Investigation of operation of newly designed anchor pile

O V Kostina\textsuperscript{1,2} and T M Bochkareva\textsuperscript{1}

\textsuperscript{1}Department of Construction Operations and Geotechnics, Perm National Research Polytechnic University, Komsomolsky ave. 29, Perm, 614990, Russia

\textsuperscript{2}up.ovg@yandex.ru

Abstract. The article describes design of a pile with new rotary anchors for foundations of buildings operating on variable loads or on heaving soils. The results of plate load tests on piles’ pressing in with one- and two anchor levels are presented. Based on calculations on bearing capacity of piles of proposed design, the adequacy of data on determination of its bearing capacity obtained by experimental method is calculated. Bearing capacity of anchor piles for pulling out is determined by calculations. Anchors located at one level at the height of pile increase its bearing capacity for pressing in by 20\%, and increase it for pulling out by 94\%. Anchors located at two levels at the height of pile increase bearing capacity of pile for pressing in by 60\%, and increase bearing capacity for pulling out by three times. A decrease in the settlement of pile of proposed design is determined by the results of plate load tests on pressing in and it amounts to 85\% for a pile with one-level anchors and to 94\% for a pile with two-level anchors.

1. Introduction
Anchor piles are well-known and are widely used for installation of foundations of buildings and structures such as supporting walls, foundations of bridges, pipelines, power transmission line supports, etc. These piles may accept both pressing-in and pulling-out loads enhancing lifting and deformation properties of foundations of structures significantly [1, 2, 3].

Heaving soils are widespread in the territory of the Russian Federation. The main problem of this type of base is bulging in case of frigidness which is caused by frost heaving force. Migration of water but not water availability is the most critical factor during freezing of these rocks, because it is water transfer that determines maximum increase of soil’s volume [4]. Also, soil dampness before freezing [5], the speed of soil’s temperature decrease [6], density, poriness and dispersion ability of a soil [7-9] and pressure of overlying rocks [10] influence on the degree of frost heaving. Buildings and structures situated in such bases can be exposed to vertical displacements during lifecycle of the project thanks to adfreezing of foundations’ constructions with the soil.

The studies show that refreezing leads to significant stress increase on the border of a contact of soil with support [11]. Vertical displacements in itself are not dangerous, but the main problem is of variation of these displacements at separate points of the structures. Different methods neutralizing negative influence of frost heaving force are applied for emergency conditions avoidance. The one of the most effective methods is installation of foundations made of anchor piles [12-15]. Because of having rough surface and scarancements as well as connecting face increase of pile and soil, anchor piles have high resistance to lifting [1, 2].
In the paper [16] a new structure of rotary anchors applied for steel hollow-shell pile with axial cone is proposed. The anchor is made of metal. According to the plan, it is \( \Pi \)-formed and equipped with three-corner blades for adhesive bond with soil (see figure 1). The anchor wall has long hole for screw pitch which links it with a pile.

![Figure 1. Design of a pile with one-level rotary anchors. Pile before immersion (a), pile during immersion (b) and pile after immersion (c). Pile (1), rotary anchor (2), screw (3), hole for screw pitch (4) and capture of silent pile driver (5).](image)

The pile of proposed design has 3 anchors placed at the same height and equispaced from each other. The pile is being immersed in case of vertical position of anchors, nevertheless, they turn to maximum up position relating to joint bolt and three-corner blades cut through the soil and do not hinder the process. The pile rotates around its axis stopping at 0.5 m near projected mark resulted in that the anchor deflects vertically and turns to horizontal position and three-corner blades are fixed in the soil. Then the pile is being immersed deeper making pressed zone of the soil under the blades. As a result, bearing capacity of the pile for pressing in and lifting is being increased.

2. Methodology
Evaluation of bearing capacity of piles for pressing in and soil settlement was determined by methods of physical tests on models of piles of proposed design. Test facility of the Research and Production Enterprise (RPE) “Geotech” for models using foundation with a tray sized 1\( \times \)1\( \times \)0.2 m was used for this purpose. This equipment has 1:30 project design scale. Loading of this installation is realized through steel stamp sized 156\( \times \)50 in plan. A load on model is passed in steps from 25 kPa to 500 kPa or to maximum displacement of stamp by 21 mm. It can resist a load at each step during 30 min for ground distortion stabilization.

