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Investigation of the behavior of the spiral micropile in soil

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ABSTRACT: The study of a new construction of a micropile are presented. The proposed vertical micropiles of a new construction has a large surface area due to the spiral shape and a bigger bearing capacity compared to the usual micropile. As a result, numerical modeling, the influence of the number of a pile spiral turn and the relative "elongation" of a spiral turn on the change in load capacity, as well as the features of its compressibility. Analysis of the results of the numerical modeling shows area of the effective constructive combinations of the spiral turns number along the length of pile and the "elongation" (width) of the turn. This area arranges the biggest load capacity of the spiral pile compared to the usual micropile. Additionally, restrictions on compressibility have been imposed to confine torsional tensions. At conclusion, the authors for-mulate the problems for continuation research.

1 INTRODUCTION

One of the areas of geotechnics, the development of which is most active, is pile foundations. This is promoted by the development of construction on areas with difficult unfavorable soils and the increasing in the technological level of execution the work.

The common goal in the development of all pile technologies is to maximize the bearing capacity of the piles. At the same time the pile must have a high technological effectiveness of the pile installation, a low unit cost and minimum settlements. Many new installation technologies for various types of piles have appeared in recent decades to solve this goal (Mangushev et al., 2015). The goal achievement is particular important during construction on soft soil, where the pile cannot be based upon hard or rock soil. Such soil conditions imply the using of friction piles only. These soils are common in Sedimentary and Residual Soils areas.

2 STATE OF THE RESEARCH

Many scientists have worked on the problem of increasing the bearing capacity of friction piles in soft soil (Xu et al., 2020). Studies were conducted on various ways to increase friction forces on the side surface of piles(Teixeira et al., 2012, Dai et al., 2007), determinate and clarify friction coefficients between soil and pile (Ivanova et al., 2016), clarify calculation assumptions and models (Basack et al., 2022), develop new pile designs (Vertynskii and Emel'yanova, 2013). Many studies have found application in civil engineering (Hajrullin et al., 2015).

One way to increase the bearing capacity of a friction pile is to increase the side surface area. Until now, this could be achieved in two ways: by increasing the cross-section of the pile or by increasing its length. However, there is another way, suggested by the authors, that does

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not affect the cross-section and length of the pile. In this case pile length will be understood as the depth of the pile tip position.

In order to describe this method, it is first necessary to explain the stages that preceded its creation. The authors encountered a problem of ensuring the verticality of the borehole at depths greater than 10 meters - the borehole axis began to deflect. The first stage included this observation about the borehole, that was made for soil investigation or the micropile installation. The maximum deflection angle of the borehole or micropile axis reached 10 degrees during vertical drilling. This led to the conclusion that the probability of borehole deviation from the vertical increases with depth. The next step was a study based on previous findings: if random deviation from vertical is possible for a vertical micropile, how will it affect on the bearing capacity of the pile? Authors found out during a series of numerical modeling experiments that a small deviation of the micropile from the vertical has no effect on its bearing capacity. Then the angles of deviation from the vertical were larger, than the bearing capacity decreased.

Analyzing the conclusions at each of the steps, the author's team decided to apply the idea of "Conversion of harm into benefit" for the method of increasing the bearing capacity of the pile. The use of this idea is expressed in the following: 1 - there is always a probability of micropile deviation from the vertical during installation; 2 - the probability of micropile deviation increases through depth; 3 - minor deviations do not affect on the bearing capacity of micropile; 4 - deviation of micropile from the vertical reduces the depth of the pile tip position.

Therefore, if the micropile axis is bent, it is possible to increase the lateral surface area, compared to the vertical micropile, which have the same tip depth. If the micropile axis is not randomly bent, but rather, it is possible to obtain a micropile of a new design. All this can have a favorable effect on the bearing capacity of the pile.

3 MATERIALS AND METHODS

A new design of spiral micropile (SMP) is proposed. A spiral shape of micropile is described by equations (1). SMP can be created with different shapes. The study was conducted with different design solutions of SMP in order to identify the general laws of the shape influence on SMP behavior in the soil. The design dimensions are shown in Figure 1: D_1 is the overall diameter of SMP, D is the diameter of the spiral, d is the cross-sectional diameter of the micropile shaft, L is the overall height of SMP, l is the pitch of the spiral. The top of the SMP has a vertical section for coaxial accommodation of the vertical load.

$$\{x = (u)\ (cos\ cos\ (v) + B)\ y = A \cdot sin(u)(cos(v) + B)\ z = sin(v) + C \cdot u \qquad (1)$$

if $u \in [-D\cdot\pi;\ D\cdot \pi]$ $v \in [-D\cdot \pi; D\cdot\pi]$

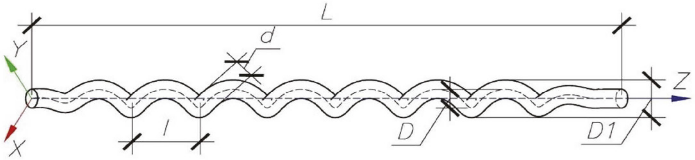

Figure 1. General design of the spiral micropile (SMP).

