Analysis of experience of using bored displacement piles in the conditions of heterogeneous weak water-saturated soils

Analyse de l'expérience d'utilisation de pieux à déplacement forés dans des conditions de sols hétérogènes faiblement saturés en eau

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ABSTRACT: The article presents the information on the screwed-in cast-in-place piles design and manufacturing process carried out in accordance with "Fundex" and "Atlas" technology. Their main advantages and disadvantages are analyzed and exemplified based on the long-term experience of using such piles in conditions of weak water-saturated soils in St. Petersburg, and a method for calculating their bearing capacity is given. The physical mechanism of defect formation in the displacement piles body based on field tests is presented and analyzed. The method of accounting and calculation of bearing capacity reduction of such piles in heterogeneous weak soils in case of their loading with static load has been developed. The influence of displacement piles on the stress-strain state of the subsoil in conditions of a real construction site is investigated. Recommendations are given on the safe execution of the cast-in-place displacement piles in dense urban development.

RÉSUMÉ: L'article présente les informations sur le processus de conception et de fabrication des pieux vissés coulés en place selon les technologies «Fundex» et «Atlas». Leurs principaux avantages et inconvénients sont analysés et illustrés sur la base de l'expérience à long terme de l'utilisation de tels pieux dans des conditions de sols faiblement saturés d'eau à Saint-Pétersbourg, et une méthode de calcul de leur capacité portante est donnée. Le mécanisme physique de formation de défauts dans le corps des pieux à déplacement basé sur des essais sur le terrain est présenté et analysé. La méthode de comptabilisation et de calcul de la réduction de la capacité portante de ces pieux dans des sols faibles hétérogènes en cas de chargement avec charge statique a été développée. L'influence des pieux à déplacement sur l'état de contrainte-déformation du sous-sol dans les conditions d'un chantier réel est étudiée. Des recommandations sont données sur l'exécution sûre des pieux de déplacement coulés sur place dans un développement urbain dense.

KEYWORDS: cast-in-place displacement piles; pile shaft defects; calculation methods; pile load-bearing capacity.

1 INTRODUCTION

The piles executed by forced displacement of soil of the Fundex, Vibrex and Atlas types belong to a wide class of bored piles and are widely used in Russia and abroad. Their obvious advantages include high productivity and economic efficiency, minimal impact on the neighboring buildings and the absence of dynamic impact during the works. The special features of these piles are as follows: 1) presence of a lost pile toe which dimensions exceed the casing diameter; 2) presence of a casing rib; 3) feeding the concrete mixture into the casing by free dumping. However, experience of Fundex type displacement piles application shows a number of features which are not considered by modern methods of calculation of their bearing capacity. Such features include: 1) overvaluation of the calculated bearing capacity; 2) presence of pile shaft defects.

2 FEATURES OF FORMATION OF A DISPLACEMENT PILE SHAFT OF FUNDEX TYPE

The concreting of the Fundex type displacement bored piles is carried out in stages and includes: 1) insertion of the reinforcement cage in the finished well, made by drilling a pipe with a lost toe tip; 2) batching of concrete mixture from the bucket into the mouth of the casing with simultaneous extraction. Such process of concreting the pile shaft in the soil is the most distinctive feature of its manufacture. While most of the bored piles are manufactured by feeding concrete mixture from the bottom to top under the influence of overpressure of 2 to 3 atm, the Fundex piles are concreted by free dropping the mixture from top to bottom.

At the same time, there is a high risk of segregation of the concrete mixture, which leads to uneven strength of the pile shaft along its length, and in certain soil conditions - to the appearance of defects in the pile shaft during the lifting of the casing and hardening of the concrete mixture (fig. 1 a).

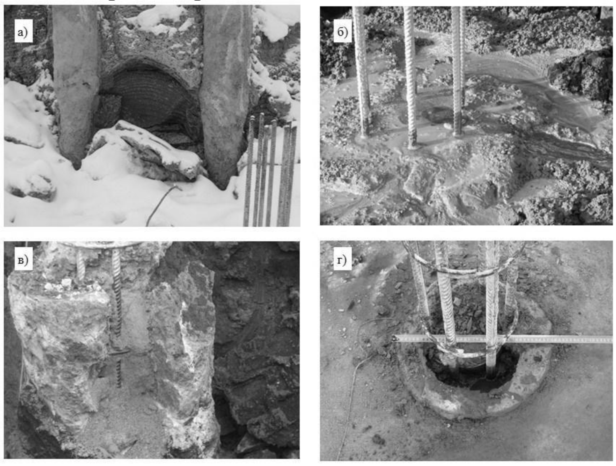


Figure 1. Field of piles with shaft defects at the top of the foundation soil

The analysis of Fundex type bored displacement piles manufacture process sequence and formation of its concrete body in the soil has allowed to prove the analytical calculation scheme of estimation of decrease in size of horizontal pressure on a lateral surface (fig. 2).

