zero, m; \( r_0 \) is the radius of the pile blade, m; \( \tau_0 \) are tangential stresses acting on the lateral surface of the 'ground cylinder', kPa; \( G \) is the initial shear modulus of ground, kPa.

Let's consider the use of M.F. Randolph et al. method (1978) [11] to calculate the settlement of a double-blade pile in a clay soil at the first stage of its loading. The tangential stresses \( \tau_0 \) are assumed to be uniformly distributed along the lateral surface of the 'ground cylinder' (see Figure 1):

\[
\tau_0 = \frac{N_f}{2\pi r_0 L},
\]

where \( r_0 \) is the radius of the screw double-blade pile 'ground cylinder' (lower blade), m; \( L \) is the height of the 'ground cylinder' (distance between the blades), m; \( N_f \) is the same as in formula (1).

The vertical displacement \( w \) of the pile in equation (3) is formed by tangential stresses \( \tau \) acting in the region around its lateral surface, limited by the distance \( r_m \) (the radius of influence). The distance \( r_m \) can be established by the formula [11]

\[
r_m = 2.5 \cdot l \cdot (1 - \mu),
\]
where \( l \) is the length of the shaft bearing pile in the soil; \( \mu \) is the Poisson's ratio for the soil.

Expression (5) was proposed by M.F. Randolph et al. [11] for determining the radius \( r_m \) of tangential stresses \( \tau \) influence around shaft bearing (driven, built-in-place) pile under the action of vertical external load \( N \). Expression (5) for screw two-bladed piles needed to be refined, since the conditions for their interaction with the clay soil of the base differ significantly from the interaction of shaft bearing driven and built-in-place piles in similar soils. The authors of this study offer the following empirical equation for determining distances \( r_m \) in clay soil from soft-plastic to semi-solid consistency:

\[
r_m = (1.5...2.5)r_0. \tag{6}
\]

The equation (6) is established according to the laboratory experimental studies’ results of clay soil deformations in the foundation by models of screw double-blade piles [12]. It follows from equation (6) that the radius \( r_m \) of influence is much less (approximately 3-4 times) in comparison with the data of M.F. Randolph et al. (1978), established by the equation (5) [11]. The decrease in the radius \( r_m \) of influence in the equation (6) takes into account the screw double-blade piles’ geometric parameters of short length (up to 3 m) and the features of their interaction with the clay soil of the earth foundation.

Substituting expression (4) into equation (3), taking into account equation (6) and taking

\[
w = S_f = S_f = S_R, \tag{7}
\]

we obtain an expression for determining the final settlements of a screw double-blade pile in the first stage of its loading (contact settlement):

\[
S_f = S_f = S_R = m \cdot \frac{N_f}{\pi LG}, \tag{8}
\]

where \( m \) is the dimensionless coefficient equal to 0.203, 0.35 and 0.46 for clay soils of soft-plastic, low-plastic and semi-solid consistency, respectively; \( L \) is the distance between the blades, m; \( G \) is the initial shear modulus, kPa.

Equation (8) includes the initial shear modulus \( G \), which depends on the tangential stresses \( \tau_0 \) distributed along the lateral surface of the ‘ground cylinder’. The characteristic of the initial shear modulus for the linear section of the pile work can be determined from the relations of the elasticity theory as

\[
G = \frac{E_0}{2 \cdot (1 + \mu)}, \tag{9}
\]

where \( E_0 \) is the soil deformation modulus determined by the results of plate-bearing tests in the linear dependence range of the graph \( S = f(p) \); \( \mu \) is the Poisson coefficient of the soil.

The load \( N_f \) (part of the external load \( N_1 \)), which corresponds to the onset of the clay’s soil limiting state at its contact with the side surface of the ‘ground cylinder’, is determined from expression (4) by substituting \( \tau_{max} \) for \( \tau_0 \):

\[
N_f = 2\pi \cdot r_0 \cdot L \cdot \tau_{max}, \tag{10}
\]

where \( \tau_{max} \) is the maximum tangential stress, kPa; \( L, r_0 \) are the same as in expression (4).

The tangential stresses \( \tau_{max} \) can be determined from the Coulomb-Mohr strength condition (§ 5.7.4, SP 22.13330.2016):

\[
\tau = \tau_{max} = \sigma \tan \varphi_1 + c_1, \tag{11}
\]

where \( \sigma \) is the normal stress acting along the lateral surface of the 'ground cylinder' (horizontal stress component of the dead weight of the soil), kPa, \( \varphi_1 \) and \( c_1 \) are the calculated values of the internal friction angle and the specific cohesion of the soil at its contact with the side surface of the 'ground cylinder' appropriately.