Taking into account different design types of SMP to study their behavior in the soil, it is necessary to introduce additional properties of SMP, allowing them to classify. Such properties will be: the relative elongation of the pitch of the spiral l/D (Figure 2) and the number of the pitch of the spiral L/l (Figure 3).

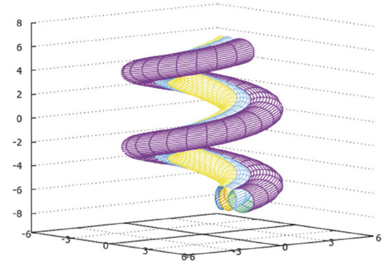

Figure 2. Influence of the relative elongation of the pitch of the spiral *l*/*D* at a constant value of *l*.

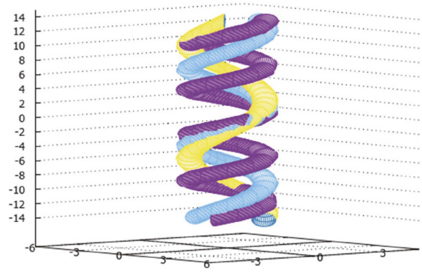

Figure 3. Influence of the number of the pitch of the spiral *L*/*l* at a constant value of *D*.

Using parameters *l*/*D* and *L*/*l*, it is possible to perform a simultaneous analysis of SMP of different shapes to identificate of trends of changes in bearing capacity and compressibility. Unfortunately, different mathematical forms of SMP cannot be reflected in reality. This is hindered by technological limitations and principles of reasonableness.

The design of the spiral micropile is new and implies many directions for its research. Given that the advantage of such piles has not yet been identified, the least time-consuming study would be numerical modeling.

4 NUMERICAL MODELING

To identify the influence of the SMP shape on its behavior in the soil, a numerical study was performed using Midas FEA NX 2022.1.1. Various SMP shapes with intersectional parameters *l*/*D* and *L*/*l* (Table 1, columns 1-7) with a constant cross-sectional diameter of the micropile shaft *d* were considered.

Table 1. Dimensions of the studied SMP.

№	*d*, m	*D*, m	*L*, m	*l*, m	*L*/*l*	*l*/*D*	IF_d, kN	$IF_{d,min}$, kN	$\mathrm{IF_d}$	ε_i, %
1	2	3	4	5	6	7	8	9	10	11
1		0.45	4			2.67	547		1.31	0.022
2		0.6			3.33	2.00	617	419	1.47	0.068
3		0.9				1.33	607		1.45	0.263
4		0.45	7			2.67	846		1.36	0.038
5	0.3	0.6		1.2	5.83	2.00	895	622	1.44	0.090
6		0.9				1.33	641		1.03	0.214
7		0.45	10			2.67	1091		1.30	0.042
8		0.6			8.33	2.00	1020	841	1.21	0.097
9		0.9				1.33	646		0.77	0.171

The general view of the computational model is shown in Figure 4. The computational model has dimensions of 26,0x21,2x20,0 m. The structure is a pile cap measuring 6,0x1,2 m and two identical spiral micropiles (Table 1, columns 2-7) with a spacing of 4,0 m. A uniformly distributed load was applied to the pile cap to determine the bearing capacity of the piles. Transmission of pressure from the pile cap to the soil was prohibited.

Additionally, vertical micropile simulations were performed with the same tip depth to determine the effectiveness of SMP (Figure 5).

Mohr-Coulomb model was used to define soil behavior, Elastic model was used to define contruction behavior (Mirnyj and Ter-Martirosyan, 2017). The parameter values are presented in Table 2. Based on the geometric model, a finite element mesh was created (Karaulov et al., 2022). The size of the finite elements increased as they moved away from the study area. The interface elements were used for modeling SMP in the soil.

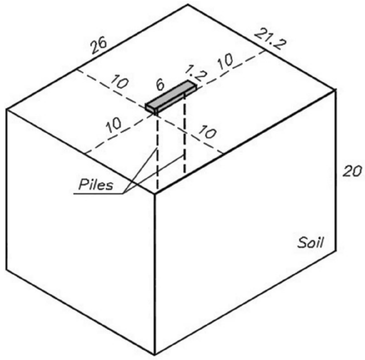

Figure 4. The general view of the computational model.