A model of hollow-shell pile of Russian National Standard (RNS) R 57991-2017 with a length of 6000 mm and with a diameter of 630 mm was accepted for experimental investigation. Corresponding model has a length of 200 mm and a diameter of 21 mm. Practically, hollow-shell piles are filled with concrete mix after establishing to final position. Decision on model construction made of solid metal core was made in case of small-scale modeling (figure 2). Proposed model of anchor in regard to real pipe with a diameter of 630 mm has a length and a width of 450 mm, and size of lower borders’ projection of blades is 300 mm. Taking into account a scale of modeling, we assumed the following: anchor is represented in the form of right-angled triangle with the legs’ sizes of 10 and 15 mm (figure 3).
In terms of investigation plate load tests of a pile both with one- and two-level rotary anchors’ placement to height along the pile shaft were conducted. Anchors of upper level are placed with shift in the plan corresponding to anchors of lower level, nevertheless, the upper level of anchors should be placed lower seasonal freeze depth (figure 4).

It is essential to determine a decrease in bearing capacity and an increase in settlement in case of unacceptable position of anchors, i.e. during its incomplete opening in comparison to horizontal placement for the piles with one- and two-level anchors’ placement respectively for effectiveness evaluation. Models of piles with anchors with an angle of 45’ were developed for modelling the state of such type (figure 5 and figure 6).
Figure 6. Model of a pile with two-level anchors with an angle of 45°. Side view (a) and anchor placement (b).

The results of conducted plate load tests of anchor piles’ models are presented in the form of table 1.

| Pressure (P; kPa) | Settlement of sand base $S_{base}$ (mm) | Settlement of a pile without anchors $S_{w.a.}$ (mm) | Settlement of a pile with horizontal anchors $S_{1a.}$ (mm) | Settlement of a pile with horizontal anchors with an angle of 45° $S_{1a.45}$ (mm) | Settlement of a pile with two-level horizontal anchors $S_{2a.}$ (mm) | Settlement of a pile with two-level horizontal anchors with an angle of 45° $S_{2a.45}$ (mm) |
|-----------------|--------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 0               | 0.00                                 | 0                                               | 0                                               | 0                                               | 0                                               | 0                                               |
| 25              | 0.56                                 | 0.24                                            | 0.05                                            | 0.07                                            | 0                                               | 0                                               |
| 50              | 1.23                                 | 0.25                                            | 0.05                                            | 0.08                                            | 0                                               | 0                                               |
| 75              | 1.92                                 | 0.19                                            | 0.05                                            | 0.10                                            | 0                                               | 0.07                                            |
| 100             | 2.58                                 | 0.50                                            | 0.05                                            | 0.35                                            | 0.03                                            | 0.12                                            |
| 125             | 3.30                                 | 0.73                                            | 0.11                                            | 0.46                                            | 0.04                                            | 0.52                                            |
| 150             | 3.81                                 | 1.88                                            | 0.22                                            | 0.67                                            | 0.06                                            | 0.89                                            |
| 175             | 4.16                                 | 2.75                                            | 0.44                                            | 0.82                                            | 0.07                                            | 1.23                                            |
| 200             | 4.61                                 | 3.38                                            | 0.80                                            | 1.02                                            | 0.08                                            | 1.74                                            |
| 225             | 5.17                                 | 3.91                                            | 1.38                                            | 1.52                                            | 0.38                                            | 2.79                                            |
| 250             | 5.57                                 | 4.45                                            | 2.03                                            | 2.45                                            | 0.96                                            | 4.57                                            |
| 275             | 5.85                                 | 4.97                                            | 2.71                                            | 3.76                                            | 1.91                                            | 5.94                                            |
| 300             | 5.94                                 | 5.55                                            | 3.33                                            | 5.59                                            | 2.88                                            | 6.86                                            |
| 325             | 20.97                                | 17.79                                           | 4.03                                            | 8.46                                            | 3.62                                            | 7.79                                            |
| 350             | 20.07                                | 19.55                                           | 4.91                                            | 14.37                                           | 4.40                                            | 8.82                                            |
| 375             | 20.07                                | 19.55                                           | 4.91                                            | 14.37                                           | 4.40                                            | 8.82                                            |
| 400             | 5.99                                 | 10.77                                           | 5.19                                            | 9.69                                            | 6.75                                            | 14.66                                           |
| 425             | 6.75                                 | 14.66                                           | 7.48                                            | 20.89                                           | 7.48                                            | 20.89                                           |
| 475             | 8.37                                 | 20.89                                           | 8.37                                            | 20.89                                           | 7.48                                            | 20.89                                           |
| 500             | 9.22                                 | 20.89                                           | 9.22                                            | 20.89                                           | 7.48                                            | 20.89                                           |
| 520             | 10.71                                | 20.89                                           | 10.71                                           | 20.89                                           | 7.48                                            | 20.89                                           |

