Calculation of widened pile settlement with regard to nonlinearity

V S Glukhov¹ and M V Glukhova¹,²
Geotechnics Department, Penza State University of Architecture and Civil Engineering, 28 German Titov Street, Penza, 440028, Russia

²glukhova.mary@mail.ru

Abstract. The authors propose a new approach to the settlement calculation of a single widened pile in a punched hole beyond the linear dependence between stresses and deformations in soil.

1. Introduction
In most cases it is required to determine pile foundation settlement when arranging piles in groups or as a solid pile field. The estimated settlement of a single driven pile is usually several times less than the allowable settlement of buildings and constructions [1].

Settlements of single drilled and bored piles are insignificant due to the relatively small area of the lower end of the piles and pressure on soil base [2].

The problem of reliable settlement determination is very relevant for widened piles in punched holes (PPH), which are arranged using the technology of tamping crushed rock into the well bottom [3].

2. Relevance and novelty
PPH piles are characterized by a cross-section area of the widening by 3.0–4.0 times in comparison with the pile shaft cross-section area. The pressure on foundation soil under the widening is 1500.0 ÷ 3000.0 kPa.

The significant area of the widening base and the pressure under the base cause large settlements of the considered single pile in comparison with the piles mentioned above [4].

Currently used methods for the design settlement calculation significantly underestimate its value [5]. This can potentially cause unallowable irregular deformations of buildings.

The applied settlement calculation schemes consider the soil base in the form of a linearly deformable half-space [6]. The definite requirement of these schemes is the fulfillment of the condition that the pressure under the foundation base should not exceed the design soil resistance. In the case of PPH this condition is practically not met because, when calculating pile bearing capacity, the design resistance under widening is taken as the resistance for driven piles according to the Table in CR 24.13330.2011 "Pile foundations”. According to the Table the stated resistance depends on the liquidity index of silty soils or the sand size but not on the soil base strength characteristics [7].

Ultimately, calculations show that condition \( R_\text{c} < P < \frac{P \cdot Y_\text{c}}{Y_n} \) is used for a more reliable settlement determination of widened piles in punched holes [8]. Where \( P \) is the pressure under the widening.
bottom, taken with account of design loads having overload coefficients equal to unity. The estimated resistance $R_c$ of the compacted base under the widening should be determined with the account of improved soil characteristics due to compaction (figure 1). The ultimate resistance of the compacted soil $P_u$, and the reliability factors $\gamma_c$ and $\gamma_n$ are taken in CR 22.13330.2016 "Foundations of Buildings and Constructions".

The authors consider V.M. Malyshev's method to be the most reliable for taking into account the nonlinear work of the foundation soil. This method is based on well-known formula (68) [9] for calculating the nonlinearity coefficient.

Given that the limit equilibrium zones (plastic zones) under condition $P = P_u$ progress to a depth of no more than $h_p < D_w$, the settlement with nonlinearity is proposed to determine from formula

$$S = S_p K_n + S_a,$$  \hspace{1cm} (1)

where $S_p$ is design settlement resulted from pressure $P = R_w$ within the plastic zones [10]; $K_n$ is nonlinearity coefficient calculated by formula (68) [9]; $S_a$ is settlement resulted from pressure $P = R_w$ and calculated as the deformation of the compression layers active zone with thickness $h_a$ (figure 2).

![Figure 1](image1.png)  \hspace{1cm} ![Figure 2](image2.png)

**Figure 1.** Calculation scheme for determining the PPH bearing capacity: 1 is the border of the compaction soil zone.

**Figure 2.** Calculation scheme for determining PPH settlement: 1 is the border of the compaction soil zone.

The calculation is recommended to reduce to the determination of the nonlinearity coefficient with a successive approximation to the fulfillment of condition $S \leq S_u$, where $S_u$ is the ultimately allowable settlement recommended by design engineers for a particular facility.
3. Calculation method
As an example, the calculations stated above were performed for a widened pile in a punched hole in typical soil conditions: a PPH 5-60 pile with a length of 5.0 m, a hole diameter of $d = 0.6$ m and the diameter of the widening equal to $D_w = 1.2$ m (figure 1).

