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Interaction of drill-injection piles with the surrounding soil

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Abstract. Nowadays, drill-injection technologies are actively used to create pile foundations in both civil and industrial construction. There are many drill-injection piles technologies which application depends on geotechnical conditions, loads, buildings and constructions purpose, technical and resources sufficiency and other points. Drill-injection piles producing occurs stress-strain state modification and physical and mechanical properties modifications in surrounding soil massive. Detection of features of soil properties modifications in drill-injection pile surrounding region allows to improve drill-injection piles bearing capacity calculations methods and to get more exact results. The article contains the analysis of physical and mechanical properties modifications in the South of Tyumen region (Russia) soils which surround drill-injection piles “Normal". The definition of soil properties was done by experimental investigations during the excavation of the piles to the depth of about 3.5 m in the site investigation with known engineering and geological conditions. There was detected a 6–10 % increase of soil density in 60 mm distance from the pile wellbores which depends on the soil type and increase of soil humidity in the waterless zone due to the high cement mixing-water ratio of the cement mortar. Also, it was found the increase of soil deformation characteristics up to 17.4 % and soil strength characteristics up to 27.3 % with reference to the original values. To the results of the excavation of the piles, it was discovered the wellbores expansion up to 4.4 % and local wellbores expansions in relative to the original values. During the inspection of the drill-injection piles there was discovered some piles defects such as massive soil penetration into the pile shaft near its wellhead and soil and mortar mixing along the perimeter of the piles owing to the insufficient mortar density and its high shrinkage. According to the results of the experimental researches, further investigations problems were defined.

1. Introduction

The application of drill-injection piles took place from the middle of the last century in Italy [1]. Further development of drill-injection piles technologies helped to extend the region of pile foundations implementation: it allowed to use them for the monuments of architecture strengthening, to create these piles in most soil and climate conditions, near the existing buildings and in the restricted conditions without requirement of organization of protective measures due to the lack of dynamic impact on the soil. Nowadays, drill-injection technologies are actively used to create pile foundations in both civil and industrial construction. Drill-injection piles producing occurs stress-strain state modification and physical and mechanical properties modifications in surrounding soil massive. Authors of the article believe that drill-injection pile technology “Normal”, which based on the repeated use of high-strength core-injector due to its extraction after wellbore crimping and subsequent immersion into the pile body a reinforcement frame or a single rod, is promising [2]. Due to the above-mentioned, the object of the investigation is drill-injection pile “Normal” which was created in the soil conditions of South of Tyumen region, and also physical and mechanical soil properties after drill-injection pile creation.

In spite of the high variety of drill-injection piles technologies [3–9], they all have the same technologies operations during their creations which are: wellbore drilling to the required depth with its simultaneous flushing and finished wellbore crimping by cement mortar. Drill-injection piles crimping

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produces wellbore expansion and/or local wellbore expansion along with the pile (often intentional) regarding the original values which contribute to the surrounding soil compression and increase the friction forces along with the pile and it, as a result, increases drill-injection piles bearing capacity. It is known that ground anchors technologies gave a start to the drill-injection pile technologies. The main difference between the above-mentioned technologies is that during the ground anchors creation of crimping takes place only in the requirement zone by using a plugging holder and subsequent mortar injection under high pressure into the cut-off area. Nowadays, many researches about examination of interaction of drill-injection anchors with variety of soil bases both in laboratory and field conditions are made. The results of these researches which in different times were done in many European countries as England, Austria, Slovakia, Belarus, Germany, Czech Republic, Bulgaria etc., are summarized and presented in [10] and others publications [11–16]. There are fewer data about the interaction of drill-injection piles with the surrounding soil [17–24]. In the scientific paper [10] this fact is also underlined.

The definition of dependences and character of physical and mechanical properties modifications in surrounding drill-injection piles soil during them creation is a very important problem for drill-injection piles bearing capacity calculation because there are many tests which show that real drill-injection pile bearing capacity is higher up to 2 and more times in comparison with bearing capacity which was calculated for the same piles according to the normative documents [1, 25–26]. This is too relevant owing to the intensive drill-injection piles usage in new construction and also in the strengthening of existing buildings and constructions.

The purpose of the study is an identification of the character of physical and mechanical soil properties modifications in the surrounding drill-injection pile zone after its creation, and an evaluation of the pile shaft geometric parameters for its later usage for drill-injection pile bearing capacity calculation method improving. For the purpose achievement the next tasks are defined: the physical and mechanical soil properties in the surrounding drill-injection pile zone determining before and after its creation; zones of physical and mechanical soil properties modifications definition; pile shafts geometric parameters measurement.

These tasks were solved after drill-injection piles “Normal” static load tests, which were done in the soils conditions of the South of Tyumen region (Russia).

2. Methods

The field experimental researches took place in the site investigation, which is located in Tyumen city centre on the territory of the reconstructing kindergarten on the Murmanskaya, 183 street (Fig. 1).

Figure 1. The site investigation location scheme.

The site investigation within the piles depth is composed by silty-clay soils with stiff and free-flowing consistency (Fig. 2). All the tested drill-injection piles were hanging and for this reason they did not especially lean on the sand layer during the drilling process.