Graphs titled “Pressure (P) and Settlement (S)” for visual presentation of plate load tests of piles on pressing in are given (figures 7 to 10). The results are grouped together according to following principles:

a) effectiveness of application of one-level horizontal anchors (figure 7);
Figure 7. Results of plate load tests in the form of graph titled “Pressure (P) and Settlement (S)” for a pile without anchors and a pile with one-level horizontal anchors. P is pressure transmitted to plate load (kPa) and S is pile settlement (mm).

b) determination of bearing capacity increase and settlement decrease for a pile with two-level anchors in comparison to a pile with one-level anchors (figure 8);

Figure 8. Results of plate load tests in the form of graph titled “Pressure (P) and Settlement (S)” for piles with one- and two-level horizontal anchors and a pile without anchors. P is pressure transmitted to plate load (kPa) and S is pile settlement (mm).
c) determination of a decrease in effectiveness of one-level anchors in case of its unacceptable position in comparison to optimal (horizontal) position (figure 9);

![Figure 9. Results of plate load tests in the form of graph titled “Pressure (P) and Settlement (S)” for piles with horizontal anchors and with anchors with an angle of 45’ and piles without anchors. P is pressure transmitted to plate load (kPa) and S is pile settlement (mm).](image)

d) determination of a decrease in effectiveness of two-level anchors in case of its unacceptable position in comparison to optimal (horizontal) position (figure 10);

![Figure 10. Results of plate load tests in the form of graph titled “Pressure (P) and Settlement (S)” for piles with two-level horizontal anchors and with anchors with an angle of 45’ and piles with one-level horizontal anchors. P is pressure transmitted to plate load (kPa) and S is pile settlement (mm).](image)
In order to evaluate the adequacy of results, calculation on determination of bearing capacity of a pile with anchors and piles without anchors for pressing in by the formula no.7.8 of point 7.2.2 of Code Specification (CS) 24.13330.2011 titled “Pile foundations” under given soil conditions was made corresponding to conducted experiments and comparison of obtained data was made with the result of this experiment.

In order to conduct an analysis, conversion of load values from model to real pile was made and values of its bearing availability were calculated. Taking into account a scale of modeling sized 1:30, a value of bearing capacity of plate load is increased to 30 times, as well as size of model of pile is taken into account in the calculation. Values of bearing capacity are the following:

\[ F_{d.w.a.p.l.} = 30P_{w.a} \cdot A = 30 \cdot 125 \cdot 0.31 = 1162.5 \text{ kN} \]  
\[ F_{d.a1.p.l.} = 30P_{a1} \cdot A = 30 \cdot 150 \cdot 0.31 = 1395 \text{ kN} \]  
\[ F_{d.a2.p.l.} = 30P_{a2} \cdot A = 30 \cdot 200 \cdot 0.31 = 1860 \text{ kN} \]

where, according to the plate load experiments, \( F_{d.w.a.p.l.} \), \( F_{d.a1.p.l} \) and \( F_{d.a2.p.l} \) are bearing capacity of a pile without anchors, pile with one-level anchors and two-level anchors respectively; \( P_{w.a} \), \( P_{a1} \) and \( P_{a2} \) are calculations of soil resistance according to the results of plate load experiments on a pile without anchors, pile with one-level anchors and two-level anchors respectively (kPa); \( A \) is the area of pile’s support to soil.

These values are from the graphs titled “Pressure and Settlement” (see figure 8) from the moment of the start of soil sliding phase (or from the moment of the end of soil compaction phase), i.e. the value of design resistance after which soil compaction cannot be characterized by linear dependence between resistances and deformations with sufficient degree of accuracy. This principle of soil (R) design resistance determination is realized in all normative documents linked with determination of soil characteristics. Similarly, the next calculations contain other soils’ design resistances, as follows:

\[ A = \pi \cdot r^2 = 3.14 \cdot 0.315^2 = 0.31 \text{ m}^2 \]  

where \( r \) is the radius of a pile shaft (m).