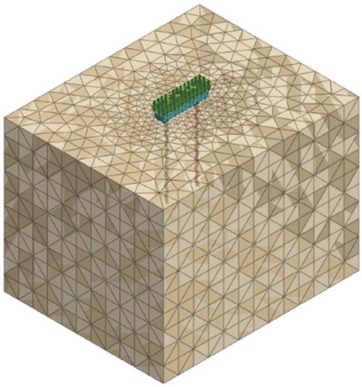

Figure 5. The computational model.

Table 2. Material models and their parameters.

Symbol	Parameter	Unit	Material model	
			Mohr-Coulomb	Elastic
E'	Young's modulus	MPa	15.2	38000
v	Poisson's ratio	-	0.39	0.2
c	Intercept cohesion	kPa	33	–
φ	Angle of internal friction	degree	17.5	–
ψ	Angle of dilatancy	degree	0	–
γ	Unit weigh	kN/m^3	18.7	25

5 ANALYSIS AND RESULTS

A series of numerical calculations with SMP of different shapes made it possible to determine their bearing capacity (Table 1, column 8). It was found that the increase of parameter l/D decreases the bearing capacity of the pile. The bearing capacity values of vertical micropiles were also obtained (Table 1, column 9). An the bearing capacity increase index $\boldsymbol{IF_d}$ for SMP was additionally determined to evaluate the obtained data (Table 1, column 10). It was defined as the ratio between the bearing capacity of the SMP of the selected shape and he bearing capacity of the vertical micropile at equal pile length L and pile cross-section d. This index allows us to evaluate the effectiveness of the SMP form, considering only the criterion of bearing capacity increase.

A polygonal surface was constructed to analyze the effectiveness of multiple SMP shapes simultaneously. Nodes of the surface were the values of the bearing capacity increase index IF_d (Figure 6), the relative elongation of the pitch of the spiral l/D and the number of the pitch of the spiral L/l of each investigated SMP shape. The polygonal surface has a delineated maximum IF_d = 1.44 (Figure 6, point 5), and a delineated minimum IF_d = 0.77 (Figure 6, point 9). This allows us to conclude that the shape of the SMP significantly affects on the bearing capacity.

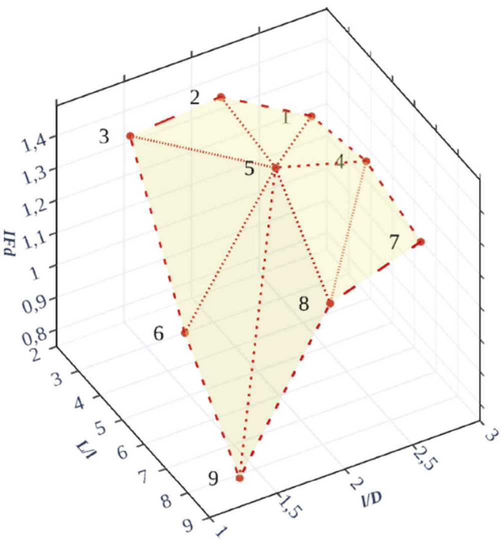

Figure 6. Polygonal surface IF_d for SMP.

For further analysis of the results, the complexity of the SMP shape compared to the vertical micropile should be considered. A reasonable application of the SMP should provide a significant increase in the bearing capacity compared to the vertical micropile (i.e., a significant increase in IF_d). In author's opinion, this would be a reasonable "price" for the increased complexity of the SMP shape. The condition $IF_d \geq 1.4$ is assigned as an area of reasonable SMP appliance. A horizontal cutting plane was drawn across the polygonal surface (Figure 6) at $IF_d \geq 1.4$ (Figure 7) to determine the many different SMP shapes that possess the accepted condition. A projection on the plane of the polygonal surface represents the outer boundaries of the effectiveness SMP forms area satisfying the condition $IF_d \geq 1.4$.

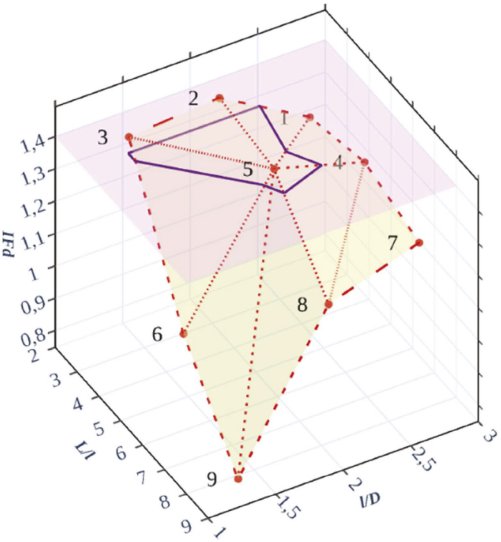

Figure 7. Polygonal surface IF_d for SMP and horizontal cutting plane.