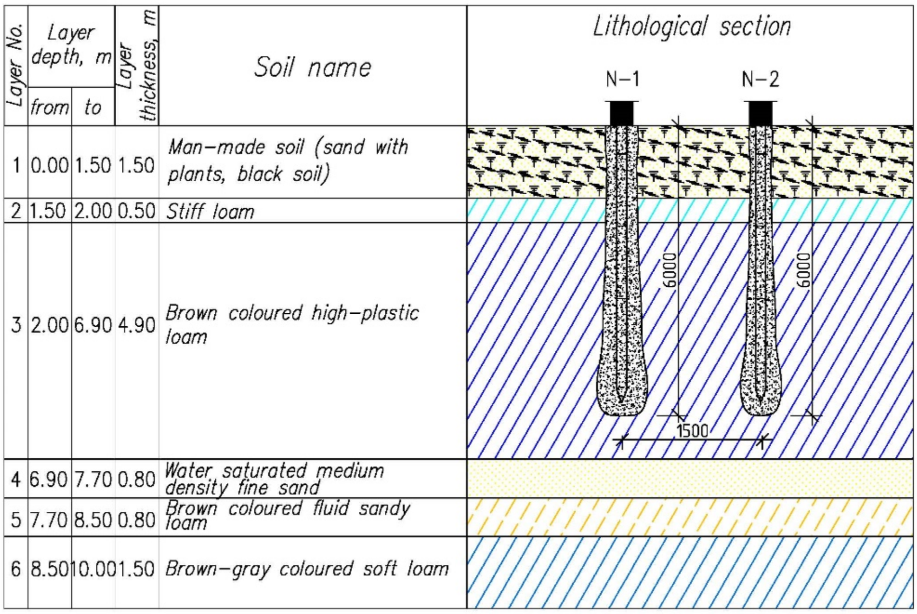


Figure 2. Piles location on the engineering and geological section.

The site investigation physical and mechanical soil properties are shown in Table 1. It's important to say that during the geotechnical surveys in August 2018 all soil samples have taken every 1 m, so soil characteristics in Table 1 are presented for all these samples.

Table 1. Physical and mechanical soil properties based on the results of the geotechnical surveys.

Soil sampling depth, m	W, %	ρ, g/cm^3	e	C, kPa	ϕ, degree	$E_{comp.}$, MPa
0.5	–	–	–	–	–	–
1.5	18	1.97	0.62	17	15	4.9
2.5	21	1.92	0.70	9	11	2.3
3.5	21	1.97	0.66	12	22	4.4
4.5	24	1.95	0.72	16	20	3.8
5.5	28	1.90	0.82	7	23	3.7
6.5	28	1.92	0.83	2	22	4.6
7.5	24	2.02	0.64	0	37	17.9
8.5	23	2.01	0.63	1	27	5.5
9.5	26	1.90	0.79	3	20	5.4

In the situ during the 15.09 – 25.09.2018 range drill-injection piles according to the "Atlant" technology [6] and by author's drill-injection piles technology which is called "Normal" for their next static tests were done. Below stages during drill-injection piles "Normal" creation were done:

1. wellbore drilling with required diameter and depth with the protection by the water-cement mortar with 1 to 1 proportion;

2. wellbore crimping by the water-cement mortar with 0.4–0.45 ratio under the pressure up to 0.7 MPa after the required depth have been achieved;

3. gradually high-strength core-injector extraction from the pile body with concurrently extra crimping each meters;

4. reinforcement frame immersion into the pile body. The reinforcement frame consists of 3 bars with 14 mm diameter.

There was used "Figaro" drilling machine and "MINI" injection complex [27] to create drill-injection piles.

After drill-injection piles "Normal" static load tests piles "N-1" and "N-2", which are shown in Fig. 2, were excavated. Drill-injection pile "N-1" had 340 mm diameter during its creation and drill-injection pile "N-2" had 200 mm diameter. Both piles had 6 m in length and reinforced with a 5.5 m triangular frame. During the pile excavation, there was defined physical and mechanical properties of the surrounding soil and piles sizes.

Soil sampling and its further density and humidity definitions were done according to the [28] by the method of cutting rings. Three cutting rings with 56 mm diameter have been located in two perpendicular planes near the "N-1" pile and one plane near the "N-2" pile. After extraction of the rings filled with soil samples, extra soil had been removed away and then the definition of its density and humidity had been started. The location scheme of cutting rings along the piles bores is presented in Fig. 3. Soil samples were taken layer by layer from 0.35 m, 0.55 m, 0.75 m, 0.85 m, 1.0 m, 1.3 m, 1.6 m, 1.9 m, 2.2 m, 2.5 m, 2.8 m, 3.1 m and 3.4 m depth regarding the ground surface. Additionally, soil samples were taken for its deformation and strength characteristics definition in according to the [29].

