Numerical Analysis of Helical Pile–Soil Interaction under Compressive Loads

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Abstract: The results of the field tests of full-scale steel helical piles in clay soils intended for prefabricated temporary buildings foundations are presented in this article. The finite element modeling was used for the evaluation of stress distribution of the clay soil around helical piles. An approach of modeling of the screw-pile geometry has been proposed through the Finite Element Analysis. Steel helical piles with a length of 2.0 m, shaft diameter of 0.108 m and a blade diameter of 0.3 m were used in the experiments. The experiments have shown the efficiency of double-bladed helical piles in the clay soils compared to single-bladed piles. It has been experimentally established that the introduction of the second blade into the pile shaft provides an increase of the bearing capacity in clay soil up to 30% compared to a single-bladed helical pile with similar geometrical dimensions. The numerical results are compared with the measurements obtained by a large scale test and the bearing capacity has been estimated. It has been found that the model results fit the field results. For a double-bladed helical pile it was revealed that shear stresses upon pile loading are formed along the lateral surface forming a cylindrical failure surface.

1. General information

In recent years pile foundations with steel double-bladed helical piles with different length (mostly 1.5 to 3.0 m) have been used in the construction of prefabricated and temporary buildings quite often. This pile type have a number of advantages in comparison with other types, for example, the lack of dynamic impact on the foundation and neighboring buildings during their construction, considerable installation speed.

Kuban State Agrarian University (Krasnodar) with South Ural State University (Chelyabinsk), jointly are engaged in research of steel helical piles (single- and double-bladed) performance estimation in clay soils. It was found that the clay soil (1), enclosed between the blades (2,3) of the helical double-bladed pile under load, takes the form of a "ground cylinder" (4) and begins to work as a single integral element with its shaft (5) (Figure 1).

The most high-quality "ground cylinder" is formed in piles with a distance L between the blades of 2.0...2.5 of their diameter (L = 2.0...2.5 D). The presence of a "ground cylinder" (4) leads to an increase of the lateral surface of the helical double-bladed pile in the area between the blades and thus leads to an increase in bearing capacity \( F_d \) in general. The external load \( N \) acting on the double-bladed helical pile is perceived by the surrounding soil through the soil resistance \( f \) on contact with the lateral surface of the "ground cylinder" and through the soil resistance \( R \) below the lower blade of the pile. The soil resistance \( f \) along the lateral surface of the steel smooth barrel (5) of the screw pile (on the
shaft above the second blade) may not be taken into account, since the share of this load for piles up to 3 m in clay soil does not exceed 5-10% of its total bearing capacity \( F_d \). The foregoing gives reasons to believe that the scheme of interaction of helical double-bladed pile with clay soil of the base does not differ significantly from the scheme of interaction of driven piles, which makes it possible to use known theoretical principles to improve the method for calculating their settlement [1-3].

2. Experimental research

Steel helical piles with a length of 2.0 m, shaft diameter of 0.108 m and a blade diameter of 0.3 m were used in the experiments. The lower blade of both pile’s structures (a single-blade and double-blade) arranged at the lower end of the cylindrical part of the shaft, and the upper blade (double-blade piles) at a distance of \( L = 2.0 \) D from the bottom of the blade (D - blade diameter). Pile tests were conducted on the experimental site, composed mainly of eluvial stiff clay at a depth of 4.1 m from the level of the natural terrain. Clay had the following physico-mechanical characteristics: density of 1.94 g/cm\(^3\); natural moisture content – 23 %; plasticity index - 0.26; liquidity index - 0.12; friction angle – 18°; cohesion – 0.047 MPa. The soil was characterized as saturated, as the ratio of water saturation (moisture content) of \( S_r \) was equal to \( S_r = 0.87 > 0.8 \) [4].

The tests involved an evaluation of the bearing capacity of full-scale two-bladed helical piles compared to helical piles with one blade. Screw piles were installed by screwing at the same depth, equal to 1.9 m from the surface. The test procedure is described in detail in [1].

Graphical dependencies of the settlement (displacement) on the applied load were constructed according to the results of parallel tests of the piles (single-bladed and double-bladed) in clay soil and their generalization (Figure 2).

In experiments with a single-bladed pile, the load preceding its failure, which was characterized by the intensive growth of the settlement \( S \), not damped in time, was taken as the bearing capacity (the particular value of the resistance) \( F_d \). In experiments with two-bladed helical pile, the load under which the pile was getting a settlement \( S \) equal to 30 mm (as provided by the testing program) was taken as the bearing capacity of piles \( F_d \). As a result of experiments in case of single-bladed pile \( F_d = 48 \) kN, and double-bladed pile \( F_d = 64 \) kN (Figure 2). Thus, the obtained results indicate that the second blade (\( L/D = 2.0-2.5 \)) increases the bearing capacity of the pile by 30% compared to the bearing capacity of the pile with one blade. It was also found that when testing a single-bladed piles an
increase of intensity of the settlement growth is observed with settlement of more than 15-20 mm, which is typical for their "failure". When testing similar helical double-bladed piles, the signs of their "failure" are not observed until the loads corresponding to the settlement $S = 30$ mm or more.