The identified area (Figure 7) determines the effective shape of the SMP, based only on the accepted its bearing capacity increasing. At the same time, it should be taken into account that the shape of SMP is more susceptible to compression than vertical micropile due to helicity. Therefore, the SMP behavior in the soil should be evaluated by the compression of the pile shaft additionally.

The fulfilled series of SMP numerical calculations made it possible to determine the relative compression of the pile shaft ε under the load equal to the bearing capacity of the pile (Table 1, column 11). It was found that the SMP length has an insignificant effect on the compressibility of the pile (less than 15%). The greatest influence on the compressibility of the SMP shaft has the relative elongation of the pitch of the spiral l/D. The increasing of D at constant l increases the relative compressibility of the SMP particularly (Figure 8). For example, for a 7 m long SMP with l/D = 2.67, the relative compressibility of the pile shaft is ε = 0.038%, and with l/D = 1.33 ε = 0.214%, higher by 463%. Relative compressibility of the pile shaft ε decreases as the parameter l/D increases.

It is necessary to establish limit values to evaluate the relative compressibility of the pile shaft ε. If parameter ε is in excess of limit values the SMP material mode of operation changes significantly. In other words, the limit value of ε should indicate the elastic limit or the beginning of the cracking process. The actual value of the limit parameter ε should depend on the SMP material and the technology of its installation. Authors specified the value of the limit of the relative compressibility of the pile shaft ε as 0.1% (horizontal red dashed line in Figure 8). It intersects with the envelope functions of compressibility development for SMP with different length. The projection of the intersection point on the X-axis indicates the minimum allowable value of the parameter *l/D = 1.95* that meets the compressibility criterion. Thus, the area of SMP design solutions according to the criterion of relative compressibility admissibility is highlighted (the green area in Figure 8).

Effective SMP shapes must meet the joint requirements of higher bearing capacity and low compressibility. Thus, it is necessary to combine the surface projection IF_d (effective SMP shapes) satisfying the condition $IF_d \geq 1.4$ (Figure 7) and the minimum allowable value of parameter l/D = 1.95 (Figure 8), assigned by the compressibility criterion $\varepsilon \leq 0.1\%$. The result is the highlighted area of the effective SMP shape, shown in Figure 9.

The coordinates of the point (l/D and L/l) inside the selected area describe the design solution of the SMP that simultaneously meets two conditions: $IF_d \geq 1.4$ and $\varepsilon \leq 0.1\%$.

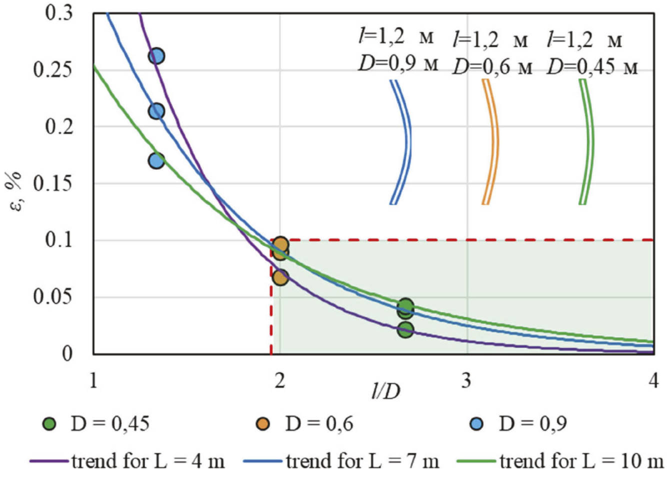

Figure 8. Analysis of change ε for SMP.

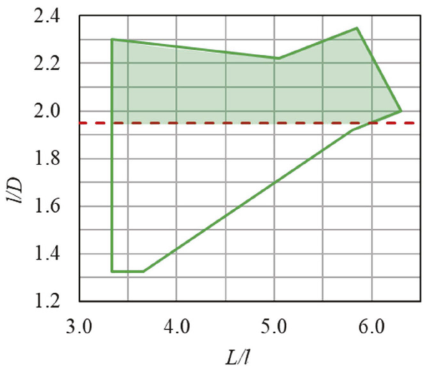

Figure 9. Surface projection IF_d for SMP that are limited by compressibility criteria.