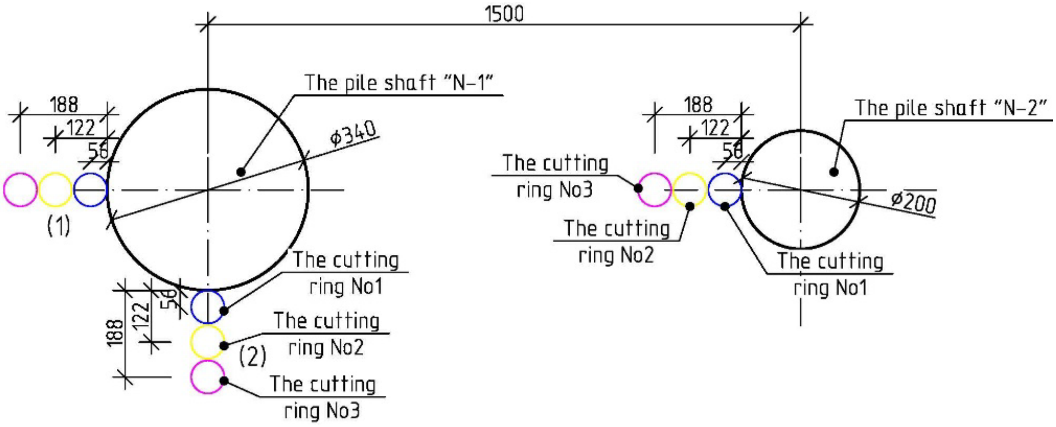


Figure 3. The location scheme of cutting rings along the piles during the excavation.

It was impossible to take continuous soil samples until the 1.5 m depth because of the fill-up soil in this zone that was discovered during the geotechnical surveys. The pile excavation depth where it was possible to do soil sampling was only 3.5 m owing to the found groundwater level below. For this reason, it was important to find the physical and mechanical properties of the fill-up soil that it had before drill-injection piles creation. So, along with the piles there was dug a prospect pit with 1.8 m width to take soil samples in natural content on the opposite side of the piles (Fig. 4).

Figure 4. The scheme of layer-by-layer soil sampling in natural content.

Therefore, till the 2.1 m depth there were additionally classified some geotechnical elements such as:

- 30 cm – dark-colored black soil;
- 70 cm – fill-up sand layer;
- 10 cm – clay layer;
- 40 cm – man-made soil layer with black soil incorporations;
- 60 cm – stiff brown colored loam layer.

Soil sampling for density and humidity extra definition was taken with 30 cm gradation in the prospect pit area. Thus, extra soil sampling was taken from the –0.6 m, –0.9 m, –1.2 m, –1.5 m, –1.8 m and –2.1 m depth relative to the ground surface and its physical properties are presented in the Table 2.

Table 2. Soil base physical properties before piles creation.

Soil sampling depth, m	W, %	ρ, g/cm^3	e
0.6	10	1.67	0.78
0.9	13	1.65	0.85
1.2	23	1.67	0.99
1.5	16	1.96	0.59
1.8	16	1.97	0.59
2.1	25	1.90	0.78

3. Results and Discussion

The results of soil density definition in the nearby area of the piles are shown in the Fig. 5.

