Method justification for calculating the final setting of injection pile in clay soil

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Abstract. Method of final setting calculation for a single injection hanging pile 3 to 5 m length in clay soils is proposed. The method is based on the separate work of the lower end and the lateral surface of the injection pile; it takes into account the linear and non-linear dependencies of its setting from external load. The method takes into account the stages of the well formation by the injector pressing, its radial expansion during the concrete injection, and the physical and mechanical characteristics improvement of the soil around the injection pile barrel at its construction stage. The obtained results are considered as an approach to solving a complex task of estimating the deformations of individual and strip foundations after their strengthening with injection piles under buildings reconstruction. It can be used to predict the buildings foundations setting under new construction.

Introduction
Method of transferring a part of the loading from above-ground building structures to injection piles is one of the effective ways to strengthen the buildings and structures foundations in operation (refer with Figure 1). The installation of such piles is carried out by the injector pressing into the clay soil with subsequent pressure feed of 500 ... 900 kPa of the mobile concrete mix and pressing it (2003–2009, TSUAB, Tomsk) [1–3 and others]. During the radial expansion of the formed well, a careful control is exercised over the process of injecting a mobile concrete mix to eliminate the possibility of hydraulic fracturing of the soil mass around the pile (especially in weak clay soils).

The external loading \( N \) effecting on the pile is perceived by the surrounding mass through the soil resistance in the place of contact with the pile lateral surface and through the soil resistance \( R \) under its lower end (refer with Figure 1, \( e \)). This suggests that the interaction scheme between injection piles and base clay soil does not significantly differ from the hanging piles operation scheme that allows us to use known theoretical principles in the calculations. Injection piles interaction with clay soil data is considered as an approach to solving a complex problem of deformations estimating of individual and strip foundations after piles under building reconstruction strengthen them. The considered approach can also be used to calculate the pile foundations setting under new construction.

Based on the analysis of the previous studies results [4, 5, 6, etc.] and this article data [7], it was found that the “linear” dependences use \( S = f(N) \) in determining the single injection piles setting can lead to significant discrepancies with actually measured values. This is due to the injection piles work in clay soils that have the dependence \( S = f(N) \) is essentially nonlinear. Therefore, to calculate the
single injection pile setting, it is necessary to apply solutions reflecting the real (non-linear) nature of its work in clay soil.

Figure 1. Technological scheme of injection piles:

- **a** is a steel perforated injector pressing;
- **b** is a plugging of the injector annular space;
- **c** is the concrete injection into the well through the injector openings under the pressure \( p_i = 500 \ldots 900 \text{kPa} \);
- **d** is the pressure testing in 20-30 minutes after the concrete injection;
- **e** is the pressure testing in 20-30 minutes after the concrete injection;
- **f** is a general view of the injection pile after excavation (A. A. Petukhov and others research results [4]);
- 1 is a steel perforated injector;
- 2 is an axial cone with widening;
- 3 is a well wall;
- 4 is an upper “closing” ring;
- 5 is the cement-sand mortar plugging;
- 6 is an injection pile body;
- 7 is an injector pressing direction;
- 8 is the direction of the injector plugging annular space;
- 9 is a concrete injection direction into the well;
- 10 is a pressure testing;
- 11 is an air gap between the well wall and the injector;
- \( N \) is a vertical external loading on the injection pile;
- \( f \) is a calculated soil resistance along the lateral surface of the injection pile, kPa;
- \( R \) is a calculated soil resistance under the lower end of the injection pile.

**Problem formulation**

In accordance with the separate work of the lower end and the lateral surface of the hanging piles [4] in clay soil principle, we assume that at the first stage of the injection pile loading (before the load \( N_1 \)), the external load \( N \) is redistributed between its lateral surface and the lower end (refer with Figure 2, **a**). The first stage of injection pile loading is characterized by the setting linear increase \( S \) and ends with some setting value (shear setting \( S_1 \)), after which the lateral surface of the injection pile slips relative to the surrounding soil. External vertical load \( N_1 \) that corresponds to the linear dependence end on the settings graph \( S = f(N) \), is:
\[ N_1 = N_f + N_R \]  

(1)

where \( N_f \) is a part of the external load transmitted to the near-pile soil mass by the lateral surface of the injection pile, kN; \( N_R \) is the part of the external load transmitted to the base ground by the lower end of the pile at the linear dependence end stage \( S = f(N) \), kN.