6 CONCLUSIONS

It should be introduced a significant clarification that the spiral micropile (SMP), at the moment, is only an idea. Completed numerical simulation of its behavior with the soil is an effort to reveal the reasonableness of its more targeted research in future. The conditions adopted in the work $IF_d \geq 1.4$(and $\varepsilon \leq 0.1\%$) reflect only the way of such search and do not yet have the necessary justification. Nevertheless, taking all this into account, it is possible to draw general conclusions:

1. The spiral shape of micropile is the result to solve the problem of the verticality of boreholes at depths greater than 10 m. The way to find such a solution was to adopt one of the **TIPS** ideas "Conversion of harm into benefit". It allows to reinforce the main defect of micropile - random deviation from verticality.
2. Giving the micropile a regular spiral shape affects its bearing capacity. The bearing capacity of some SMP structural forms exceeds the vertical micropile bearing capacity with the same length by more than 40%. The bearing capacity of the SMP depends to a greater extent on the elongation of the pitch of the spiral.
3. The regular spiral shape of the micropile significantly effects on its compressibility. The elongation of the pitch of the spiral is more significant than the number of the pitch of the

spiral along its length. The compressibility of the SMP exceeds the compressibility of the vertical micropile. Therefore, the structural shape of SMP should be based on the condition of its ultimate compressibility.

The idea of the SMP is inherently revolutionary. The pile shaft was traditionally perceived only as straight, and its deviation (curvature) was considered as a defect. That was the inertia of thinking. SMP appeared by looking at this problem from a different angle and turning the disadvantage to the advantage. A wine corkscrew can be considered as the prototype of SMP in normal life. The bearing capacity of such "anchor pile" is very high. Research of the SMP behavior as an anchor will be conducted.

The material of SMP and the technology of its installation into the soil are a fair question. At this stage the authors see the implementation of SMP from metal or reinforced concrete. SMP can be screwed into the soil or arranged in the soil by directional drilling. Be that as it may, the questions of SMP material and technology have not been answered.

The authors are convinced that the idea of SMP should be protected. That is why a patent application has been filed for future research.

REFERENCES

Basack, S., Karami, M., Karakouzian, M., 2022. Pile-soil interaction under cyclic lateral load in loose sand: Experimental and numerical evaluations. Soil Dynamics and Earthquake Engineering 162, 107439.

Dai, Z., Su, M., Hu, C., 2007. Two numerical solutions of piles subjected to laterally parabolic distributed loads with biparameter method. Yanshilixue Yu Gongcheng Xuebao/Chinese Journal of Rock Mechanics and Engineering 26, 1463–1469.

Hajrullin, V.A., Zencov, V.N., Shakirova E. V., 2015. Ocenka ekonomicheskogo effekta ot vnedreniya novyh konstruktivnyh reshenij v stroitel'stve [WWW Document]. Izvestiya vysshih uchebnyh zavedenij. Sociologiya. Ekonomika. Politika. № 1.

Ivanova, T. v., Albert, I.U., Kaufman, B.D., Shulman, S.G., 2016. The load-bearing capacity of hanging piles by the strength criterion of a pile or soil material. Magazine of Civil Engineering 67, 3–12.

Karaulov, A.M., Korolev, K. v., Kuznetsov, A.O., 2022. Bearing Capacity Assessment of Soil Foundation. Soil Mechanics and Foundation Engineering 59, 111–118.

Mangushev, R.A., Gotman A. L., Znamenskij V. V., Ponomarev A. B., 2015. Svai i svajnye fundamenty. Konstrukcii, proektirovanie i tekhnologii [WWW Document]. Moscow. ASV.

Mirnyj, A.Yu., Ter-Martirosyan, A.Z., 2017. Oblast' primeneniya sovremennyh mekhanicheskih modelej gruntov [WWW Document]. Geotekhnika № 1.

Teixeira, A., Honjo, Y., Gomes Correia, A., Abel Henriques, A., 2012. Sensitivity analysis of vertically loaded pile reliability. Soils and Foundations 52, 1118–1129.

Vertynskii, O.S., Emel'yanova, T.A., 2013. Development and investigation of the performance of a new design of cast-in-place pile. Soil Mechanics and Foundation Engineering 50, 206–211.

Xu, X.B., Hu, M.Y., Zhang, T.Y., Chen, K.L., Wang, J.C., 2020. Model tests on the bearing capacity of precast open-ended micro pipe piles in soft soil. Proceedings of the Institution of Civil Engineers: Geotechnical Engineering 173, 500–518.