3.1. Calculation of pile bearing capacity according to CR 24.13330.2011
Pile bearing capacity is determined by formula:

$$F_d = \gamma_c (\gamma_{cr} R_w A_w + \sum \gamma_{cfr} f_i h_i),$$

(2)

where all symbols correspond to formula (7.8) in CR 24.13330.2011 and are taken as follows $\gamma_c = 1.0$; $R_w = 2050.0$ kPa; $A_w = 1.12$ m$^2$; $U = 1.9$ m; $f_1 = 12.0$ kPa; $f_2 = 28.0$ kPa; $h_1 = 4.0$ m; $h_2 = 1.0$ m.

Then the compacted soil bearing capacity beneath the widening is equal to

$$F_w = \gamma_c \gamma_{cr} R_w A_w = 1.0 \times 1.0 \times 2050.0 \times 1.12 = 2296.0 \text{ kN}.$$ 

The pile bearing capacity along the side faces is

$$F_s = \gamma_c U \sum f_i h_i = 1.9 \times 1.0 (12.0 \times 4.0 + 28.0 \times 1.0) = 144.0 \text{ kN}.$$ 

Then $F_d = 2296 + 144 = 2440$ kN. The allowable design load on the compacted soil base under the widening is

$$N_{\text{ul}} = \frac{F_d}{\gamma_0} = \frac{2440.0}{1.4} = 1743.0 \text{ kN}.$$ 

(3)

The calculated load on a pile in the project should be taken from the condition

$$N_i \leq N_{\text{ul}}$$

(4)

In the example we accept $N_i = 1740.0$ kN. The load share $N_{\text{ul}}$ on the soil base under the widening is

$$N_{\text{ul}} = 2296.0 / 1.4 = 1640.0 \text{ kN}.$$ 

When calculating soil base deformations, the pressure under the foundation bed is determined taking into account the design loads $N_i$ with overload factors equal to 1.0. In the example we accept $N_i = N_{\text{ul}} / 1.15 = 1640.0 / 1.15 = 1426.0$ kN.

3.2. Calculation of pile deformations according to CR 22.13330.2016
To estimate the stress-strain state of the compacted soil under the widening, it is necessary to determine the design soil resistance using well-known formula (5.5) from CR 22.13330.2016:

$$R_c = \frac{\gamma_{cfr} \gamma_{cfr} k}{k} \left[ M_c k z D_w y_{\text{II}} + M_d q_{\text{II}} + M_c c_{\text{II}} \right],$$

(5)

where all symbols correspond to the formula and are taken with the account of soil compaction: when $\varphi_{\text{lc}} = 18.0^\circ$; $M_r = 0.43$; $M_q = 2.73$; $M_z = 5.30$; $c_{\text{II}} = 22.5$ kPa; $\gamma_{\text{lc}} = 19.5$ kN / m$^3$; $\gamma_{\text{II}} = 19.0$ kN / m$^3$; $\gamma_{c1} = 1.2$; $\gamma_{c2} = 1.1$; $D_w = 1.2$ m; $k = 1.0$; $k_z = 1.0$.

Then $R_c = 512.0$ kPa.

The pressure under the widening is

$$P = \frac{1426.0 + 1.12 \times 5 \times 20}{1.12} = 1270.0 \text{ kPa}.$$ 

The pressure is significantly higher than the above given design resistance of the compacted soil base $R_c = 512.0$ kPa.

3.2.1. Determination of the limit soil resistance
The ultimate soil resistance under the base of the widening $P_u$ is determined by formula (5.32) in CR 22.13330.2016. In the example we accept the following parameters $N_r = 2.50$; $N_q = 5.20$; $N_z = 13.10$; $\gamma_1 = 19.5$ kN / m$^3$; $\gamma_2 = 19.0$ kN / m$^3$; $c_1 = 22.5$ kPa; $d = 5.0$ m; $\xi_1 = 0.75$; $\xi_2 = 2.5$; $\xi_3 = 1.3$.