With the external load increase \( N (N > N_f) \), the soil begins to slip (cut) along the lateral surface of the injection pile. From this point the second stage of the injection pile loading begins, where its lower end work in the ground is fully manifested (refer with Figure 2, b). In this case, the graph \( S = f(N) \) becomes non-linear. The second loading stage is completed when the load \( N_2 \) is reached that corresponds to the complete bearing pile capacity exhaustion for the ground and the unstabilized (failed) setting \( S_1 \). Thus, the load \( N_2 \) will be:

\[ N_2 = N_1 + (N_n - N_R) \],

(2)

where \( N_n \) is the part of the external load transmitted to the ground by the lower pile end and the corresponding loss of its bearing capacity along the ground, kN.

**Figure 2.** Injection pile setting dependence \( S \) from the external pressing load \( N \):

- \( a \) is the first stage of injection pile loading (linear setting growth);
- \( b \) is the second stage of injection pile loading (non-linear setting growth)

The final pile setting \( S \) for a given load \( N_1 \):

\[ S = S_1 + \Delta S, \]

(3)

where \( S_1 \) is the setting formed at the first (linear) loading stage, mm; \( \Delta S \) is the increments of settlement at the second (nonlinear) loading stage, mm.

**Research results**

Determine the injection pile setting \( S_1 \) at the first loading stage (with \( N_f = N_f + N_R \)). We use the M.F. Randolf et al. analytical method [8] for the hanging pile setting calculation that is in a linearly
deformable medium. Z. G. Ter-Martirosyan et al. [9] obtained similar solution, but taking into account the rheological properties of clay soils. The authors of this method (M.F. Randolf and others) believed that the pile loading was accompanied by the development of mainly shear deformations in the near-pile soil mass. The soil deformations around the pile were conditionally assumed to be concentric cylinders and shear acts on their faces. The proposed solution is based on the V.A. Barvashov’s opinion [5] that the vertical soil movements around the pile practically do not vary in depth, and fade away with the distance from the pile (“telescopic shift”).

Consider the M.F. Randolf et al. method application [8] on the calculation of the injection pile setting in the clay soil at the first stage of its loading. We believe that the setting $S_1$ occurs simultaneously from the $N_f$ load (due to the soil shear on the lateral surface of the injection pile - $S_f$) and partly from the $N_R$ load (due to the soil compaction under the lower pile end- $S_R$). In this case, on the basis of the pile continuity condition, the $S_f$ and $S_R$ settings are equal to each other. Given the above, the formula for the setting determination of the injection pile $S_1$ in clay soil at the first stage of its loading (the linear dependence end at the pile setting graph) takes the form:

$$S_1 = \frac{N_f}{2 \cdot \pi \cdot L \cdot G} \cdot \ln \left( \frac{r_m}{r_0} \right)$$

(4)

where $L$ is the injection pile length (injection site of fine concrete), m; $G$ is the initial shear modulus of the soil shear, kPa; $r_m$ is the horizontal distance from the vertical axis of the pile $z$ to the border, where the vertical soil displacements are zero (influence radius), m; $r_0$ is the injection pile radius, m.

According to [8], the vertical pile movement is formed due to the tangential stresses acting around its lateral surface limited by the distance $r_m$ (influence radius). According to the Z.G.Ter-Martirosyan et al. [9], A.I. Polishchuk, A.A. Petukhova et al. [3, 10, 11] study results, as well as the numerical modeling data of the screw injection pile in clay soils, performed by the authors of this article in 2012–2014, it is proposed to take no more than 3–5 diameters of the influence radius $r_m$ (6 ... 10 radii) pile:

$$r_m = 6...10 \cdot r_0.$$  

(5)

In this case, the $r_m$ smaller values are accepted for clay soils that are less durable (weak).