3. Numerical modeling method of helical piles

MIDAS GTS NX software package which is now widely used in geotechnical calculations [5,6] was used for the numerical analysis of the operation of helical piles in clay soils. One of the advantages of MIDAS is the possibility of using various soil models in the calculation, which allows model (evaluate) their behavior under loading and unloading. The considered models are acceptable for different classes of soils according to the interstate standard GOST 25100-2011.

A soil model called the "Modified Mohr-Coulomb Model" was used in the numerical analysis of helical piles [6]. This choice was made based on the study of the results of research V Fedorovsky (1985-1988), V Shirokov and V Solomin (1987-1990), A Fadeev (1998-2011), L Strokova (2008-2011), A Shashkin (2011) and other experts in the evaluation of soil behavior.

Experimental determination of the parameters of the soil model ("modified Mohr – Coulomb model") requires the use of special equipment such as triaxial compression, which in practice is not always possible. However, data on these parameters for various soil classes, which are recommended (possible) to use in geotechnical and other calculations, are provided in the scientific and technical literature [5-9]. The initial data corresponding to real static tests conditions of helical piles was used for the calculations in MIDAS. In addition, the ground parameters required for calculations were taken on the basis of the results of engineering and geological surveys, taking into account processing and the recommendations [10,11].

Data processing of laboratory tests of clay soil deformation according to the results of the compression test according to Strokova method, described in [10] was conducted for assigning stiffness parameters of the considered soil model ("modified Mohr – Coulomb model"): tangential modulus of primary compression $E_{ordref}$, unloading modulus $E_{ur}$, the exponent of the non-linearity of the curve $m$, the overconsolidation ratio OCR. Poisson's ratio $\mu$ was taken on the recommendations of Tsytovich [11], as for clays and loams ($\mu = 0.1$ to 0.15). This range of values of $\mu$ is confirmed by experimental studies given in [12-14]. Parameters of soil stiffness ($\phi$ and $c$) are taken from the results of clay soil tests using the single-plane cut method: specific weight of 19.4 kN/m$^3$; the tangent modulus of primary compression $E_{ordref} = 8.3$ MPa; the unloading modulus – secondary loading $E_{ur} = 21$ MPa; the non-linearity of the curve degree $m=0.8$; the overconsolidation ratio OCR=1.5; Poisson's ratio $\mu=0.15$; $K_0=0.8$; cohesion $=0.047$ MPa; friction angle $\phi = 18^\circ$; the dilatancy angle $\psi=0^\circ$. The design schemes geometry of helical piles was created in the SolidWorks and then imported into the MIDAS using CAD-interfaces (Figure 3).

![Helical piles models](image_url)

**Figure 3.** Helical piles models.

Geometric parameters as well as physical and mechanical characteristics of helical piles are given in Table. 1. Elastic model was used for analysis of the material of steel helical pile; their modeling was carried out in a three-dimensional setting. At the stage of modeling it was considered that the models
were embedded in the clay of semi-solid consistency to a depth of 1,9 m, which corresponds to their real position for static tests.

Table 1. Geometric parameters and physical and mechanical characteristics of helical piles.

| No. | Parameters and physical and mechanical characteristics of helical piles | Values |
|-----|---------------------------------------------------------------|--------|
| 1   | Length of the pile                                           | 2,0 m  |
| 2   | Shaft diameter                                                | d=0,108 m |
| 3   | Blade diameter                                                | D=0,3 m |
| 4   | Distance between the blades (for a double-bladed pile)        | L = 0,6 m |
| 5   | Material of helical pile                                      | Steel |
| 6   | Modulus of elasticity of steel                                | 2,1 E+005 MPa |
| 7   | Density of steel                                              | 7,85 g/cm³ |
| 8   | Poisson’s ratio of steel                                       | 0,3    |

To increase the accuracy of calculations in places of maximum concentration of stresses and significant displacements, the finite element grid had a smaller breakdown. The boundary conditions are:

- vertical model boundaries with their normal in x-direction are fixed in x-direction (\(u_x = 0\)) and free in y-direction
- the model bottom boundary is fixed in all directions

The following processes were modeled for analysis of helical piles (single- and double-bladed):

- formation of initial conditions stress representing the weight of soil layers.
- step-by-step vertical displacement of helical piles within 45 mm.