The load \( N_R \) (part of the external load \( N_1 \)) in equation (1) can be determined for a hard round die by the Egorov-Schleicher equation

\[
S_R = \frac{N_R \cdot (1 - \mu)}{4G \cdot r_0}, \tag{12}
\]
where the designations are the same as those adopted in the equations (1), (4), (5), (9).

In the case of the shear settlement equality of the 'ground cylinder' $S_f$ and the settlement of the lower blade $S_R$ ($S_f = S_R$) at the time of the external load application $N_i$, the value $N_R$ will be

$$N_R = 4G \cdot n_0 \cdot S_R / (1 - \mu),$$

(12a)

where the designations are the same as those adopted in the equations (1), (4), (9), (12).

Thus, equations for calculating settlement $S_i$ and external load $N_i$ of screw double-blade pile on the first stage of its loading (linear relationship fallout from applied external loads) are received.

After reaching the settlement $S_i$ of the pile with the corresponding load $N_i$, the increment $\Delta S$ of the settlement occurs only due to the soil work under the lower pile blade, as the soil around the lateral surface loses the ability to dissipate the stresses. The settlement of a screw double-bladed pile in the second stage of its loading is determined by the concept of M.V. Malyshev and N.S. Nikitina [14]. The concept assumes a nonlinear dependence of the pile settlement on the applied external load. The nonlinear dependence is due to the fact that the shear modulus in the design scheme is adopted in the fractional linear function form of shear deformation. According to [14], the method for calculating the final settlement $S$ was developed for shallow foundations in the nonlinear stage of the soil deformation, where

$$S = \frac{p_0 (p_2 - p_1) - (p - p_1) \cdot p_1}{p_1 (p_2 - p)} + \Delta S,$$

(13)

where $p_1$ is the initial pressure on the ground foundation, which corresponds to the beginning of the plastic deformation spaces’ onset, kPa; $p_2$ is the pressure corresponding to the bearing capacity exhaustion of the base, kPa; $\Delta S$ is foundation settlement at pressure $p_1$; $p$ is the pressure at the base of ground foundation which the settlement $S$ is determined at.

Let's transform equation (13), having replaced pressure $p$, $p_1$, $p_2$, operating on footing base, on values of the loads passed through the bottom blade in the end of the first $(N_i)$ and second $(N_2)$ loading (working) steps of the screw two-blade pile. We shall replace pressure $p$ with value of a load $\Delta N$. Instead of pressure $p_1$ we shall substitute value of load $N_R$ transferred to a foundation soil through the bottom blade of a pile. Let's replace pressure $p_2$ with value of load $N_a$ relevant to exhaustion of bearing capacity of the bottom blade’s basis of a pile at external load $N_2$ (see Figure 2). Having executed replacement $p$, $p_1$, $p_2$ in the equation (13) on $\Delta N$, $N_R$, $N_a$ accordingly, after simple transformations we shall receive the equation for definition of an settlement increment $\Delta S$, the load caused by action of $\Delta N = N - N_i$ in a range of values $N_i < N < N_2$ (see Figure 2),

$$\Delta S = \Delta N \frac{(N_a - N_R) - (\Delta N - N_R) \cdot N_R}{N_R (N_a - \Delta N)}.$$

(13a)

The final settlement $S$ of the screw double-blade pile from the action of the external load $N$ in reliance on (2a) is defined as

$$S = S_i + \Delta S = S_i + \Delta N \frac{(N_a - N_R) - (\Delta N - N_R) \cdot N_R}{N_R (N_a - \Delta N)}.$$

(14)

The load $N_R$ is determined by the condition (12a), and the load $N_a$ — in accordance with the limit equilibrium theory of soils [16]. It should be noted that M.V. Malyshev and N.S. Nikitina [14] recommend the use of the Terzaghi formula with three coefficients, two of them associated with the soil adhesion and the surcharging, determined according to the Prandtl scheme, and the coefficient associated with the weight of the foundation soil, determined on the basis of the decision of V.B. Sokolovsky.

Thus, the obtained equation (14) allows predicting the final settlements of screw double-blade metal piles in clay soil.
4. Analysis of the research results
Calculations of the double-blade pile settlement by the proposed method [equation (14)] were carried out for clay soils — clays of a stiff-plastic consistency. Data on soils are presented in Table 1. Parameters of the screw pile are as follows: the pile shaft diameter \( d \) of the screw pile was equal to \( d = 0.108 \) m; diameter of blades \( D = 0.3 \) m; the distance between the blades (blade pitch) was \( L = 0.6 \) m; depth of immersion of a screw double-blade pile into the ground \( z = 2.0 \) m.

Table 1. Characteristic values of soils.

| Soil        | \( \gamma \), kN/m\(^3\) | \( I_\ell \) | \( E \), MPa | \( \nu \) | \( \varphi \), deg. | \( c \), kPa |
|-------------|-----------------|-----------|-------------|------|-----------------|-------|
| Tough clay  | 1.85            | 0.45      | 9           | 0.37 | 15              | 18    |

Figure 3. Dependence of the settlement \( S \) of the screw double-blade pile from the external load \( N \) in clay soil: 1 — data calculated by the proposed method; 2 — data according to numerical experiment.