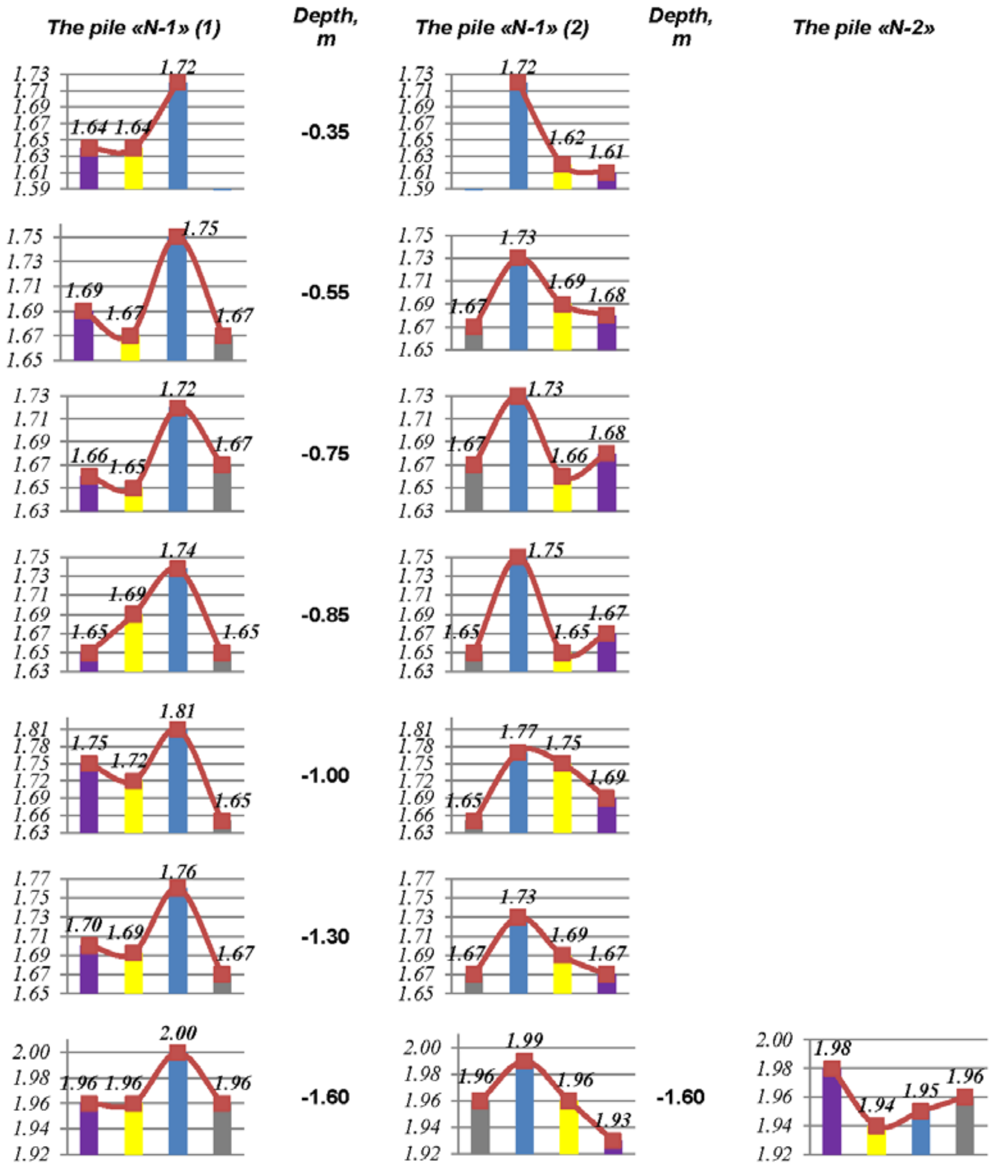


Figure 5. Soil density (g/cm^3) modifications graphs along the piles depth (beginning).

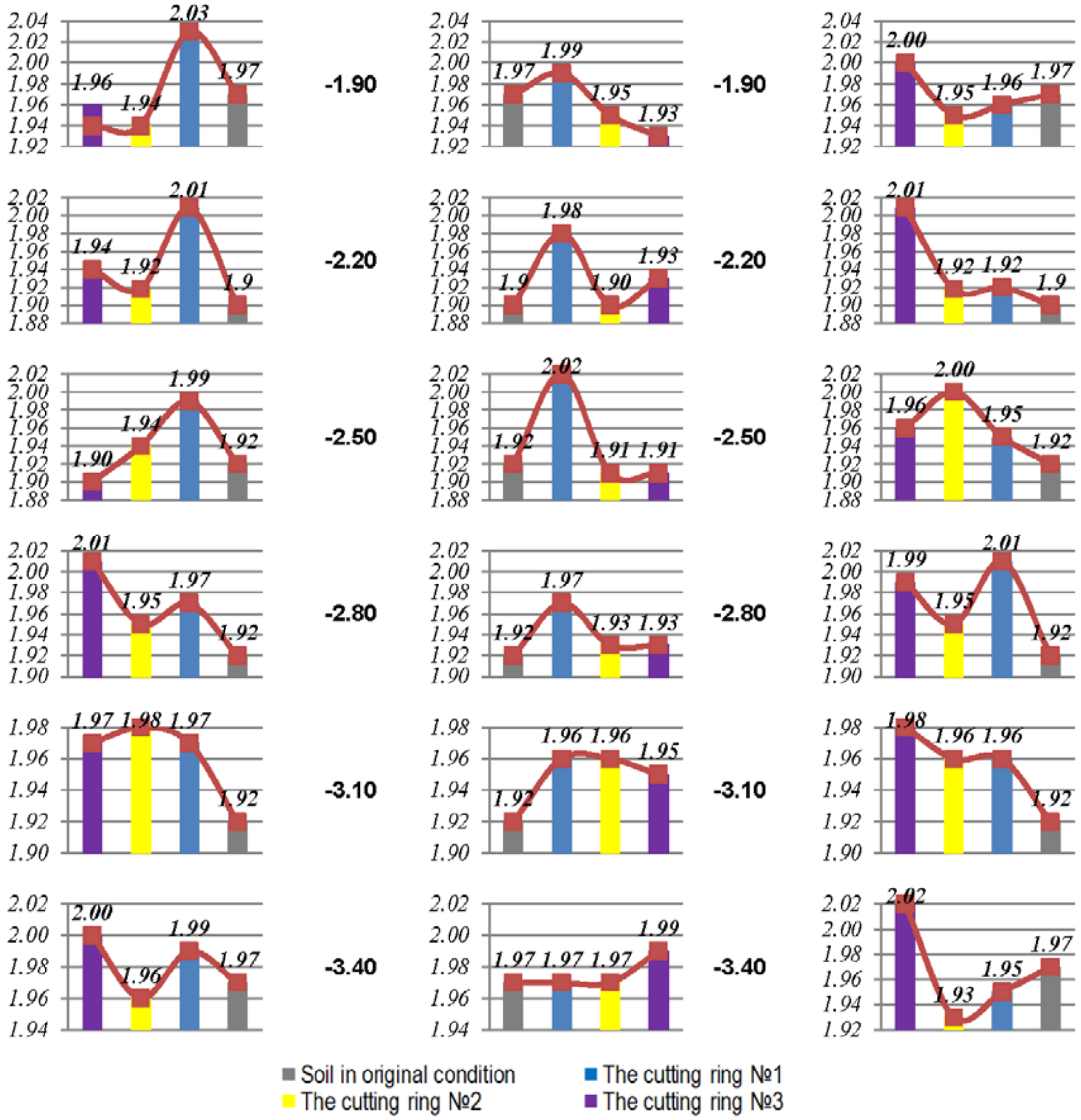


Figure 5. Soil density (g/cm^3) modifications graphs along with the piles depth (ending).