Calculation on bearing capacity of a pile without anchors for pressing in was determined by the formula no. 7.8 of point 7.2.2 of CS 24.13330.2011 titled “Pile foundations” and is done according to calculation scheme of tests given in figure 11 (a), this is given by:

\[ F_{d.w.a} = \gamma_p(\gamma_{R,R} \cdot R \cdot A + u \sum \gamma_{R,f} \cdot f_i \cdot h_i) \]

where \( F_{d.w.a} \) is bearing capacity of a pile without anchors according to calculations, \( \gamma_p \) is coefficient of pile’s working conditions in soil which equals 1; \( \gamma_{R,R} \) and \( \gamma_{R,f} \) are coefficients of soil’s working conditions under lower edge and on the side of a pile respectively which take into account the influence of method of pile’s immersion on soil’s design resistances and are taken from Table 7.4. In the process of hollow-shell piles’ silent pile driving into fine sands \( \gamma_{R,R} = 1 \), \( \gamma_{R,f} = 1 \); \( R \) is design resistance of soil under lower edge of a pile which is taken from Table 7.2 of CS 24.13330.2011 titled “Pile foundations”. The soil used for tests is fine sand of medium density (density of soil (\( \rho \)) is 1.63 gr/cm\(^3\)). Design resistance of soil (R) is 2300 kPa on the depth of 6 m, A is the area of pile’s support to soil determined by the formula (4), \( u \) is outer perimeter of cross-sectional area of a pile that equals as follows:

\[ u = 2\pi \cdot r = 2 \cdot 3.14 \cdot 0.315 = 1.98 \text{ m} \]

where \( r \) is the same given in the formula (4); \( h_i \) is the thickness of soil layer (i) contacting to a side of a pile (m); \( f_i \) is design resistance of soil layer (i) of the base on a side of pile (kPa) taken from Table 7.3 of CS 24.13330.2011 titled “Pile foundations” and is given by:

1) \( z_1 = 1 \text{ m} \Rightarrow f_1 = 23 \text{ kPa} \);  
2) \( z_2 = 3 \text{ m} \Rightarrow f_2 = 35 \text{ kPa} \);  
3) \( z_3 = 5 \text{ m} \Rightarrow f_3 = 40 \text{ kPa} \).
Figure 11. Design scheme of piles’ plate load test without anchors (a) and with anchors (b). P is pressure transmitted to plate load.

In this case bearing capacity of a pile without anchors for pressing in \((F_{d.w.a})\) equals as follows:

\[
F_{d.w.a} = 1(1 \cdot 2300 \cdot 0.31 + 1.98 \cdot 1 \cdot 2(23 + 35 + 40)) = 1100.73 \text{kN} \quad (7)
\]

In order to determine bearing capacity of a pile with one-level anchors for pressing in according to CS 24.1333.2011 titled “Pile foundations”, we should transform formula no. 7.8 of point 7.2.2 of this normative document taking into account presence of anchors. Then a formula of bearing capacity is represented in the following way:

\[
F_{d.a1} = y_p (y_{R,R} \cdot R \cdot A + y_{Ranch} \cdot A_{anch} + u \sum y_{R,f} \cdot f_i \cdot h_i) \quad (8)
\]

where \(F_{d.a1}\) is bearing capacity of a pile with one-level anchors according to calculations; \(y_p, y_{R,R}, R, A, u, y_{R,f}, f_i\) and \(h_i\) are the same parameters that are given in formula (5); \(R_{anch}\) is design resistance of soil under blades of first-level-anchors that is taken from Table 7.2 of CS 24.1333.2011 titled “Pile foundations” for fine sands of medium density. Anchors press soil only during rotation and following deeper immersion of a pile. Soil column which is pressed by anchors during its way across it is determined by anchor’s length (0.45 m) and the depth of deeper immersion (0.5 m). Using method of interpolation, soil resistance at initial state was determined approximately, which equals 1700 kPa. Resistance increases to 100 kPa for every meter of immersion. In this case design resistance of soil under anchor blades will be 1800 kPa; \(A_{anch}\) is the area of anchors. This equals as follows:

\[
A_{anch} = 3 \cdot (0.5 \cdot 0.45 \cdot 0.3) = 0.2025 \text{m}^2 \quad (9)
\]

Design scheme of this calculation is given in figure 11 (b).