At the same time, modeling of the double-blade screw piles’ operation in the Midas GTS NX software was performed. As the basic initial data, an elastoplastic model of clay soil with hardening was adopted. The method for substantiating the calculation model of the soil, determining its parameters and performing calculations is given in [15]. The obtained results of the screw double-blade piles’ settlement were analyzed, generalized, and based on their basis, the corresponding graphs were constructed (Figure 3). It was found that in the range of external loads \( N = (0.6 ... 0.8)N_2 \) on the screw double-blade piles the values of the settlements determined from the numerical studies’ results (simulation) of their work in the Midas GTS NX and based on the calculation results of the proposed
method, differ in the range of 20-30%. At the same time, the calculated values of the settlement are usually smaller than the values obtained in the simulation of the screw double-blade piles’ operation.

5. Conclusion
1. On the basis of the numerical and analytical studies’ results, a method has been developed for calculating the settlement of screw double-blade metal piles up to 3.0 m in length for foundations of lightly loaded prefabricated buildings. The method is based on the effective constructive solution use of screw two-blade piles, which is characterized by a distance $L$ between the blades equal to $L = 2.0 \ldots 2.5$ of the blade diameter. Taking into account the previously performed studies [8, 9, 15], the area of the method extends application to clay soils (loams, clays) from soft to semi-solid consistency.

2. To assess the reliability of the calculation results using the proposed method, they were compared with the calculation results established on the numerical studies (simulation) basis of the screw double-blade piles operation in clay soils. It was found that for clay soils (clay loam, clay) of a stiff-plastic consistency, the discrepancy between the final sediment values of the screw double-blade piles, established in numerical simulation, with the calculation data by the proposed method does not exceed 20-30%.

References
[1] Narasirnha Rao S, Prasad Y V S N and Shetty M D 1991 J. Soil Foundations 31 35–50
[2] Zhang D J Y 1999 Predicting Capacity of Helical Screw Piles in Alberta Soils Master’s Thesis (Edmonton: University of Alberta)
[3] Hoyt R M and Clemence S P 1989 Uplift capacity of helical anchors in soil Proc. 12th Int. Conf. Soil Mechanics and Foundation Engineering Rio de Janeiro, Brazil. pp. 1019–22
[4] Amy B and Cerato P E 2009 J. Performance of Constructed Facilities 23 4 251–61
[5] Andina S and Leonids P 2010 Helical pile behaviour and load transfer mechanism in different soils Modern Building Materials, Structures and Techniques Proc. Int. Conf. (Vilnius, Lithuania: GediminasTechnical University) pp. 1174–80
[6] D Kim, K Baek and K Park Analysis of the Bearing Capacity of Helical Pile with Hexagonal Joints 2018 Materials 2018 11(10) 1890
[7] Donal J and Calyton P E 2005 Basic Helical Screw Pile Design (Kansas: Earth Contact Products) 1–28
[8] Salhi L, Nait-Rabah O, Deyrat C and Roos C 2013 Electronic Journal of Geotechnical Engineering 18 4319–38
[9] Polishchuk A I and Maksimov F A 2016 Osnovaniya Fundamenti Mekhanika Gruntov 4 37–40
[10] Polishchuk A I and Maksimov F A 2017 Osnovaniya Fundamenti Mekhanika Gruntov 6 9–14
[11] Maksimov F A 2017 Vestnik YuUrGU. Seriya Stroitelstvo i Arkhitektura 17 3 5–11
[12] Randolph M F and Wroth C P 1978 J. Geotech. Eng 104 1465–88
[13] Maksimov F A, Serebrennikova E N and Skomorokhov M M 2013 Issledovaniya sovmestnog raboty dvuhklopastnyx vintovoy svai s gruntom v laboratornyx uslovijakh Proc. Conf. Geotechnic: Theory and Practic (SPb: St. Petersburg State University of Architecture and Civil Engineering) 52–5
[14] Maksimov F A 2018 Improving the Design and Methods for Calculating Double-Cavity Screw Piles in Clay Soils Abst. PhD Thes. Tech. Sci. (Volgograd: Volgograd State Technical University) p 23
[15] Malyshev M V and Nikitina N S 1982 Osnovaniya Fundamenti i Mekhanika Gruntov 2 21–4
[16] Polishchuk A I 2017 Numerical Analysis of Helical Pile–Soil Interaction under Compressive Loads IOP Conference Series:Materials Science and Engineering 262 012099
[17] Soil Bases of Buildings and Structures Set of RF Rules SP 22.13330.2016 (Moscow: Standartinform)