These graphs show that for the pile "N-2" there was detected an increase of soil density in the depth range of –2.2 – 3.1 m. At the other depths for the pile "N-2" there is no change in the soil density. These graphs also show the stable trend of soil density increment in the range of the cutting ring No. 1 (in the area up to 60 mm near the piles) for the drill-injection pile "N-1". And, to the –1.3 m depth occurs an extensive density increment for the surrounding pile soils with a maximum 10 % increment value at –1 m depth (from 1.65 g/cm^3 to 1.81 g/cm^3). Below this level the density increment in the range of the cutting ring No. 1 is only about 1 – 6 %. This occurs because till the –1.5 m depth man-made soils with low density (1.65 – 1.67 g/cm^3) and high porosity ratio (0.78 – 0.99) lay (look at Table 2), and under this layer are clay soils with higher density and lower porosity ratio is situated. It should also be noted that for the drill-injection pile «N-1» with a larger diameter takes place more density increment concerning the drill-injection pile "N-2" with a less diameter: the relation of the soil compaction radius to the pile "N-1" wellbore radius is 0.74, and this value for the pile "N-2" is only 0.63. Soil density in the cutting rings No. 2 – 3 range (in the area up to 190 mm near the piles) little changes for both drill-injection piles regarding the original density despite the small jumps in the envelope graph because in according to the [28] the permissible difference in the results of determining the density of clay soil is up to 0.03 g/cm^3. Thus, after drill-injection piles creation the soil density increment up to the 60 mm distance near the piles takes place. This occurs because the cement particles incorporated into the nearby area of the piles (Fig. 6) during wellbores crimping and it allows increasing soil specific gravity.

This too short soil density modification distance is connected with free cement mixture flow near piles wellhead during its crimping. On the other hand, during ground anchors crimping there uses plugging holders which allow to create higher pressure in this zone and modify surrounding soil density up to 3.5 – 4 wellbore radiuses distance [10, 11]. A larger soil compaction zone occurs during the formation of drill-injection piles with controlled broadening at the pile end due to the use of a membrane cup: the average radius of the soil compacted zone is 0.15 – 0.6 m which is depending on the injected volume of the mortar [18]. In addition, in [18], it is noted that during constant pressure on the walls of the drill-injection pile shaft, the density of the surrounding soil increases to an average of 17 %.

Figure 6. Cement particles incorporation into the range of the cutting ring No. 1.

The results of soil humidity definition in the nearby area of the piles are shown in the Fig. 7.