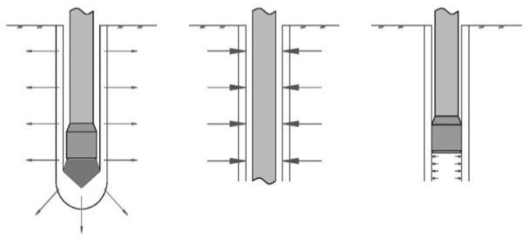
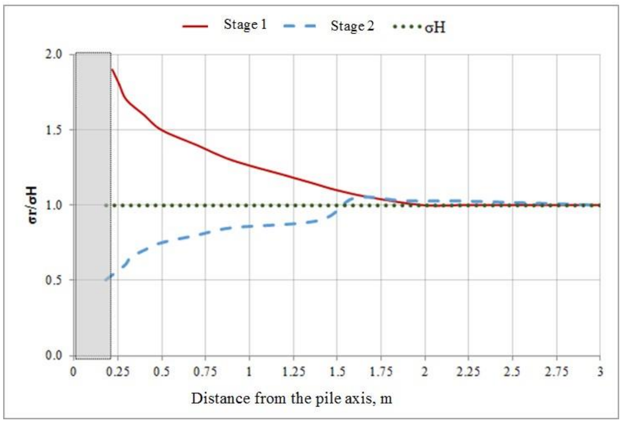


Figure 2. The main stages of pile arrangement with a lost tip: a) Displacement of the soil by a lost tip; b) Unloading the soil on the side surface - formation of a contact layer in the inventory casing area; c) Casing removal with simultaneous concrete feeding

3 ANALYTICAL EVALUATION OF THE FUNDEX PILES LOAD-BEARING CAPACITY

Assuming that the soil predominantly moves horizontally during the pile arrangement, let us consider the formation of the pile body as an expansion of the cavity with radius r_0 to radius R1. Then, at known values of displacement of the well walls u_1,



it is possible to determine the stress distribution near the pile array (fig.. 3).

Figure 3. Radial stresses in the soil mass as a result of the analytical solution at different stages of pile execution

To determine the degree of influence of an oversized tip, let us consider the stepwise insertion of the pile (fig.. 2 a, b). The value of the backward movement is u_2 = 50…100 mm, which corresponds to the difference between the oversized tip radius R_1 and the casing radius $R_2 << R_1$.

The displacement of the well wall was evaluated analytically in several steps, taking into account the increase of radial stresses at the boundary of the plastic zone. Stresses in the strengthening zone were determined by formula (1) taking into account boundary conditions $u_{(r=R_1)} = u_1$; $u_{(r=2Ra)} = 0$; The maximum value of radial stresses in the strengthening zone is limited to the value of the beginning of the plastic flow (Formula 2). The maximum radial stress in the soil was limited by the limiting load of the pile (probe) insertion and was calculated on the basis of Fedorovskiy V.G. solutions by formula (3).

$$\sigma_r(r) = \frac{E}{1-\mu^2}\frac{u_1 r_1}{r_1^2-r_2^2}\left[1+\mu+\frac{r_2^2}{r^2}(1-\mu)\right] \qquad (1)$$

$$\sigma_\rho \approx \frac{\sigma_H}{a}\cdot\left[1+\xi-\sqrt{(1+\xi)^2-2\cdot a\cdot(1-\xi)-2\cdot\xi\cdot a\cdot\frac{\sigma_u}{\sigma_H}}\right]+\sigma_H (2)$$

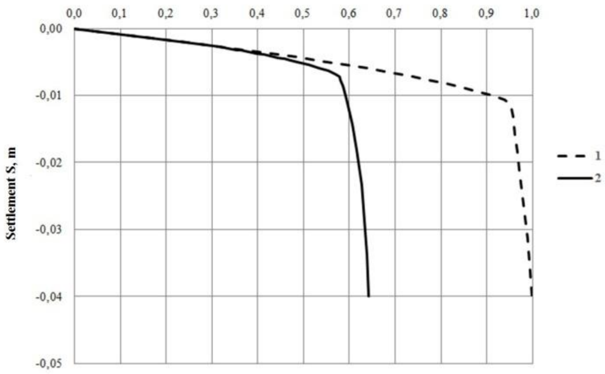
$$\sigma_{ult} = (\sigma_H + c\cdot\cot\varphi)\left[1{,}3\cdot\left(\frac{E}{(\sigma_H+c\cdot\cot\varphi)^2\cdot(1{,}15-0{,}5\mu)}\right)^{0{,}369\cdot\sin\varphi+0{,}03}\right] - c\cdot\cot\varphi \quad (3)$$