Using the approach in the form of a vertical displacement of the helical pile is more preferable, because it allows to avoid a high stress concentration in the area near the pile. During the formation of the design schemes, points corresponding to the center of the piles top were selected on the finite element grid. The "load-settlement" curves were made for these points as a result of the pile under compression loads.

4. Helical pile modeling results

Based on the results of numerical simulation in the Midas GTS NX PC, the bearing capacity \(F_d\) of helical piles (single- and double-bladed) and the stressed condition of clay soil in the near-well space were estimated. It was found that for helical single-bladed piles an external load \(N\) of 40 to 45 kN leads to an increase of the settlement growth rate, which indicates their "failure" during loading. Such an increase in the intensity \(S\) begins when the piles settlement \(S = 15-20 \text{ mm}\) (Fig. 4). The load \(N\), preceding its "failure", which was characterized by intensive settlement growth (by analogy with full-scale tests) was taken as a criterion of bearing capacity of the single-bladed helical pile \(F_d\) according to the results of numerical analysis. The bearing capacity of the single-bladed helical pile was \(F_d = 43 \text{ kN}\). The load under which the pile had a settlement \(S = 30 \text{ mm}\) (as provided by the program field tests) was a criterion of the bearing capacity of double-bladed helical pile \(F_d\). The bearing capacity of the double-bladed helical pile according to the results of numerical analysis was \(F_d = 58 \text{ kN}\) (Figure 4).

In order to better understand the failure mechanism of helical piles under compressive loading, it is most convenient to analyze the state of stress in the soil in terms of shear stress of the soil.

The stress condition of clay soil in the near-well space of the helical pile models was estimated using the example of the shear stresses distribution \(\tau_{yz}\). It was found that an increase of the external load \(N\) leads to a change of the soil stressed condition around the blades.
Under external load on the single-bladed helical pile \( N = 40-45 \) kN, the shear stresses \( \tau_{yz} \) are developed intensively, they are concentrated in the soil at some distance from the blades (in Figure 5).

The shear zones development observed during the field experiments can be an explanation for the "failure" of single-bladed helical piles with their settlements \( S = 15-20 \) mm and more. For double-bladed helical piles it was revealed that shear stresses \( \tau_{yz} \) (shear zones) with an external load \( N = 56-60 \) kN are formed along the lateral surface of the "ground cylinder" interacting with the surrounding soil (Figure 6). It was explain that the helical double-bladed pile under load in the stiff clay soil has cylindrical shear behavior occurs at relative spacing 2 D. In the research Lakhdar Salhi [15] shows that in the cohesionless soils of cylindrical shear mechanism of helical pile – soil interaction occurs at a relative distance of less than 1.5 D.

The areas of shear stresses \( \tau_{yz} \) (shear zones) under the lower blade of the helical double-bladed pile extend downward and to the sides. The absence of clear data on the bearing capacity loss ("failure") of the pile, in our opinion, is associated with a more gradual development of the shear zones at the base of the lower blade under loading. Even in the critical state \( (N = 58 \) kN or more), the shear stresses \( \tau_{yz} \)
(shear zones) in clay soil under the lower blade do not close (as in the case of single-bladed piles), but spread downwards and to the sides.

Comparison of the results of full-scale tests of helical piles (single- and double-bladed) in clay soil with numerical analysis data has allowed to establish the following (Figure 7).

The settlements graphs of the helical piles $S = f(N)$ based on the results of field tests and numerical analysis are qualitatively similar to each other, but a quantitative difference is observed. Settlements of helical piles $S$, determined from numerical analysis in the range of external loads up to 70 kN, is approximately 10-15% less than the experimental values obtained during field tests. This pattern is typical for both single- and double-bladed piles. Based on the results of numerical simulation, it is established that the bearing capacity $F_d$ in clay soils for single-bladed helical piles can be assumed $F_d = 43$ kN, and for double-bladed piles $F_d = 58$ kN. The difference in estimating the bearing capacity $F_d$ according to the results of field tests and numerical modeling data is 10% for single-bladed and double-bladed piles.

5. Conclusions
On the basis of experimental and theoretical studies, the efficiency of double-bladed helical piles with a length of 2.0 m, with shaft and blade diameters of 0.108 and 0.3 m and a distance L between the blades $L = 2.0...2.5$ D was revealed. The considered designs of double-bladed helical piles are recommended to be used for the foundation of prefabricated and temporary buildings.

It was established that the results of numerical analysis in the PC software Midas GTS NX can be used for the evaluation of the bearing capacity of double-bladed helical piles in clay soil. Thus, on the basis of comparison of results of experimental and theoretical studies it was found that the difference in the evaluation of the bearing capacity of piles did not exceed 10%.

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