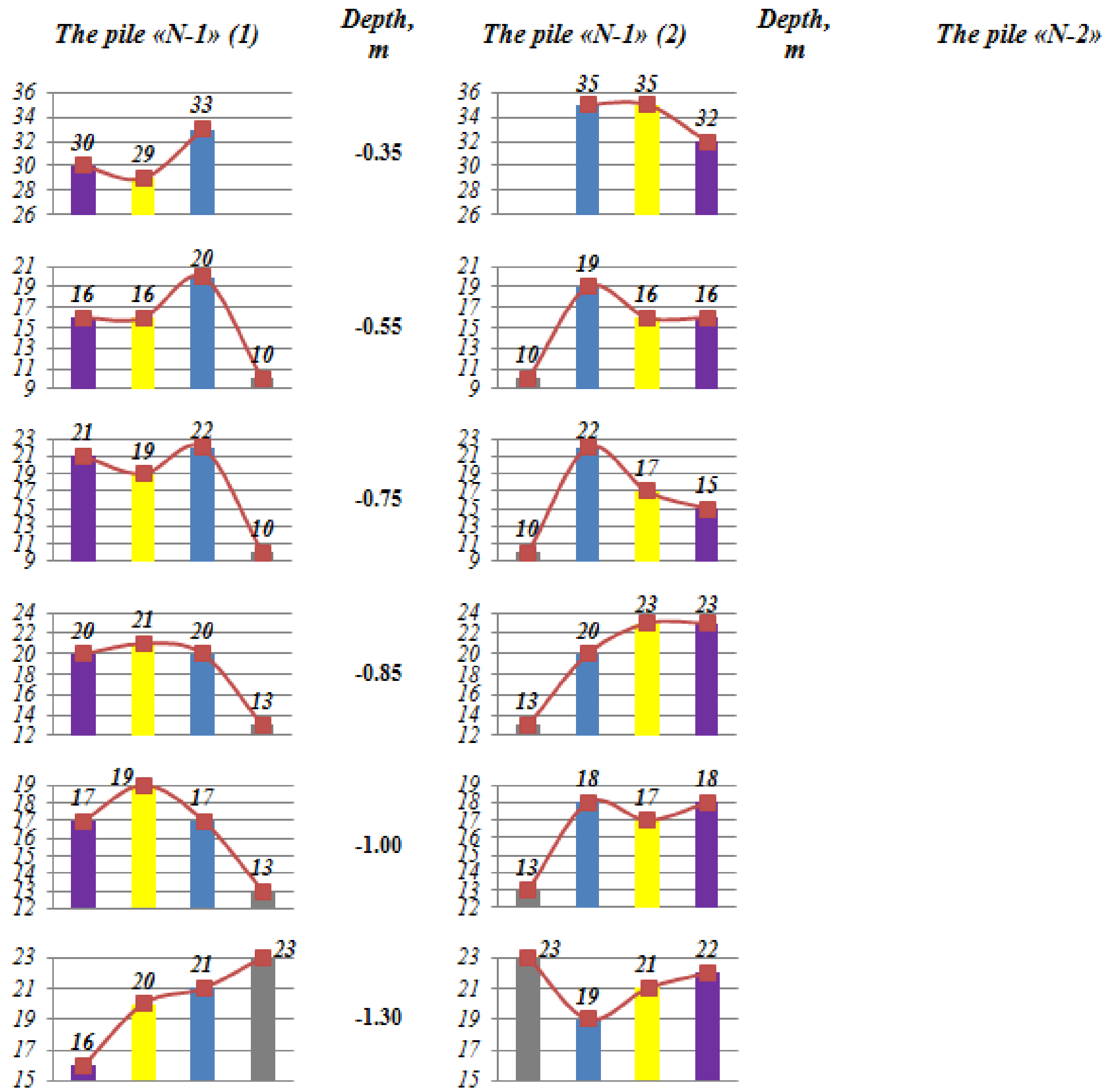


Figure 7. Soil humidity (%) modifications graphs along with the pile depth (beginning).

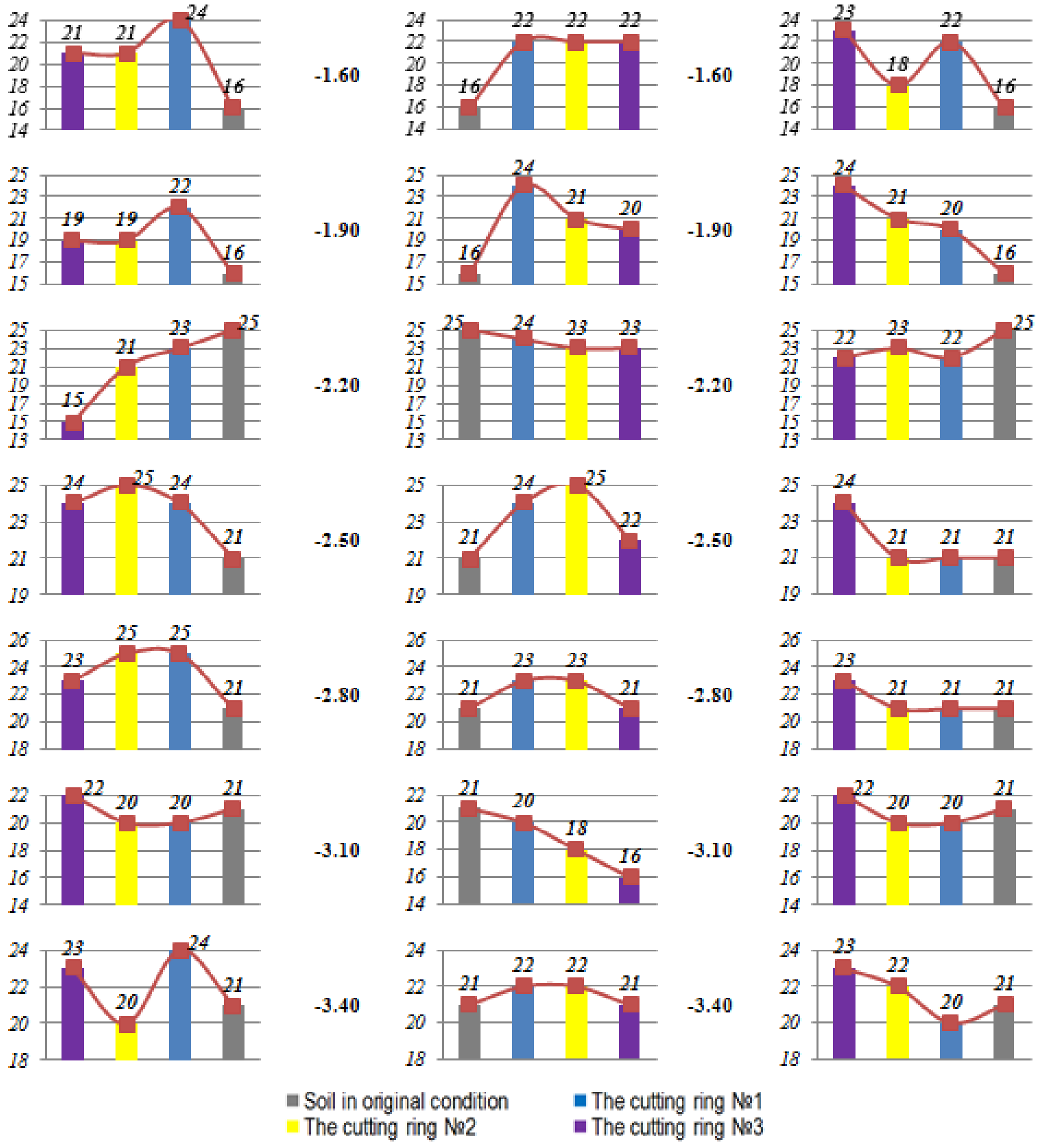


Figure 7. Soil humidity (%) modifications graphs along with the pile depth (ending).