Since the movements of the well wall are known, to determine radial stresses σ_r, we use the formula of the theory of expanding cylinders taking into account the positions of Vesic A.S., Mecsi J.:

$$\sigma_r = \left(\sigma_{R_a} + \frac{c}{tan\varphi}\right)\cdot\left(\frac{R_a}{r}\right)^{\frac{2\cdot sin\varphi}{1+sin\varphi}} - \frac{c}{tan\varphi} \quad (4)$$

where σ_r- horizontal stress in the soil at a distance r from the well wall, kPa; σ_{R_a} - horizontal stress of the plastic zone beginning at the well wall, kPa; c - soil specific cohesion, kPa; φ - soil friction angle, degr.; R_a - active zone radius, m.

The calculation results show a significant reduction in horizontal stresses after the pile arrangement (fig.. 3). Thus, it can be assumed that when the pile is operated under load, the reduced radial stress of stage 2 will cause a reduction in friction on the side surface. The actual value of friction reduction mainly depends on the deformation modulus E, internal friction



angle φ, specific cohesion c, Poisson's ratio μ and natural stress σ_H.

Figure 4. Results of numerical simulation of bearing capacity on the side pile surface:1 - Prismatic indentation pile; 2 - Cast-in-place pile with lost tip

The reduction of friction on the side surface of the pile should be taken into account by introducing a reduction factor $k_т$ when assigning friction characteristics. Calculated factor $k_т$ values for sandy and clayey soils are in the range of 0.5 to 0.8 (table 1).

Table 1. Factor $k_т$ values

Name of soils	Factor $k_т$
Medium density sands	0.8
Clayey soils, I_L < 0.25	0.8
Clay soils, 0.25 < I_L < 0.75	0.6
Clayey soils, I_L > 0.75	0.5

Based on the results of the study, the reduction of the friction factor on the side surface of the pile is taken into account in the general formula for determining the load-bearing capacity of the Fundex pile, which is:

$$F_d = \gamma_c\,(\gamma_{cR}\cdot R\cdot A + u\cdot\sum\gamma_{cf}\cdot k_т\cdot f_i\cdot h_i) \quad (5)$$

where, γ_c - the factor of pile conditions in the soil; R - the design resistance of the soil under the lower end of the pile; A - the area of the pile bearing on the soil; u - outer perimeter of the pile cross section; fi - design resistance on the pile side; hi - the thickness of the soil contacting the side surface of the pile; γ_{cR},γ_{cf} - the factors of soil conditions under the lower end and on the side surface of the pile, respectively; $k_т$ - the reduction factor

At the calculated analysis of bearing capacity of 72 piles by formula (5) satisfactory convergence with the results of field tests was obtained. A histogram of ratio of the calculated bearing capacity distribution and test results is shown in Figure 5.

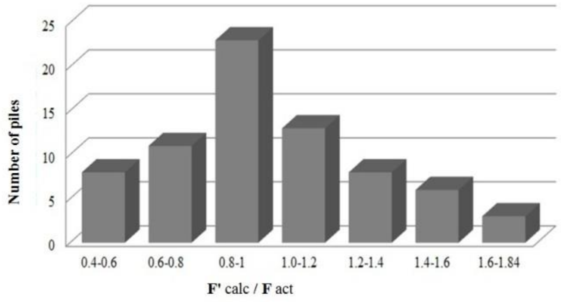


Figure 5. Distribution of the ratio of the calculated, taking into account the reduction factor on the side surface, and the actual bearing capacity

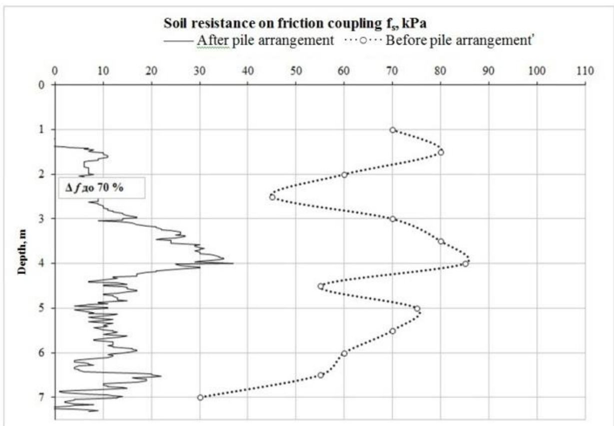
It follows from Figure 5 that the average value of the distribution of the ratio of expected and actual value taking into account the proposed coefficient k_T is 1.0, while without it, the average value of the expected to actual value ratio is 0.6.