Bearing capacity of a pile with one-level anchors for pressing in \((F_{d.a1})\) equals as follows:

\[
F_{d.a1} = 1(1 \cdot 2300 \cdot 0.31 + 1 \cdot 1800 \cdot 0.2025 + 1.98 \cdot 1 \cdot 2(23 + 35 + 40)) = 1465.58 \text{kN} \quad (10)
\]

In order to determine bearing capacity of a pile with two-level anchors for pressing in, we should reflect an increase in bearing capacity by operation of upper level of anchors in formula (8). These anchors are similar to lower level of anchors and press soil to the same depth, so its design parameters are equal respectively. Formula of bearing capacity is given by:

\[
F_{d.a2} = y_p (y_{R,R} \cdot R \cdot A + 2y_{R,R} \cdot R_{anch} \cdot A_{anch} + u \sum y_{R,f} \cdot f_i \cdot h_i) \quad (11)
\]
where \( F_{d.a2} \) is bearing capacity of a pile with two-level anchors according to calculations; \( \gamma_p \), \( \gamma_{R,R} \), \( R \), \( A \), \( u \), \( \gamma_{R,f} \), \( f_i \) and \( h_i \) are the same parameters that are given in formula (5); \( R_{anch} \) and \( A_{anch} \) are the same parameters that are given in formula (8).

Bearing capacity of a pile with two-level anchors for pressing in \( (F_{d,a2}) \) amounted to
\[
F_{d,a2} = 1(1 \cdot 2300 \cdot 0.31 + 2 \cdot 1 \cdot 1800 \cdot 0.2025 + 1.98 \cdot 1 \cdot 2(23 + 35 + 40) = 1830.08 \text{ kN}
\]

The results of bearing capacity determination of piles with anchors and without anchors for pressing in according to calculations and conducted plate load tests are presented in table 2.

**Table 2.** Bearing capacity of piles with anchors and without anchors for pressing in according to the results of calculations and plate load tests.

| Method of bearing capacity determination | Without anchors | With one-level anchors | With two-level anchors |
|-----------------------------------------|-----------------|-----------------------|-----------------------|
| According to calculation                | 1100.73         | 1465.58               | 1830.08               |
| According to experimental tests         | 1162.50         | 1395                  | 1860                  |
| Spread of results                       | 5.6\%           | 5.05\%                | 1.6\%                 |

We can conclude from the analysis of points presented above that values of piles’ bearing capacities obtained from experiments are comparable with the results of calculations, are adequate and can be accepted for the following investigation.

According to all conducted plate load tests, anchor piles showed an increase in bearing capacity for pressing in and a decrease in piles’ settlement.

Load by which a pile without anchors reaches to bearing capacity \( (P_{w,a}) \) to 125 kPa (see figure 7) for anchor pile \( (P_a) \) reaches up to 150 kPa. Anchors increase bearing capacity of a pile for pressing in to 20% respectively. In order to compare the differences in settlements, a load of 125 kPa was accepted. Settlement of a pile without anchors was 0.73 mm and settlement of a pile with anchors was 0.11 mm during such load, i.e. deformations decreased to 84%. The results are given in table 3.

**Table 3.** Bearing capacity and settlement of piles with one-level anchors and without anchors for pressing in obtained from the results of plate load tests.

| Controlled parameters | Type of pile | Improvement of controlled parameters of a pile with two-level anchors in regard to a pile without anchors |
|-----------------------|--------------|---------------------------------------------------------------------------------------------------|
| Pressure on plate load during which bearing capacity of a pile is being chosen (kPa) | Without anchors | With one-level anchors | 20% |
| Settlement during ultimate loading of a pile without anchors (125 kPa; mm) | 0.73 | 0.11 | 84% |

Tests of a pile with two-level rotary anchors in horizontal state (see figure 8) showed its high effectiveness. While carrying out experiment, load on plate load reached to maximum value of 500 kPa which can be transmitted to facility of plate load, however, deformations reached to 10.71 mm that is much less than maximum value of 21 mm. Due to the fact that data of value are beyond direct ratio on the graph “Pressure and Settlement” (figure 8), these were not taken into account.
Pressure on plate load during which a pile with two-level anchors has its bearing capacity for pression reaches to 200 kPa. This value is greater to 60% of similar parameter for a pile without anchors and is greater to 33% of similar parameter for a pile with one-level anchors. Settlement of a pile with two-level anchors with a load of 125 kPa estimated to 0.04 mm which is less to 40% than a settlement of a pile without anchors and is less to 63% than a pile with one-level anchors. The results are presented in table 4.