According to the diagrams, which are shown in the Fig. 7, soil humidity modifications in the nearby area of the drill-injection pile “N-1” with 340 mm diameter are characterized by mostly increment concerning its original values. Moreover, within the range of the man-made soil location humidity increment is up to 120 % at the 0.75 m depth. This high humidity increment occurs because of the surfaces water permeation into the soils with a high permeability ratio. Further, after -1.6 m depth (clay soils level) soil humidity increment is up to 50 % with its minimum value 10 %. From the -3.0 m depth, there is mostly no humidity modifications due to the found underground water level.

For the drill-injection pile “N-2” with 200 mm diameter at the 1.5 – 2.0 m depth the soil humidity increase with a maximum value of up to 38 % also takes place. Further, at the investigation depth, there is mostly no soil humidity modification nearby the pile.

Soil humidity modification nearby the piles in the range of all cutting rings is constant (Fig. 7) concerning its original values despite the small jumps in the envelope graph because in according to the [26] the permissible difference in the results of determining the humidity of clay soil with $W < 50$ % is up to 2 %.

Soil humidity increment in clay soils takes place owing high enough cement mixing-water ratio of about 0.4 – 0.45 during drill-injection piles crimping when the process of cement hydration needs about 0.20 – 0.25 value of cement mixing-water ratio [10]. This way, it promotes to appear extra water in the wellbore that later drain into the surrounding soil. Because of the low permeability ratio in clay soils and soil porosity decrement owing to the cement mud injection a consolidation process in the surrounding soil near drill-injection piles needs a lot of time. During the wellbore crimping in accordance to the “Atlant” or «Norma» technology, due to the free release of the mortar from the wellbore top, no extra pressure takes place, otherwise, there is a decrease of soil humidity up to 28 % [16, 18].

Additionally, after soil sampling for its density and humidity definition, there were taken another soil samples by inserting into the soil base a cylinder with 100 mm diameter and 300 mm height close to the drill-injection pile "N-1" (about 5 – 10 mm distance from pile shaft) at the –2.5 m and –3.0 m depth for soil deformation and strength properties definition. Due to the done compressive tests it was detected that soil Young's modulus E, MPa, is 2.4 MPa at the –2.5 m depth and 2.7 MPa at the –3.0 m depth. Soil Young's modulus increment is 4.3 % and 17.4 % respectively in relations to the original value (2.3 MPa). In [10, 18, 22], an increase of Young's modulus in the compacted zone up to 35 % concerning the initial values is noted due to the creation of extra pressure along the pile shaft during its crimping.

An angle of internal friction ϕ, degree, is 13° and 14° at the –2.5 m and –3.0 m depths respectively that higher than its initial value in 18.2 % and 27.3 %. Soil specific cohesion values, c, kPa, have grown up to 11 % in relation to its original value and is 10 kPa for both soil samples.

In addition, during the pile excavation its diameter modifications along with the depth and its defects were inspected. So, due to the pile "N-1" with an initial 340 mm diameter inspection within the excavated depth (about 4 m), there was detected its diameter increment in the man-made soil layer (till the 1.5 m depth) regarding the pile diameter in clay soils, which is shown in Fig. 8. For the drill-injection pile "N-2" there was no emphasized diameter expansions or modifications.

Figure 8. Drill-injection piles inspecting.

Pile shafts for both drill-injection piles within the investigation depth are straight without any seeing defects. Along the pile perimeter, there is a "ground shell", which represents geotechnical elements order in accordance to the geotechnical surveys (Fig. 8–9).

Figure 9. A "soil shell" along the pile perimeter.

After inspection both drill-injection piles were extracted for further investigations. Due to the pile shafts cutting it was detected that pile "N-1" diameter after its creation was 355 mm concerning the initial 340 mm wellbore diameter (Fig. 10). The diameter increment owing to the pile crimping was 4.4 %.

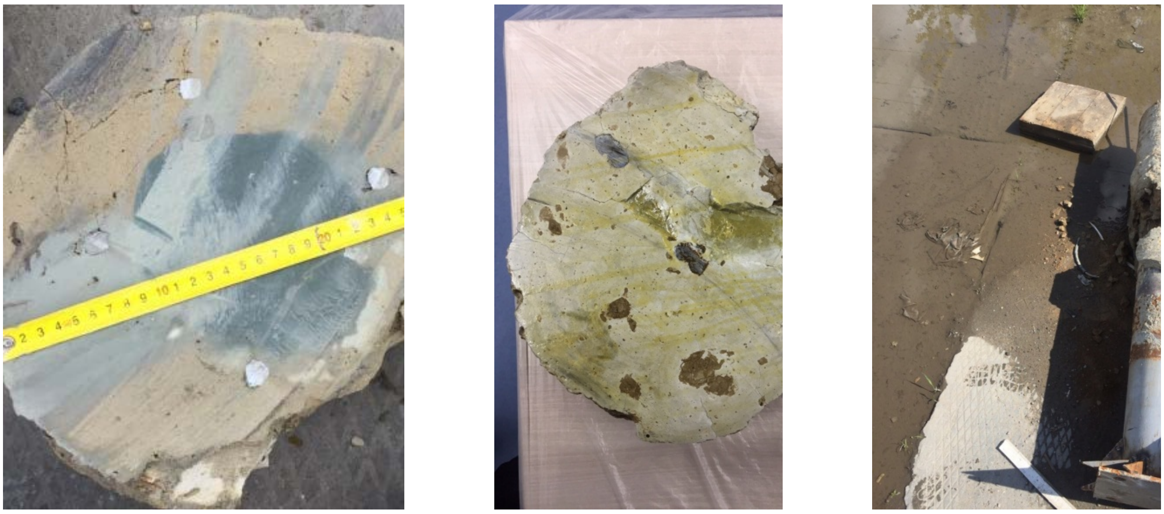
Figure 10. Diameter of drill-injection pile "N-1" after extraction.