Then $P_u = 2.5 \times 0.75 \times 1.12 \times 19.5 + 2.5 \times 2.5 \times 19.0 \times 5.0 + \times 13.1 \times 1.3 \times 22.5 = 40.1 + 1235 + 383.2 = 1658.3 \text{ kPa}.$
3.2.2. Calculation of pile settlement with regard to nonlinearity

Under condition $R_c < P = 1270.0 < P_u$, the PPH settlement is calculated taking into account the nonlinearity. The nonlinearity coefficient is found from the modified Malyshev’s formula (68) [9]:

$$K_n = 1 + \frac{(P_u - R_c)(P - R_c)}{(P - \sigma_{zg,0})(P_u - P)},$$

where $\sigma_{zg,0} = 5.6 \times 19.0 = 106.0$ kPa.

Then

$$K_n = 1 + \frac{(1658.3 - 512.0)(1270.0 - 512.0)}{(1270.0 - 106.0)(1658.3 - 1270.0)} = 1.9.$$

The PPH settlement is calculated by the traditional scheme (figure 2).

The deformation modulus is taken equal to $E_c = 20.0$ MPa [11] within the compaction zone. The total settlement is calculated by formula (1), according to which the settlement within the plastic zones $S_p$ resulted from pressure $P = R_c$ is determined for a compressible soil layer with a thickness of $h_p = D_w$ using the formula of layer-by-layer summation:

$$S_p = \beta \sum \frac{\sigma_i h_i}{E_{ci}}.$$  (7)

4. Results

The deformation of compacted soil layers resulted from pressure $P = R_c$ within the plastic zone with thickness $h_p$ is equal to $S_p = 3.8$ cm. With the regard to coefficient $K_n = 1.9$ the total deformation of these layers is $S_p K_n = 7.2$ cm.

The layers deformation with the total thickness $h_a$ in the traditional linear problem formulation is $S_a = 2.6$ cm. Thus, the total PPH settlement is $S = 9.8$ cm. The design PPH settlement without taking into account plastic zones is 6.4 cm, i.e. it is less reliable and 1.53 times less than the one with nonlinearity.

5. Conclusion

Some experts have an opinion that an excess of allowable foundation settlement is not so much dangerous. The more important is the avoidance of significant settlement differences during the building operation. In most cases, non-uniform base deformations are the definite reasons for the construction emergency conditions. Therefore, the prediction accuracy of foundation settlement at the design stage is the key to the structures and buildings reliable work, as a whole.

References

[1] Melnikov V A, Alekseev N S, Ionov K I 2015 A comparative analysis of methodologies for calculating precipitation pile foundations Modern sci. res. and innov. 9–1(53) 37–45
[2] Konyushkov V V and Le V T 2020 Side friction of sandy and clay soils and their resistance under the toe of deep bored piles Arch. and Eng. 5 1 36–44.
[3] Krutov V I, Kogai V K and Glukhov V S 2010 Foundations formed from piles cast in punched holes Soil Mech. and Found. Eng. 47 2 45–51
[4] Glukhov V S, Hryanina O V and Glukhova M V 2011 The study of the effect of widening of piles in punched holes on the settlement Pros. of S-Western State Univer. 5–2(38) 351a–54
[5] Konyushkov V V 2020 Analysis of methods for analytical calculation of foundation settlement in time Bul. of Civil Eng. 4(81) 106–14
[6] Egorov K E 1949 Methods for calculating the final sediment of foundations Col. of works of the Sci. Res. Inst. of Base and Found. "Phys. and Soils Mech." 13
[7] Glukhov V S and Glukhova M V 2019 Considering the non-linear soil deformation in the settlement of pile in punched holes with broadening House. and Commun. Infr. 4(11) 45–52
[8] Glukhov VS and Glukhova M V 2019 Efficient use of sand cushions Proc. in Earth and Geosci. vol 2 Geotech. fund. and app. in constr. 74–6
[9] Malyshev M V 1994 *Strength of Soils and Bed Stability of Structures* (Moscow: Stroiizdat)
[10] Pilyagin A V 1996 Deformation-based bed design using linear and nonlinear methods *Soil Mech. and Found. Eng.* **33** 1 12–5
[11] Abelev M Y, Romanov N V and Kopteva O V 2018 Soil densification with dynamic compaction *Ind. and civil eng.* **4** 16–21