3 EXPERIMENTAL EVALUATION OF THE STRESS-STRAIN STATE OF THE SOIL NEAR THE PILE SPACE

Surveys of the soil mass in the pile arrangement area with length L = 31 m and diameter d = 0.5 m were performed by the method of static sounding at a distance of one diameter from the face of the pile using a probe of CPTu type.

The result of field studies evidences that the largest changes in strength and deformation properties of the soil occur at a distance of one to three pile diameters, which is consistent with the results of analytical calculations to determine the active zone R_a. The most sensitive parameter in the process of probing a near-surface array was the value of f - specific friction on the probe coupling associated with soil consistency I_L.

Apart from that, the results of field studies of the stress-strain state of soils showed a significant reduction in soil resistance on the side surface after the bored displacement piles arrangement, which is consistent with the results of the analytical solution and numerical simulation. Figure 6 shows a comparison of the probing results after the bored displacement piles arrangement with the probing results of soils in natural



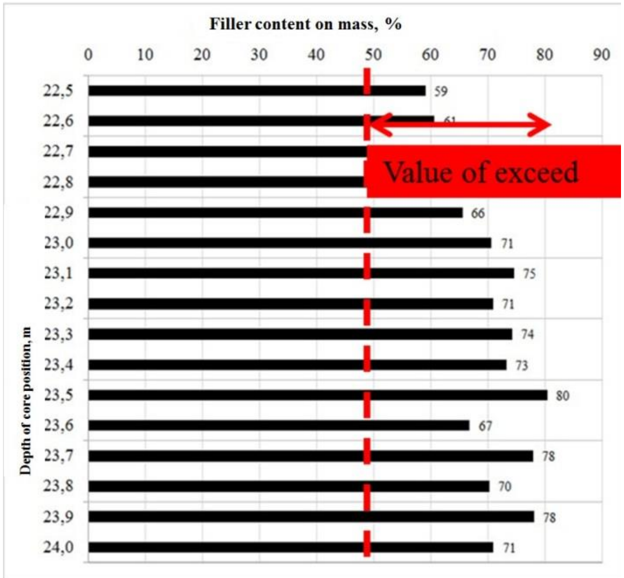
state.

Figure 6. Results of soil probing before and after pile making, Δf - soil resistance decrease after pile making

4 ANALYSIS OF THE CONCRETE PILE SHAFT FORMATION OF THE FUNDEX TYPE SEAL

As per Russian Technical Code (SP 24.133300. 2016), it is accepted that the bearing capacity of a pile on a material should be not lower than the value of bearing capacity of a pile on a soil and have one and a half marginal load capacity on a pile. Closer attention should be paid to the strength of the concrete in the area of pile head coupling and rostering, where the greatest transverse forces and moments will take place.

To this end, field tests were carried out to determine the height strength of the pile body concrete by selecting cores from the excavated pile (fig. 7). The bored displacement pile was made by dropping the concrete mixture from the height H



= 24 m.

Figure 7. Distribution of the filler material by height in field studies

In the fracture test of the selected samples along the length of the pile, it was noted that the concrete class at the top of the pile was lower than expected, and there was determined the actual density of concrete in compression along the height of the shaft. The upper part of the pile was of concrete class B7.5, and the lower part of the pile was of concrete class B22.7. It is noted that the lower part is characterized by 30% excess of the expected value of the crushed stone fraction content (diameter d > 5 mm).

This allows to suggest that concreting by the method of free dropping has a negative influence on uniformity of concrete properties on height of the pile executed on Fundex process. Defect in pile diameter reduction (formation of necks, see fig. 1 a) should also be associated with the peculiarities of batch concreting (1.5 m3 each) by dropping concrete mixture with simultaneous lifting of the casing. The casing diameter is almost half the diameter of the executed well (fig. 1 b), therefore, when extracting the casing, the concrete mixture hydrostatic pressure continuously drops (fig. 8). In the presence of weak clay soils, a defect should be expected in the section of geotechnical layers "dense sands - weak clay soils" in which there is a sharp increase in the rate of casing lifting.