**Table 4.** Bearing capacity and settlement of piles with one-level, two-level anchors and without anchors for pressing in obtained from the results of plate load tests.

| Controlled parameters                                          | Type of pile                  | Improvement of controlled parameters of a pile with two-level anchors in regard to a pile |
|---------------------------------------------------------------|-------------------------------|--------------------------------------------------------------------------------------------|
| Pressure on plate load during which bearing capacity of a pile is being chosen (kPa) | Without anchors | With one-level anchors | With two-level anchors | Without anchors | With one-level anchors |
| Settlement during ultimate loading of a pile without anchors (125 kPa; mm) | 125 | 150 | 200 | 60% | 33% |
| Settlement during ultimate loading of a pile without anchors (125 kPa; mm) | 0.73 | 0.11 | 0.04 | 94% | 63% |

Practically, situations when anchors cannot reach horizontal placement during pile’s rotation can happen. Plate load tests of pile’s model with anchors with an angle of 45° (figure 9 and figure 10) were conducted for evaluation of a decrease in bearing capacity of a pile.

A curve “Pressure and Settlement” has definitely another form in comparison to a curve of standard pile or of a pile with horizontal anchors during testing a pile with one-level anchors with an angle of 45° (figure 9). This can be explained by the fact that anchors in this position transformed to directional ones by which a pile was immersed to soil deeper. Anchors cut through land and did not give additional area of bearing on soil. Settlement of a pile is being significantly increased while a load increases and values approximate to parameters of a pile without anchors but positive effect still be. Tests of a pile with two-level anchors with an angle of 45° (figure 10) showed similar result. In this case direct ratio of settlement changes from load is explicit only up to 100 kPa which is less than results in regard to tests of a pile without anchors. This suggests that full “opening” of anchors, i.e. its reaching to horizontal placement should be controlled during immersion of anchor piles to planned placement.

Plate load tests of piles’ models presuppose investigation of pile’s work only for pressing-in loads. In order to evaluate bearing capacity of piles for pulling out, we made a decision to calculate using formula no. 7.10 of point 7.2.5 of CS 24.13330.2011 titled “Pile foundations” which is acceptable for piles without anchors, is given by:

\[
F_{du.w.a.} = \gamma_p u \sum \gamma_{R.f} f_i \cdot h_i
\]  

(13)

where \(F_{du.w.a.}\) is bearing-capacity of a pile without anchors for pulling out; \(u, \gamma_{R.f}, f_i\) and \(h_i\) are the same parameters that are given in formula (5); \(\gamma_p\) is coefficient of pile’s working conditions in soil and \(\gamma_p = 0.8\) for piles immersed to 4 m and more.

Thus, bearing capacity of a pile without anchors for pulling out \((F_{du.w.a.})\) amounts to

\[
F_{du.w.a.} = 0.8 \cdot 1.98 \cdot 1 \cdot 2(23 + 35 + 40) = 310.18 \text{ kN}
\]  

(14)
In order to determine bearing capacity of a pile without anchors for pulling out according to CS 24.1330.2011 titled “Pile foundations”, we added to formula (13) summand which describes an increase in bearing capacity of a pile thanks to operation of anchors. Formula is as follows:

\[
F_{du,a1} = y_p(y_{R,R} \cdot R_{anch} \cdot A_{anch} + u \sum y_{R,f} \cdot f_i \cdot h_i)
\]  

(15)

where \(F_{du,a1}\) is bearing capacity of a pile with one-level anchors for pulling out; \(y_{R,R}, R_{anch}, A_{anch}\), \(u\), \(y_{R,f}, f_i\) and \(h_i\) are the same parameters that are given in formula (5); \(y_p\) is the same parameter that is given in formula (13).

