Method of the cast-in-place friction pile well walls local soil compaction

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Abstract. For improving the bearing capacity of the foundations on cast-in-place friction piles, the well walls local soil compaction technology is proposed to be used. The idea of the local soil compaction technology is to form the well having a cross-section different from the traditional round one. The application prospects theoretical justification of the shortened hypocycloid as a cast-in-place friction pile cross-section shape was carried out. The possibility of the cast-in-place friction pile bearing capacity considerable improvement is shown. The pile bearing capacity as compared to the traditional circle section without additional costs can theoretically be increased by the value of up to 80%. The basic arrangement of the attached working body for forming the well having a cross section in the shortened hypocycloid shape is presented. The proposed technical solution application when constructing foundations only in housing construction will make it possible to save annually on the piles material over 400 million rubles.

Key words: cast-in-place pile, bearing capacity, shortened hypocycloid

1. Introduction
The modern stage of the building technologies development is characterized by searching for the material resources and technical equipment rational use technologies [1-4]. The manufactured products competitiveness is currently possible including by reducing the capital costs during the construction process of the industrial facilities and technological infrastructure ones. The materials efficient use implies not only the energy and resource private saving, but also the search for the technologies comprehensively solving the problem of simultaneous providing the constructed foundation necessary lifting properties and costs reducing.

Currently the cast-in-place friction piles (CFP) supported foundations have become widespread. The main advantage of this pile as compared to the driven friction piles (DFP) is the possibility of using the lower quality and strength materials aimed only for operating loads. Another advantage is CFP installation practically without wastes. At the same time, CFP main disadvantage is low (reduction to 40 %) bearing capacity in comparison with the similar in size DFP. FCP bearing capacity improving problem solution is seen in the comprehensive problem solution. The bearing capacity improvement of the pile should not be followed by the materials consumption increase for producing, should not be followed by the increased environmental impact, should not result in the increased complexity of the developed technology and equipment used for its implementation. The local compaction technologies have a certain potential to deal with such complex problems. At present, various technologies are used for the formation and compaction of CFP well walls. One of such technologies is punching the wells with compacted walls by means of gravitational, hydraulic or vibrating punches (figure 1). Such technologies advantage is the possibility of the cross-section of different shapes formation including...
non-circular section, as well as the formation of the side surface inclination to the CFP axis which significantly improves its bearing capacity. However, a significant disadvantage of such technologies is the specialized energy-intensive equipment requirement for sinking into the soil and subsequent pulling the profiled punch out of it. Another promising direction of the well walls soil compaction is rolling with the help of the specialized working body. The advantage of this technology is the low energy consumption, only rotary motion using when developing the well body which essentially simplifies the base machine choice (figure 2). The technology main drawback is the impossibility to form the well cross-section different from the round one.

Figure 1. The attached equipment UKS-7 for sinking the punch into the soil (A) and the hydraulic power unit for the subsequent pulling out (B).

The development of the equipment that would simultaneously allow, by using operating base machines, to form the wells with the compacted soil into the walls and cross-section, different from the round one, would make it possible to solve the material costs reducing problem comprehensively and, as the ultimate objective, the capital costs reducing problem at the stage of the foundation works.
The use of the wells rolling attachable equipment technical idea (figure 2) seems to be the most reasonable one as the CFP well walls local soil compaction working body prototype due to the low power-to-weight ratio and easy technical implementation.

2. Problem statement
The CFP well walls local soil compaction problem solution, hence the bearing capacity improving one seems to be in the search of the closed smooth curve to be used as the working body sealing elements motion trajectory and further development of the mechanism design for the chosen soil moving elements motion trajectory execution.

3. Theory
According to the current normative documents, the CFP bearing capacity is defined by the following dependence [5]:

\[ F_d = \gamma_c \left( \gamma_{cR} RA + \gamma_{cf} u \sum_{i=1}^{n} f_i h_i \right) \]  

(1)

where \( \gamma_c \) is the pile operating conditions coefficient; \( \gamma_{cR} \) is the soil operating conditions coefficient under the pile tip; \( R \) is the soil calculated resistance under the pile tip, kPa; \( A \) is the pile bearing area, m\(^2\); \( \gamma_{cf} \) is the soil operating conditions coefficient of the pile skin; \( u \) is the cross-sectional perimeter of the pile shaft, m; \( f_i \) is the calculated resistance of the soil \( i \)-layer of the pile shaft side surface, kPa; \( h_i \) is the thickness of the soil \( i \)-layer touching the pile skin, m.

The dependence (1) analysis makes it possible to define the promising directions of CFP bearing capacity improving. The pile skin area increase without its cross-section area one may be one of these directions. In the formula (1) the parameter \( u \), the pile shaft cross-section perimeter, directly impacts on the CFP pile skin area. Thus, the perimeter length increase without increasing the area limited by the perimeter will result in the pile bearing capacity improvement. In such a case, the design of the working body required to form the well having the cross-section complex profile in the ground, should meet several requirements:

- the working body moving elements should trace out closed smooth trajectory;
- the working body kinematic scheme should be as simple as possible.
The flat curve, hypocycloid, kinematically defined as the trajectory of the point on a circle rolling along another inner circle without or with sliding (figure 3), satisfies the mentioned requirements.