The load $N_f$ corresponding to the ultimate state onset of the soil at the site of its contact with the lateral surface of the injection pile is determined provided that $\tau_0 = \tau_{\text{max}}$:

$$N_f = 2 \cdot \pi \cdot r_0 \cdot L \cdot \tau_{\text{max}}.$$  

(6)

where $\tau_{\text{max}}$ is the maximum values of the tangential stresses in the place of contact of the drained clay soil with the lateral surface of the injection pile, determined from the Coulomb-Mohr strength condition (GOST 12248-2010).
Figure 3. The design injection piles model to determine the linear setting $S_1$ (first loading stage of)

The Coulomb-Mohr law application for the drained clay soil and determination the maximum tangential stresses $\tau_{\text{max}}$ is due to the fact that when injecting fine-grained concrete, pore water release takes place from the near-pile mass. This is confirmed by the full-scale tests of injection piles in weak, water-saturated soils (loamy sand), performed by A. A. Petukhov and others [10]. Within the zone of soil compaction around the pile (distance 0.5 m from the shaft), changes in humidity and density were observed 20–24 hours after its installation; humidity decreased 1.10–1.16 times, and density increased 1.04–1.08 times.

The clay soil around the injection pile shaft has a compacted state that was formed at the stage of its construction. Therefore, the Coulomb-Mohr strength condition to determine the maximum values of tangential stresses $\tau_{\text{max}}$ can be written in the form:

$$\tau_{\text{max}} = \sigma_{r_{\text{red}}} \cdot \tau g \varphi_{\text{dens}} + C_{\text{dens}} \quad (7)$$

where $\sigma_{r_{\text{red}}}$ - the normal radial reduction stress of an injection pile with clay soil, kPa; $C_{\text{dens}}$ and $\varphi_{\text{dens}}$ are the specific adhesion (kPa) and the angle of internal friction (hail) of the compacted base clay soil around the injection shaft pile respectively.

R.V. Shalginov et al. (2008–2010) were engaged in the problem of the parameter estimation $\sigma_{r_{\text{red}}}$ when developing a determination method of the injection piles carrying capacity. The authors of this article believe that the reduction stress appearance in the ground is due to the injection pressure $p_i = 500 ... 900$ kPa when the injection pile is erected. After the concrete injection completion the stress decreases for a certain period of time to values of approximately $\sigma_{r_{\text{red}}} = 50–100$ kPa [4]. Radial reduction stress $\sigma_{r_{\text{red}}}$ is proposed to be determined by the following formula:
\[ \sigma_{r}^{\text{red}} = \sigma_{\text{res}} + \sigma_{0} \]  

(8)

where is the soil residual stress; -is the horizontal stress due to the weight of the soil.

The residual stress \( \sigma_{\text{res}} \) is such soil stress that forms along the wall of the expandable well after the fine-grained concrete injection under the pressure \( p_0 = 500 \ldots 900 \text{ MPa} \) and its relaxation. The value \( \sigma_{\text{res}} \) in clay soils where the injection pile is arranged varies in the range of \( \sigma_{\text{res}} 25–60 \text{ kPa} \). The value \( \sigma_{\text{res}} \) is established experimentally [10]. In this case, smaller values are accepted for clay soils less durable.

The \( N_{R} \) load in condition (1) can be determined by the following formula for a hard round stamp [6]:

\[ S_{R} = \frac{N_{R} \cdot (1 - \mu)}{4 \cdot G \cdot r_{0}} \]  

(9)

from which:

\[ N_{R} = \frac{4 \cdot G \cdot r_{0} \cdot S_{R}}{(1 - \mu)} \]  

(10)

Thus, formulas (1) and (4) have been obtained for calculating the injection pile load \( N_{I} \) and setting \( S_{I} \) at the first stage of its loading.