Bearing capacity of a pile with one-level anchors \((F_{du,a1})\) is estimated as follows:

\[
F_{du,a1} = 0.8(1 \cdot 1800 \cdot 0.2025 + 1.98 \cdot 1 \cdot 2(23 + 35 + 40)) = 602.06 \text{ kN}
\]  

(16)

In order to determine bearing capacity of a pile with two-level anchors for pulling out, an increase in bearing capacity of a pile thanks to operation of anchors of upper level was reflected in formula (15). These anchors are similar to anchors of lower level and its calculation parameters are equal. Formula of bearing capacity is estimated as follows:

\[
F_{du,a2} = y_p(2 \cdot y_{R,R} \cdot R_{anch} \cdot A_{anch} + u \sum y_{R,f} \cdot f_i \cdot h_i)
\]  

(17)

where \(F_{du,a2}\) is bearing capacity of a pile with two-level anchors for pulling out; \(y_{R,R}, R_{anch}, A_{anch}\), \(u\), \(y_{R,f}, f_i\) and \(h_i\) are the same parameters that are given in formula (5); \(y_p\) is the same parameter that is given in formula (13).

Bearing capacity of a pile with two-level anchors \((F_{du,a2})\) is estimated as follows:

\[
F_{du,a2} = 0.8(2 \cdot 1 \cdot 1800 \cdot 0.2025 + 1.98 \cdot 1 \cdot 2(23 + 35 + 40)) = 893.66 \text{ kN}
\]  

(18)

Since results of determination of piles’ bearing capacity for pulling out obtained according to calculations and results of tests differ insignificantly and, consequently, calculations correspond to tests, we accepted the values of bearing capacity of piles for pressing in obtained earlier in experimental way for further analysis, and values of piles’ bearing capacity for pulling out were accepted according to results of calculations. Values of controlled parameters are given in table 5.

Table 5. Bearing capacity for pressing in and pulling out of piles with anchors and piles without anchors obtained from the results of calculations and plate load tests.

| Bearing capacity (kN) | Type of pile | An increase in bearing capacity in regard to a pile without anchors while using a pile with anchors |
|-----------------------|--------------|--------------------------------------------------------------------------------------------------|
|                        | Without anchors | With one-level anchors | With two-level anchors | In one level | In two levels |
| For pressing in        | 1162.5        | 1395                  | 1860                   | 20%          | 60%          |
| For pulling out        | 310.18        | 602.06                | 893.66                 | Doubled      | Tripled      |
| Decrease in bearing    | 73%           | 57%                   | 52%                    |              |              |
| capacity of piles      |              |                       |                        |              |              |
| during operation for   |              |                       |                        |              |              |
| pulling out in         |              |                       |                        |              |              |
| regard to operation    |              |                       |                        |              |              |
| for pressing in        |              |                       |                        |              |              |


The results of conducted plate load tests and results obtained on the base of calculations showed effectiveness of piles with rotary anchors of proposed design both during operation for pressing in and pulling out (much more effectively). These anchors are able to double bearing capacity of piles for pulling out which contributes to its relevance for using in foundations of buildings operating on variable loads, as well as in foundations of buildings placed at heaving soils.

3. Results and discussion.

Acceptance of plate load tests of piles’ models is confirmed by comparison of piles’ bearing capacity values according to calculations and results of experiments (table 2). Difference in values of bearing capacities is about 6%. Difference in measures can be explained by the following aspects.

Firstly, value of design resistance of soil accepted according to the results of tests can differ from real value within incremental step of load on plate load, i.e. 25 kPa.

Secondly, formula describing bearing capacity of anchor pile of similar type does not exist in CS 24.13330.2011 titled “Pile foundations”. Consequently, we added to formula no. 7.8. of point 7.2.2 of this normative document a summand which describes an increase in bearing capacity of a pile thanks to operation of anchors. Mathematical formula of second summand was composed by authors corresponding to first summand which determines bearing capacity of pile from the edge. Actual value of bearing capacity which is given to a pile by anchors can differ from calculated value respectively.

Thirdly, value of design resistance of soil under blades of anchors in formula (8) is determined by interpolation, thus it can differ a little from real value.