![Figure 3. The examples of hypocycloids.](image)

The hypocycloid equation in the parametric form is as follows [6]:

\[
\begin{align*}
    x &= (R - r)\cos \varphi + \lambda r \cos \left( \frac{R - r}{R} \varphi \right) \\
y &= (R - r)\sin \varphi + \lambda r \sin \left( \frac{R - r}{R} \varphi \right)
\end{align*}
\]  

(2)

where \(R\) is the director circle radius; \(r\) is the generating circle radius; \(\varphi\) is the parameter changing in the following range \([0; 2\pi]\); \(\lambda\) is the sliding coefficient. The radii of the director \(R\) and generating \(r\) circles have the dependence:

\[
n = \frac{R}{r}
\]  

(3)

where \(n\) is the integer number equal to 3, 4, 5, etc. The integer value of the variable \(n\) is required to form non-self-intersecting closed curve.

4. Results discussion

Calculations show that at the same limited area, three-rayed hypocycloid (deltoid) has more length than four-rayed astroid, therefore the hypocycloid with a relation of the director circle radius \(R\) to the generating circle one \(r\) equal to \(n=3\) is suggested to be chosen for further research. For CFP bearing capacity improvement possibility evaluation the necessary theoretical calculations were performed. CFP wells cross-section areas values were used as the initial data of the comparative analysis. The required areas values were calculated in advance for CFP installation typical wells diameters: 0.1, 0.15, 0.2, 0.25, 0.3, 0.4 and 0.5 m. Additionally, the geometric data of the sections in the form of a square and an equilateral triangle were used in the comparative analysis. For the ease of comparison, the obtained theoretical data are presented in the graphical form (figure 4).
Figure 4. The impact of CFP cross-section area on the perimeter length depending on the cross section shape.

The presented graphs show that the pile having the cross-section in the shape of hypocycloid has the perimeter maximum value. The given curve using as a working body moving elements motion trajectory can theoretically improve CFP bearing capacity up to 80% compared to the traditional CFP having the circular cross-section. It is evident from the graphical data that the square cross-section applying provides CFP bearing capacity improvement due to the pile skin increase of 12.8% as compared with a circular cross-section. The triangular section using improves the bearing capacity in comparison with the circular section by 28.6%.

The design implementation is proposed in the form of the combined working body mounted as the attached equipment on the hydraulic excavators of II and III dimensional groups. The attached equipment consists of the guide support 2 attached to the base machine handle 1 (figure 5). In the guide support upper part 2 there is the hydraulic drive 3 which provides the rotational movement of the working body consisting of three consecutively assembled interconnected units: cone auger 6, roller 5 and hypocycloidal crossing profile shaper 4.
Figure 5. The working body mounted on the base machine.

The shaper design provides for the coaxial arrangement with the roller and leader auger and drive rotary motion sharing for the following screwing, well rolling and final forming the well cross-section in the form of hypocycloid.

For evaluating the economic efficiency of CFP bearing capacity improvement proposed way, the comparative analysis was carried out. The expenses calculation both for DFP producing, necessary for the commissioned housing pile foundations construction and for CFP manufacturing for the same purposes was conducted. According to the Federal State Statistics Service (Rosstat), the total area of the residential buildings put into operation in the last years constituted: in 2015-85.3 mln. m$^2$, in 2016 – 80.2 mln. m$^2$, during the period of January-September 2017-61 mln. m$^2$ [7] (figure 6).
Figure 6. The total area of the commissioned residential buildings and economic effect from the applying of CFP produced by the local compaction technology.

For the comparative analysis conducting, the following assumptions were accepted:

- for the foundations construction, DFP of grade S120.35 GOST 19804-2012 and 12 meters long CFP having the hypocycloidal cross-section equal to DFP area of 0.1225 m² are used;
- 1 m² of housing is equivalent to 12.5 kN of pile load;
- pulverescent clay soil with the flow index of \( I_L = 0.3 \) was chosen as a foundation soil;
- DFP are made of concrete of class B22.5 in the compressive strength, CFP are made of concrete of class B15 in the compressive strength;
- calculations do not take into account the «cluster» effect of the friction piles combined action.

The calculations show that considering the assumptions made, the bearing capacity of DFP of grade S120.35 GOST 19804-2012 equals to 1105.65 kN, while the bearing capacity of 12 meters long CFP having the hypocycloidal cross-section equal to DFP area is 1182.13 kN. Thus, taking into account the used concrete cost differential in manufacturing only DFP, the total costs in 2015 would be 4 bln 253 mln RUB, and when using only CFP - 3 bln 779 mln RUB. The economic effect CFP using in 2015 would be 474 mln RUB, in 2016 - 445.7 mln RUB and for the first nine months of 2017 - 339 mln RUB (figure 6).

5. Conclusions

The choice of the hypocycloid as a working body moving elements motion trajectory for CFP well walls soil local compaction will theoretically make possible to improve CFP bearing capacity up to 80% without additional material costs. In this case, the trajectory is kinematically formed only by rotation, which simplifies the design implementation of CFP well walls soil local compaction working body mechanism. Using the cast-in-place friction pile well walls soil local compaction technology will make possible to save over 400 mln RUB annually just while constructing the residential buildings.
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