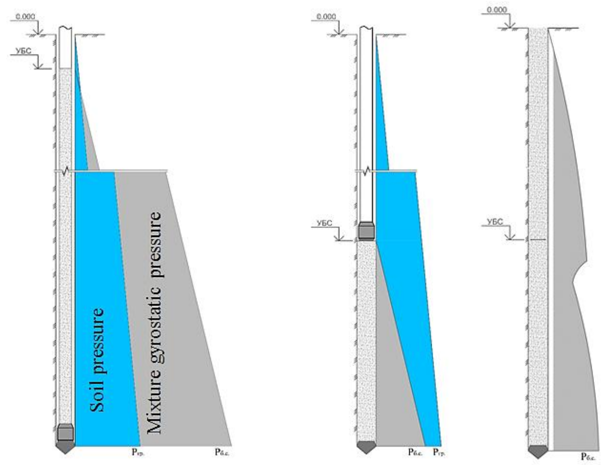
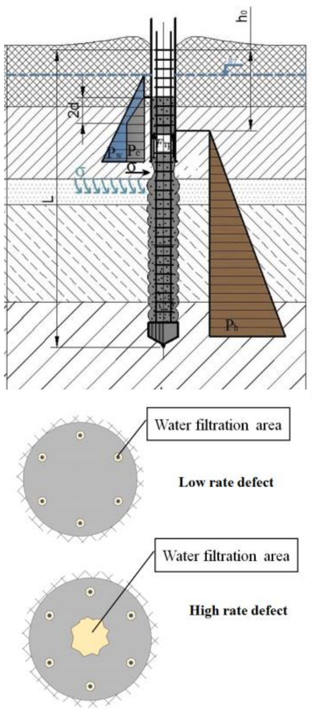


Figure 8. Effect of concreting sequence on actual pile diameter

Ground water filtration through the displacement pile body with a lost oversized tip is caused by two factors. Firstly, by the presence of pressure soil horizons, and secondly, by a sharp increase in pore pressure at the adjacent pile insertion. In this case, the filtration mechanism and violation of concrete curing conditions are the same - when removing the casing, the ground water pressure is discharged along the path of the least resistance, i.e. through the pile body. At low intensity of water filtration through the concrete mixture, the water flow is realized mainly along the reinforcement - in the contact zone "reinforcement - concrete mixture" (fig. 9).



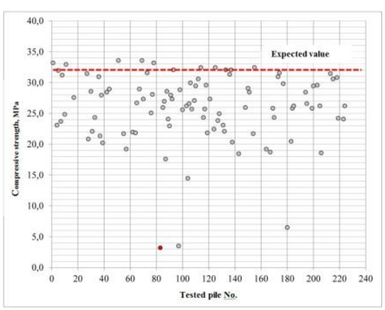


Figure 9. Effect of water filtration through the pile shaft on material integrity

A defective contact zone is formed due to an impaired adhesion of the concrete mixture with the metal of the reinforcing frame. Additional factors of the Fundex pile shaft concrete integrity disturbance include the occurrence of tubules, washout zones and large cavities in them (fig. 1 g). Curing conditions and ground water filtration on reinforcement, with a low water permeability class of concrete, can lead to cavities in the concrete.

5 CONCLUSIONS

The arrangement of Fundex piles is characterized by a number of process and structural features, which, in some cases, lead to a significant reduction in load-bearing capacity and heterogeneous strength of concrete in terms of pile shaft height. An analysis of 380 piles shows a significant discrepancy between the expected and actual bearing capacity of a Fundex type displacement pile on the soil. The results of pile material testing on 253 piles manufactured show that the strength of the material is reduced within a wide range.

For an accurate forecast of the bearing capacity of this type of piles, a model for changing the stress-strain state of soils is proposed. This model takes into account the stage of pile production and determines the input of a reduction factor kf when calculating soil friction on the pile side surface.

Laboratory and field studies allowed classifying defects and determining the reasons for their appearance. The main cause of defects should be considered the concreting method - free drop. This method reduces the strength of concrete by 30-50% in favorable soil conditions. The heaviest destruction of the pile material will be in case of realization of ground water filtration flow through the pile body. This leads to chemical corrosion of the binder concrete mixture. In this case, the strength will be reduced by 70 to 80%. To prevent risks of deformation of buildings on these piles, there were given recommendations on restriction of area of application of these piles - to use only in low-rise building, for temporary buildings and structures. Methods have also been developed to survey the buildings constructed. To reduce the risks of the above mentioned defects formation, it is necessary to carry out concreting by means of a vertically rising pipe, reduce the mobility of the concrete mixture and use specially developed formulations with increased waterproofing of concrete.

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