During the pile "N-2" shaft inspection after its extraction there were discovered some zones with local wellbore expansions about 150 mm length at the –2.0 m depth on the "man-made soil – clay soil" border and at the –3.5 m depth on the underground water level. These diameters are 280 mm and 300 mm that higher on 40 % and 50 % respectively in relations to the initial 200 mm wellbore diameter. Drill-injection pile "N-2" diameter is constant on the other length and the same with the wellbore diameter (Fig. 11). An extensive increase of the initial diameter (up to 2 or more times) is achieved by creating an extra pressure (about 0.2 MPa or more) in the wellbore during its crimping, as noted in [10, 17, 18].

Figure 11. Expansions of drill-injection pile "N-2" shafts.

Moreover, due to the drill-injection piles cutting and its inspection there were noticed some pile shafts defects, which are presented in the Fig. 12:

- soil and mortar mixing along the perimeter of the piles;
- massive soil penetration into the pile shaft near its wellhead.



a b c

Figure 12. Drill-injection piles defects due to its creations.
a – soil and mortar mixing along the perimeter of the piles;
b – soil incorporations into the pile shaft;
c – massive soil penetration into the pile shaft near its wellhead.

These defects occurred owing to the use of cement/water/water-glass mixtures during wellbore crimping which has low mixture density (about 1.5 – 1.7 g/cm^3), too much shrinkage and low strength of about 10–15 MPa.

4. Conclusion

There are some main conclusions, due to the tests of soil physical and mechanical properties near drill-injection piles "N-1" and "N-2" with 340 mm and 200 mm diameters respectively and due to the pile geometry properties measuring, which are:

1. During drill-injection pile crimping under pressure of about 0.7 MPa there occurs surrounding soil density increment up to 10 % in the range of man-made soil layers and up to 6 % in the range of clay soils owing to the soil particles packing and cement mixture incorporations into the soil pores. Soil density modification in relation to its initial value is noticed up to 60 mm distance from pile shafts regardless of drill-injection pile diameter. This too-short soil density modification distance is connected with free cement mixture flow near piles wellhead during its crimping.

2. For both drill-injection piles was detected surrounding soil humidity increment up to 190 mm distance from pile shafts around 120 % at the range of man-made soil layers with high permeability ratio. At the range of clay soil layers around drill-injection pile with 340 mm diameter soil humidity increment up to 50 % takes place, for the pile with 200 mm diameter within the clay soil layers there is no soil humidity modification. From the depth, where the underground water level starts, soil humidity modifications for both piles do not happen. Soil humidity increment at the range of clay soil layers occurs because of high enough cement mixing-water ratio about 0.4–0.45 during drill-injection piles crimping, when the process of cement hydration needs about 0.20–0.25 value of cement mixing-water ratio.

3. Due to the pile shafts injection crimping there is observed the increment of clay soil Young's modulus up to 17.4 % in relations to its value before drill-injection piles creation and the increment of an angle of internal friction and specific cohesion values up to 27.3 % and 11 % respectively in the contact region.

4. Wellbore crimping under pressure up to 0.7 MPa allowed to increase drill-injection pile "N-1" diameter by 4.4 % within clay soil layers in relation to its 340 mm initial value. Moreover, there was noticed more extensive diameter increment at the range of man-made soil layers in relations to the clay soil layers.

There are some zones with local wellbore expansions within the drill-injection pile "N-2" shaft at the "man-made soil – clay soil" border and at the underground water level. These expansions zones are 40 % and 50 % respectively bigger than the initial 200 mm wellbore diameter. Drill-injection pile "N-2" diameter is constant on the other length and the same with the wellbore diameter

This small wellbore expansion ratio is connected with free cement mixture flow near piles wellhead during its crimping and it does not allow creating a stable extra pressure into the wellbore.

5. There were discovered some piles defects such as massive soil penetration into the pile shaft near its wellhead and soil and mortar mixing along the perimeter of the piles owing to the insufficient mortar density and its high shrinkage. The most vulnerable for ensuring the quality of the continua cement body structure drill-injection pile zone is the top of the pile shaft up to 2–3 its diameters.

Due to obtained results of interaction of drill-injection piles with the surrounding soil authors of the article defined the issues for further investigations, such as:

- laboratory explorations to definition soil physical and mechanical properties modifications and residue stress state owing to the wellbore expansion which occurs during drill-injection piles creation in clay soil with various consistency in relations to the South of Tyumen region soils conditions;
- engineering of an inventory, quick-disassembly plugging holder analogue, which prevents free cement mixture flow near piles wellhead during its crimping. This tool will contribute to bigger wellbore expansion, surrounding soil packing and its physical and mechanical characteristics increment;
- selection of mixture parameters with high density (about 1.90–2.20 g/cm^3), fluidity of mixture, resistibility and low shrinkage based on the existing resources and drill-injection equipment;
- creation of an improved calculation method of drill-injection piles bearing capacity due to surrounding soil physical and mechanical properties modifications and residue stress state.

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