To calculate the increments of settlement \( \Delta S \) [see formula (3)] from the load \( \Delta N \) (refer with Figure 2, b) we use the Malyshev – Nikitina method [12] to determine the of foundations setting on a natural basis in the nonlinear stage of the foundation soil operation. Taking into account the transformations made by F.A. Maximov when calculating the setting of a screw two-blade pile (2017) [13], we get:

\[ \Delta S = S_{1} \cdot \frac{\Delta N \cdot (N_{n} - N_{R}) - N_{R} \cdot (\Delta N - N_{R})}{N_{R} \cdot (N_{n} - \Delta N)} \]  

(11)

Final sediment \( S \) of the injection pile from the external load action \( N \) with regard to (3) will be:

\[ S = S_{1} + \Delta S = S_{1} + S_{1} \cdot \frac{\Delta N \cdot (N_{n} - N_{R}) - N_{R} \cdot (\Delta N - N_{R})}{N_{R} \cdot (N_{n} - \Delta N)} \]  

(12)

To assess the setting calculation results reliability according to the proposed method, they were compared with the results of injection piles field tests in clay soils [7, 10]. The comparison showed that in the range of the loads under consideration (100–180 kN) the calculated settings values are close to the experimental ones, the deviations in the considered sections are 20–30%.

Thus, the obtained equation (12) allows predicting the final injection piles settings \( S \) in clay soils. It takes into account the linear and non-linear dependencies of piles displacements (settings) from the applied external load \( N \) and allows evaluating their work in a wide loading range.

Summary

The method of final setting calculation for a single injection hanging pile 3 to 5 m length in clay soils was developed according to the experimental and theoretical studies results. The method is based on the separate work of the lower end and the lateral surface of the injection pile; it takes into account the linear and non-linear dependencies of its setting from external load, as well as changes peculiarities of the physical and mechanical characteristics of clay soils at the stage of its construction.

To assess the setting calculation results reliability according to the proposed method, they were compared with the results of injection piles field tests in clay soils. Settings comparison showed satisfactory data convergence of field piles tests and calculated by the proposed method.

References

[1] Polishchuk A I, Gerasimov O V, Petuhov A A, Andrienko Yu B, Nujkin S S 2004 The method of injection piles (Patent, 2238366).
[2] Tarasov A A 2015 Application of the static penetration test results to calculate the bearing capacity of injection piles in soft clay soils (Bulletin of Civil Engineers) 5 68-71.

[3] Polishchuk A I, Samarin D G, Filippovich A A 2013 Assessment of load capacity of piles in clay soil by means of the PLAXIS 3D Foundation (Journal of Construction and Architecture) 3 351-359.

[4] Dalmatov B I, Lapshin F K, Rossiihin Yu V 1975 Design of the pile foundations in the conditions of weak soil ( strojizdat, Leningrad).

[5] Barvashov V A 1968 Method of calculating the rigid pile grillage taking into account the mutual influence of the piles (Soil Mechanics and Foundation) 3 35-37.

[6] Baholdin B V, YAstrebov P I, Parfenov E A 2007 Peculiarities in settlement calculations for foundations formed from cast-in-place piles (Soil Mechanics and Foundation) 6 12-16.

[7] Polishchuk A I, Semenov I V 2018 Development of a method for calculating the precipitation of a single injection pile in clay soils (4th IV International Scientific Practical Youth Conference on Geotechnics, Tyumen) 67-69.

[8] Randolph M F and Wroth C P 1978 Analysis of vertical deformation of vertically loaded piles (Geotech Engineering) 104(12) 1465-1488.

[9] Ter-Martirosyan A Z, Ter-Martirosyan Z G, Trinh Tuan Viet, Luzin I N 2015 Settlement and bearing capacity of long pile (Scientific and Engineering Journal for Construction and Architecture) 4 52-60.

[10] Petuhov A A 2006 Improving the method of injection piles in weak clay soils for building renovation conditions (Ph.D. Synopsis of thesis, Tomsk).

[11] Shalginov R V 2010 Improving the method of calculating injection piles in clay soils for the foundations of reconstructed buildings (Ph.D. Synopsis of thesis, Tomsk).

[12] Malyshev M V, Nikitina N S 1982 Calculation of sediment foundations with a nonlinear relationship between stresses and strains in soils oil (Mechanics and Foundation) 2 21-24.

[13] Maksimov F A 2018 Improving the design and calculation methods of screw two-blade piles in clay soils (Ph.D. Synopsis of thesis, Volgograd).