Rotary anchors contribute to improvement of controlled parameters of piles during operation for pressing in (table 3 and table 4). Bearing capacity of one-level and two-level anchor piles is 20% and 60% more than the same parameter of a pile without anchors respectively. As for deformation characteristics, they also improved. Settlement of a pile with one-level anchors is 84% less than the same parameter of a pile without anchors and this parameter reaches to 94% for two-level anchor pile.

Rotary anchors increase significantly bearing capacity of piles in the process of operation for pulling out (table 5). One-level anchors almost double this parameter and two-level anchors almost triple it. These results approve effectiveness of application of anchor piles for foundations at heaving soils, as well as for foundations of buildings operating on variable loads.

4. Conclusion

Rotary pile anchors showed its effectiveness according to the results of carrying out plate load tests and calculations. Metal anchor blades split soil in-situ, fix a pile in given position vertically, thus resistance of a pile to displacements from loads increases.

1. According to results of experiments, we defined the following: anchors placed at one level increase bearing capacity of a pile for pressing in up to 20% and decrease settlement up to 84% in comparison to a pile without anchors. An advantage in terms of bearing capacity amounts 94% during operation for pulling out.

2. Application of two-level anchors increases bearing capacity of a pile for pressing in up to 60% and decreases settlement up to 94%. Bearing capacity for pulling out triples regarding the same pile.

3. In case of not full “opening” of anchors, positive effect decreases significantly but controlled parameters still above the parameters of a pile without anchors.

It is evident that piles with rotary anchors show its effectiveness mostly while operating for pulling out by analyzing these parameters. This can be applied for foundations of buildings operating on variable loads, such as towers, masts, chimneys and power transmission line supports, as well as for foundations of buildings placed at heaving soils.
References

[1] Yang Y-S and Qiu L-Ch 2020 MPM simulation of uplift resistance of enlarged base piles in sand Soils and Foundations 60 5 1322–30
[2] Saravanan R, Arumairaj P D and Subramani T 2018 A study on behavior of vertical pile in sand under uplift load Geotechnical Engineering 49 3 67–72
[3] Dobrynin A O 2015 Improving the efficiency of pile foundations organized in heaving soils Online journal Science studies 7 6 (31) 143
[4] Zheng H, Kanie Sh, Niu F, Akagawa S and Li A 2016 Application of practical one-dimensional frost heave estimation method in two-dimensional situation Soils and Foundations 56 5 904–14
[5] Sviderskikh A V 2014 Investigation of different types of soil on frost heaving under optimal humidity conditions and its analysis Pedagogical education in Altai region 2 239–40
[6] Wang P and Zhou G 2018 Frost-heaving pressure in geotechnical engineering materials during freezing process International Journal of Mining Science and Technology 28 2 287–96
[7] Kazantseva P A, Sazonova S A and Ponomarev A B 2016 Laboratory research of influence of soil density on the degree of frost heave Geotechnics 4 4–9
[8] Zhitaol L, Caichu X and Qiag L 2018 Experimental and numerical study on frost heave of saturated rock under uniform freezing conditions. Journal of Geophysics and Engineering 15 2 593–612
[9] Sokolova O V and Sokolova V S 2017 On nature and main regularities of frost heaving development in macrofragmental soils Kulagin readings: techniques and technologies of production processes 111–14
[10] Feng M and Dong-qing L 2015 Experimental and Theoretical Investigations on Frost Heave in Porous Media Mathematical Problems in Engineering 2015 1–9
[11] Wen Zh, Qihao Y, Mingli Zh, Ke X, Liangzhi Ch and Desheng L 2016 Stress and deformation characteristics of transmission tower foundations in permafrost regions along the Qinghai–Tibet Power Transmission Line Cold Regions Science and Technology 121 214–25
[12] Marahtanov V P 2013 Pipelines pile foundation cryogenic deformations Pipeline transport: theory and practice 5 (39) 18–22
[13] Kostina O V and Bochkareva T M 2019 Analysis and classification of anchor fastening the foundations of trunk pipelines on loosened soils Master's Journal 2 119–26
[14] Eloev T V and Gudieva I N 2018 Deformations of buildings during frost heaving of soils Innovations in science and practice 93–6
[15] Kostina O V and Bochkareva T M 2020 Study of the efficiency of the pile with the anchor system when constructing the foundations of main pipelines on heaving soils Modern technologies in construction. Theory and practice 2 pp 369–34